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Middle Atlantic Outer Continental Shelf Environmental Studies Volume 1: Executive Summary

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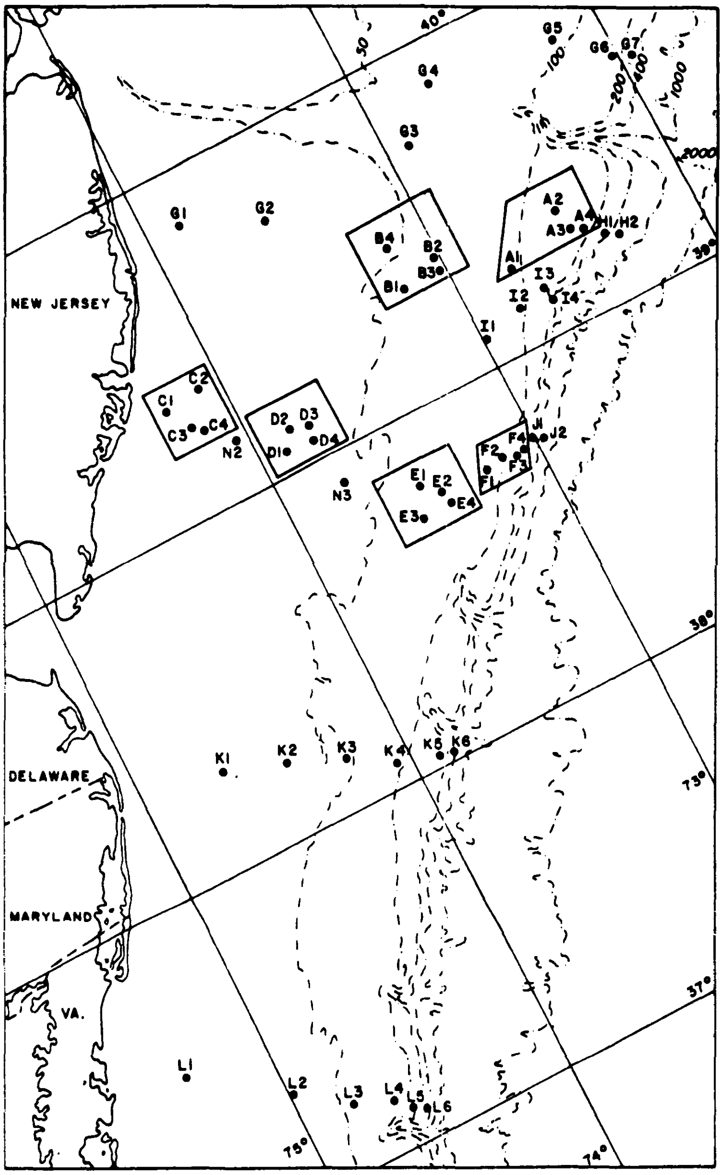
MIDDLE ATLANTIC OUTER CONTINENTAL SHELF ENVIRONMENTAL STUDIES

VOLUME I. EXECUTIVE SUMMARY



CHEMICAL AND BIOLOGICAL BENCHMARK STUDIES

Conducted by the

Virginia Institute of Marine Science
Under Contract No. AA550-CT6-62

and

GEOLOGIC STUDIES

Conducted by the

U.S. Geological Survey
Under Memorandum of Understanding
No. AA550-MU7-31

With the

Bureau of Land Management
United States Department of Interior

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Summary and synthesis of chemical, physical, geological and biological OCS benchmark studies conducted in the Middle Atlantic Bight. Included are field and laboratory methods, significant findings, cross shelf patterns in the pelagic and benthic realms and patterns related to local ridge and swale topography. Importance of swales as sites of deposition is stressed.

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Gloucester Point, Virginia 23062

July 1979

Special Report in Applied Marine Science
and Ocean Engineering No. 204

This report has been reviewed by the Bureau of Land Management and approved for publication. The opinions expressed in this report are those of the authors and not necessarily those of the Bureau of Land Management, U. S. Geological Survey, U. S. Department of Interior, the Virginia Institute of Marine Science, or the Commonwealth of Virginia.

PREFACE

The final report on contract AA550-CT6-62 between the Bureau of Land Management and the Virginia Institute of Marine Science consists of the following:

Volume I. Executive Summary.

This volume contains the Executive Summaries of the work conducted by VIMS under contract AA550-CT6-62 and the U. S. Geological Survey under Memorandum of Understanding AA550-MU7-31.

Volume IIA, IIB, IIC and IID. Chemical and Biological Benchmark Studies.

This volume contains the individual program element reports for the work completed by VIMS during the second year of the Chemical-Biological Benchmark Studies in the Middle Atlantic outer continental shelf region. Microfiche appendices containing field, laboratory, and data processing forms are included at the end of Volume IID.

Volume III. Geologic Studies.

This volume contains the individual program element reports for the work completed by USGS during the second year of the Geologic Studies in the Middle Atlantic outer continental shelf region. Microfiche appendices are included.

In addition to the printed and microfiched material, the final report also includes a complete, documented set of the environmental data generated by VIMS which has been deposited with the Environmental Data Service, National Oceanic and Atmospheric Administration, U. S. Department of Commerce, Washington, D. C. 20235. Data documentation has also been provided to BLM.

Copies of computer programs developed by VIMS during this study have been deposited with BLM as has a microfiched set of the raw data. Anyone desiring access to the computer programs, data documentation, or raw data can contact:

Environmental Studies Field Coordinator
Bureau of Land Management
New York Outer Continental Shelf Office
26 Federal Plaza, Suite 32-120
New York, New York 10007

Eugene M. Burreson
Program Manager

ACKNOWLEDGEMENTS

This report is the result of the cooperative efforts of the principal investigators of the various program elements and the program management staff, primarily the Reports Coordination personnel. Dr. Donald F. Boesch developed the synthesis format for the 1975-1976 Final Report and is largely responsible for that section in this report, as well as the section concerning Implications for Resource Managers. His thorough understanding of shelf processes was a source of knowledge for everyone involved with the study. Beverly Laird coordinated the preparation of the entire report and without her editing expertise, organizational abilities, patience, and attention to even the most minute detail, it could not have been completed. Dr. Maurice P. Lynch offered valuable advice during this program and I am especially grateful for his assistance. This report was produced by the VIMS Report Center. Special thanks are due word processing supervisor Cheryl Ripley and operators Annette Stubbs, Patty Alderman, and Ruth Edwards for typing and proofreading the entire report.

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[1] Detailed Tables of Contents are provided with each volume.

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[1] Appendices are provided on microfiche at the end of Volume IID.
[2] Appendices are provided on microfiche at the end of Volume III.

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CHEMICAL AND BIOLOGICAL BENCHMARK STUDIES EXECUTIVE SUMMARY REPORT

E. M. Burreson

INTRODUCTION

Purpose and Scope of the Study

Increasing demand for petroleum and natural gas in the United States has led to a need for development of reliable new domestic sources. The Outer Continental Shelf of the United States holds great interest among the oil companies for possible exploration and development of oil and gas resources to meet this need. This interest was demonstrated for the Middle Atlantic Outer Continental Shelf in the oil companies' response to the lease sale conducted in August 1976. Of the 154 tracts comprising 876,750 acres offered for lease in August 1975 for exploratory drilling in the Baltimore Canyon Trough (Figure 1), oil companies purchased drilling rights to 101 tracts comprising 575,011 acres. The Bureau of Land Management Environmental Studies Program was established to provide information needed for prediction, assessment, and management of impacts on the human marine and coastal environments of the Outer Continental Shelf and the nearshore area which may be affected by these drilling activities. The studies are designed to:

1. "Provide information on the status of the environment upon which the prediction of the impacts of Outer Continental Shelf oil and gas development for leasing decisionmaking may be based,

2. provide information on the ways and extent that Outer Continental Shelf development can potentially impact the human, marine, biological, and coastal areas,

3. ensure that information already available or being collected under the program is in a form that can be used in the decisionmaking process associated with a specific leasing action or with the longer term Outer Continental Shelf minerals management responsibilities, and

4. provide a basis for future monitoring of Outer Continental Shelf operations."

The Virginia Institute of Marine Science began Bureau of Land Management supported research on the Middle Atlantic Outer Continental Shelf in October 1975. The principal objectives of the first year studies were to provide chemical and biological data on conditions existing prior to oil and gas development, and on processes regulating biological community structure or levels of chemical constituents in

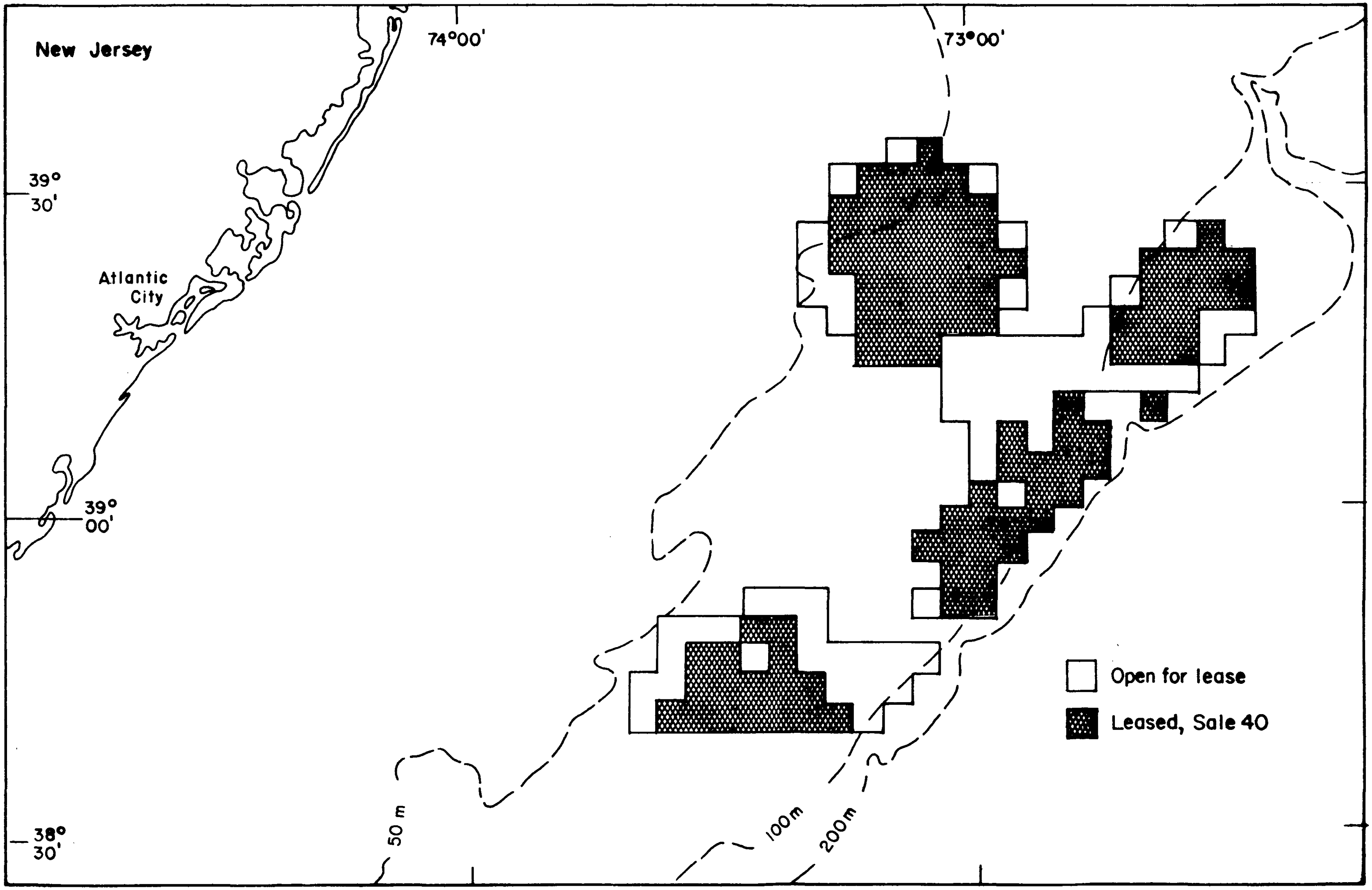

Figure 1. Middle Atlantic OCS lease tract area, Sale 40.

the shelf environment. For environmental impact assessment it is insufficient to know only the organisms or chemical constituents present and their spatial and temporal distribution. An understanding of controlling mechanisms or processes is imperative before causality of future change can be determined with any degree of certainty.

During the initial sampling year (October 1975 through September 1976, Contract No. 08550-CT5-42) specific goals of the Middle Atlantic chemical and biological benchmark studies were as follows:

1. summarization of shelf hydrographic and meteorological characteristiscs such as temperature, salinity, dissolved oxygen, and micronutrients during the four sampling seasons with particular emphasis on frontal systems and water mass identification;

2. characterization of the water column in terms of zooplankton, neuston, bacteria, particulate trace metals, and dissolved and particulate hydrocarbons as related to each other and temporal (seasonal and/or diurnal), spatial (geographic), and hydrographic variability as determined during the study;

3. characterization of the dominant infauna and epifauna in the macro- and mega- faunal ranges, foraminifera, and bacteria along with sediment characteristics such as grain size, organic carbon and nitrogen, sediment hydrocarbons, and sediment trace metals in relation to temporal, spatial, and hydrographic variability as determined during the sample year;

4. description of the histopathology of selected epifaunal and infaunal species and discussion of histopathological conditions in relation to hydrocarbon and trace metal concentrations in the selected species;

5. discussion of temporal and spatial hydrocarbon degradation potential of microbial populations in surficial water and sediments and determination of the effect of hydrocarbon products on this potential and the mineralization of chitin and cellulose, the normal substrates for microbial populations; and

6. extension of the Virginian Sea Wave Climate Model for the region from Cape Hatteras, North Carolina, to Long Island, New York.

Preliminary findings based on the first year of study (1975-1976) were documented in a Final Report (V.I.M.S. 1977) and can be summarized as follows.

1. The waters of the Middle Atlantic Bight were characterized by two vertical frontal zones dividing three water mass

types--the coastal boundary layer, shelf water, and slope water.

2. Water mass structure was generally reflected in the plankton community with distinct coastal, shelf, and slope assemblages.

3. Spring neuston tows were dominated by eggs and larvae of fishes and crustaceans.

4. Sediments on the Middle Atlantic shelf are characteristically medium to coarse sands grading to slightly muddy fine sands at the shelf break.

5. Trace metals and hydrocarbons tend to associate with fine sediment particles and thus the distribution of these chemical constituents closely reflected the distribution of fine sediments rather than potential sources of origin.

6. Density of heterotrophic bacteria in sediments appeared to be related to both proximity to shore and silt/clay content.

7. Macrobenthos, which demonstrated little seasonality, was most abundant on the outer shelf and least abundant on the continental slope. However, species diversity and richness increased offshore.

8. The most significant finding from the first sampling year probably was documentation of the influence of local ridge and swale topography on the distribution of sediments, sediment constituents, and benthic biota. Ridges were characterized by coarse-skewed medium sands grading to fine sands in the swales. Concomitant with the shift in sand size was an increase in the silt and clay content. Trace metal, hydrocarbon, organic nitrogen, and organic carbon concentrations are closely related to silt and clay content of sediments and thus levels were higher in swales. Increases in density from ridge to swale were also characteristic for bacteria, foraminifera, and macrobenthos.

During the second sampling year (1976-1977, Contract No. AA550-CT6-62), specific goals of the Middle Atlantic studies remained the same as during the first year. Thus all programs initiated during the first year were continued to provide comparative data with which to re-evaluate the preliminary findings discussed above. However, some sampling stations were added or deleted based on first year results. New studies were also initiated, primarily to examine the factors controlling benthic community composition. Included were programs to assess 1) relationship of macrobenthos to mesoscale sedimentary and topographic patterns; 2) response of benthos to catastrophic disturbance; 3) biotic interrelationships of macrobenthos and demersal fishes; and 4) community composition of meiobenthos.

Other new studies included zooplankton biomass estimates, replication of zooplankton bongo sampling to provide an estimate of sampling variability, and an analysis of historical finfish catch data from the Middle Atlantic shelf.

The majority of the two-year Middle Atlantic environmental studies program was conducted with VIMS in-house personnel. Subcontracts were made with the Marine Science Consortium for carbon analysis to be conducted at American University, the Universiy of Delaware for taxonomic assistance, the Virginia Associated Research Campus (VARC) of the College of William and Mary for some trace metal analysis, and the University of Virginia for foraminifera analysis. A listing of principal investigators and associate principal investigators is provided in Table 1.

Liaison was established between VIMS and the U. S. Geological Survey (USGS) and between VIMS and the Environmental Data and Information Service (EDIS) to coordinate other phases of the BLM OCS studies program related to the Middle Atlantic and to provide for data archiving with the National Oceanographic Data Center (NODC) of EDIS.

Relationship of Study to Other Studies in the Same Area

Extensive geological studies of the Middle Atlantic OCS were conducted during this approximate time frame by the U. S. Geological Survey (USGS), Office of Marine Geology, Woods Hole, Massachusetts. The general objectives of these studies, funded under Memoranda of Understanding (08550-MU5-33 and AA550-MU7-31) between USGS and BLM, were to assess the potential geologic hazards to oil and gas development; to describe the sedimentary environments; to establish geochemical benchmark data; and to define rates of movements and pathways of pollutants. Results of these studies are included in this report.

Although many of the USGS and VIMS studies were conducted independently, there were several areas in which both institutions were involved. USGS supplied detailed bathymetry for use in the wave climate model. A preliminary sedimentary texture map was provided for bio-lithofacies interpretation.

USGS personnel from the Atlantic-Gulf Coast Branch (hydrocarbon laboratory) participated in each VIMS benthic cruise. Sediment samples for hydrocarbons were analyzed by both USGS and VIMS personnel. USGS performed analyses on a blended sample taken at each benthic station each season while VIMS performed replicate analysis once at each station.

During the first sampling year, sediments collected on VIMS cruises were provided to USGS, Woods Hole, for analysis of total trace metal concentrations. Under the VIMS contract, sediments were

Table 1. Program Elements and Responsible Principal Investigators, Contract 08550-CT5-42 (1975-1976) and AA550-CT6-62 (1976-1977).

Program Elements	Principal Investigator(s) Associate Principal Investigator(s)
I. Chief Scientist	D. Boesch
II. Principal Elements	
Benthic Studies	D. Boesch
	J. Kraeuter (megabenthos)
	K. Serafy (macrobenthos)
	D. Hartzband (meiobenthos)
	L. Watling (Univ. Delaware, taxonomic consultant)
	R. Ellison (Univ. Virginia, foraminifera)
Hydrocarbon Studies	C. Smith
	W. MacIntyre (December 1976 - May 1977)
	C. Su (laboratory analyses)
	R. Bieri (GC-MS)
	K. Cueman
Trace Metals	R. Harris
	R. Huggett
	R. Jolly (VARC, PIXE analysis)
	G. Grant (VARC, AA analysis)
Zooplankton-Neuston Studies	G. Grant
Bacteriological Studies	H. Kator
Histopathological Studies	C. Ruddell
Finfish Studies	J. Musick
	E. Foell
	G. Sedberry
III. Supporting Elements	
Physical Oceanography and Meteorology	E. Ruzecki
	C. Welch
	D. Baker

Table 1. (Concluded).

Program Elements	Principal Investigator(s) Associate Principal Investigator(s)
III. Supporting Elements (cont.)	
Carbon Analysis	M. Champ (American University)
Nitrogen Analysis	R. Wetzel
Sediment Grain Size	R. Byrne
Program Management	E. Burreson M. Lynch (October 1976 to May 1977) J. Jacobson (January 1976 to September 1976) B. Laird (reports) W. Athearn (logistics) (May 1977 to April 1978) J. Brokaw (logistics) (September 1975 to April 1977)
Data Management	G. Engel
Statistics	W. Roller
IV. Special Studies	
Baltimore Canyon Trough Wave Climate Model	V. Goldsmith
Degradation (Bacterial) Studies	H. Kator
Recolonization Studies	D. Boesch K. Serafy
Historical Finfish Analysis	J. Musick J. Colvocoresses

analyzed for leachable metals and USGS total digestates were analyzed for barium and vanadium. During the second year VIMS analyzed sediments for both leachable and total metal concentrations.

VIMS collected suspended sediments for USGS analysis and, using a USGS instrument, provided USGS with records of nephelometer/ transmissometer traces.

VIMS biologists participated in USGS submersible cruises in the lease area during the first year to obtain quantitative and qualitative estimates of animal distributions.

National Oceanic and Atmospheric Administration (NOAA), U. S. Department of Commerce, analyzed historical finfish and benthos data related to the Middle Atlantic Bight OCS area under Interagency Agreement No. AA550-IA7-35 with BLM. The National Data Buoy Office maintained two meteorological data buoys in the region, one of which, in addition to standard meteorological wind-sea surface data, recorded wave data (AA550-IA6-3). This data, particularly the wave data, was used by VIMS in wave model studies. The Environmental Data and Information Service (EDIS) Center for Experiment Design and Data Analysis (CEDDA) of NOAA under Interagency Agreement No. AA550-IA6-12 analyzed historical oceanographic and meteorological data for long term and seasonal trends. VIMS physical oceanographers worked closely with CEDDA on this project and provided a complete set of all oceanographic data in the VIMS data base for offshore areas. A list of personnel responsible for liaison between BLM supported studies in the Middle Atlantic Region is provided in Table 2.

Other BLM funded studies in the region that did not directly relate to the benchmark study included two literature surveys. A literature survey of the 200 m - 2000 m slope area from the Gulf of Maine to Cape Hatteras, North Carolina, was conducted by The Research Institute of the Gulf of Maine (TRIGOM) under Contract No. 08550-CT5-47. An update of the TRIGOM 1974 socio-economic and environmental inventory which covered the northern portion of the Middle Atlantic Bight, and a University of Rhode Island (URI 1973) coastal and offshore environmental inventory of the region from Cape Hatteras to Nantucket Shoals was completed by the Center for National Areas (CNA) under Contract No. AA550-CT6-45. VIMS personnel have provided data and reports to CNA for their update.

Major non-BLM studies in the region include the ground fish surveys conducted annually by the National Marine Fisheries Service (NMFS), the Marine Ecosystems Analysis Program (MESA) New York Bight Studies, both of NOAA, and Environmental Protection Agency (EPA) funded dump site studies off Delaware Bay.

VIMS' other major offshore study in the Middle Atlantic Bight is a National Science Foundation (NSF) funded study of the Norfolk Canyon ecosystem which focuses on shelf and canyon ichthyofauna, zooplankton,

Table 2. Liaison Responsibilities for the Middle Atlantic Bight BLM Supported Studies.

Agency (Project)	Agency Liaison	VIMS Liaison
USGS	D. Folger	M. Lynch (1975-1976)
	M. Ball	E. Burreson (1976-1977)
EDS	K. Hughes	G. Engel
Middle Atlantic Physical/ Meteorological Summary	G. Falk	E. Ruzecki
NOAA, N.E. Fisheries Center	R. Reid	E. Burreson
NODC Archiving	S. Marcus	G. Engel

and epifauna. The investigators associated with the zooplankton and physical oceanographic and meteorological aspects of the Norfolk Canyon Study are program element principal investigators for the comparable element in the BLM benchmark study.

BLM Personnel

Contract monitoring personnel within BLM responsible for these studies were Contracting Officers Authorized Representatives - Drs. J. Snyder and A. Horowitz and Mr. P. Thomas; and Contracting Officers - Mssrs. W. Hamm, F. Galinsky, A. Guida, and P. Lubetkin. Liaison with the Branch of Environmental Studies, BLM, was the responsibility of Dr. R. Beauchamp and Mr. J. Cimato.

The Study Area and Study Plan

The region studied during the benchmark program covers an area of over 13,000 square nautical miles, or about 45,000 km^2, extending off New Jersey, Delaware, Maryland, and Virginia over the broad continental shelf and upper slope (Figure 2). Sampling had to be extensive enough to characterize this expansive environment and also intensive enough to characterize the diversity of environments within regions of this topographically complex continental shelf. General requirements of the sampling scheme, including number of stations, were set forth by BLM in the contract; VIMS was responsible for selection of the actual location of stations in consultation with USGS and BLM.

1975-1976 Sampling Year

In order to provide both the extensive coverage required of the area under consideration for leasing and the intensive coverage desired in the portion of the lease area of most interest to industry, 51 benthic stations (A's through L's, Figure 2) were allocated as follows:

- 24 stations (A's through F's), grouped in 6 clusters, each containing 4 stations, primarily concentrated in the outer shelf area but extending into central and inner shelf areas were located in a corridor bounded roughly by 38.5°N and 39.5°N.
- A 7 station transect (G series) positioned near the northern border (40°N) of the lease area.
- A 6 station transect (K series) positioned along the southern border (38°N) of the lease area.

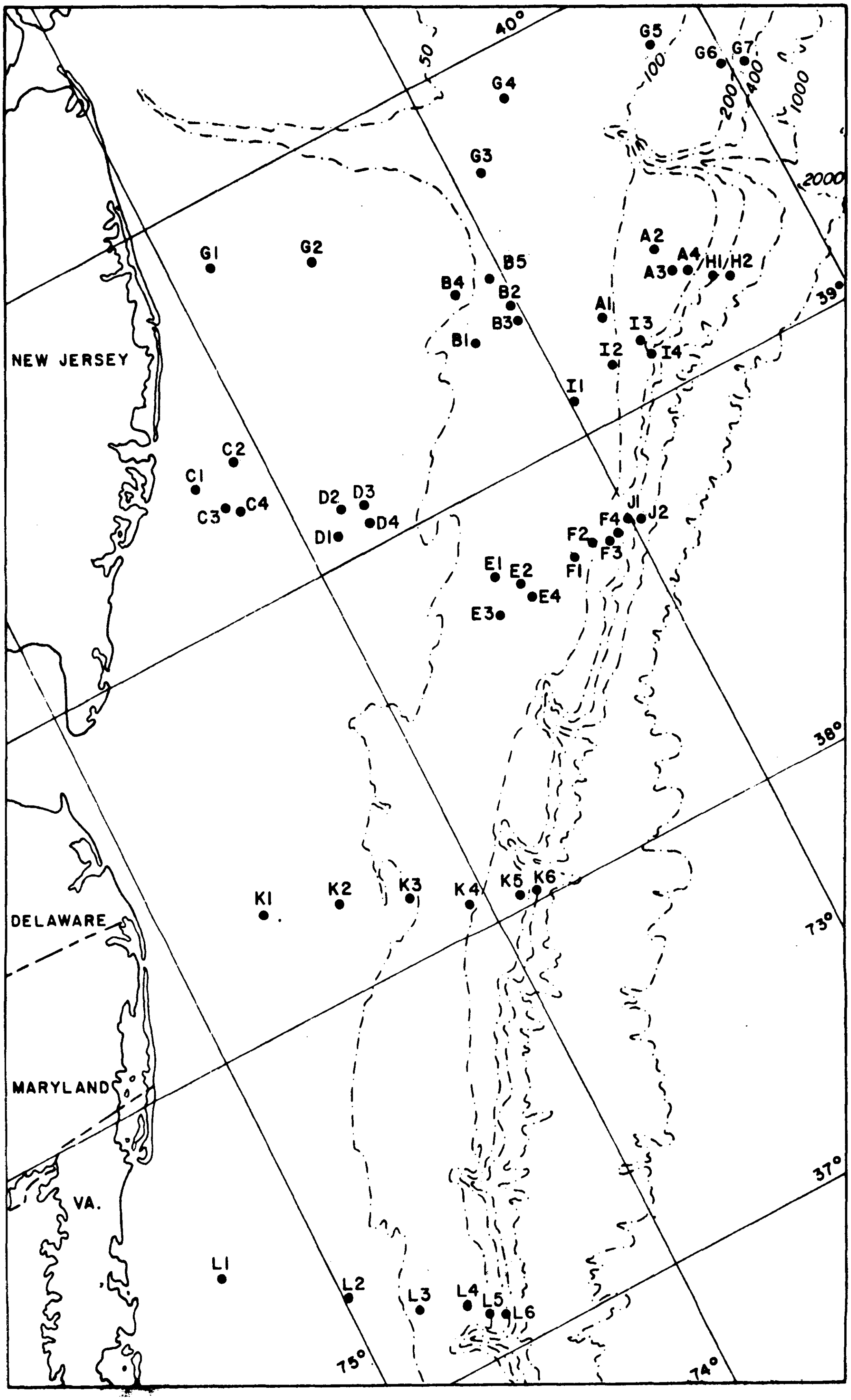

Figure 2. Stations sampled for macrobenthos.

-- A 6 station transect (L series) positioned off Chincoteague, Virginia between 37°N and 37.5°N south of the lease area and

-- 8 stations (H, I, and J series) positioned on the continental slope or in or near submarine canyons in the central area.

The 24 cluster stations in the central area were sampled quarterly to provide intensive sampling in time and space such that refined assessments of bathymetric, topographic, sedimentological, and seasonal effects could be determined. The remaining 27 stations were sampled twice yearly (during summer and winter) to provide the broad geographic coverage necessary for distinguishing bathymetric and latitudinal patterns over the region.

Nine stations (C2, D1, N3, E1, F1, J1, A1, B1, I1) were chosen for collection of larger organisms by dredge and trawl (megabenthos) to be used for histopathological and chemical studies. They were located in the central area corresponding, wherever possible, with stations sampled for macrobenthos and sediments. These stations were sampled quarterly.

The 6 water column stations (C1, D1, N3, E3, F2, J1) were located on a cross shelf transect extending from C1 off Atlantic City, New Jersey, to J1 on the slope edge. These stations were positioned based on the known hydrographic characteristics of the area and located, where possible, in the vicinity of benthic stations. Because of the small number of stations, these sites were restricted to the central study area.

The identity of the tracts that would be offered for leasing under the initial Middle Atlantic OCS sale (Sale 40) was not available at the time of station selection. USGS identified three areas of possible interest based on geophysical data. Stations in the central study area sampled during this initial year are shown in Figure 3 along with tracts actually leased in Sale 40. Comparison of stations with actual leases shows coverage with regard to potential development was good, with the exception of water column studies in the northeastern and northwestern lease areas.

Rationale for Location of Stations

Cluster Stations. Six areas (Areas A-F) (Figure 2) were chosen as representative of bathymetric zones and/or reflective of high interest for oil and gas development. Within each area, 4 permanent stations were fixed to cover the range of presumed biological and sedimentary habitats. In the 4 areas situated totally on the continental shelf (B-E), stations were chosen to at least represent ridge, flank, and swale environments of the first-order topographic system (McKinney et al. 1974). Existing geological information indicated that sediments and sedimentary processes varied considerably

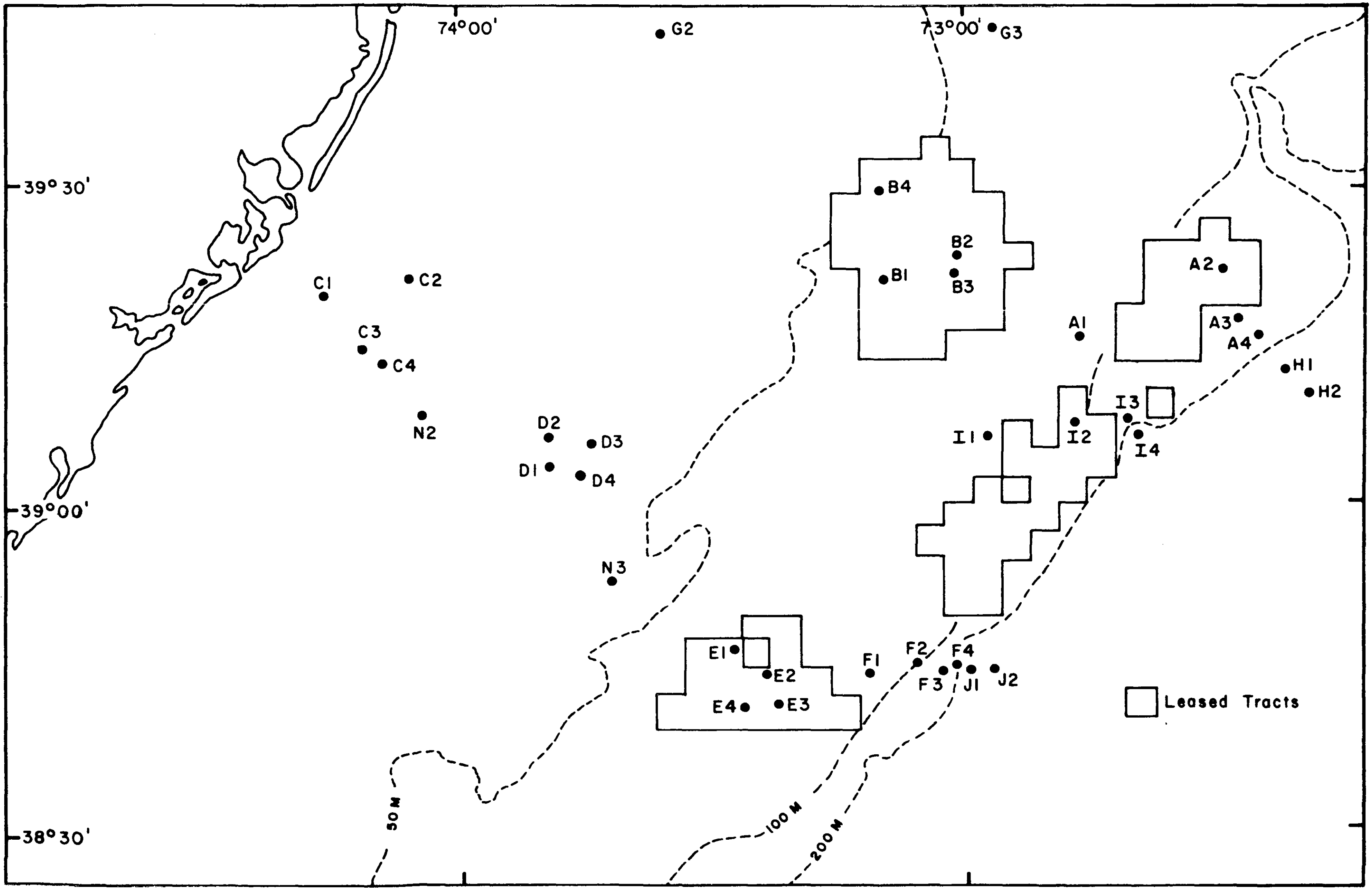

Figure 3. Stations in the central study area and tracts leased for oil and gas development in BLM Sale 40.

with respect to topography; however, comparable biological and chemical information was lacking, making this sampling design criterion hypothetical. The stations in areas A and F were located at depths lying beyond the presence of ridges and swales, thus the stations were established to cover the bathymetric ranges within these outer shelf-shelf break zones.

Three of the cluster areas (A, B, and E) are located in regions in which the USGS conducted bathymetric surveys because of potential oil and gas development activities. Area A covers a comparatively gently sloping portion of the outer shelf and shelf break south of Hudson Canyon. Low relief hummocks are found in the outer part of the area, and it is crossed by several sea level stillstand shore features (Milliman 1972; Cousins et al. 1977). Sediments in this region are generally muddier than elsewhere on the shelf to the South.

Area B is crossed by the southwest-northeast trending Tiger Scarp, representing a portion of the Fortune Shore (Milliman 1973). Area B includes a shallow terrace (<50 m deep), which contains cuesta-like features (Swift et al. 1972), and deeper ridge and swale topography (56-74 m). The distribution and variability of surface sediments (Knebel 1975) and the structure of the surficial sand sheet (Knebel and Spiker 1977) in this region have been studied by USGS.

Area E covers outer shelf ridge and swale topography (55-90 m) north of the head of Wilmington Canyon. Knebel and Spiker (1977) also studied the surficial sand sheet in this area, and Knebel and Folger (1976) reported large sand waves in the southern part of this region.

Area F, to the east of Area E, was selected as an outer shelf-shelf break parallel of Area A. The depth gradient is much steeper and the sediments less muddy in this region than in Area A.

Two other cluster areas were selected to represent inner shelf and central shelf conditions. The central shelf area (Area D) is located on a segment of the shoal retreat massif of the Great Egg Valley (Swift et al. 1972; Swift 1975). This region is one of the most intensively studied shelf areas in terms of sedimentology, having been the subject of a number of investigations by staff of the Atlantic Oceanographic and Meteorological Laboratories (AOML) of NOAA (McKinney et al. 1974; Stubblefield et al 1975; Stubblefield and Swift 1976). Area D is characterized by a well-developed system of NE-SW oriented ridges and swales (30-50 m depth range) superimposed by lesser order topographic features (McKinney et al. 1974).

Area C, located near the shoreward termination of the shoal retreat massif northeast of the ancestral Great Egg Valley (Swift et al. 1972) off Atlantic City, New Jersey, is characterized by well-developed ridges and swales which range in depth from 15-35 m. The sediments in Area C include coarser sands than found in other cluster areas, but swales locally cut into underlying clay deposits.

Transect Stations. Transect G extended from northern New Jersey, across the Hudson Shelf Valley to the upper continental slope north of Hudson Canyon. Transect K extended from the Maryland-Delaware region to the upper slope south of Baltimore Canyon. Transect L extended from off Virginia's Eastern Shore to the upper slope north of Norfolk Canyon. Along each transect, stations at approximately 25, 40, 55, 100, 165, and 350 m depths were sampled. On transect G an additional station (G3) was located in the axis of the Hudson Shelf Valley at 73 m.

Except for G3, those stations on the continental shelf were positioned on flat or flank bottoms, and topographic high and lows were avoided in order to minimize the effect of topography on apparent cross-shelf patterns.

These transect stations (Figure 2) are useful in describing the broad-scale biogeographic, sedimentologic, and hydrographic patterns in the Middle Atlantic Bight.

Continental Slope and Canyon Stations. Four stations (H and J series) were positioned on the upper continental slope off Areas A and F (Figure 2). The shallower of each pair of stations was located at 350-400 m and the deeper at 700-750 m. Many tracts leased under BLM-OCS Lease Sale 40 are located at the shelf break, and many tracts located at slope depths have been nominated for leasing in a future sale. This underlines the importance of sampling the little-known slope environment.

Study plans initially stipulated at least one station in one of the submarine canyons incising the Middle Atlantic continental shelf. The canyon chosen for study was Toms Canyon which is smaller than the major canyons such as Hudson, Wilmington, and Baltimore, but is much closer to Sale 40 lease tracts than the larger canyons. Four stations (I series) were positioned along a transect extending from the outer continental shelf (ca. 80 m) through the head and upper part of the axis of Toms Canyon (to 460 m) (Figure 2).

Dredge and Trawl Stations. Only nine stations were sampled quarterly by dredge and trawl. The megabenthos captured was used for ecological studies, analyses of trace metals and hydrocarbons, and histological material. One station from each of the cluster areas plus 3 others, I1, J1, and N3 (located between cluster areas D and E) were selected (Figure 2). This sampling scheme gave broad coverage from the inner shelf to the upper slope over the central study area, but did not allow sampling of various topographic features within bathymetric zones or broad latitudinal sampling.

Water Column Stations. In order to correspond with benthic stations, a cross-shelf transect extending through cluster areas C, D, E, and F was selected. One station from each of these areas, C1, D1, E3, and F2, were designated as water column stations together with N3, between areas D and E, and J1 on the continental slope off Area F. These stations constituted a section roughly perpendicular to the shoreline and slope break and extending from 9 km (15 m depth) to 145 km (400 m depth) offshore (Figure 2).

1976-1977 Sampling Year

Second year study objectives remained unchanged and thus, except for a few minor changes and the initiation of some new studies, the sampling scheme for the 1976-1977 sampling year was similar to the first year.

Benthic Cluster Stations.

Preliminary first year results suggested that some stations could be eliminated due to faunal similarity with other locations. Thus sampling was discontinued at the four cluster stations, C1, C3, D2, and D3 (Figure 2). These stations are a considerable distance inshore from the lease areas and were yielding little additional information. It was decided to retain only one ridge and one swale station in each of these two cluster areas.

Benthic Transect Stations.

Sampling at seven transect stations, L1, L3, K1, K3, G1, G3, and G7, (Figure 2) was discontinued after the first sampling year. Stations L1, K1, and G1 were located far from the lease areas and any pollution event associated with oil development. Thus it was only necessary to document general community structure over a one year period. Stations L3, K3, and G3, although some distance seaward of L2, K2, and G2, were only about 10 m greater in depth than the latter stations and thus faunistically similar. Sampling at Station G7 was discontinued because it was faunistically similar to H1 and H2 and was peripherally out of the study area.

Water Column Stations.

In order to more completely define seasonal neuston and subsurface zooplankton community structure in the present and future lease areas, a transect of 4 stations (L1, L2, L4, L6) from the coast of Virginia to the shelf-edge near Norfolk Canyon was added, as well as two stations (B5, A2) to the north of the original transect.

Habitat Delineation Study.

In order to determine if it was possible to extrapolate results from fixed stations located in topographically complex areas to other regions of the same features, or to similar features in other areas, and to document the relationship between benthic invertebrates and demersal fishes, a habitat delineation study was conducted. Cluster areas B and E were chosen because many of the prime lease tracts are in these regions. Both regions were stratified based on existing bathymetry and sediment data and stations were determined by random selection of Loran C coordinates. Sampling was conducted during fall 1976 for megabenthos and macrobenthos, but demersal fishes were sampled each season throughout the year.

Recolonization Study. This study, also initiated during the 1976-1977 sampling year, was designed to assess the effects of oiled sediment on recolonization of benthic invertebrates following catastrophic disturbance. The location chosen for this experiment (Station B5, Figure 2) is an area of fine sediment with relatively high silt and clay content which could retain oil.

Station Location. Accurate navigation and positioning is essential for studies of the seabed in the Middle Atlantic continental shelf because of its considerable topographic and sedimentologic complexity. High precision navigation systems are not available over much of the region. The Loran C system of radionavigation with normal position variation from 15-60 m in the study area (U. S. Coast Guard 1974) is available and was used during this study.

Because the sampling design relied on sampling topographic features, it proved more important to locate the feature to be sampled than to return to an electronically fixed position. Normal procedure was to cruise to the assigned position determined by Loran C and to locate the precise feature with a precision depth recorder (PDR).

Cruise Organization

The field sampling program throughout the first year consisted of separate cruises for water column and benthic studies. Each sampling season, one water column and at least one benthic cruise (two during winter and summer) occurred. During the summer season, a separate trawl cruise saved considerable time and expense. An additional bacteriological cruise (04G) was conducted one week after the summer water column cruise to resample bacteriological samples lost in a laboratory mishap.

During the second sampling year a three-cruise system was implemented with separate water column, benthic, and trawl cruises; deployment or recovery of recolonization boxes was also conducted on a separate cruise. Dates of all cruises and vessels utilized are listed in Table 3.

Participating in the majority of all cruises was a multidisciplinary scientific crew headed by a chief scientist. Composition of this party was dependent upon cruise; e.g. on benthic cruises there were representatives from physical oceanography, microbiology, benthic ecology, hydrocarbon chemistry, and trace metal chemistry. Each discipline was headed by a group leader or member skilled in field sampling procedure. All members of the scientfic party were divided into watch sections, supervised by a watch captain or party chief. This shipboard party was supported by a shoreside

Table 3. Cruises conducted under contracts 08550-CT5-42 (1975-1976) and AA550-CT6-62 (1976-1977).

Cruise No.	Vessel	Dates
01W*	R/V Columbus Iselin	27 Oct. - 6 Nov., 1975
01B	R/V G. W. Pierce	22 Oct. - 31 Oct., 1975
02W	R/V G. W. Pierce	4 Feb. - 17 Feb., 1976
02B	R/V G. W. Pierce	19 Feb. - 23 Mar., 1976
03W	R/V Virginian Sea	7 Jun. - 17 Jun., 1976
03B	R/V J. M. Gilliss	14 Jun. - 24 Jun., 1976
04B	R/V G. W. Pierce	14 Aug. - 2 Sep., 1976
04T	R/V Cape Henlopen	23 Aug. - 27 Aug., 1976
04W	R/V Virginian Sea	30 Aug. - 10 Sep., 1976
04G	R/V John Smith	12 Sep. - 14 Sep., 1976
05B	R/V H. J. W. Fay	3 Nov. - 8 Nov., 1976
05W	R/V Virginian Sea	4-7 Nov.17-26 Nov., 1976
	R/V H. J. W. Fay	19 Nov. - 27 Nov., 1976
05T	R/V Cape Henlopen	8 Nov. - 18 Nov., 1976
05R	R/V Cape Henlopen	19 Nov. - 3 Dec., 1976
06B	R/V H. J. W. Fay	4-17 Feb. 6-13 Mar., 1977
06W	R/V H. J. W. Fay	19 Feb. - 6 Mar., 1977
06T	R/V J. M. Gilliss	18 Mar. - 28 Mar., 1977
07T	R/V Cape Henlopen	16 May - 21 May , 1977
07W	R/V H. J. W. Fay	17 May - 28 May , 1977
07B	R/V H. J. W. Fay	30 May - 5 Jun., 1977
07R	R/V Henlopen	2 Jun. - 6 Jun., 1977
08B	R/V H. J. W. Fay	3 Aug. - 17 Aug., 1977
08R	R/V Cape Henlopen	11 Aug. - 18 Aug., 1977
08W	R/V H. J. W. Fay	19 Aug. - 30 Aug., 1977
08T	R/V Cape Henlopen	7 Sep. - 15 Sep., 1977
09R	R/V Cape Henlopen	29 Nov. - 5 Dec., 1977

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* W = water column
B = benthos
T = trawl
G = special bacteriology
R = recolonization

logistics team at VIMS consisting of logistics assistant, logistics technician, and graduate assistants.

Mobilization for all cruises occurred at VIMS and, where applicable, at the chartered vessel's home port. All vessels except R/V Cape Henlopen embarked and debarked at VIMS facilities or nearby U. S. Government installations. Crew changes and equipment repair or replacement were effected at Atlantic City, New Jersey, or Lewes, Delaware.

Shipboard Procedures

Because a three-cruise system was elected, the mission and sequence of events differed for each cruise. Table 4 illustrates the procedures followed.

Sample and Data Archives
BLM Cruises 01 to 08 (Fall 1975 to Summer 1977)

Several classes of samples and records are archived at VIMS for possible future needs. The types and numbers archived, together with their mode of storage are listed in Table 5.

Tapes and Logs

Included in this category are the raw analogue tapes from the CTD systems and the three groups of digital tapes generated from the analogue tapes. There are 71 analogue tapes and 95 digital tapes in all from cruises 01 to 04 and 95 analogue tapes and 186 digital tapes from cruises 05-08. The analogue tapes are stored in individual plastic tape containers and the digital tapes are in the custody of the Physical Oceanography Department.

Hydrographic logs, meteorological logs, and Loran C logs with recorder readouts are available. Depth recorder records from the eight cruises are available as are copies or transcripts of ships' logs and benthic data sheets. Original benthic data sheets are in the custody of the several principal investigators. All of these logs and data sheets are also on microfiche and stored at MERRMS.

Bottom Photographs

Black and white negatives and color slides are archived in cruise notebooks in the custody of the Invertebrate Ecology group. A listing of all photographs is presented in Tables 6 and 7.

Summary of Samples Collected

A summary of samples collected is presented in Tables 8 and 9.

(TEXT CONTINUES ON PAGE 28)

Table 4. Sequence of sampling procedures followed at each station on benthic, trawl and water column cruises.

Benthic Cruises	Trawl Cruise	Water Column Cruises
Station acquisition by Loran C	Station acquisition	Station acquisition
↓	↓	↓
Bathymetric verification by precision depth recorder (PDR)	Bathymetric verification by precision depth recorder (PDR)	Bathymetric verification
↓	↓	↓
Buoy deployment or ship anchored	Hydrographic cast, meteorological data	Neuston (1200 hrs)
↓	↓	↓
Loran C & PDR recheck	Anchor dredging	Hydrographic cast
↓	↓	↓
Hydrographic cast, meteorological data	Small biological trawling	Neuston (1500 hrs)
↓	↓	↓
Microbiological water sampling	Otter trawling	Surface & Bottom water collections
↓		↓
Benthic (grab) sampling		Neuston (1800 hrs)
↓		↓
Buoy or anchor recovery		Hydrographic cast
		↓
		Neuston (2100 hrs)
		↓
		Zooplankton (bongo) tows
		↓
		Neuston (2400 hrs)
		↓
		Hydrographic cast
		↓
		Neuston (0300 hrs)
		↓
		Neuston (0600 hrs)
		↓
		Hydrographic cast
		↓
		Neuston (0900 hrs)

Table 5. Samples Archived under Contract 08550-CT5-42 (1975-76) and AA550-CT6-62 (1976-77).

Type of Sample	Number of Samples 1975-76	1976-77	Containers	Location
Zooplankton	48	194	buffered formalin in jars	Conrad House
Neuston	192	309	buffered formalin in jars	Conrad House
Sediment Cores	840	1,521	ziploc bags in freezer	Ferry House
Foraminifera	234	248	ziploc bags in freezer	Ferry House
Bottom Photographs	594	1056	laboratory notebooks	Melville House
Macrobenthos	950	770	70% ethanol in jars	Melville House
Megabenthos	10,000	11,100	70% ethanol in jars and vials and 200 bags of dried echinoderms	Wachapreague Laboratory
Histopathology:				
Slides	6,250	7,350	slide files	Davis Hall
Tissue Blocks	3,470	3,600	block drawer	Davis Hall
Tarballs	48	35	ziploc bags in freezer	Byrd Hall

Table 6. Detailed listing of BLM Bottom Photographs (Contract No. 08550-CT5-42), 1975-1976.

Cruise	Station	Type	Number
01	A1	B&W	6
	A2	"	6
	A3	"	6
	A4	"	6
	B1	"	7
	B2	"	4
	B3	"	6
	B4	"	6
	C1	"	6
	C2	"	6
	C3	"	8
	C4	"	6
	D1	"	12
	D2	"	6
	D3	"	4
	E1	"	7
	E2	"	3
	E3	"	8
	E4	"	7
	F1	"	6
	F2	"	6
	F3	"	5
	F4	"	6
02	B1	B&W	5
	B2	"	7
	B3	"	7
	B4	"	6
	C2	"	6
	C3	"	7
	C4	"	6
	D2	"	6
	D3	"	6
	E1	"	6
	E2	"	4
	E3	"	7
	E4	"	6
	F1	"	5
	F2	"	3
	F3	"	5
	F4	"	6
	H1	"	6
	H2	"	5
	I1	"	6
	I2	"	5
	I3	"	5
02(cont.)	I4	B&W	4
	J2	"	4
	K1	"	7
	K2	"	5
	K3	"	8
	K4	"	4
	K5	"	4
	K6	"	4
	L1	"	5
	L3	"	6
	L4	"	6
	L5	"	6
	L6	"	6
03	A1	B&W	12
	A3	"	7
	A4	Color	6
	B2	B&W&C	12
	B4	B&W	6
	C1	Color	6
	C2	Color	7
	C3	B&W&C	12
	C4	"	8
	D1	"	13
	D2	B&W	7
	D3	B&W&C	13
	D4	"	8
	E1	"	12
	E2	"	11
	E3	Color	4
	E4	B&W&C	12
	F1	"	11
	F2	"	12
04	D1	B&W	6
	D2	B&W&C	13
	D3	B&W	5
	D4	"	9
	E1	"	6
	E2	"	6
	E3	"	5
	E4	"	6
	F1	"	8
	F2	B&W&C	14

Table 7. Detailed listing of BLM bottom photographs (Contract No. AA550-CT6-62) 1976-1977.

	05		06		07		08	
Station	B&W	Color	B&W	Color	B&W	Color	B&W	Color
A1	6	7	6	0	7	5	8	0
A2	5	6	4	0	5	5	6	0
A3	7	6	0	0	0	5	5	0
A4	7	0	0	5	11	0	7	5
B1	6	6	6	0	4	5	7	0
B2	6	0	6	5	7	4	8	0
B3	7	7	7	0	6	2	13	0
B4	7	4	6	0	7	0	9	0
B5	0	1	0	0	6	4	9	0
C2	2	0	6	6	7	0	0	6
C4	1	0	6	6	0	5	8	0
D1	6	0	4	7	6	3	5	0
D4	5	0	5	8	6	6	6	0
E1	9	0	6	6	7	6	5	0
E2	5	0	6	4	0	6	4	0
E3	3	0	6	7	4	6	8	0
E4	6	0	6	4	2	0	7	6
F1	6	0	6	6	0	0	6	5
F2	6	0	8	0	6	6	6	0
F3	6	6	7	0	0	5	8	0
F4	6	6	6	0	6	6	6	0
G2	0	0	8	0	0	0	4	5
G3	0	0	1/2	0	0	0	4	6
G4	0	0	0	0	0	0	4	6
G5	0	0	0	0	0	0	4	6
G6	0	0	0	0	0	0	4	6
H1	0	0	0	0	0	0	4	7
H2	0	0	7	0	0	0	6	6
I1	0	0	0	0	0	0	4	6
I2	0	0	0	0	0	0	4	6
I3	0	0	0	0	0	0	4	6
I4	0	0	0	0	0	0	4	6
J1	0	0	7	0	0	0	4	6
J2	0	0	8	0	0	0	7	5

Table 7. (continued)

	05		06		07		08	
Station	B&W	Color	B&W	Color	B&W	Color	B&W	Color
K2	0	0	0	0	0	0	2	6
K4	0	0	0	0	0	0	4	6
K5	0	0	0	0	0	0	4	6
K6	0	0	20	0	0	0	0	6
L2	0	0	0	0	0	0	3	6
L4	0	0	7	0	0	0	0	12
L5	0	0	0	0	0	0	4	6
L6	0	0	12	0	0	0	5	6
BD*	0	8	0	0	0	0	0	0
BF	0	7	0	0	0	0	0	0
BM	0	6	0	0	0	0	0	0
BP	0	10	0	0	0	0	0	0
BR	0	9	0	0	0	0	0	0
BS	0	10	0	0	0	0	0	0
ED	0	11	0	0	0	0	0	0
EF	0	7	0	0	0	0	0	0
EL	0	6	0	0	0	0	0	0
ER	0	9	0	0	0	0	0	0
ES	0	9	0	0	0	0	0	0
Totals	112	141	180	64	97	79	230	153

*Area B and E habitat delineation samples.

Table 8. Summary of samples collected and analyzed during BLM cruises 01-04.

Samples	Required	Collected	Analyzed
Sediment characteristics			
Grain size	1350	1169	1169
Organic carbon (Champ)	900	891	887[1]
Nitrogen	900	891	732[2]
Benthic samples			
Macrobenthos (grabs)	900	891	891
Megabenthos (SBT, anchor dredge trawl)	variable	115	115
Foraminifera	234	234	234
Photographs	594	594	594
Histopathology samples	variable	1726	1231[3]
Trace metals			
Sediments	522	522	522
Megabenthos	144	144	144
Zooplankton	48	48	48
Neuston	variable	25	25
Suspended particulates	48	48	96[4]
Hydrocarbons			
Sediments	306	306	306
Megabenthos	144	156	156
Zooplankton	48	49	49
Neuston	variable	4	4
Dissolved hydrocarbons	24	24	24
Particulate hydrocarbons	48	48	48
Surface film hydrocarbons	variable	15	15
Tarballs	variable	71	0
Zooplankton	48	53	53
Neuston	192	196	196
Bacteria			
Field collection and enumeration:			
Sediment	300	304	304
Surface water	24	30	30
Microlayer	24	15	15
Physical Oceanography			
CTD/DO casts	variable	246	246
XBT's	variable	220	220
Salinities	348	1188	1188
DO's	348	1112	1112
Micronutrients	492	1471	1471
Organic carbon (water column) (Champ)			
DOC	48	48	48
POC	48	96	96

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[1] 4 samples lost during analysis.

[2] Reagent contamination resulted in loss of 159 samples

[3] No minimum number of analyses was specified. The samples not analyzed are stored in paraffin embedded tissue blocks.

[4] Includes leachable and refractory analyses.

Table 9. Summary of samples collected and analyzed during 1976-1977 (BLM cruises 05-08).

Samples	Required	Collected	Analyzed
Sediment characteristics			
Grain Size	1400	1515	1400
Organic carbon	1400	1400	1400
Nitrogen	768	780	768
Benthic samples			
Macrobenthos (grabs)	768	770	770
Megabenthos (SBT, anchor dredge trawl)	282	270	270
Meiobenthos	384	384	288*
Foraminifera	244	248	248
Photographs	variable	1056	1056
Histopathology samples	variable	1717	1717
Trace metals			
Sediments	732	746	732
Megabenthos	144	146	144
Zooplankton	168	168	168
Neuston	variable	8	8
Suspended particulates	96	96	96
Hydrocarbons			
Sediment	246	242	242
Megabenthos	144	144	144
Zooplankton	168	168	168
Neuston	variable	8	8
Dissolved hydrocarbons	96	96	96
Particulate hydrocarbons	96	96	96
Surface film hydrocarbons	variable	28	28
Tarballs	variable	35	0
Zooplankton	168	194	168
Neuston	300	309	300
Fish Food Habits (Stomach)	4000 min.	8132	5290
Bacteria			
Field collection and enumeration:			
Sediment	248	248	248
Surface water	48	48	48
Microlayer	48 max.	22	22
Thermocline	variable	23	23

Table 9 (continued)

Samples	Required	Collected	Analyzed
Physical Oceanography			
CTD/DO casts	variable	246	246
XBT's	variable	220	220
Salinities	340 min.	2324	2324
DO's	340 min.	2266	2266
Micronutrients	340 min.	1063	1063
Organic carbon (water column)			
DOC	110 max.	202	110
POC	96	96	96
Habitat delineation			
Megabenthos	66	66	66
Macrobenthos	88	88	88
Grain size	88	88	88
TOC	88	88	88

* One core archived, one core analyzed for grain size at each station

METHODS

Sampling Methodology

Physical Oceanography and Meteorology

Meteorological Parameters. Observed parameters consisted of windspeed and direction, atmospheric pressure, wet and dry bulb air temperature, sea surface temperature, and direction, period, and height of wind waves and swell. Also, estimates of visibility, cloud cover and type, and concurrent weather conditions were made and recorded. Measurements were made every three hours on water column cruises and once per station on the benthic cruises. In addition, continuous records of atmospheric pressure were obtained with a barograph.

Oceanographic Parameters. Measured parameters were water temperature, conductivity, pressure, electrical current generated in a dissolved oxygen probe, temperature of the dissolved oxygen probe, light transmission and light scattering. In addition to these in situ measurements, water samples for dissolved oxygen, salinity, micronutrient, and suspended sediment analyses, were obtained from various levels in the water column (near surface and near bottom levels were always sampled with as many as ten additional samples taken at various intermediate levels). Water samples, and in situ measurements listed above were obtained with a CTD/DO Rosette Sampler combination. Optical properties of the water column measured during benthic sampling cruises were obtained with a nephelometer-transmissometer. Measurements of water temperature as a function of depth were made with an expendable bathythermograph (XBT) at positions halfway between water column and benthic stations.

Sampling frequency varied between water column and benthic stations.

I. Water Column Stations. Water column stations were of two kinds - 24 hour stations and single occupancy stations. At the 24 hour stations, four CTD casts were taken at 0000 hrs., 0600 hrs., 1200 hrs., and 1800 hrs. Exceptions occurred during fall, 1975 and winter, 1976 (BLM01W and BLM02W) when only a single CTD cast was performed at each station. At the single occupancy stations only one CTD cast was taken. Each set of in situ measurements was augmented with near surface and near bottom water samples for salinity and DO determinations. Intermediate levels (10, 20, 30, 50, 100, 150, 200, 250, and 300 m) were also sampled. Additionally, water samples for determination of micronutrients, particulate organic carbon (POC), and dissolved organic carbon (DOC) concentrations were sampled once each station at near surface and near bottom.

II. Benthic Stations. Benthic station sampling was similar to water column station sampling except that sampling occurred only once per station, and POC-DOC samples were omitted. Added to the sampling were near surface and near bottom water samples for suspended sediments, and continuous nephelometer-transmissometer records of light transmission and scattering as a function of depth. The suspended sediment samples were obtained at the first numbered station in each cluster group (A1, B1, C1, etc.) and at all transect stations (G, K, and L). When a thermocline was evident an additional suspended sediment sample was obtained near or in the thermocline.

Subsurface Zooplankton

Double-oblique tows, from surface to near-bottom and back to surface, were made at each of the 12 stations with 60 cm opening-closing bongo systems (McGowan and Brown 1966), first with paired 202 μm mesh nets, then with 505 μm mesh nets. The track of tows followed a broad arc, except in heavy weather when waves were quartered. All tows were taken using either a 1/4-inch (0.7 cm) stainless steel cable or a plastic coated cable, towed at a vessel speed of approximately 1.5 knots. To avoid surface contaminants, samples were submerged in closed position, opened below the surface, then re-closed before retrieval through the surface layer. Flowmeters (General Oceanics, Inc.) were excluded from the net utilized for chemical analysis.

Samples collected in the metered half of bongo net pairs and reserved for taxonomy were washed down with the ship's seawater system into collecting buckets, concentrated on 110 μm netting, transferred to glass jars and preserved in 5-8 percent buffered formaldehyde in seawater.

During the second year (1976-1977), additional bongo collections were made at stations A2, B5 and E3 on each cruise to provide replicate samples for statistical purposes. At these stations the initial two bongo tows (202 μm and 505 μm nets) were followed in succession by three additional tows. The latter utilized an array of two 60 cm bongo samplers and a time-depth recorder. Bongos were fitted with paired 202 μm and 505 μm nets, the upper pair closed on descent for chemistry samples and unmetered, the lower pair open on descent and with both sides metered for taxonomy and biomass collections. After immersion below the surface layer, the upper bongo system was opened by messenger, the array towed obliquely to near-bottom, then back to below the surface. The upper bongo system was then closed before retrieval through the surface layer. All such tows were conducted at night, usually between the hours of 2000 and 2400 EST.

Surface Zooplankton (Neuston)

Neuston collections were obtained every three hours for a 24-hour period at each station during each quarterly cruise. At stations D1, N3, and F2 during the second year only a single neuston tow was made, in conjunction with bongo sampling. The neuston sampler, designed at Woods Hole Oceanographic Institution, consisted of two hydrodynamically-shaped, foam-filled floats connected by an endless fiberglass belt, accommodating a standard one-meter plankton net and towed by a four-point bridle. A 505 µm mesh net was employed in all neuston sampling. The unit sampled the surface layer to an approximate depth (floating depth) of 12 cm and a width of one meter. Tows were made from an extended boom in a widely circular track to keep the net away from the ship's wake and, except where abundance of salps or ctenophores dictated a shorter tow, were of 20 minutes duration.

Collected samples were washed into buckets, where they were inspected for tarballs and large, readily identified species. Tarballs, if present, were removed to labelled plastic zip-bags and frozen. Large species, if present, were transferred to acid-washed, teflon-capped jars and frozen for trace metal and hydrocarbon analysis. A maximum of two species was selected at each station, with specimens accumulated for a given station through the eight neuston tows at 24-hour stations. Numbers and identity of removed specimens and the occurrence of tarballs were noted on collection log sheets.

Sediments

Sediment samples for grain size, organic carbon, and nitrogen analyses were collected at each grab station. At each station, 12 replicate 0.1 m^2 Smith-McIntyre grab hauls were made except at some deep stations where, because of long haul time, fewer hauls were made. Into each of these successful grabs, a 3.5 cm inside diameter clear acrylic core was inserted, removed, and capped on both ends for grain size analysis. The cores generally contained the top 10 cm of sediment. During the first year, cores from the six grabs taken for trace metal or hydrocarbon samples, usually the first six, were sent to the USGS, Woods Hole, where a single grain size analysis was performed on composited aliquants from the cores and the remaining material returned to VIMS. At VIMS grain size analyses were performed on all six sediment samples from the grabs taken for faunal analysis and two of the individual samples returned by USGS. During the second year all twelve sediment samples were analyzed at VIMS.

Organic carbon and nitrogen samples were collected in a similar fashion but in smaller diameter core tubes (2.2 cm inside diameter). One core sample each was taken from the six grabs collected for analyses of macrobenthos. Samples were quickly frozen and remained so until analysis.

Macrobenthos

A 0.1 m^2 Smith-McIntyre grab sampler of stainless steel construction modified to accommodate a Benthos Edgerton 35 mm camera (Model 371) and flash (Model 381) was used for macrobenthos sampling. The camera's shutter was activated by a bottom trip switch when the camera was approximately 1 m off the bottom, except during the last two seasonal sampling periods when a focal distance of 0.6 m was used to enhance resolution of bottom features. Maximum depth of penetration, sediment temperature, and depth of the redox potential discontinuity (RPD) were measured and recorded for each grab sample. The Smith-McIntyre grab sampled to a sediment depth of 7-18 cm and generally depth of penetration exceeded 10 cm.

Small cores (2.2-3.5 diameter) were removed from each sample for grain size, organic carbon, and nitrogen analyses. The remaining contents of the Smith-McIntyre grab were emptied into a 5-gallon galvanized bucket which was then placed on a specially constructed elutriation stand. Sea water was run into the bucket and allowed to elutriate light-bodied organisms until no macrofauna was seen overflowing. The overflow was caught on a small 0.5 mm mesh Nitex screen in a frame at the bottom of the elutriator. This screen with the trapped organisms and debris was then removed and placed in a labeled cloth bag. The remaining sediment and heavy organisms in the bucket were sieved through a similar, but larger surface area, 0.5 mm Nitex screen, and the debris placed in a large cloth bag. Because of coarse sediments, a majority of the original sediment collected often remained on this screen after washing. The "light" and "heavy" fractions were anesthetized in isotonic $MgCl_2$ for about 30 minutes, then transferred to separate 30-gallon drums containing 10% buffered formalin with Rose Bengal as a vital stain.

Megabenthos

Two pieces of equipment were utilized to sample the megabenthic fauna, a small biology (Menzies) trawl (SBT) and a modified anchor dredge. The trawl was lined with 4 mm mesh fishing seine. The trawl mouth was 1 m wide and 10.5 cm high. The anchor dredge had a 39.5 cm wide and 10.5 cm high mouth (maximum cutting depth) and was modified by attaching a 1.35 m long tail section covered with a 4 mm stainless steel mesh to allow finer materials to winnow through.

The two different samplers were used in order to provide accurate representation of both vagile, surface dwellers as well as the infauna. The SBT skimmed the surface layers and obtained shrimp and other motile forms as well as shallow infaunal species. The anchor dredge dug much deeper and thus sampled infaunal forms more efficiently.

Three samples were taken with both SBT and anchor dredge at each station. The SBT was towed for three minutes except at J1 where five minute tows were utilized. The anchor dredge was towed on the bottom for two minutes.

When the sampler was brought on board, the catch was placed in wooden buckets to prevent contamination of specimens to be used for chemical analysis. All animals not used for chemical studies were preserved in 10% buffered formalin.

Habitat Delineation Study

The habitat delineation study was planned to delineate the mesoscale (0.1-1.0 km) patterns of distribution of megabenthos, macrobenthos, and demersal fishes within two topographically complex regions on the outer continental shelf. The areas chosen were portions of cluster areas B and E which included the repetitively sampled fixed stations in those areas. These areas were chosen because results of the first year's sampling showed major and consistent differences in the macrobenthos of the topographic features represented by the fixed stations and because these two areas include many of the prime lease tracts of OCS Sale 40.

The goals of the habitat delineation study were to determine whether one could extrapolate results based on limited fixed stations, to map or delineate the habitats and communities of macrobenthos and megabenthos, to uncover the causes of the mesoscale distribution patterns represented, and to relate the distribution of benthic invertebrates to the distribution of fishes and their food habits.

Both regions were stratified based on an interpretation of existing data on bathymetry and sediment distribution. Detailed charts contoured in meters developed by the U. S. Geological Survey, Woods Hole, were used. Sediment data from several stations sampled by USGS were available for Area B, but sediment data for Area E, except for the fixed stations, were scant. Area B was divided into six *a priori* habitat strata: the terrace atop Tiger Scarp, ridges below the scarp, shallow flanks and flats, deep flanks and flats, a muddy flat region, and swales. Area E was divided into five *a priori* strata: ridges, shallow flanks and flats, deep flanks and flats, swales, and the shelf break. Non-replicated samples of macrobenthos and megabenthos were collected at stations randomly positioned within each stratum during the fall 1976 sampling period.

Locations of stations were determined by random selection of Y and Z Loran C coordinates with a certain number of stations assigned to each *a priori* stratum. At each station selected for sampling of macrobenthos, one Smith-McIntyre grab sample was collected. Sediment samples were removed and the sample was preserved in 10% formalin. Stations sampled for megabenthos coincided with those sampled for demersal fishes during fall 1976. Three stations in each stratum were sampled during the night by a single three-minute SBT haul. Samples were processed as usual for the fixed station sampling. The stations sampled for megabenthos and macrobenthos did not always coincide.

Recolonization Study

The recolonization study was designed to experimentally determine the response of outer shelf macrobenthos to catastrophic disturbance and the effects of incorporation of crude oil in the sediments on the recolonization process. The results would not only enhance the capability to predict the nature and duration of impacts which may be associated with oil and gas development, but would also provide insight into the role disturbances play in the natural community.

The experiment involved placement of boxes of sediment from which macroorganisms were artifically removed by freezing sediments collected in situ on the seabed for varying lengths of time. Sediments in some of the boxes were contaminated by mixing small quantities of crude oil with the sediments (2.0 mg/g dry wt. sediment). Other boxes of azoic sediments were covered by screen to exclude or include epibenthic predators in order to test the hypothesis that cropping of infaunal prey by these predators had important effects on the structure of the macrobenthic community.

The site chosen for the recolonization study, Station B5, was located in the large depression in the center of Area B at a depth of 65 m. The site was selected because such depressions contained somewhat finer sediments with appreciable silt and clay content which could retain oil. Furthermore, the amphipods which are important constituents of swale communities are known to be relatively sensitive to the effects of petroleum hydrocarbons.

Boxes of sediment were scheduled to be deployed and retrieved on a staggered basis so that the time series of colonization and sucession could be followed for the various experimental treatments.

Some boxes were loosely covered with 10 mm mesh screen to exclude large epibenthic predators. One or two specimens of the most common predatory asteroid at B5, *Leptasterias tenera*, were added just prior to deployment of some of the screened boxes during June 1977 as predator enclosure experiments.

Sediment samples were removed from each box for analysis of grain size, organic carbon and nitrogen, trace metals, and hydrocarbons. Boxes were then placed in a freezer truck and covered by dry ice. The boxes were kept in the truck at least overnight and were checked for complete freezing. Boxes containing frozen sediment were then placed on ship for deployment.

On recovery, also accomplished with divers, the contents of the box were sampled by inserting a template partitioning the contents with a 6 by 6 array of equal quadrants each 8 by 8 cm square. Certain squares were used for collection of sediment samples for grain size determination, chemical analyses, foraminifera, bacteriological characterization, and fluorescent particle distribution. The contents of the rest of the quadrants were spooned into jars labeled so that the position of the quadrants within the box was referenced. These samples were preserved with 10% buffered formalin. These samples were sieved at the shore laboratory through a 0.5 mm sieve for macrobenthos assessment.

Meiobenthos

Samples of meiobenthos were taken as subsamples from a single 0.1 m^2 Smith-McIntyre grab. Maximum penetration depth of the redox potential discontinuity (RPD) was measured and recorded. The Smith-McIntyre grab sampled to a depth of 7-18 cm into the sediment, but any grab that did not penetrate at least 8 cm was not subsampled for meiobenthos.

Subsampling methodology was designed in order to elucidate small scale spatial patterns in the distribution and abundance of meiofaunal taxa. Samples were taken with a series of 12 contiguous square corers arranged in a three by four (3 x 4) array. Each core was 2.5 x 2.5 cm or 6.25 cm^2.

The 12 square corers were inserted into the sediment obtained with the Smith-McIntyre grab to a depth of at least 8 cm and withdrawn with as little disturbance as possible. Cores 1-11 were then rinsed into separate, labeled containers with an isotonic solution of magnesium chloride ($MgCl_2$) and allowed to relax for 15-20 minutes. Each container was agitated and the supernatant decanted through a 0.5 mm and a 0.063 mm sieve. This was repeated 6-8 times and then the material on the 0.063 sieve was washed into a jar of 10% formalin. Core 12 was frozen for later sediment analysis.

Foraminifera

Two plastic coring cylinders, 2 cm in diameter, were inserted into one grab at each benthic station. After the cores of sediment were withdrawn from the grab, the top 3 cm of sediment was cut off and preserved in buffered formalin, shaken, and stored on deck in storage boxes.

Bacteria

Microlayer. Surface microlayer samples were obtained only under favorable sea conditions. All samples were collected upwind of the research vessel using a self-propelled inflatable rubber boat. Replicate microlayer samples were obtained using a sterile screen (Nitex monofilament nylon, 6.5 mesh/cm) held in a stainless steel frame to which a handle was attached. Samples were collected in replicate by rapidly plunging the screen vertically through the water surface and smoothly raising the screen into the air parallel to the interface. After allowing water coating the frame to drain, the screen sample was collected in a sterile, calibrated test tube using a sterile funnel/support stand configuration.

Surface (1 m), Thermocline, and Bottom Water. Hydrocasts were performed quarterly at each of the stations using Niskin sterile bag samplers. Precautions were taken to prevent contamination by the vessels' bilges. Seasonal thermoclines at stations with depths greater than 50 m were located by CTD cast immediately prior to sampling. Bottom water samples were collected at 2 m above the sediment. Surface water temperatures were determined at the time of sampling and reversing thermometers were used on bottom samplers to corroborate proper sampler operation.

Hydrocast and microlayer samples were processed for enumeration of heterotrophic and petroleum-degrading marine bacteria immediately after collection.

Two replicates were removed from each water sample collected for determination of filterable ATP concentration. Replicates were filtered through 0.45 μm membrane filters. ATP was extracted using boiling Tris buffer. Following extraction samples were frozen for storage at -4°C prior to laboratory assay. Three replicate aliquots were assayed per sample using an ATP photometer (SAI Technology Corporation).

Sediments. Sediment samples were collected quarterly at cluster stations using a Smith-McIntyre grab. Additional sediment stations (along transects G, H, I, J, K, and L) were sampled only during the summer and winter seasons. Undisturbed central areas of the grab were sampled to obtain an uncontaminated sample using sterile "minicorers", plastic syringes with the luer end removed. "Mini-corers" were pushed into the sediment sample to a depth of about 5-6 cm yielding a sample volume of about 10 ml. Four samples were obtained at each station, two for determination of heterotrophic and petroleum-degrading bacterial populations and two for the determination of the ratio of sediment dry to wet weight. Sediment temperatures were also measured at this time by mercury thermometer and recorded.

Sediment samples for dry weight determinations were immediately frozen for processing at a later date. "Mini-cores" for enumeration were then processed as follows. After weighing the "mini-corer" the sediment sample was extruded into 90 ml of sterile sea water in a Waring blender and homogenized for one minute. One ml volumes of this homogenate (1:10 dilution of sediment v/v) were diluted by appropriate powers of ten and used to inoculate media for enumeration of heterotrophic and petroleum-degrading marine bacteria.

Histopathology

Organisms Chosen for Analysis. Twelve benthic marine invertebrates were chosen for histopathological analysis from SBT, anchor dredge, or otter trawl catch:

Molluscs: *Astarte undata*, *A. castanea*, and *Placopecten magellanicus*
Shrimp: *Dichelopandalus leptocerus*, *Pontophilus brevirostris*, and *Crangon septemspinosa*
Crabs: *Cancer irroratus* and *C. borealis*
Echinoderms: *Echinarachnius parma*, *Asterias forbesi*, *A. vulgaris* and *Astropecten americanus*.

Organs and Tissues Sampled. For routine work, the smaller crustacea, specifically the shrimp and small crabs, were fixed whole without any attempt to dissect out discrete organ systems. The echinoderms and small molluscs were dissected to yield only broad anatomical units such as the arms or disk area in the echinoderm or portions of gut, mantle, and foot in the smaller molluscs. The larger crabs and the giant scallop, *P. magellanicus*, were dissected to provide portions of gill, digestive diverticula, stomach (crabs only), gonad, muscle, heart, mantle (scallops only), or kidney (scallops only). Fine dissections of other animals were occasionally performed when it was desired to obtain material for plastic embedding.

Fixation. Samples to be processed in the "routine" manner were preserved in Dietrich's fluid. Although Dietrich's fixative was an adequate histological fixative, it did not preserve the fine structural elements of tissues and appeared to wash out glycogen from tissues. In order to appreciate the finer morphological details, selected portions of the animals referred to above were preserved in aqueous phosphate-buffered, acrolein-formaldehyde mixture (PAF). Small portions of tissue, generally less than 5 mm in diameter, were placed in PAF, transported back to the laboratory and embedded in glycol methacrylate for routine examination at the light microscope level.

Community Structure and Food Habits of Fishes

Sampling for demersal fishes consisted of 15-minute tows with a 45 ft. (13.7 m) headrope, lined, semi-balloon trawl. Six stations, three day and three night, were randomly selected in each *a priori* habitat stratum for each cruise. Samples were collected seasonally on four cruises during 1976 and 1977.

All fishes captured were identified, counted, measured, and weighed. Each fish was dissected and its stomach excised if not conspicuously empty. On large catches of some dominant species, subsamples (at least 30 stomachs) were collected. Each stomach was labeled, individually wrapped in cheesecloth and fixed in 10% seawater formalin.

Historical Finfish Analysis

Two data sets were used in the historical finfish analysis: the VIMS Chesapeake Bight data collected during 1967 and 1968 and data from the NMFS Groundfish Survey conducted from 1967 through 1976.

Chesapeake Bight. Cruises were conducted by the Virginia Institute of Marine Science (VIMS) in the Chesapeake Bight during the four seasons of 1967 and the winter of 1968 aboard the 88 gross ton side trawler *Sea Breeze*. The survey area, bounded by the 9 and 274 m isobaths, was divided into grids (15' latitude x 12.5' longitude). Attempts were made to sample each grid once during each seasonal cruise. At each station a model IV Atlantic Western trawl (16 m head rope, 24 m foot rope) was towed for one hour. All fish captured were identified, counted, and weighed by species. Very large catches were subsampled of necessity. Most trawls were made during daylight hours, except during winter when short day-length required some night sampling in order to complete synoptic seasonal collections within a reasonable time period. Water temperature and salinity were measured at surface and bottom at each station.

NMFS. Groundfish Survey cruises were conducted by the U. S. National Marine Fisheries Service during the fall and spring from fall 1967 through spring 1976, aboard either the *RV Albatross IV* or *RV Delaware II*. In addition a summer cruise was made during 1969. The survey area extended from the 15 fathom (27 m) contour offshore to 200 fathoms (365 m). A stratified random sampling design was utilized, based on depth and geographical zones. Catch data from strata 1-12 and 61-76 (Cape Hatteras to Cape Cod) were analyzed for the present study. Sampling intensity in each stratum was allocated according to the geographic area of each stratum (2-16 tows per stratum). Most cruises used a standard #36 Yankee trawl (18 m headrope, 24 m footrope). The spring cruises from 1973-1976 used a modified high-opening #41 Yankee trawl (24 m headrope, 30 m footrope). The catches were identified, counted, and weighed by species. A bathythermograph cast was made at each station. For further details of sample processing, see Grosslein (1969).

Trace Metals

Zooplankton. Subsamples collected from each bongo tow (202 μm and 505 μm) at the water column stations were transferred into nitric acid pre-washed glass jars and frozen at -4°C or lower until analyzed.

Neuston. A maximum of two species per water column station sampled were stored in acid-washed jars and frozen at -4°C or lower.

Sediment. At each benthic station, six individual replicate samples (at least 100 g) were obtained from the six separate grabs using a non-contaminating plastic scoop or corer. These were then stored in plastic bags at -4°C or lower until analyzed. Care was taken not to subsample sediment in close proximity to the sides of the metal sampler.

Epifauna and Infauna (Megabenthos). Four species were collected at each dredge and trawl station, stored in nitric acid pre-washed glass jars, and frozen at -4°C or lower.

Particulate Matter. Surface and bottom water samples were obtained using a non-contaminating 30 liter Niskin sampler at each of the 12 water column stations. After prefiltering with methanol to open air-clogged pores, the sea water was vacuum-filtered from polyethylene reservoirs through pre-washed 0.4 μm, 47 mm Nuclepore membranes contained in inline, Millipore filter holders. The membranes were then rinsed with distilled and deionized water. Filter holders were transferred to polyethylene bags containing desiccant, sealed, and stored at -4°C or lower.

Hydrocarbons

Water Samples. Water samples were obtained using a specially designed 40 liter sampling bottle capable of being opened and closed at depth, and capable of collecting water at depths up to 700 meters. After retrieval the water was filtered and transferred to stainless steel storage bottles. All valves and tubing were stainless steel, and valves were teflon packed. Material collected on the filter pad was classified as particulate, and material passing to the storage bottles was considered dissolved. About 100 ml of $CHCl_3$ was immediately added to each filled storage bottle to retard biological activity while the bottles were returned to the laboratory for solvent extraction. The filters were folded, wrapped in $CHCl_3$ washed aluminum foil, placed in $CHCl_3$ washed bottles, and kept frozen until analyzed.

Surface Film Samples. A teflon disc sampler of 0.166 m^2 was used to collect surface film for hydrocarbon analysis. Multiple samples were taken at each station to provide approximately 0.5 m^2 of film. Hydrocarbons on the disc were carefully rinsed off with CCl_4 and collected in a $CHCl_3$ cleansed glass bottle. Bottles were closed with a teflon lined cap and frozen for later analysis.

Zooplankton. Samples were taken using nylon plankton nets. Net contents were removed in the ship's laboratory, subsampled for hydrocarbon analysis, and the subsample immediately placed in $CHCl_3$ cleansed glass bottles with teflon lined caps. Zooplankton samples were kept frozen until analyzed.

Neuston. Neuston was taken in a surface towed plankton net. Handling precautions to avoid shipboard contamination were as for zooplankton. The samples were placed on $CHCl_3$ washed sorting trays and sorted to isolate sufficient individual species biomass (>5.0g) for hydrocarbon analysis. Species from all tows at a station were combined.

Sediment. Samples for hydrocarbon analysis were taken in a stainless steel unlubricated Smith-McIntyre grab. Approximately one kilogram of sediment was removed from the central undisturbed portion of each grab, using an ethanol washed stainless steel scoop. Sediment was scooped to a depth of approximately 5 cm. Additional precautions taken to avoid contamination from the ship included covering the grab with a teflon shroud when not in use, and dispersing of surface slicks (when present) with a stream of clean water before deployment of the grab. The scoop contents were placed directly in wide mouth glass bottles with teflon lined caps, and the filled bottles quick frozen by solid CO_2 and stored at -20°C in a freezer to await analysis onshore.

Benthic Organisms. The organisms were collected in bottom trawls and dredges and placed in wooden buckets for later sorting and measurement in the laboratory. The organisms were placed in solvent washed one quart wide mouth, glass bottles with teflon lined caps. Several individuals of a species were often placed in one bottle to achieve enough biomass for analysis. The bottled samples were quick frozen on solid CO_2 and stored at -20°C to await analysis onshore.

Laboratory Methodology

General laboratory methods are presented below. Refer to individual chapters (Volume II) for detailed methodologies.

Physical Oceanography

Sample Analysis.

I. Salinity. During the first sampling year (cruises 01-04) temperature and conductivity ratios (relative to Copenhagen standard seawater) of the water samples were measured with a laboratory salinometer (Beckman model R57-B). During the second sampling year (cruises 05-08) salinity samples were analyzed aboard ship with a GUILDLINE AUTOSAL.

II. Dissolved Oxygen. Water samples which had been field processed for DO analysis were titrated with sodium thiosulfate solution.

III. Micronutrients. Frozen field samples were thawed overnight in a refrigerator and anlyzed on a Technicon Auto Analyzer.

IV. Particulate and Dissolved Organic Carbon. Frozen filters and water samples were allowed to thaw at room temperature. The filters were air dried with a water aspirator. Six 10 ml precombusted glass ampules were used for each sample giving triplicate analysis for each POC and DOC sample. A filter (POC) or filtrate (DOC) was placed in an ampule, and purged of inorganic carbon constituents, and heated to oxidize the organic carbon to CO_2. CO_2 content of each ampule was then analyzed in an ampule-breaking apparatus which allowed the CO_2 to be flushed through an infrared analyzer (Model 524, Oceanography International Carbon Analyzer).

Computation of Parameters from Values on CTD/DO Tapes. Reported values of temperature, salinity, depth, DO, and σ_t were computed from measurements recorded at sea on audio tape from CTD/DO casts.

The audio tapes of the CTD casts were transcribed on 9-track tape in the lab using the same audio recorder and CTD deck terminal.

The transcribed digital tapes were processed on the VIMS IBM 370/115 computer. All variables were ordered by 0.5 meter depth slots into which the samples (frames) were averaged with equal weight.

Analysis of XBT Data. XBT data was analyzed with an X-Y digitizer which placed selected points from the XBT trace directly on computer compatible magnetic tape.

Zooplankton/Neuston

Biomass Measurements. Collections preserved for taxonomic study were also utilized for biomass estimates. The non-destructive measurement of displacement volume was employed, after allowing a minimum of one week after collection for stabilization of zooplankton volume. The method described by Kramer (1972) was followed.

Sorting of Preserved Samples. Large and rarer taxa such as fish larvae were sorted from whole collections. Collections were then quantitatively split into successively smaller aliquots, for the progressively smaller and more numerous taxa, using a VIMS splitter

(Burrell et al. 1974). Where samples were large, one-half the collection (from first split) was archived. Taxa were sorted in the above manner into major categories such as copepods, fish larvae, decapod larvae, etc., enumerated and preserved in separate vials or small jars.

Sorted major taxa were then distributed among specialists for identification and counts of species. Representatives of identified species were separated for inclusion in an archived reference collection.

Data Analysis. Three measures of diversity in zooplankton and neuston communities were used (Pielou 1975): the Shannon index (H') using base-2 logs, evenness (J'), and the Margalef species richness index ($S-1/\log_e N$). All diversity measures were based on total number of species and individuals in each sample.

The principal method of community analysis used was a cluster analysis, both normal and inverse, based on a matrix of Bray and Curtis (1957) similarity coefficients. Data employed in these analyses were first standardized to numbers of individuals per 100 m^3 in the case of subsurface zooplankton (bongo tows) and to numbers per standard 20-minute tows for surface zooplankton (neuston).

Sediments

Granulometry. Since the sediments encountered in the bottom sampling program varied in composition from predominantly sand and gravel to predominantly silt and clay, no single size analysis technique could cover the size range for all samples. Consequently a combined analysis was performed using sieve separation, pipette analysis, rapid sand analyzer, and coulter electronic particle counter.

A Model TA coulter counter with 140 μm and 30 μm apertures was used for fine determination. The sand analyzer used was modelled after the design of Zeigler et al. (1960).

Calculations of Size Parameters. In order to construct the cumulative frequency curve for a sample, the various subanalyses were recombined in terms of the total sample weight. The total sample weight was determined as the sum of the gravel plus sand plus the weights of silt and clay which were determined by pipette analysis. The recombination in terms of total weight is necessary since both the rapid sand analyzer and the Coulter Counter represent their results as fractional percentages of the material introduced into the respective devices. Once the cumulative frequency distribution for the entire sample was constructed, the needed percentile levels were read from the curve and the desired graphic moments were calculated.

Total Organic Carbon. Sediment samples were oven dried sieved through a 1 mm sieve to remove shell and pebbles, powdered on an analytical mill, weighed, and placed in an ampule. The ampule was purged of inorganic carbon constituents, sealed, and heated to oxidize the organic carbon to carbon dioxide. The carbon dioxide of each ampule was flushed with a nitrogen stream and measured by an infrared analyzer (Model 524, Oceanography International Carbon Analyzer).

Total Nitrogen. Total nitrogen was estimated using the persulfate digestion method of D'Elia et al. (1976) for samples from the fall 1975 cruise. Because of the unavailability of contaminant-free persulfate, this method could not be employed for the remainder of the samples. Instead, a gas chromatographic technique was employed and calibrated by the persulfate digestion method.

Macrobenthos

Samples were first soaked for several hours in fresh water. The "light" fractions were sorted into major taxa by examination with a binocular dissecting microscope. The heavy fractions were processed by placing a small amount of sediment in a metal pan, elutriating and decanting repeatedly through 0.5 mm Nitex screen. This material was examined as with the "light" fraction, while the remaining sediment was spread out in a white enamel pan and examined for the stained organisms with the naked eye. All organisms were sorted in major taxonomic groups, at a minimum, Annelida, Mollusca, Crustacea, Echinodermata, and other taxa, and stored in 70% ethanol.

Wet weight biomass was determined for each major group in each replicate grab sample following removal of external fluid by blotting on paper towels. The weights include skeletal material such as shells and tests and in some cases tubes and protective encrustations not easily removable.

Organisms were identified and counted for each replicate grab sample. Determinations were possible to species with most individuals; however, only genus, family, or higher taxon identifications were possible in some cases.

Megabenthos

Megabenthos samples were rinsed with fresh water to remove excess formalin and any remaining sediment. The samples were then spread in pans, the animals removed from the debris. The major groups (molluscs, echinoderms, and decapod Crustacea) and representatives of some minor groups were identified and counted while being sorted. Others were separated, placed in containers and stored or shipped to an appropriate taxonomic authority. Wet weight biomass for each species was determined during the second year study after blotting excess liquid on paper towels.

Benthic Data Analysis

Data Processing. Abundance and biomass data for megabenthos and macrobenthos were entered on specially designed coding forms using the 10-digit NODC code based on a scheme originally developed by Swartz et al. (1972).

Multivariate Analyses. Patterns of community similarity and species distribution were determined using numerical classification (cluster analysis) and ordination, as appropriate. Numerical classification attempts to optimally group entities whereas ordination develops a spatial model of the relationship among entities (Clifford and Stephenson 1975; Pielou 1975). Classification is usually more efficacious with large heterogeneous data sets where it is necessary to simplify relationships. Ordination is useful when the range of variation of entities is limited (more homogeneous data sets) and when it is helpful to view the environment as gradational rather than discrete.

Species Diversity. Species diversity was measured by the commonly used index of Shannon (Pielou 1975), which expressed the information content per individual. The index denotes the uncertainty in predicting the specific identity of a randomly chosen individual from a multispecies assemblage.

Meiofauna

Sorting. Laboratory processing was initiated by sorting meiofauna from cores 1-9 from each station and season into major taxa. The abundance of each major taxon was determined during sorting and recorded by core for each station and season. Biomass values for each major taxon and total biomass values for each core were also computed. Biomass values were not directly measured but were estimates based on empirical mass/individual values obtained from other studies. This method was chosen because of the inherent difficulties of consistently measuring the mass of organisms which might be as small as 0.5 μg.

Taxonomic determination of dominant organisms was carried out to genus and, where possible, species level. These determinations were accomplished by microscopic morphologic differentiation at high magnification (up to 1250x) using phase contrast optics. Nomenclature of marine free-living nematodes has been summarized several times in the last five years, but the system of Gerlach and Riemann (1973) was followed in this work. The recent summarization of Coull (1977) was followed for harpacticoid copepods.

Data Analysis. Several indices were computed from species abundance data. A harpacticoid/nematode ratio was computed as

$$\frac{H}{N} = R$$

where H is the abundance per core of harpacticoid copepods and N is the abundance per core of nematodes.

Species diversity as reflected by the Shannon-Wiener information function H' (bits/individual) was computed by sample for both nematodes and harpacticoid copepods. Species evenness, J' (Pielou 1975), was also calculated by sample for nematodes and harpacticoid copepods.

Multivariate analyses (cluster analysis and ordination) were used to define between-station and between-cruise patterns in multi-species assemblages. Analysis of seasonal patterns was accomplished primarily by graphical comparisons.

The analysis of small scale spatial heterogeneity patterns was approached in a number of ways. Patterns of raw data were mapped for nematodes and harpacticoids among the nine core samples at each station. These patterns were visually compared and assessed by computing a coefficient of dispersion and determining the distribution type of these taxa with respect to a Poisson model. Potential biological interactions on the spatial scale of the replicate cores was identified and tested by spatial autocorrelation (Jumars et al. 1977). A technique was derived similar to Cliff and Ord (1972) to compare the spatial autocorrelation of two taxa at the same time.

Product-moment correlation coefficients were computed between total meiofaunal abundance, abundance of selected taxa, biological indices (H/N, H', and J') and sedimentary, physical, and chemical parameters.

Foraminifera

Upon delivery to the laboratory, the samples were refrigerated until sieved. In all cases, the samples were sieved within two weeks of delivery to the lab. Before sieving, the samples were stained overnight in rose Bengal. Sieving was done through a nest of two sieves (one 0.5 mm and one 0.063 mm), using flowing tap water.

The stained and sieved samples were then oven-dried at low heat ($28^{o}C$) and floated in a mixture of acetone and bromoform. The floated material was filtered, washed, dried, placed in labeled vials, and catalogued for later study.

The sample to be picked was spread as evenly as possible over a 100-square grid in a glass Petri dish, and moistened with just enough water to wet the specimens. Working with a binocular microscope (50x to 100x), all (up to 300) live foraminifera were picked from the sample, and transferred into a cardboard micropaleontology slide that had been covered with water-soluble glue, gum tragacantha. After the living specimens were picked and mounted and the fractional volume of picked sediment was recorded, the empty tests were counted and recorded.

Bacteria

Enumeration. Inocula from dilution blanks or concentrated seawater samples on membrane filters (1m and microlayer), sediments, or experimental degradation studies were enumerated for total heterotrophic bacteria using a three tube MPN technique in a heterotrophic medium (HM) modified after ZoBell's marine agar (2216). Petroleum-degrading bacteria were enumerated using a three tube MPN technique employing a minimal salts enriched sea water (ESWB) to which was added following inoculation, approximately 1% sterile unweathered South Louisiana crude oil as the sole added carbon source.

HM enumeration tubes were incubated at 20-22°C for two weeks and read at weekly intervals. ESWB tubes were incubated at the same temperature on a rotary shaker (140 rpm) for one month and read at bi-weekly intervals. HM tubes were scored positve when turbid; ESWB tubes were scored positive when turbid, when the oil showed obvious signs of degradation with associated cellular debris, or a combination of both. The highest positive dilutions were retained for taxonomic analysis. MPN values were calculated using standard tables for three tube MPN distributions. Counts were expressed as bacterial units/ml sea water or bacterial units/g dry sediment. Sediment counts were corrected for dry weight, and a volume/weight conversion of the original 10 ml sediment sample was made.

Isolation of Chitinoclastic Bacteria. Chitinoclastic bacteria were isolated by spread plating appropriate dilutions of water samples (1m) and sediment homogenates on chitin containing bi-layer plate medium.

Taxonomic Analysis of Bacterial Isolates. Isolates were obtained from selected microlayer, surface and bottom water, and sediment stations using the highest positive dilutions of HM and ESWB MPN tubes. Three to five MPN tubes from dilutions were streaked on HM agar plates, the numerically dominant isolates chosen, subcultured to ensure purity, and placed on coded HM agar slants.

Isolates for taxonomic analysis were freshly streaked on HM agar plates to describe colony characteristics. Wet mounts of log phase HM broth cultures (generally 24 hour cultures) were examined by phase contrast microscopy for motility, size, shape, and cell arrangement. Gram staining was also performed.

Biochemical tests relevant to the classification scheme of Schewan (1963) were performed.

Petroleum Degradation Experiments. Petroleum degradation experiments were performed using samples of seawater and sediment as inocula. Samples from surface water (1 m) stations, enumerated quarterly, were used for inocula. Seawater collected at each station was used to fill sterile 250 ml Erlenmeyer flasks with 100 ml inocula. At the time of inoculation, water samples were also enumerated for petroleum-degrading and heterotrophic marine bacteria. Replicate flasks for each station were treated as follows: one series was immediately autoclaved providing sterile controls, a second series received inorganic nutrient enrichment and a final series was neither enriched nor autoclaved. All three series of replicate flasks then received 100 ml of membrane sterilized South Louisiana crude oil. An additional control in the form of an inoculated, non-enriched, oil-free flask was included to compensate for surface growth effects.

Sediment inocula were provided from sediment homogenates used for enumeration of heterotrophic and petroleum-degrading marine bacteria at selected benthic stations. Ten ml volumes of the respective homogenates were added to a series of replicate 250 ml Erlenmeyer flasks containing 100 ml of sterile seawater. Experimental treatment of replicate flasks was the same as described for seawater inocula. Flasks were incubated on a rotary shaker (120 rpm) at temperatures chosen as representatives of each shelf season.

At selected intervals a flask from each series of treatments (i.e. sterile control, nutrient enriched, and non-enriched) was harvested. The oil-free control was enumerated and replaced in the incubator. Flasks were described as to the condition of the oil, turbidity, and other manifestations of bacterial degradation. Non-enriched, enriched, and oil-free flasks were enumerated after swirling using a three tube MPN technique for heterotrophs and petroleum-degrading bacteria.

Residual crude oil was extracted from flasks and fractionated into a saturated paraffin and an aromatic fraction using silica gel column chromatography. Gas chromatographic analysis of residual oil fractions was performed using a Tracor 560 gas chromatograph equipped with flame ionization detectors and a Grob capillary injector.

Chromatograms were evaluated for indications of degradation reflected as loss of specific normal saturated paraffins (nC_{10} to nC_{25}, inclusive). Identification of n-paraffins was by comparison with retention times of authentic standards.

Continuous Dilution Degradation Experiments. A continuous dilution system was designed to simulate weathering of oil in an "open" system under ambient nutrient conditions. Seawater samples (lm) collected at various stations were used to continually dilute a seawater-oil system. Initially, replicate series of sterile, solvent washed 500 ml Erlenmeyer flasks received each of three different treatments:

Treatment

A. 50 ml sterile seawater and 0.01 to 0.1% sterile South Louisiana crude oil

B. 50 ml seawater and 0.01 to 0.1% sterile South Louisiana crude oil

C. 50 ml seawater

Flasks were incubated at selected seasonal temperatures. During the incubation period, flask contents were continually diluted using a Desaga (Brinkmann) peristaltic pump from reservoirs containing either seawater and 1% formalin or freshly collected seawater. At selected harvest intervals four flasks consisting of one from treatment A, two from treatment B, and one from treatment C were harvested for processing. Populations of heterotrophic and petroleum-degrading bacteria were enumerated from one treatment B flask and one treatment C flask. ATP analysis (Strickland and Parsons 1972) was also performed on these flaks. The two remaining flasks (one treatment A and one treatment B) were "pickled" with 10 ml of methylene chloride for analysis of residual petroleum as previously described.

Chitin-Petroleum Degradation Studies. Mixed culture inocula were obtained from four (4) sampling locations during each seasonal cruise. These inocula consisted of 3 dominant chitinoclastic bacterial isolates and either 2 dominant petroleum-degrading isolates (fall) or a natural, petroleum-degrading mixed bacterial population (winter, spring, summer). The four sampling locations consisted of the water column, inner shelf sediments (<50 m), outer shelf sediments (50-100 m), and shelf break sediments (>100 m). Mixed cultures were maintained on a chitin-peptone-yeast extract seawater broth (CPY-broth).

Mixed culture inocula for chitin-petroleum degradation studies were prepared from 18 hour CPY-broth cultures by centrifugation of cells and re-suspension in seawater to an optical density of 0.1 (625 nm). Appropriate dilutions of washed suspensions were used to inoculate 150 ml bottles containing 50 ml CPY-broth. Three series of replicate bottles for each mixed culture were treated as follows: one series received the mixed culture inoculum plus 50 ml sterile Louisiana crude oil (chitin plus oil), the second received the mixed culture inoculum but no petroleum (chitin minus oil), and the third received only 50 ml sterile Louisiana crude oil (sterile control). All bottles were sealed with gauze-cotton plugs to allow for aerobic growth. Initial levels of each inoculum were enumerated for petroleum-degrading, heterotrophic, and chitinoclastic marine bacteria as described in previous sections.

Following inoculation all bottles were incubated in the dark on a rotary shaker at ambient temperatures (20-22°C). At selected intervals one bottle from each of the three treatments (i.e., chitin plus oil, chitin minus oil, sterile control) for each of the four inocula was randomly selected and inoculated bottles enumerated for the bacterial groups mentioned previously. Methylene chloride was then added to each bottle to terminate bacterial activity.

Recovery of residual chitin and crude oil was achieved by filtration of the spent medium onto tared Whatman #54 hardened filter paper pre-washed with methylene chloride. Residual chitin and petroleum were removed from each bottle using rinses of methylene chloride and water. The filterable material was additionally used with methylene chloride to remove adsorbed petroleum. Following extraction of the filtrate with methylene chloride, the extract was fractionated using silica gel column chromatography and analyzed by glass capillary gas chromatography as previously described. Residual chitin was dried in the presence of desiccant, allowed to equilibrate to room humidity and weighed. Chitin weight losses were expressed as a percentage of the uninoculated sterile controls.

Pure Culture Growth Experiments. Selected bacterial isolates obtained from enumeration of heterotrophic or pertroleum-degrading bacteria in microlayer, surface water (1 m), bottom water and sediment samples were utilized to examine the effects of an unweathered petroleum and selected weathered products on growth in a dilute nutrient broth. Isolates were maintained on HM agar and were passed three times in a dilute basal medium (BGM) prior to growth experiments.

Weathered crude oil and a water soluble fraction thereof were prepared in the laboratory by addition of 20 ml of unweathered South Louisiana crude to one liter of aged seawater (26 ppt) in a glass carboy containing a teflon stirbar. The bottle was left unsealed in the dark and the contents slowly stirred to avoid breakup of the oil layer for 48 hours at 20°C. After cessation of stirring for 10 minutes a soluble fraction was collected by draining the aqueous layer beneath the quiescent oil followed by collection of the residual weathered crude. Similarly, photo-oxidized crude oil and resulting soluble fraction were prepared by exposure of an oil-seawater mixture to sunlight for approximately 16-20 hours during a 48 hour period of ambient air temperatures (-1.1 to 38°C). On two occasions the crude oil was weathered in the dark for 48 hours at ambient air temperatures (21-32°C) to compare with oil simultaneously photo-oxidized at the same temperatures. All experiments involving laboratory weathered oil were performed on isolates from the fall cruise while experiments employing photo-oxidized oil occurred during the remaining three seasons of the year.

Immediately prior to growth experiments, isolates were inoculated into BGM and incubated approximately 18 hours at 20°C. Cells were harvested by centrifugation and resuspended in seawater (26 ppt) to an absorbance of 0.1 (625 nm). These suspensions were diluted 100x and 0.1 ml of the final suspension used to inoculate tubes containing 5 ml BGM and unweathered South Louisiana crude oil (1% w/v); laboratory weathered, photo-oxidized or dark weathered South Louisiana crude oil (1% w/v); the soluble fraction of laboratory weathered South Louisiana crude oil (1% v/v), photo-oxidized or dark weathered South Louisiana crude oil (100% v/v); and no petroleum (control). Additional experiments were conducted to examine the effects of various concentrations of photo-oxidized oil extracts in seawater.

One ml of 100x BGM was added to 100 ml membrane sterilized soluble fraction in seawater at concentrations of 1, 10, 50% v/v and "undiluted" 100%. A seawater control was provided. Cultures were incubated at 20°C on a New Brunswick Tissue Culture Rollerdrum (10-11 rpm). Growth was measured turbidimetrically at 2-4 hour intervals or longer (for slow growers) during logarithmic growth. Measurements were terminated when absorbance values decreased in all tubes or for as long as 10 days. Replicate experiments were occasionally performed to check on the reproducibility of the results. Absorbance data were plotted against time on semilog paper. Parameters routinely noted were growth yield, growth rate, and "lag" time.

Histopathology

Preparation of Tissues for Sectioning. On arrival at the laboratory, material preserved in Dietrich's fixative was trimmed and then washed in tap water overnight or decalcified if tissues were encased with a calcified exoskeleton (all echinoderms and shrimp were routinely decalcified) by placing them in several changes of 0.1 N HCl for 12-18 hours. Tissues were dehydrated and cleared on a "Technicon" - brand Automatic Tissue Processor, employing Technicon's dehydration and clearing agents, S-29 and UC-670, and infiltrated with paraffin under vacuum and embedded.

Tissues preserved in phosphate-buffered acrolein-formalin (PAF) were dehydrated in pure methanol, infiltrated with a variant of Ruddell's (1971) glycol methacrylate monomer mixture, and polymerized under an incandescent lamp.

Sectioning.

I. Paraffin blocks. Material preserved in Dietrich's fixative was sectioned at 5 μm with a steel knife on a standard rotary microtome.

II. Plastic blocks. Glycol methacrylate blocks were sectioned on a standard rotary microtome using steel knives sharpened on a "Temtool" knife sharpener. Sections were cut at 2-4 μm and stored in small boxes.

Staining.

I. Paraffin sections. After paraffin sections had been fixed to glass slides with the aid of Haupt's gelatin fixative (without phenol) they were dried and stained on the "Technicon". Slides were stained with Harris' hematoxylin and eosin or Astrablue, Mayer's hematoxylin, and eosin.

II. Glycol methacrylate sections. Glycol methacrylate (GMA) sections were stained with a variety of histological stains and histochemical substrates.

Preparation of Photomicrographs. Elements of five major anatomical units were photographed and included 1) the gills or branchial system, 2) the excretory system, 3) the digestive system, 4) the reproductive system, and 5) the integumentary system.

A standard table model Zeiss microscope was employed and projected an image into a Leitz "Aristophot" bellows camera with 4x5" back. Kodak plus-X panchromatic (A.S.A. = 125) 4x5" professional film was used.

Fish Food Habits

Sorting. After proper fixation, stomachs were soaked in water and transferred to either 40% isopropanol or 70% ethanol. For analysis, each stomach was cut open and its contents sorted by taxa and counted. Fragments such as crustacean parts, polychaete setae, or fish bones were counted as one animal, unless abundance could be estimated by counting pairs of eyes or antennal scales (crustaceans), otoliths (fishes), and other parts.

Volume displacement of food items was measured either by using a graduated cylinder or a calibrated vial and buret. Displacement of small species was estimated by measuring the volume of several species together and using a grid to estimate the percent of this total volume contributed by each species (Windell 1971; Sedberry and Musick 1978).

Data Analysis. Since methods of food habits analysis are variously biased the relative contribution of different food items to the total diet was determined using three methods: (1) the number of stomachs in which a food item occurred was expressed as a percentage of the total number of stomachs of a series containing food (percent frequency of occurrence); (2) the number of individuals of each type of food was expressed as a percentage of the total number of food items from all stomachs for a series (percent numerical abundance); (3) the volume displacement of food items was expressed as a percentage of the total volume of food from all stomachs examined of a series (percent volume displacement).

From these three measurements an index of relative importance, IRI (Pinkas et al. 1971), was calculated for each prey species and higher taxon. The IRI was used in the present study to describe the food habits of each species and to determine seasonal differences in the relative importance of food items.

Selectivity of predators on the macrobenthos was determined using Ivlev's (1961) index of electivity.

Overlap in diet among dominant predators was measured using numerical classification techniques (cluster analysis). Stomachs of predators were treated as collections and were subjected to normal cluster analysis on the basis of prey similarity, using log-transformed log(x + 1) numerical abundance.

Historical Finfish Analysis

The catch data were analyzed separately for each of the seasonal cruises. Assemblages of fishes were defined by computing a similarity coefficient, $D_{(j,k)}$, among species and subsequently classifying species into clusters or groups. Stations were clustered in the same manner, and species and station (site) groups were compared by nodal analysis. Species were eliminated from cluster analysis if they occurred at less than five percent of the stations occupied during a sampling period.

The faunal affinities of most species of fishes captured could be determined by examining published records of their usual ranges of occurrence. Most warm-temperate species had resident populations south of Cape Hatteras in the "Carolinian" faunal province and had their normal northern range limit somewhere within the mid-Atlantic Bight south of Cape Cod. Boreal species had permanent populations north of Cape Cod, and most had their southern range limit somewhere within the mid-Atlantic Bight north of Cape Hatteras. A few boreal species transcended Hatteras through bathymetric submergence. Certain components of the fauna tended to be residents on the inner shelf or outer shelf and many species were resident on the shelf edge and upper slope.

Trace Metals

Preparation of Sediment. Samples were thawed and sieved to separate coarse shell fragments and pebbles. The six replicate grabs from each station were blended thoroughly to form two sub-blends and one superblend as follows: (A) sub-blend 1 (B1) obtained by blending 100 g of sediment each from grab numbers 1,2, and 3; (B) sub-blend 2 (B2) obtained by blending 100 g of sediment each from grab numbers 4,5, and 6; and (C) superblend (SB) obtained by blending 100 g of blends B1 and B2. A weighed portion (∿100 g) of each blend (or unblended sample) was dried at 60°C to constant weight.

Sediment Leachate Preparation. A 15.00±.02 g portion of dried sediment was shaken for two hours after addition of 5N HNO_3. After shaking, the tube was centrifuged and the supernatant gently decanted into a volumetric flask. The remaining sediment was repeatedly mixed with water, shaken, centrifuged, and decanted into the volumetric flask. The leachate solution in the volumetric flask was spiked with ∿1000 μg of Indium, and transferred to a storage tube for AA and PIXE analysis.

Sediment Total Digest Preparation. During the first year of this study, total digest preparation and AA analysis were done by USGS (Bothner 1977). During the second year (Cruises 05-08) dried sediment blends were ground at VIMS in a non-metallic grinder. Samples were digested with heat after the addition of HCl, HNO_3, and HF. The solution was then doped with ∿250 μg In for PIXE and AA analysis.

Preparation of Total Digest Solutions from Benthic Macrofauna, Neuston, and Zooplankton. All macrofauna were rinsed in deionized water prior to preparation for digestion. The wet weight of the dissected or whole tissue sample was then determined. The sample was then dried to a constant weight and dry weight determined. The sample was digested in concentrated HNO_3, ashed, and redissolved in concentrated HNO_3. A 30% solution of H_2O_2 (10 to 50 ml) was continually added to the mixture dropwise until the solution was clear yellow in color. The solution was again taken to near dryness, and concentrated HNO_3 added to redissolve the sample. The solution was doped with Indium and decanted into plastic tubes for storage in a refrigerator for PIXE and AA analyses within 48 hours.

Analysis of the Dilute Acetic Acid Leachable Fraction. The dried, weighed Nuclepores with the suspended particulate matter deposited on them were placed in acid leached polypropylene Buchner funnels and leached with 25% (v/v) acetic acid poured on top of the filter and, after two hours, drawn through by suction. After adding 500 μl of HCl, the solutions were diluted to 10 ml and analyzed for Cd, Cr, Cu, Fe, Ni, Pb, and Zn by flameless AA.

Analysis of Refractory Fraction. The filter, after the dilute acetic acid leach was placed in an acid leached all-teflon bomb. HCl was added to the bomb, the bomb sealed and heated in a water bath, cooled, and HNO_3 added. The bomb was then heated, cooled, and high purity HF added prior to additional heating and cooling. The contents of the bomb were transferred to a preweighed polystyrene centrifuge tube, doped with In, and analyzed.

AA Analysis. All analyte solutions for every sample type were prepared at the Virginia Associated Research Campus (VARC) and appropriately split between VARC and VIMS for analysis. All flame analyses were performed at VIMS; only flameless at VARC. Sediment leaches were analyzed at VIMS for Cd, Cr, Cu, Fe, Ni, Pb, and Zn. Total sediment digests were also analyzed at VIMS for Cr, Cu, Fe, Ni, and Zn, and at VARC for Cd, Ni, and Pb. Biota was analyzed for Cd, Cu, Fe, and Zn at VIMS and Cr, Ni, and Pb at VARC. All particulate matter analyses were performed at VARC. Splitting of the analyses between VARC and VIMS was done primarily to minimize disruption of flameless operation at VARC as frequent changes from flameless to flame and back are very time consuming because of the problems of instrument alignment, different dilutions and standards, etc.

Hydrocarbons

Analysis of Field Samples. Each type of sample was solvent extracted by a method appropriate for its physical characteristics. Water samples were extracted by a batch liquid-liquid process; sediment samples were saponified and extracted in reflux apparatus. Benthic fauna and zooplankton samples were homogenized, saponified, and extracted with solvent reflux. Surface film samples were saponified and liquid-liquid extracted.

The processing of solvent extracts containing hydrocarbons was common (excepting a few details) for all sample types. Extracts were concentrated by evaporation at low temperature, dried, weighed, and loaded onto liquid chromatography columns.

Liquid Chromatography. All sample analyses listed above arrive at a common final step. The entire sample was loaded onto the liquid chromatograph column if the total extract weight of the sample was less than 5 mg. Otherwise, the sample was diluted to an appopriate volume and then 1 ml, containing about 5 mg of the total extract lipid, was loaded on the liquid chromatograph column.

Columns were standard 10 x 300 mm with coarse glass frit and were packed with a hexane slurry of Bio-Sil® A silica gel (100-200 mesh) activated at 235°C for 16 hours.

Gas Chromatography. A glass capillary system was used for gas chromatography (GC) of all samples reported here. Gas chromatographs were Varian 2700's with direct data outputs to strip chart recorders and a Hewlett-Packard 3352B laboratory data system.

Conditions of GC were:

Injector: Splitless (Grob and Grob 1972)
Injector temperature: 260°C
Detector temperature: 265°C
Column inside diameter: 0.28 mm
Column Length: 20 m
Liquid phase: SE-52
Column flow: 5 ml/min He carrier gas
Column temp. program: 50-240°C at 6°C/min (then hold until C_{32} detected).

Glass capillary columns were coated in this laboratory by the method of Grob et al. (1977). The data system provided a tabulation of retention times and corresponding peak areas for each gas chromatogram. After retention times for hydrocarbons were identified, sample chromatograms were processed manually to identify compounds using GC-MS information. This involves human judgments in treatment of multiple and overlapping peaks. The chromatographic data was then entered into an IBM 370 FORTRAN program which calculates individual hydrocarbon concentrations and concentration ratios.

Compound Identification by Gas Chromatography - Mass Spectrometry. A 21-492-B mass spectrometer (DuPont) with a 21-094B data system, interfaced to a model 2740 (Varian) gas chromatograph modified for wall coated glass capillaries was used. After sample injection and passage of the solvent front, the mass spectrometer was operated in a continuous scan mode, covering the mass range from m/e = 30 to m/e > 550 at 1 sec/decade at a resolution R 10^3. An approximately 20 m long capillary coated with SE-52 liquid phase and an i.d. of 0.32 mm provided the separation. The effluent of the GC column was transferred via a 0.12 mm i.d. platinum capillary, heated to 250°C, directly into the mass spectrometer source. In order to prevent evacuation of the glass capillary, a Henneberg-type interface was employed (Henneberg et al. 1975). Electrons of 70eV in an elecron impact source formed the fragments observed in the mass spectra. Fragment masses were calibrated with a perfluoroalkane mixture. All data were first stored on a magnetic disc and, after analysis, transferred to magnetic tape.

For compound analysis, two different approaches were used. First, the mass spectrum of each peak in the reconstructed chromatogram was generated and printed out if the number of ions was sufficient to generate an intelligible mass-spectrum. This was followed by a preliminary identification of the compound. Second, after the identity of a number of compounds in a particular sample type was known, a systematic search for missing isomers (or other compounds that logically should be present) was performed. This was done by using specific mass-searches and retention data. During the second year the Cyphernet MSSS system was also used.

Chemistry Quality Control

A number of procedures were utilized by both hydrocarbon and trace metal chemists to reduce sample contamination to the lowest possible levels and provide maximum precision and accuracy.

Trace Metals. All reagents used in the laboratory were of the highest purity possible. Water was doubly deionized and triple filtered. Nitric, hydrochloric, and acetic acids were doubly distilled at sub-boiling temperatures in a fused silica still. All reagents were checked for trace metal content prior to use in sample analyses. At least 5% of all analyses were procedural blanks. All glassware was nitric acid washed and rinsed with deionized water.

Calibration of the AA spectrophotometer was performed using at least three standard solutions with concentrations in the linear absorption range. Readings were sequentially replicated at least 4 times during calibration, and at least one was remeasured in the middle and at the end of each group of 10-30 samples.

Precision and accuracy were checked by analyses of bovine liver, USGS rock standards, and master mix aqueous solutions.

Because of the possibility of sample contamination by paint chips aboard ship, paint chip samples were collected from each vessel, analyzed for trace metals and compared with results of other samples.

Hydrocarbons. Great care was taken aboard ship to prevent sample contamination from diesel oil, winch grease, and hydraulic fluid. Sediment samples were collected with an unlubricated grab which was ethanol washed between grabs and covered with a teflon shroud between stations. Surface slicks, if present, were dispensed prior to sampling. Biological samples were placed in wooden buckets until sorted. All samples were eventually placed in solvent washed glass jars with teflon lined lids. During each cruise samples of diesel oil, engine lube oil, winch grease, and hydraulic fluid were taken, and analyzed to assist in the identification of contamination if detected in the sediment biota, or other samples.

In the laboratory, freeze dryer blanks, solvent blanks, extraction blanks, and deionized blanks were analyzed; spikes were also added to samples for determination of procedural recovery efficiency. Each day, a qualitative and quantitative standard was run for both the hexane (aliphatic) and benzene (aromatic) fractions. The standard was used to establish gas chromatographic response curves, and to calibrate retention times.

In addition to the above procedures, actual quality control samples were analyzed by the University of New Orleans. These consisted of separate samples of sediment, zooplankton and benthic organisms, taken by the same methods and contemporaneously with VIMS samples. Other sediment samples were collected, homogenized, and split for intercalibration between VIMS and USGS Reston laboratories.

SIGNIFICANT STUDY FINDINGS

Conceptual Framework

In evaluating the data generated during the two-year Middle Atlantic Study it is convenient to focus on the properties and processes in the pelagic realm (Figure 4) and in the benthic realm (Figure 5). When combined, these two study areas result in an integrated picture of the OCS environment (Figure 6).

The Pelagic Realm

Studies in the water column itself have addressed physical properties, dissolved constituents, zooplankton and suspended matter (seston). Measurements of hydrographic properties (salinity, temperature, dissolved oxygen), nutrients, and dissolved and particulate carbon were made routinely, coincident with benchmark sampling. These data are, of course, useful in interpretation of biological and chemical benchmark data, but have also been used to characterize water masses. Characterization of water masses, coupled with the meteorological observations made routinely during the sampling, allows inferences to be made on major physical processes, such as currents and movement of water mass boundaries, occurring in the Middle Atlantic Bight. Understanding these dynamic physical processes is critical to thorough interpretation of biological and chemical properties in both pelagic and benthic realms.

Studies of the seston of the continental shelf are important in that particulate suspended matter may be an avenue of contamination of the OCS environment. USGS studies in the Middle Atlantic study area were designed to describe the distribution and concentration of seston and to characterize its mineral composition. VIMS investigations focused on analyses of the trace metals and hydrocarbon associated with the particles. Investigations of the living component of the pelagic environment were on two levels, microbes and zooplankton. Microbiological studies aimed at measuring the natural population levels of heterotrophic bacteria and, in comparison, those bacteria which could utilize petroleum hydrocarbon as a food source. Because bacterial populations respond to environmental change quickly, the

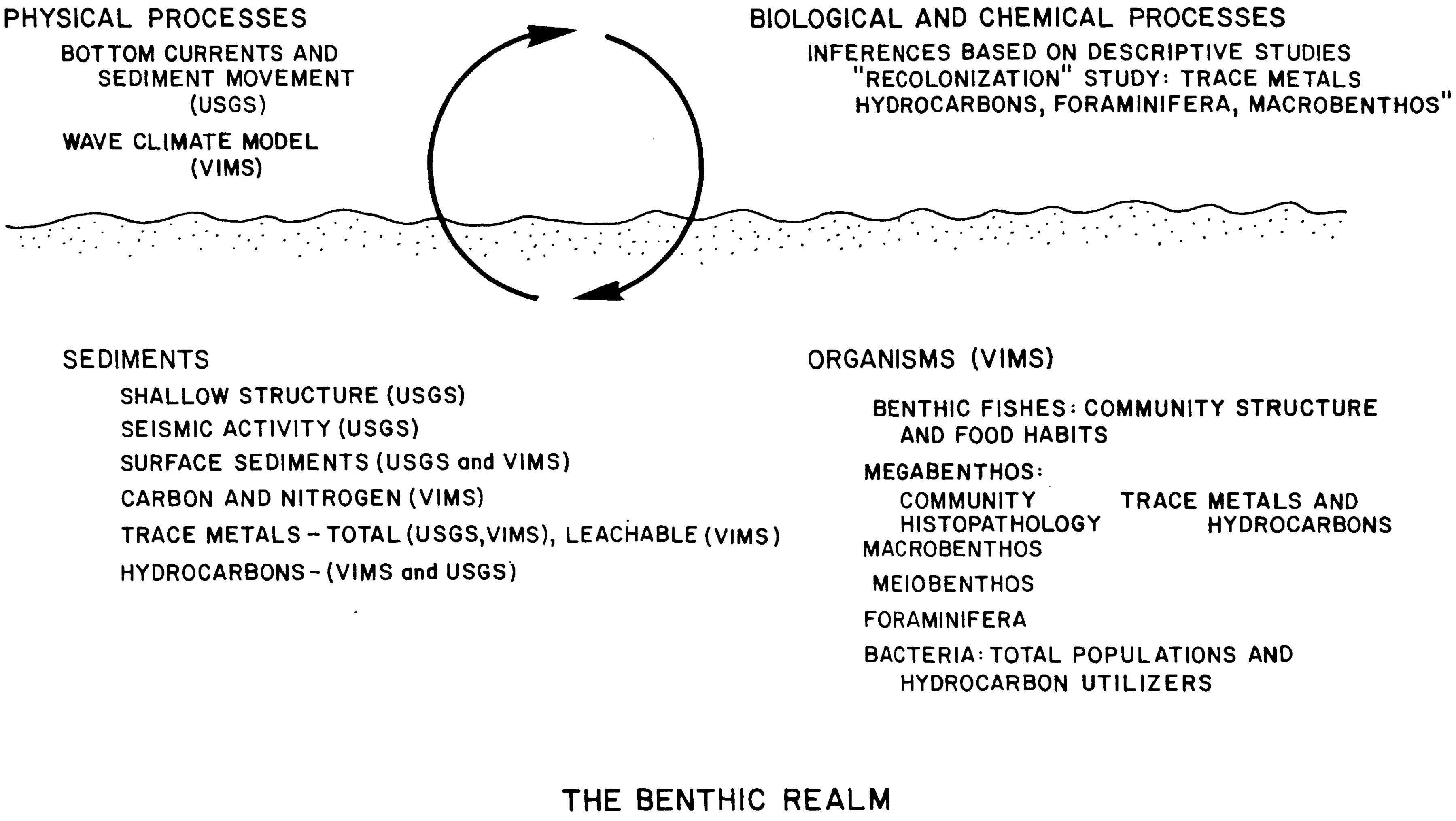
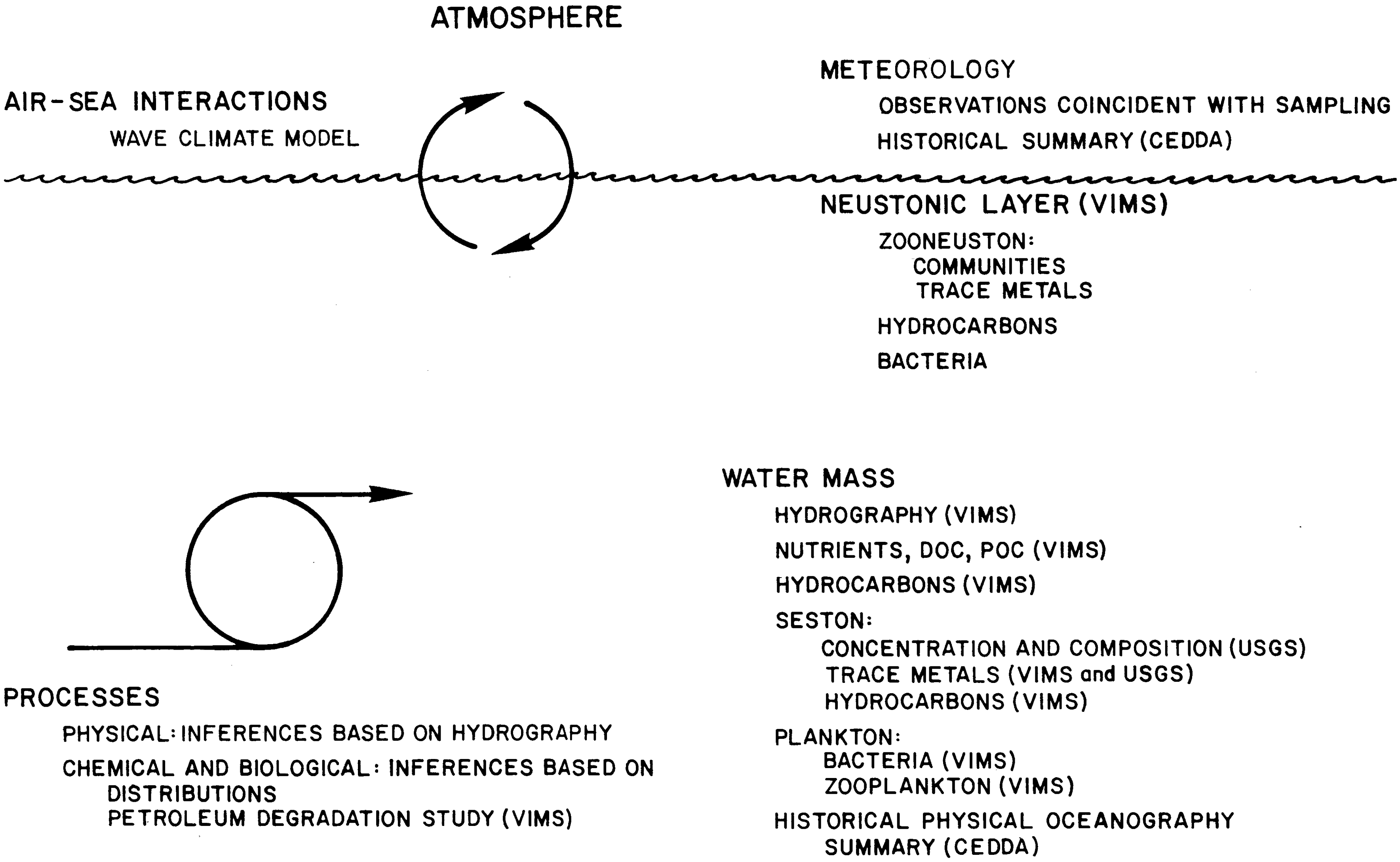


Figure 5. Study components focusing on the Benthic Realm during BLM studies in the Middle Atlantic.



ATMOSPHERE

AIR-SEA INTERACTIONS
- WAVE CLIMATE MODEL

METEOROLOGY
- OBSERVATIONS COINCIDENT WITH SAMPLING
- HISTORICAL SUMMARY (CEDDA)

NEUSTONIC LAYER (VIMS)
- ZOONEUSTON:
  - COMMUNITIES
  - TRACE METALS
- HYDROCARBONS
- BACTERIA

WATER MASS
- HYDROGRAPHY (VIMS)
- NUTRIENTS, DOC, POC (VIMS)
- HYDROCARBONS (VIMS)
- SESTON:
  - CONCENTRATION AND COMPOSITION (USGS)
  - TRACE METALS (VIMS and USGS)
  - HYDROCARBONS (VIMS)
- PLANKTON:
  - BACTERIA (VIMS)
  - ZOOPLANKTON (VIMS)
- HISTORICAL PHYSICAL OCEANOGRAPHY SUMMARY (CEDDA)

PROCESSES
- PHYSICAL: INFERENCES BASED ON HYDROGRAPHY
- CHEMICAL AND BIOLOGICAL: INFERENCES BASED ON DISTRIBUTIONS
  - PETROLEUM DEGRADATION STUDY (VIMS)

THE PELAGIC REALM

Figure 4. Study components focusing on the Pelagic Realm during BLM studies in the Middle Atlantic.

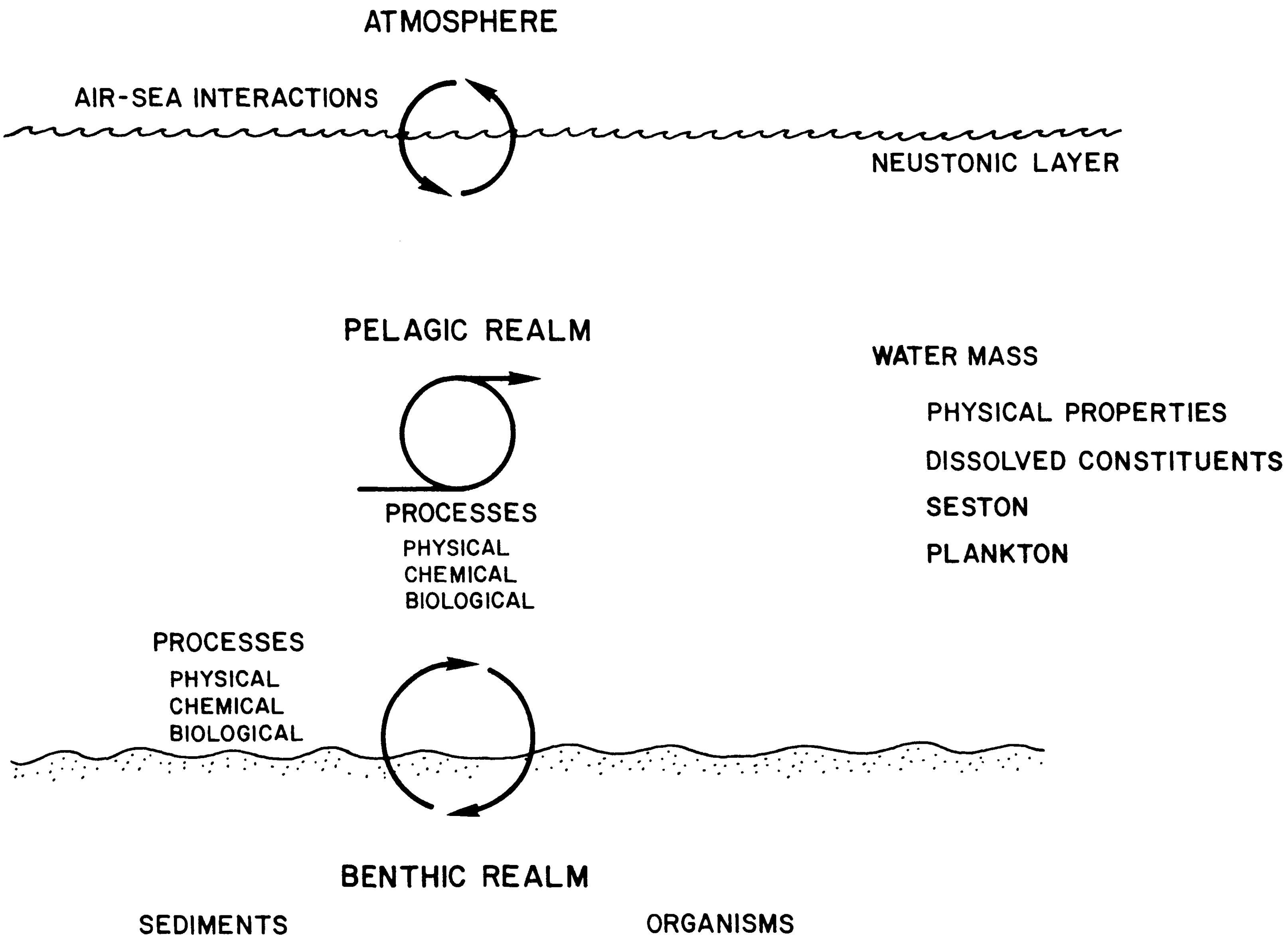


Figure 6. A conceptual depiction of the integrative framework of the first year Middle Atlantic OCS Chemical and Biological Benchmark Studies.

proportion of the bacterial community which can degrade oil may serve as a sensitive indication of petroleum contamination. Zooplankton are important food chain organisms which may play an active role in determining the fate of particulate contaminants in the environment. VIMS studies have been directed at describing zooplankton communities and the levels of hydrocarbons and trace metals found in zooplankton.

A particularly important segment of the pelagic ecosystem is the neustonic layer, defined here as the upper 12 cm of the water column, because many organisms undergo critical life history stages in this habitat. Studies have focused on the zooplankters living in the neustonic layer (zooneuston) and the hydrocarbons and bacterial populations of the surface film.

VIMS studies of the pelagic realm have concentrated on physical, chemical, and biological properties. This work is only indirectly oriented toward determining the processes which affect these properties. Inferences regarding these dynamic processes have been made on the basis of measurements of properties as a part of data interpretation. For instance, diurnal sampling of zooneuston has provided insight into the process of vertical migration. The investigation on the rate of degradation of petroleum by indigenous bacteria is an example of a direct analysis of a dynamic process.

The Benthic Realm

Geological, chemical, and biological studies focused more intensively on the benthic realm. The rationale for this emphasis includes the facts that 1) contamination may be of greater intensity and of longer duration in the benthic environment than in the more voluminous water mass which flows through the shelf environment; 2) the biota is more stationary; and 3) planning of oil and gas development requires knowledge of the structure and stability of the bottom for construction purposes.

Geological studies by USGS have been directed to describing the shallow geologic structure and seismic environment on the Middle Atlantic shelf with the aim of identifying potentially hazardous conditions. In addition, the USGS conducted studies on the physical processes which are responsible for the movement and distribution of bottom sediments on the outer shelf. Model predictions of the wave climate also assist in understanding benthic boundary layer processes influenced by surface waves which may cause sediment movement. The grain size distribution, or texture, of bottom sediments has been extensively investigated by both VIMS and USGS in support of chemical and biological studies. Coordinated studies of the trace metal and hydrocarbon composition of bottom sediments were also performed by both organizations.

Studies of benthic organisms encompassed a wide size range of organisms, from larger animals living on the bottom and captured by dredges and trawls to microbes in bottom sediments. The levels of trace metal and hydrocarbon concentrations in the larger animals were measured, and some species were the subjects of routine histopathologic examination. The distribution of species and communities of foraminifera, meiobenthos, macrobenthos, and demersal fishes, was intensively studied. Heterotrophic bacterial populations were enumerated as was the proportion of these populations which can utilize petroleum hydrocarbons.

As in the case of studies of the pelagic realm, the processes affecting the distributions of chemical and biological properties were not directly measured, and our understanding of these processes must rely on inferences based on these descriptive studies. Research on dynamic processes is generally difficult and should logically follow definition of properties. However, an attempt was made during the second year to measure the process of colonization after catastrophic disturbance.

Findings

The Pelagic Realm

Shelf Hydrography. Physical oceanographic studies were designed to support the biological and chemical studies by characterizing the hydrographic environment in which those samples were taken. Results from fall 1976 through summer 1977 are presented here.

During fall 1976, cooling and vertical mixing of the water column was proceeding from inshore to offshore. A tongue of cold water (11.3°C) was present at the surface apparently moving into the study region from the north (Figure 7). A corresponding band of warm water at the bottom appeared to be associated with a mid-level intrusion from offshore (Figure 8). The fall season was noteworthy due to the absence of the "cold pool", a feature present during fall, 1975 and currently a subject of considerable interest.

The winter of 1976-1977 was much colder than the previous year (Figure 9). The temperature along the inshore part of the study area was 4°C lower in 1977 and isotherms were vertically oriented (Figure 10). Winter salinity values during 1977 were several parts per thousand greater than those during 1976. This may have been a result of the differential runoff during the two years, or an indication of substantial cross-shelf mixing during 1977 as suggested by the small density contrast throughout the region. The oxygen and nutrient values reflect the temperature and salinity data with oxygen decreasing and nutrients increasing seaward across the shelf. Analysis of nutrient patterns indicate the presence of two exchange events which preserve cross-shelf mass transport. These events

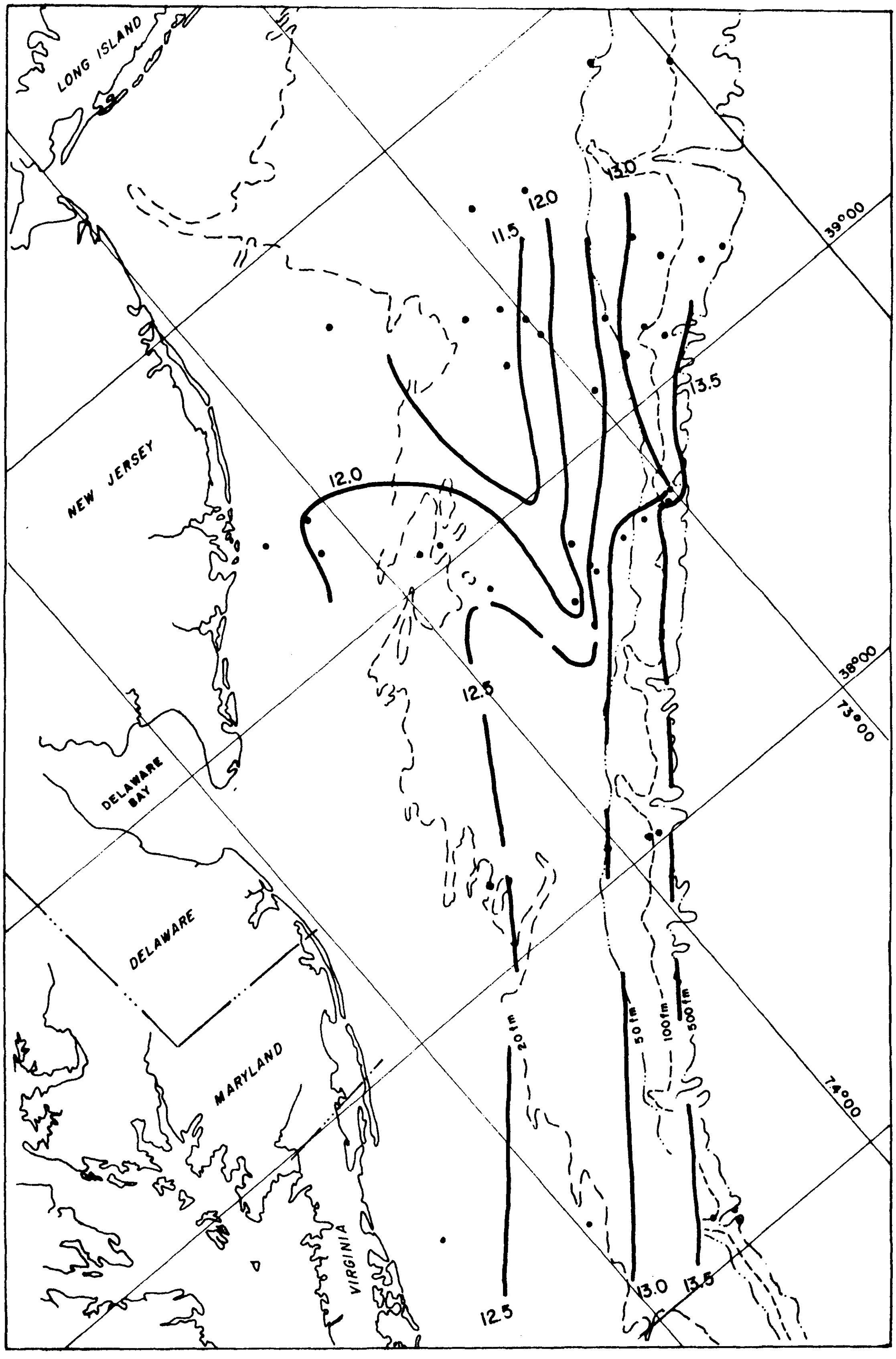


Figure 7. Surface temperature (°C) distributions in the Middle Atlantic Bight during the period 4-18 November 1976 (Cruise BLM05B).

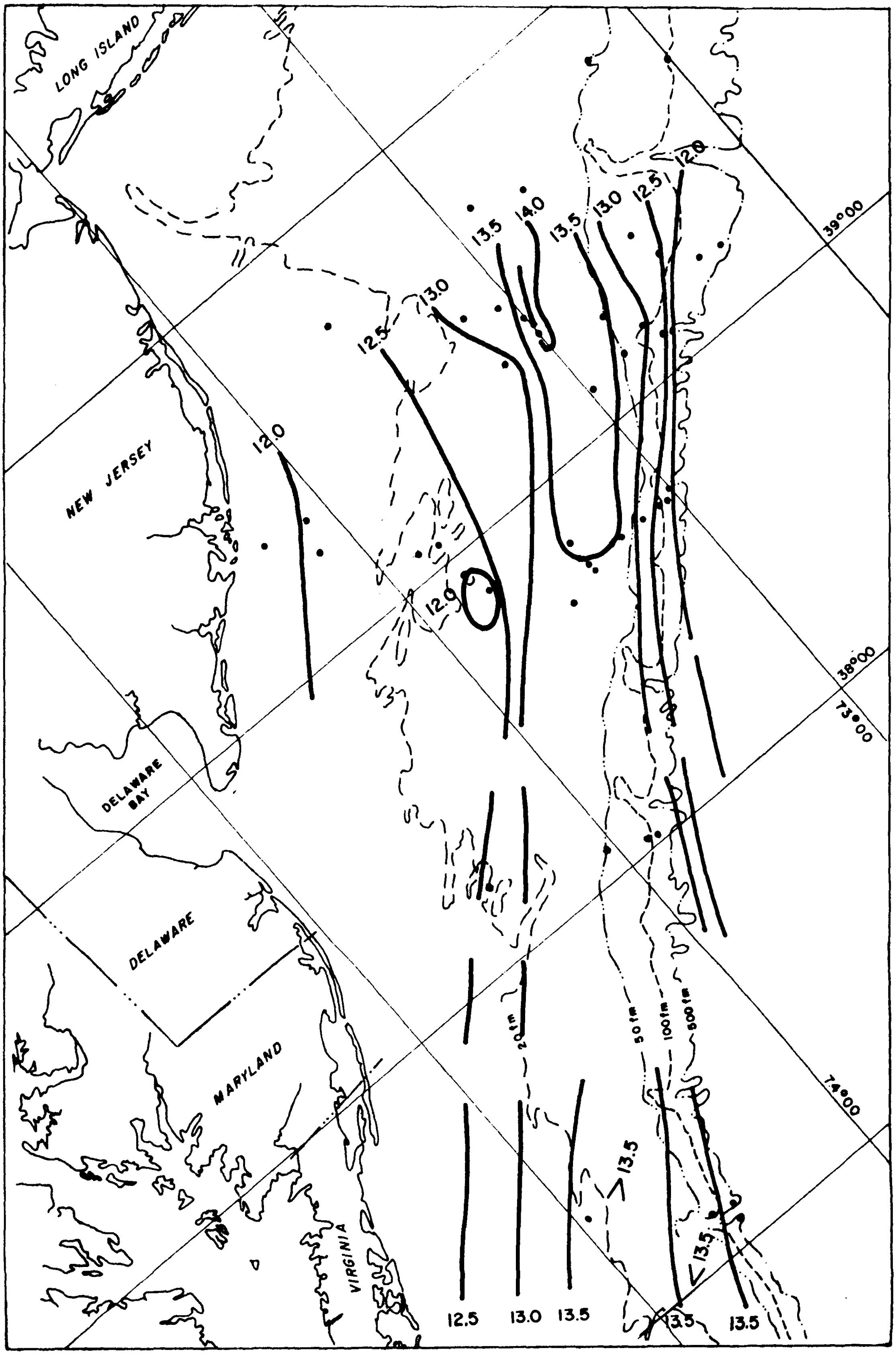


Figure 8. Bottom temperature (°C) in the Middle Atlantic Bight during the period 4-18 November 1976 (Cruise BLM05B).

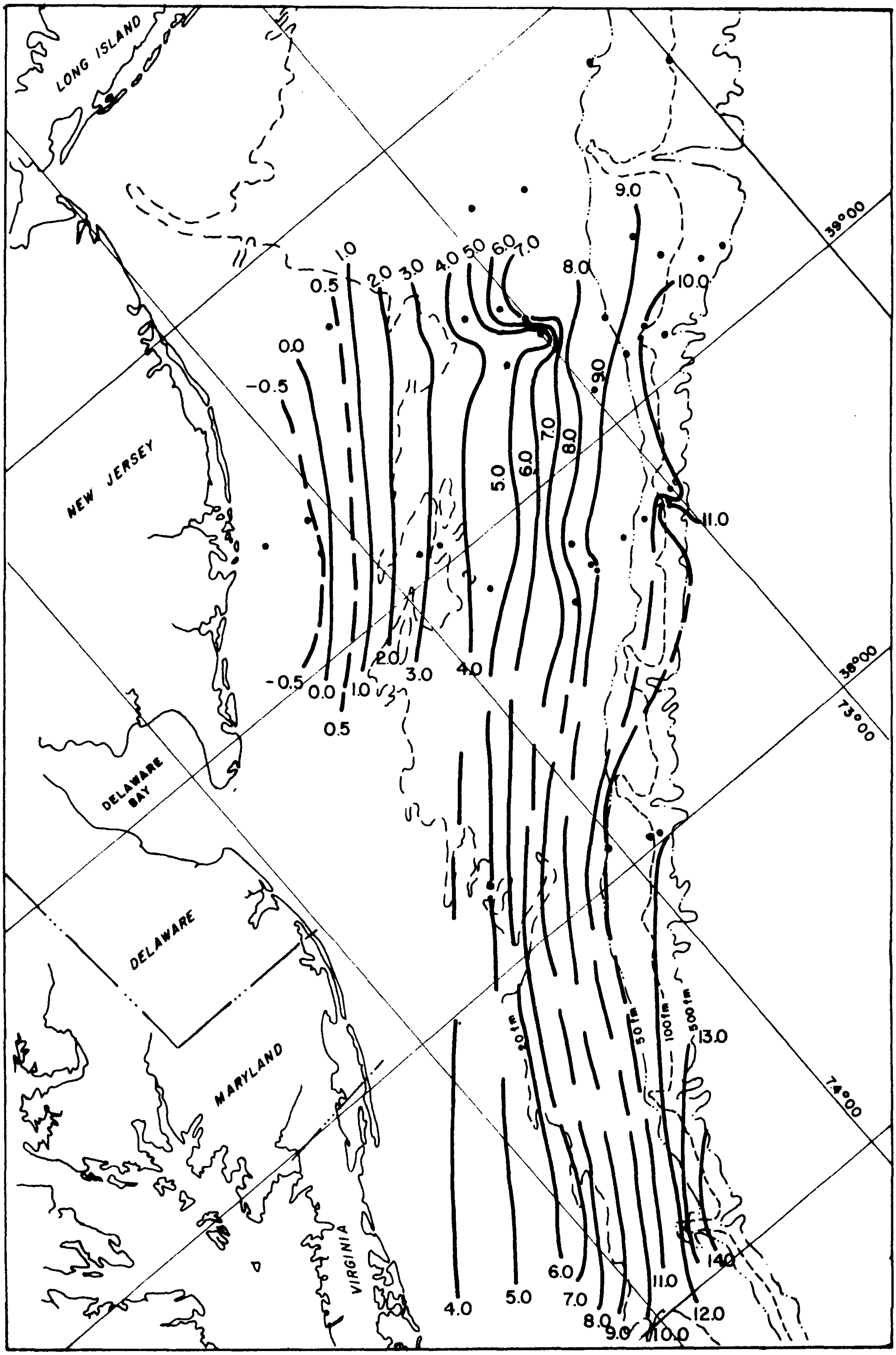
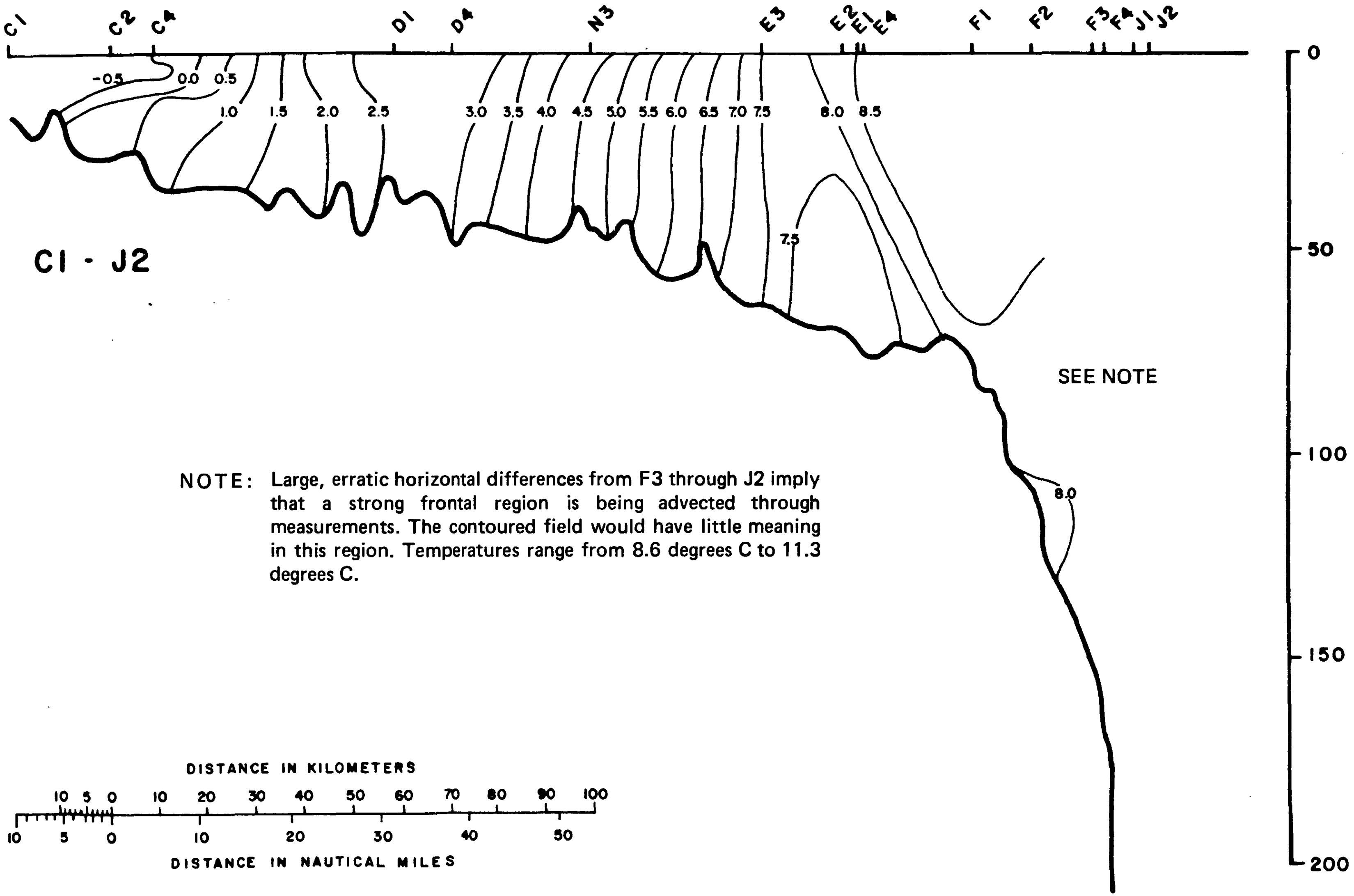


Figure 9. Surface temperature (°C) distribution in the Middle Atlantic Bight during the period 5-17 February 1977 (Cruise BLM06B).



NOTE: Large, erratic horizontal differences from F3 through J2 imply that a strong frontal region is being advected through measurements. The contoured field would have little meaning in this region. Temperatures range from 8.6 degrees C to 11.3 degrees C.

Figure 10. Temperature (°C) contours for section III (Figure 3-6) during cruise BLM06B. Station locations on the section and designations are indicated at the top of the section. Depths are in meters.

include intrusions throughout the water column south of Hudson Canyon and near Baltimore Canyon balanced by an extrusion at Lindenkohl Canyon.

The spring cruise in 1977 was conducted in late May and early June, a period of uniformly calm, fair weather. A very strong pycnocline was present below a mixed layer 10-12 meters deep. The pycnocline had a characteristic summer transverse pattern. A marked temperature minimum in the bottom water ("cold pool") was present with values below 4°C resulting from the extremely cold winter (Figure 11). A Gulf Stream warm core ring was present seaward of the shelf/slope front in the central study area and Gulf Stream water was present from the surface to 100 m.

During summer 1977, the water column was strongly stratified with a well-mixed surface layer, a thin but strong pycnocline at 10 to 15 meters, and a well mixed bottom layer (Figure 12). This was similar to the first year pattern except that the pycnocline was deeper during the first year. This suggests that a summer hydrographic regime is produced each year and is dynamically maintained by large lateral displacements of water independently above and below the pycnocline. The resulting temperature/salinity patterns are complex. The cold pool persisted during summer. A region of low dissolved oxygen was again apparent at inshore stations (Figure 13), but values (<3 mg/l) were not as low as those recorded during the previous year.

Water Mass and Type Analysis. Based on an analysis of temperature and salinity curves such as the agglomeration point analysis presented in the first year report (Ruzecki et al., 1977), the Middle Atlantic Bight can be divided into a number of water types (Figure 14). The most consistent part of the pattern is the high salinity, deep water found eastward of the shelf, and termed slope water. The shelf is covered most of the year by coastal water, but after winter cooling this water is termed winter coastal water. A persistent feature of winter coastal water is called the "cold pool". The mixture of coastal water and slope water near the shelf edge is termed shelf-slope water. Occasionally, high salinity, high temperature water is encountered which has its source in the Gulf Stream and occurs near the shelf edge during passage of warm core Gulf Stream eddies. Some lateral mixing appears to occur between coastal water and Gulf Stream water, and this region of the temperature-salinity plane has been termed shelf-Gulf Stream water.

Subsurface Zooplankton. The principal separation of samples across the shelf from the two sampling years was not by season, but by location. Three distinct communities were generally present (Figure 15), but were most apparent during summer and fall: 1) a coastal community, presumably associated with the Coastal Boundary Layer, 2) a central-outer shelf community, and 3) a shelf-edge/slope community.

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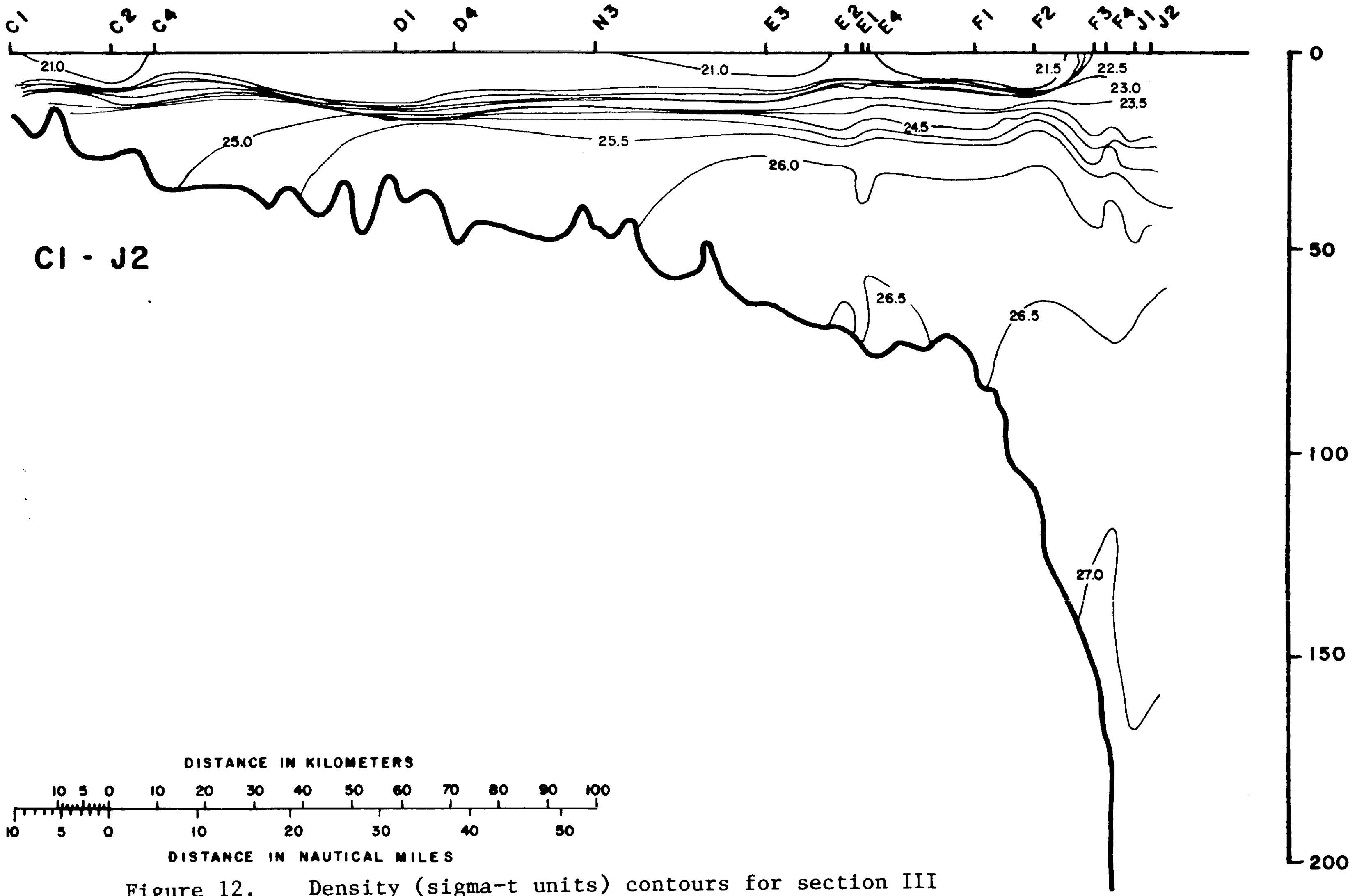

Figure 12. Density (sigma-t units) contours for section III (Figure 3-6) during cruise BLM08B. Station locations on the section and designations are indicated at the top of the section. Depths are in meters.

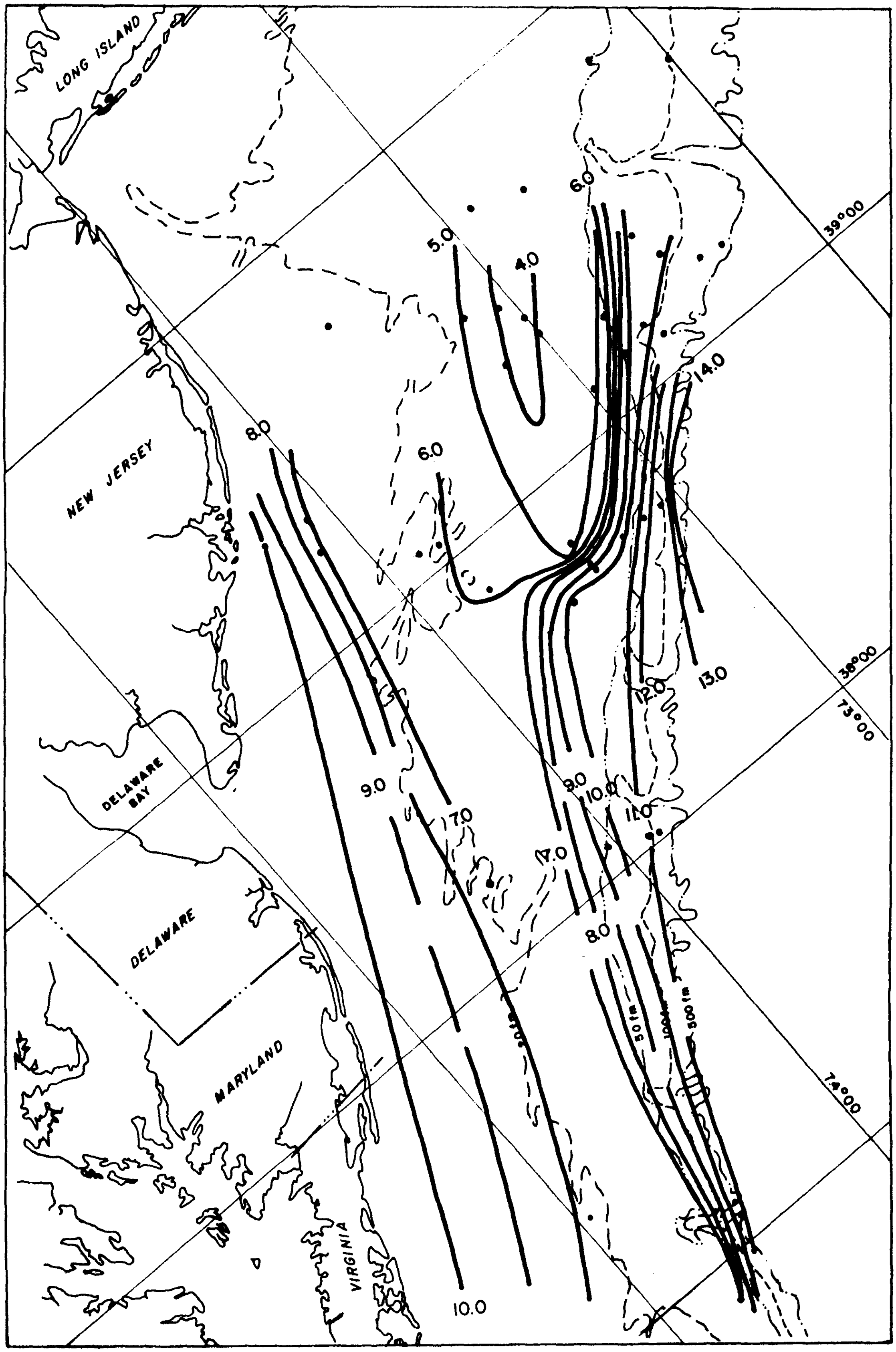

Figure 11. Bottom temperature (°C) distribution in the Middle Atlantic Bight during the period 30 May to 5 June 1977 (Cruise BLM07B).

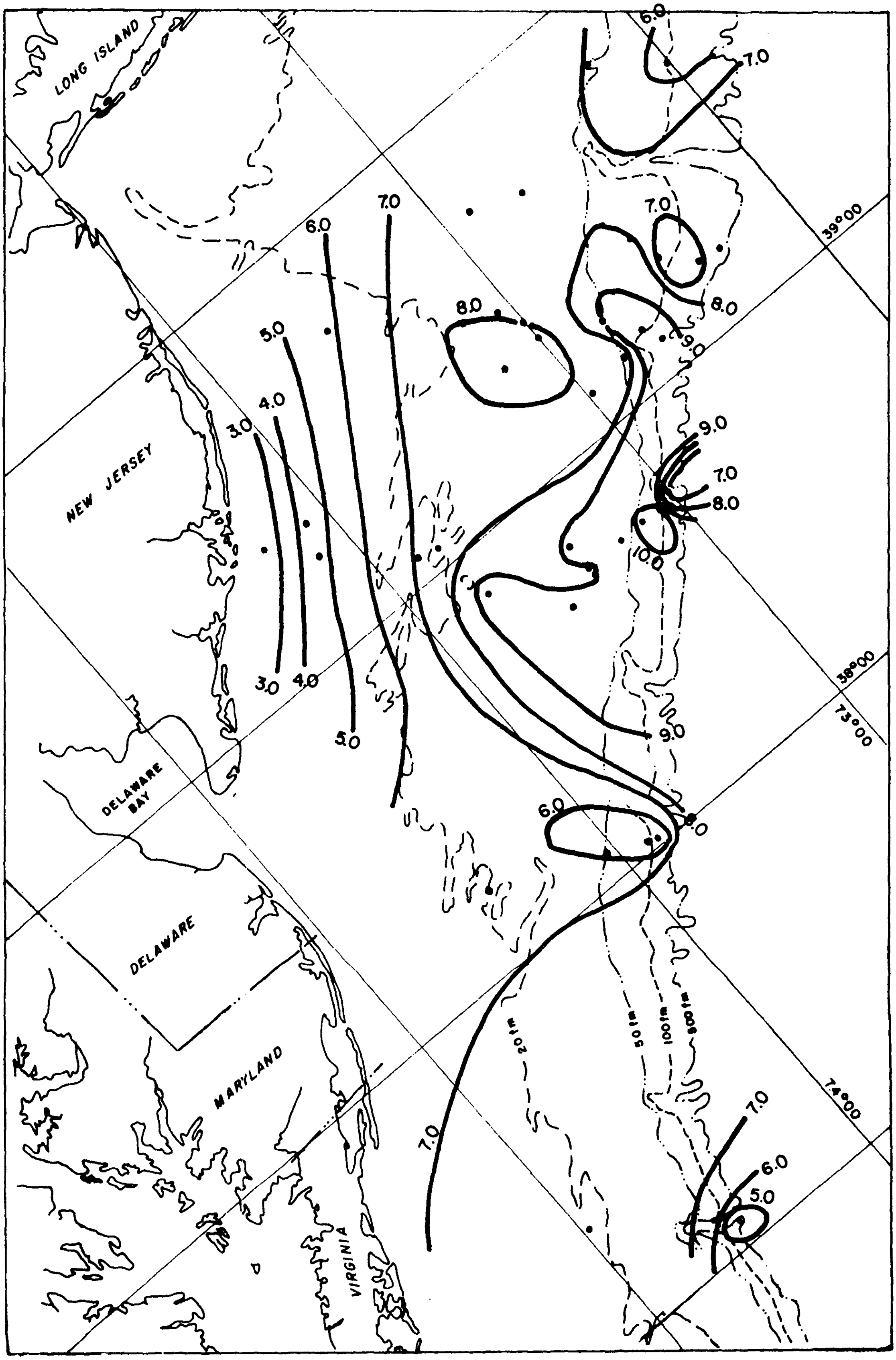

Figure 13. Bottom dissolved oxygen (mg/l) distribution in the Middle Atlantic Bight during the period 4-16 August 1977 (Cruise BLM08B).

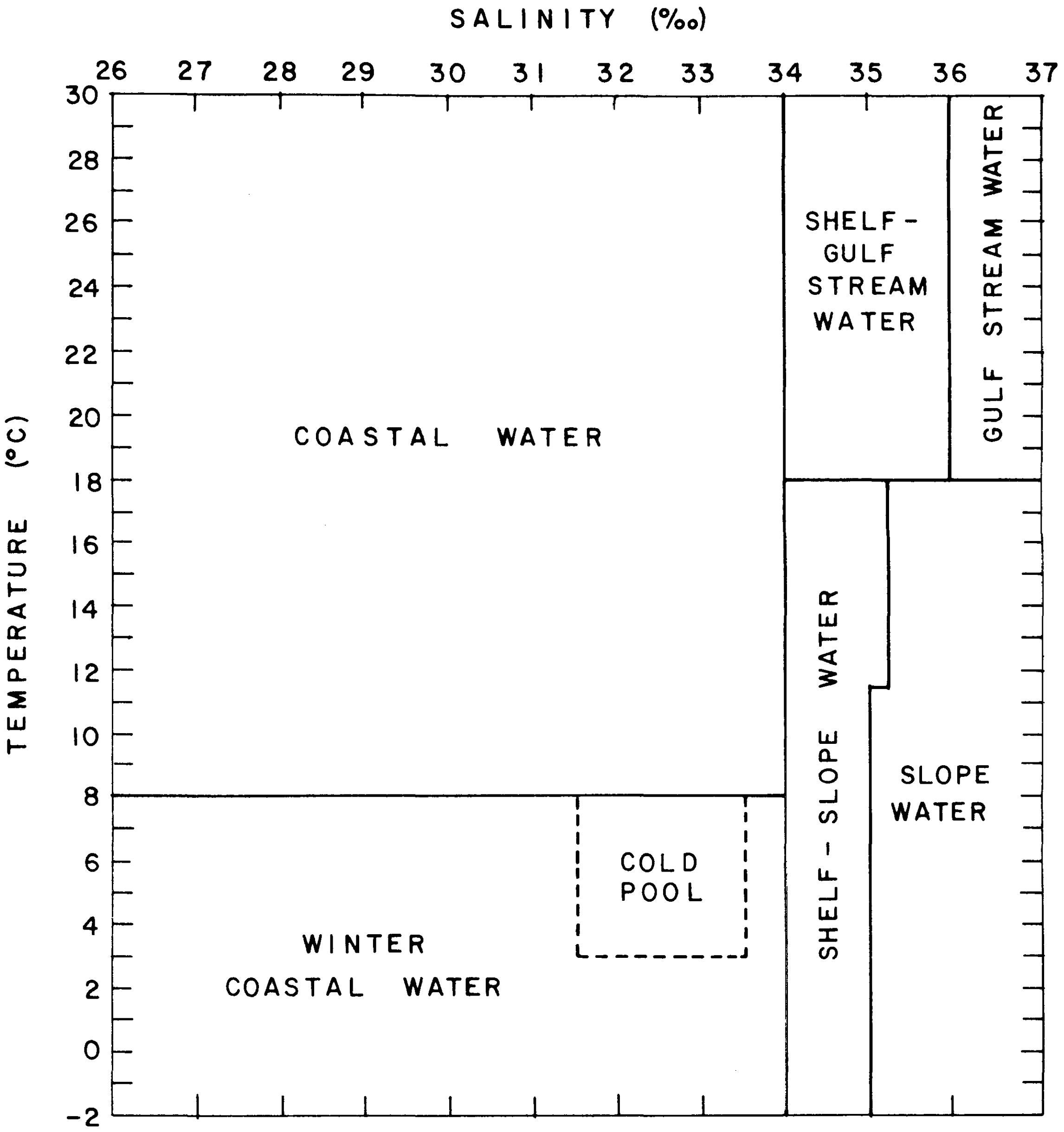

Figure 14. Water mass identification diagram used to interpret data on the Mid Atlantic Bight. Water mass labels are shown within the regions for which they are applicable.

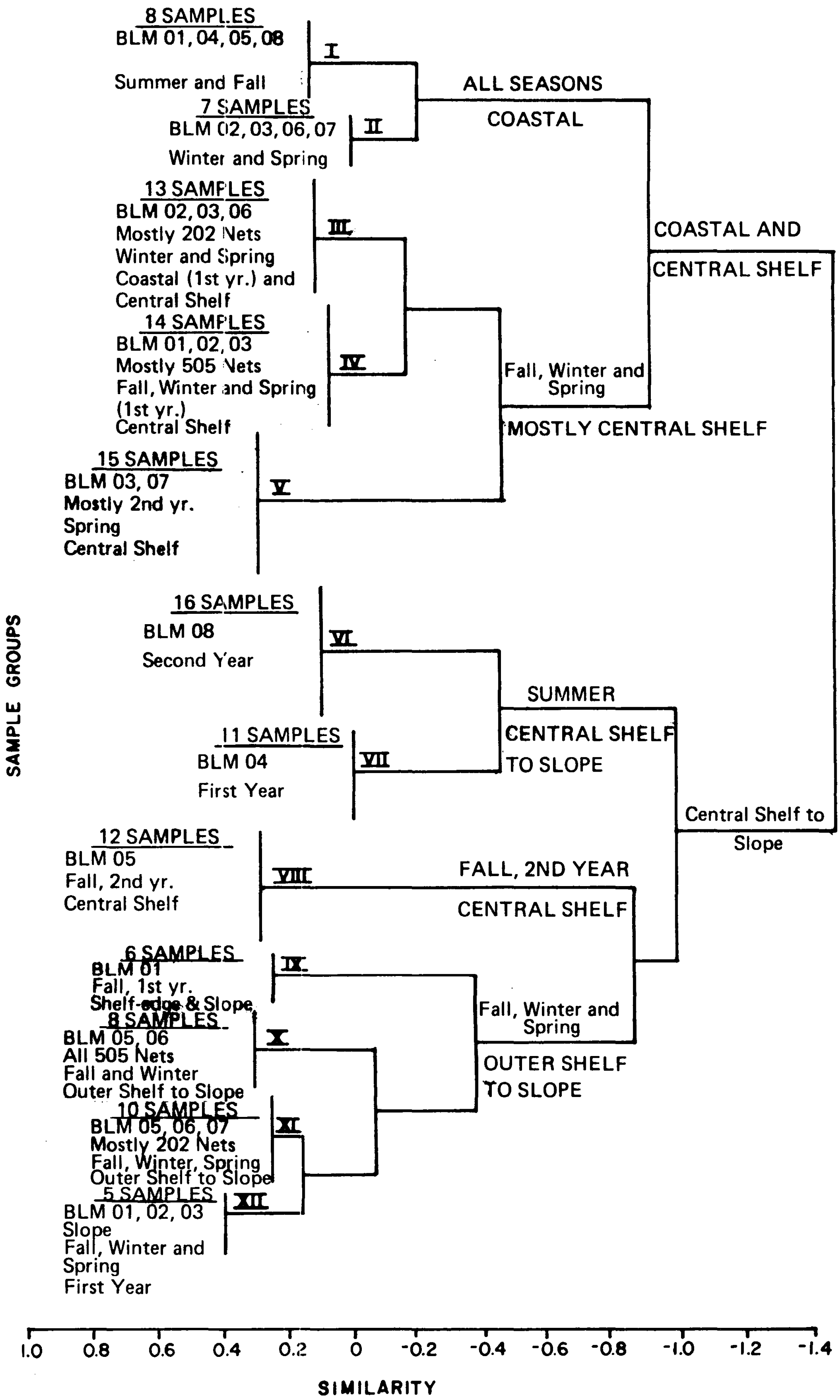

Figure 15. Bongo sample clusters, BLM01W-BLM08W (two years), southern New Jersey transect. Based on the Bray-Curtis coefficient, all identified species occurring in at least 5% of the samples, and catch data standardized to numbers per $100m^3$.

The coastal community was continuous throughout the Middle Atlantic Bight and was always distinct from shelf communities. Species composition alternated semiannually with the copepods, *Acartia tonsa* and *Labidocera aestiva*, and the chaetognath, *Sagitta tenuis* dominant during summer and fall, and the copepods, *Centropages hamatus* and *Temora longicornis*, and the shrimp *Crangon septemspinosa* dominant during winter and spring. Unlike the coastal community, the shelf community differed strongly between the two sampling years, especially during spring and summer. During the first year (1975-1976) and fall and winter of the second year, the dominant copepod on the shelf was *Centropages typicus*. However, during spring and even into summer of 1977, *Calanus finmarchicus* was the dominant copepod. This species and other members of the typical northern (Gulf of Maine) community were widespread across the shelf during spring, a direct result of the cold winter on the southern extent of this community. During summer 1977 the shelf fauna was also quite different from the first year with an increase in decapod and fish larvae, and the presence of a group of warm-water species including the cladocerans, *Evadne spinifera* and *Penilia avirostris*, the copepods, *Temora stylifera* and *Lestrigomus bengalensis*, and the chaetognath, *Sagitta enflata*. The shelf-edge/slope community consisted of the copepods *Pleuromamma* spp., euphausiids, and the chaetognaths *Eukrohnia hamata* and *Sagitta hexaptera* all present from fall through spring in both years. In addition, during the same period of the second year, typically subtropical species occurred including the annelid worm *Tomopteris planctonis*, ostracods, the copepod *Euchirella rostrata*, the decapods *Sergestes arcticus*, and *Solenocera* sp., and the chaetognath, *Sagitta helenae*. Thus only at the coastal stations was the species composition predictable from year to year. Shelf and slope assemblages depended on temperature patterns, intrusions of offshore water, or passage of anticyclonic Gulf Stream eddies.

Neuston. Neuston collections off New Jersey illustrated a progressive change from a highly structured and predictable pattern in coastal waters to a relatively unpredictable faunal structure at the shelf edge. A distinct coastal community was present each season, but the species composition changed with season and the two years were somewhat different except in winter. A distinct Coastal Boundary Layer community was always present at Station C1 although species composition changed with season and the two years were somewhat different except in winter. Annual differences are at least partially attributable to the very cold winter of 1976. Dominant species in the winter included the copepods *Centropages hamatus*, *Pseudocalanus* sp. and *Temora longicornis*, barnacle larvae, and sand lance (*Ammodytes* sp.) larvae. Spring 1977 fauna was similar to the winter fauna, but the spring 1976 community was dominated by bivalve and crustacean larvae. Coastal neuston in the two summers differed mainly by the presence in 1977 of large numbers of salps and the retention of certain cold-winter species such as *Temora longicornis*. The 1976 summer community was dominated by the cladoceran *Evadne tergestina*, chaetognaths, *Sagitta* spp., and inshore fish and decapod crustacean larvae. Fall collections also differed between years, with 1975 characterized by the ctenophore, *Beroe ovata*, and the isopod, *Idotea metallica*, and 1976 dominated by the copepod, *Centropages furcatus*, the mysid, *Mysidopsis bigelowi*, and the chaetognath, *Sagitta enflata*. Despite these yearly differences, it should be stressed that overall similarity was closer between samples from a given season (e.g. winter 1976 and winter 1977) than between different seasons of the same year (Figure 16).

Shelf and slope communities were not as structured as the coastal community and species assemblages depended on intrusions of offshore water, or passage of Gulf Stream eddies. Common summer shelf neustonts included the cladoceran, *Penilia avirostris*, the copepods, *Labidocera aestiva* and *Pontella meadii*, the isopod, *Idotea metallica*, and the amphipod, *Lestrigonus bengalenses*. Winter and spring collections were dominated by the copepods, *Centropages typicus* and *Calanus finmarchicus*. The slope community was dominated by the common offshore, warm-water copepods, *Labidocera acutifrons*, *Pontella meadii*, and *Temora stylifera*, the isopod, *Idotea metallica*, the chaetognaths, *Sagitta enflata* and *S. helenae*, the pteropods, *Atlanta* spp., *Cavolina* spp., and *Limacina* spp., and various amphipods.

Although annual differences did exist, two years of neuston collections have confirmed the importance of the surface layer as a nursery habitat for reproductive stages of Middle Atlantic Bight decapod crustaceans and fishes. These were often numerically dominant in spring and early summer. Any widespread degradation of the surface layer during this annual reproductive peak could have a serious effect on survival and recruitment of many commercially and trophically important species, including squids, *Loligo* and *Illex*; blue crab, *Callinectes sapidus*; rock and Jonah crabs, *Cancer* spp.; American lobster, *Homarus americanus*; deep sea red crab, *Geryon quinquedens*; hakes, *Urophycis* spp.; silver hake, *Merluccius bilinearis*; bluefish, *Pomatomus saltatrix*; dolphin, *Coryphaena hippurus*; mullet, *Mugil curema*; Atlantic mackerel, *Scomber scombrus*; Atlantic bonito, *Sarda sarda*; butterfish, *Peprilus triacanthus*; black sea bass, *Centropristes striata*; and yellowtail flounder, *Limanda ferruginea*; all of which are neuston dependent for the development of young.

Dissolved and Particulate Hydrocarbons. Dissolved and particulate hydrocarbons were sampled simultaneously by passing water through a glass-fiber filter into a storage bottle. Material collected on the filter pad was classified as particulate; material passing to the bottle was considered dissolved. Dissolved aliphatic hydrocarbon concentrations from fall 1976 through summer 1977 ranged from 0.004-114 μg/l; dissolved aromatic hydrocarbon concentrations ranged from 0.012-259 μg/l. No seasonal trends were detected and no systematic relationship between surface and bottom values occurred. Neither an onshore-offshore nor a north-south trend was observed. Water mass type had no apparent correlation with dissolved hydrocarbon content. The ratio of total dissolved hydrocarbon concentration to

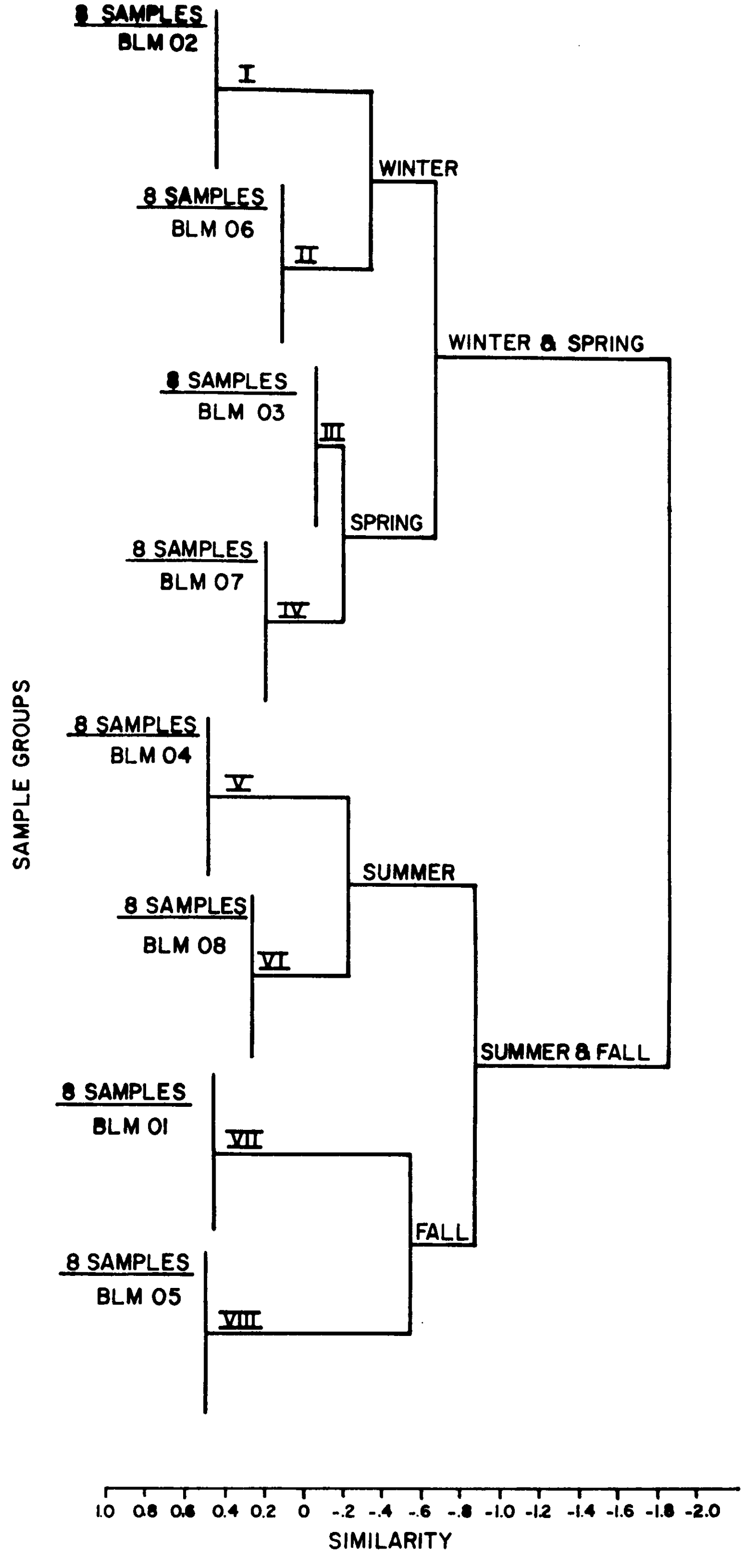

Figure 16. Neuston sample clusters, BLM01W-BLM08W (two years), station C1. Based on the Bray-Curtis coefficient, all identified species occurring in at least 5% of the samples, and catch data standardized to 20-min. tows.

dissolved organic carbon concentration was highly variable from station to station and season to season, and thus the two parameters were not closely related.

Particulate aliphatic hydrocarbon concentrations from fall 1976 through summer 1977 ranged from 0.001-1.88 μg/l; particulate aromatic hydrocarbon concentrations ranged from 0.001-0.02 μg/l. Concentrations in spring and summer samples were generally higher than fall and winter samples suggesting a seasonal trend. Trends between surface-bottom, north-south, onshore-offshore, or hydrocarbon concentration-water mass type were not observed. As for dissolved hydrocarbons, no correlation was present between particulate hydrocarbon concentration and particulate organic carbon.

Zooplankton and Hydrocarbons. Zooplankton samples formed copious emulsions during extraction, and the presence of large amounts of lipid material masked individual aromatic hydrocarbon compounds during analysis. Aliphatic compounds, however, were identified. Concentration of aliphatic hydrocarbons in zooplankton ranged from 2.0-3218 μg/g, those of aromatic hydrocarbons ranged from 2.2-650 μg/g, and those of total hydrocarbons from 2.2-3387 μg/g. Zooplankton from the closest inshore stations, C1 and L1, had consistently lower aliphatic hydrocarbon concentrations than samples from further offshore. The percentage of pristane was also consistently lower in nearshore samples. Zooplankton species composition at stations C1 and L1 was different from that at offshore stations and this may account for the differences in hydrocarbon concentration. Concentrations of aliphatic hydrocarbons were considerably higher in zooplankton from the northern transects A-B and C-J collected during spring and summer 1977 (cruises 07 and 08) than from fall and winter samples (cruises 05 and 06). Apparently this was due to the predominance of a typical northern *Calanus* community which penetrated the Middle Atlantic Bight in spring and remained abundant through summer. The *Calanus* community, known to be richer in hydrocarbons (Lee and Hirota 1973), replaced the normally dominant *Centropages* community found from fall 1975 through winter 1977 (cruises 01-06).

Bacteria. Significant microlayer enrichment of heterotrophic or petroleum-degrading bacteria was not observed relative to subsurface samples when considering all samples collected during the two year study period. However, individual samples occasionally indicated enrichment of petroleum-degrading bacteria in the microlayer. Microlayer samples were dominated by the genus *Pseudomonas*, with *Alcaligenes* and *Vibrio* subdominant.

Viable counts of both heterotrophic and petroleum-degrading bacteria in surface (-1m), thermocline, and bottom water samples from both sampling years generally decreased seaward across the shelf (Figure 17). Exceptions to this basic pattern occurred occasionally over the two year period, usually at Station F2. This station is close to the highly mobile frontal zone between shelf and slope water

05B

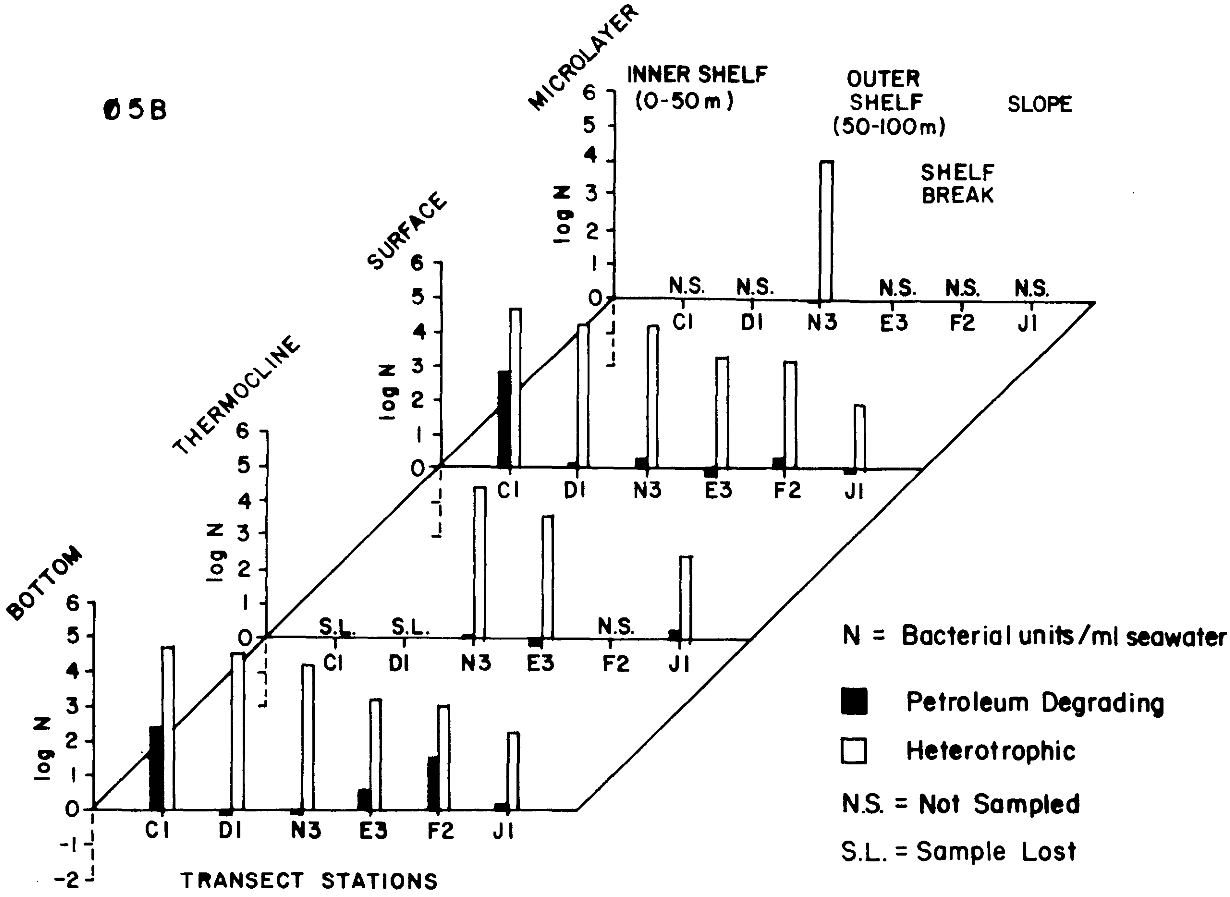

Figure 17. Viable counts of petroleum-degrading and heterotrophic marine bacteria from microlayer and water column samples collected at stations along the New Jersey transect, Fall 1976.

and, depending on front location, may be in an area of upwelled nutrient rich slope water. Consistent correlations of bacterial counts with inorganic nutrients were not found, however.

Statistical analyses indicated no significant differences in heterotroph or petroleum-degrading bacteria counts between surface and bottom water, and no consistently significant relationship between bacterial data and physical chemical parameters.

ATP concentrations in water samples generally decreased with depth and distance from land. However, during the severe winter of 1976-1977 surface ATP levels at some stations fell below corresponding bottom water values. ATP levels are an indication of biological biomass, but not necessarily bacterial biomass.

More than 90% of the isolates identified from subsurface samples were assigned to the genera *Alcaligenes*, *Flavobacterium*, *Pseudomonas*, and *Vibrio*. The generic composition was not influenced by season.

Particulate Trace Metals. General concentrations for all metals and their form in the water column are listed in Table 10. Concentrations of Ba and V were low and these metals were not well quantified above blank levels. Cd, Pb, and Zn were found mainly in the leachable fraction, while Cr and Fe were refractory (unleachable).

Surface and bottom particulate trace metal concentrations generally decreased seaward across the shelf. Several exceptions occurred, however, in near bottom samples where fine sediments had been resuspended by storms. Thus, near bottom concentrations at most stations were greater than corresponding surface values during fall and winter, but not during spring and summer.

There was no clear relationship between water mass type and particulate trace metal levels, other than higher concentrations in the coastal boundary layer.

Trace Metals in Zooplankton/Neuston. Trace metal levels in zooplankton were highly variable and no temporal or spatial trends were apparent nor was any trend observed with species composition. Typical values are given in Table 11. High titanium levels, not normally found in zooplankton, indicate the presence of suspended sediments in zooplankton collections and this may account for much of the trace metal variability.

No temporal or spatial trends were observed in neuston trace metal data (primarily *Idotea metallica*), but the small number of samples and high variability hindered interpretation.

No correlations were found between particulate matter trace metal concentrations and zooplankton trace metal concentrations.

Table 10. General concentrations and percent of metals in leach or refractory fraction of particulate matter.

Metal	General Concentrations (µg/l sea water)	Metal Form
Ba	<0.4	refractory analysis only
Cd	<0.01	>95% leachable
Cr	<0.1	>90% refractory
Cu	<0.6	>40% leachable
Fe	<90	>80% refractory
Ni	<0.1	>40% leachable
V	<0.4	refractory analysis only
Pb	<0.3	>80% leachable
Zn	<1.0	>70% leachable

Table 11. 202 µ zooplankton metal concentrations, Station A2, fall 1976 (n = 4)(ppm dry weight).

Metal	Concentration Range
Ba	<30
Cd	2.9 - 6.1
Cr	0.6 - 2.2
Cu	9 - 11
Fe	130 - 280
Ni	2.2 - 5.1
Pb	49 - 130
V	<10
Zn	110 - 180

The Benthic Realm

Bottom Sediments.

I. Granulometry. The continental shelf of the Middle Atlantic Bight is topographically complex and is covered by sandy palimpsest sediments which reflect both ancient sources and contemporary redistribution. Although the scale of spatial variation in sedimentary parameters is essentially continuous, the widespread system of ridges and swales with spacing on the order of one kilometer particularly affects the distribution of sediments. Bottom currents due to surface waves and meteorological forcing are important in resuspending sediment over most of the shelf, which prevents the accumulation of the scarce silt and clay.

Analysis of sediments from 52 stations show the predominance of medium and coarse sand over much of the shelf and muddy finer sands in the shelf break region, grading into predominantly silt and clay sediments on the slope. Silt and clay were scarce at shelf stations except in topographic depressions and at the shelf break where this component makes up 5-10% of sediments. The sand component of the sediments tended to be finer in topographic depressions, at the shelf break, and off the southern Delmarva Peninsula.

Organic carbon content was closely related to the distribution of silt and clay. Thus, organic carbon concentrations were very low (<1 mg/g) over most of the shelf, but higher (1-2 mg/g) in topographic depressions and at the shelf break. Still higher concentrations (to 10 mg/g) were found in muddy slope stations. Nitrogen concentrations were variable, but correlated with organic carbon concentrations. The lower carbon:nitrogen ratios in clean sand suggests that living organisms comprise much of the organic material in these sediments.

Variability in grain size distribution and carbon content both among replicate and seasonal samples was low at most stations. Instances of apparently great seasonal variability could be explained in terms of variability in station location or extreme patchiness in the local distribution of sediments.

Habitats recognized on the basis of the distribution of benthic organisms in two topographically complex outer shelf regions were also clearly distinguished by distribution of grain size and organic carbon parameters. This emphasizes the strong relationship among shelf topography and resulting hydraulic regimes, sediment grain size distribution, sediment chemistry, and biota.

II. Trace Metals. The metals analyzed were Ba, Cd, Cr, Cu, Fe, Ni, Pb, V, and Zn. Generally, leachable concentrations increased seaward across the shelf (Figure 18) and were greater in topographic depressions, except for Ba, V, and Cd, which occurred in concentrations too low to determine trends. Another exception was the anomalously high values at stations C4 and D4, especially for Cr, Pb, and Zn. Total metal concentrations also tended to increase seaward across the shelf, but the trend was not as apparent as for leachable metals. Ba concentrations were actually fairly uniform across the shelf. No seasonal differences were observed in either leachable or total concentrations, and values were similar over the two year study period.

Significant positive correlations were observed among most leachable metals, total organic carbon, nitrogen, and the silt-clay sediment fraction (Figure 19). Low correlations of Ba, V, and Cd with sediment parameters is a result of the near detection limit levels of these metals. The increase in metal concentration seaward across the shelf is due to increased silt/clay content of offshore sediments.

III. Hydrocarbons. Concentrations of both aliphatic and aromatic hydrocarbons in sediments averaged less than 1 $\mu g/g$ during the two year study period. Both aliphatic and aromatic levels correlated strongly with the amount of silt-clay in the sediments, thus, like trace metals, concentrations tended to increase seaward across the shelf, and were also greater in topographic depressions due to the increase in fine sediments (Table 12). Sediment hydrocarbons contained characteristic n-paraffins, biogenic olefins, and polynuclear aromatics, but there was no evidence of extensive petroleum contamination of sediments.

Benthic Fauna.

I. Bacteria. Petroleum degrading and heterotrophic marine bacteria were consistently isolated over the two year study period. Mean viable counts of both petroleum-degrading and heterotrophic bacteria from inner shelf sediments were significantly greater than counts from mid or outer shelf or shelf-break sediments, except during winter 1977 when very cold water nearshore suppressed bacterial populations (Table 13). However, within each region, viable counts were remarkably consistent from season to season. Mean counts of petroleum degrading bacteria in sediments were generally 2-4 orders of magnitude smaller than viable counts of heterotrophs at the same location.

Maximum values of the ratio of petroleum-degrading to heterotrophic bacteria were always encountered in inner shelf

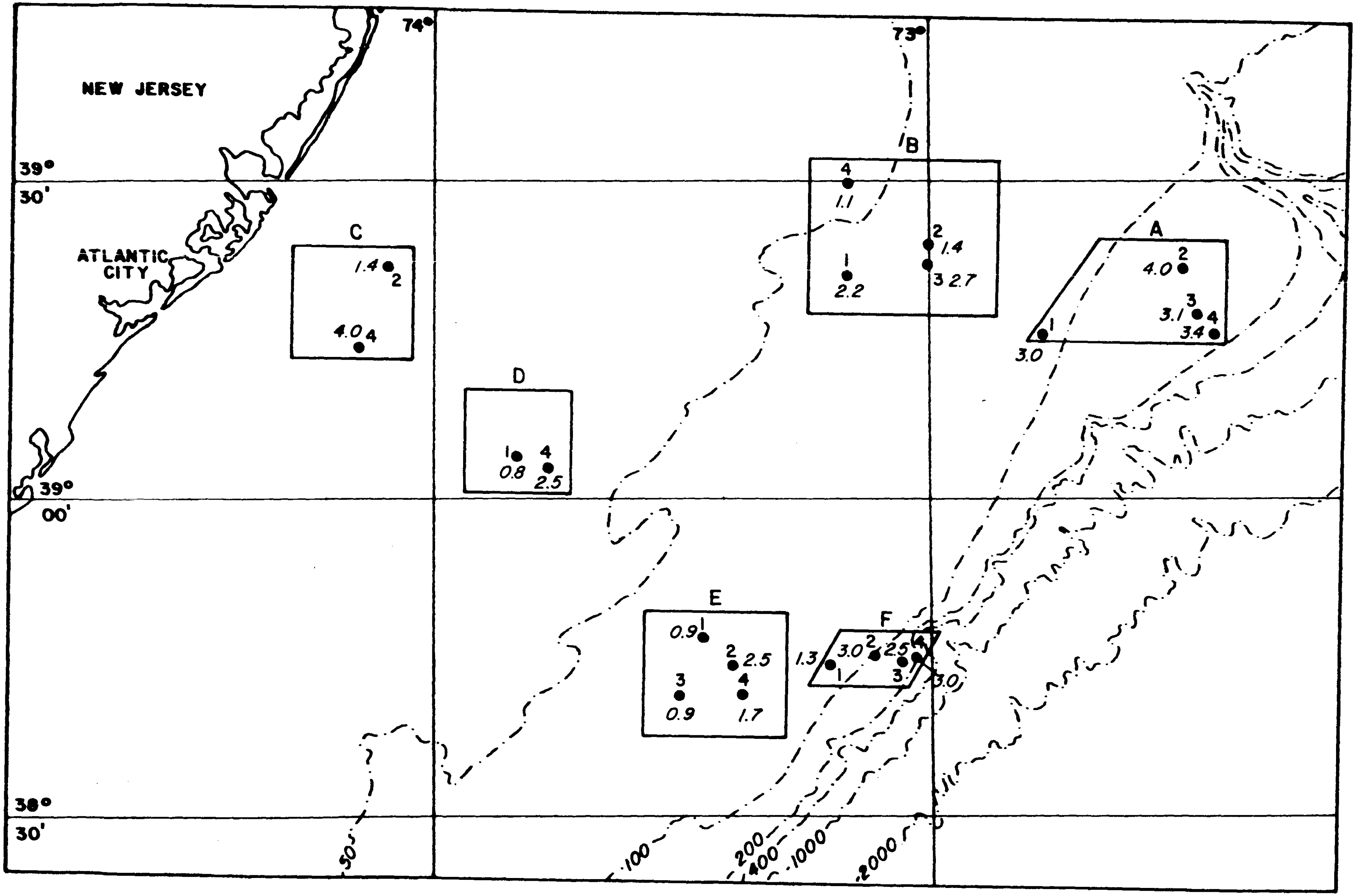

Figure 18. Leachable Cr in ppm dry weight for superblends, cruise 06.

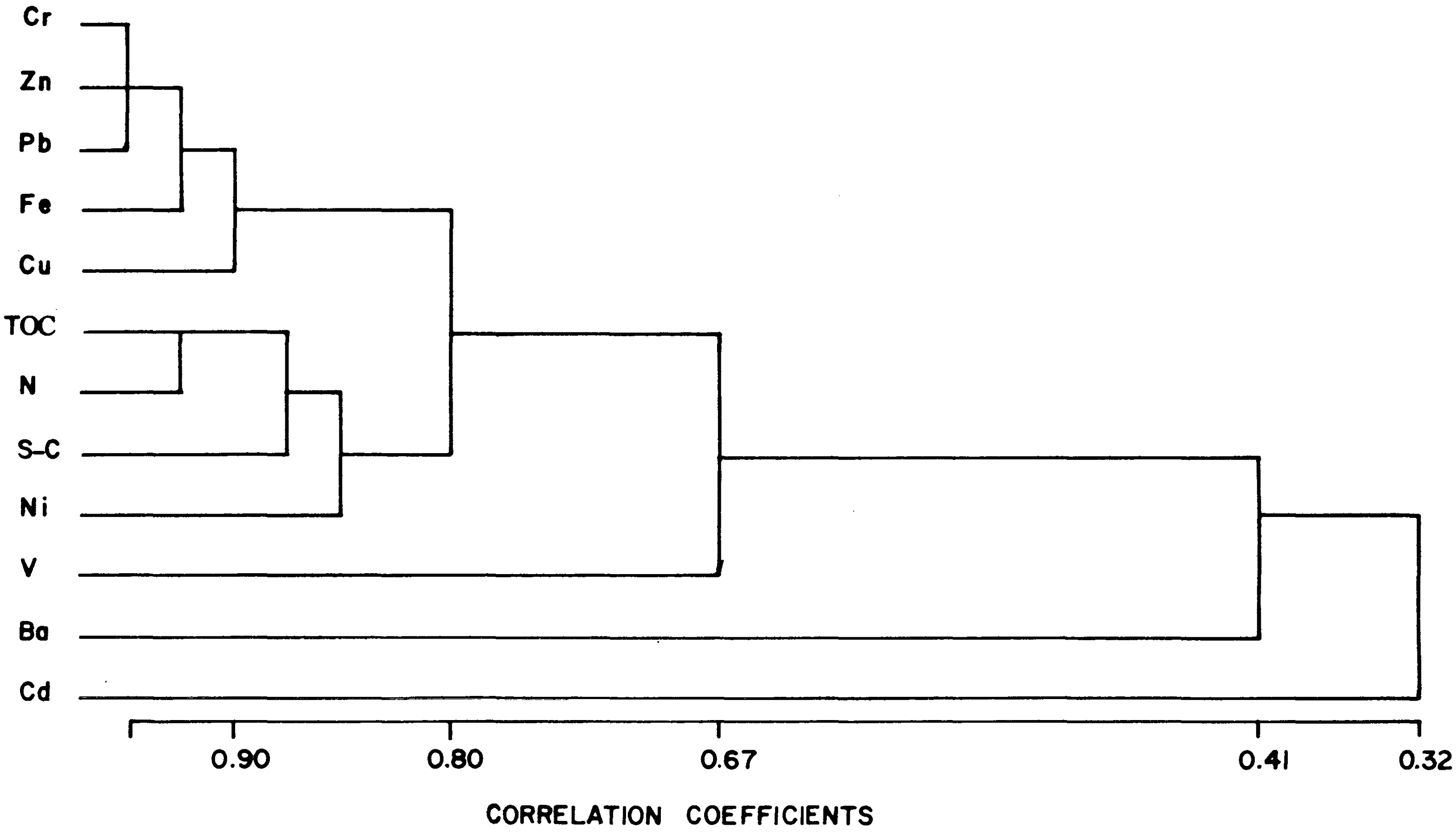

Figure 19. Cluster diagram of leachable metals showing correlation coefficients at all stations across the shelf. S-C = silt-clay; N = nitrogen; TOC = total organic carbon.

Table 12. Average total sediment hydrocarbon concentrations in swale and ridge stations.

Area	Concentration μg/g	
	Swale	Ridge
B	0.289	0.072
C	1.953	0.036
D	0.328	0.034
E	0.045	0.025

Table 13. Geometric means of heterotrophic (HET) and petroleum-degrading (HC) bacterial counts* by season for inner shelf (depth < 50m), outer shelf (depth > 50m < 100m), and shelf break (depth > 100m) sediment stations (1975-1977).

		Season							
	Bacterial	Fall		Winter		Spring		Summer	
Area	Type	1975	1976	1976	1977	1976	1977	1976	1977
Inner shelf	HC	3.4±0.7	4.2±1.1	2.8±0.7	2.0±1.4	3.4±0.8	3.4±1.5	2.4±1.0	2.7±1.6
	HET	5.6±0.5	6.3±0.8	5.7±0.7	5.9±0.6	6.4±0.6	6.5±0.8	6.1±0.6	5.6±0.9
	HC/HET	-2.4±0.8	-2.4±1.0	-3.1±0.7	-4.1±1.3	-3.7±1.0	-3.7±1.2	-4.2±0.9	-2.9±1.0
Outer shelf	HC	2.0±0.5	1.7±1.1	2.0±0.6	1.6±1.1	1.6±0.5	1.5±0.9	1.7±1.1	1.3±1.0
	HET	5.2±0.4	5.8±0.5	5.4±0.6	5.7±0.7	5.6±0.4	5.6±0.5	5.8±0.5	5.5±0.6
	HC/HET	-3.3±0.3	-4.1±1.0	-3.4±0.6	-4.5±0.8	-4.0±0.4	-4.2±0.4	-4.0±1.0	-4.1±1.0
Shelf break	HC	2.3±0.6	1.7±1.0	2.1±0.7	2.2±0.9	1.8±0.7	1.7±1.0	2.3±0.9	0.9±1.2
	HET	4.9±0.4	5.7±0.7	5.8±0.6	5.2±0.6	5.4±0.5	6.0±0.4	5.2±0.5	5.3±0.6
	HC/HET	-2.7±0.3	-3.9±0.5	-3.7±0.4	-3.1±1.0	3.7±0.5	-4.3±0.7	-3.0±0.7	-4.4±0.9

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* Log viable bacterial units/g dry sediment

sediments and values tended to decrease across the shelf. Values of the ratio were dependent upon the number of viable petroleum degrading bacteria.

Bacterial populations could not be consistently correlated with sediment properties such as % silt-clay, median grain size, total organic carbon, or temperature. However, if only data from ridge and swale stations were compared, significantly larger populations were present in swales.

Greater than 90% of all identified isolates from sediments were assigned to the genera *Alcaligenes*, *Flavobacterium*, *Pseudomonas*, and *Vibrio*. Generic composition was temporally and spatially stable.

II. *Foraminifera*. Density of foraminifera in the upper 3 cm of shelf sediments ranged from fewer than 10 per 20 cm^3 to over 5,500 per 20 cm^3, with an average of approximately 200 per 20 cm^3. The average number of species per sample was about 20. *Reophax atlantica* was, by far, the most abundant and ubiquitous species, and fluctuations of this species strongly influenced fluctuations of the community as a whole.

Although many species were widely distributed across the shelf, the foraminiferal fauna can be roughly classified into three bathymetric zones: 1) an inner and central shelf zone characterized by *Elphidium* spp.; 2) an outer shelf zone characterized by *Reophax* spp., *Cibicides* spp., and *Fursenkoina* spp.; and 3) a shelf break zone characterized by a more rotaliid fauna such as *Gyroidina* spp.

Significantly larger populations occurred in swales than on ridges, principally due to greater numbers of *R. atlantica*. High density in swales is the reason for the significant correlations between number of living foraminifera and percent silt-clay and total organic carbon.

Seasonality was not apparent in density or species composition of foraminifera.

III. *Meiofauna*. The density of meiofauna (those organisms passing through a 0.5 mm sieve and retained on a 0.063 mm sieve) on the Middle Atlantic continental shelf ranged form 59 to 1123 organisms per 10 cm^3. Numerically nematodes dominated the samples usually comprising 40-80% and occasionally up to 88% of the individuals. Fifty-eight nematode taxa were recorded. Harpacticoid copepods comprised between 5 and 30% of the individuals in all collections, and 22 harpacticoid taxa were recorded. Together these two taxa comprised 60-90% of all individuals recovered. The only other taxa which occurred in significant numbers in the collections were juvenile ostracods and juvenile polychaetes, adults of which were not members of the meiofauna.

Ridge and swale mesoscale (0.1 - 1.0 km) topography had no statistically significant effect on total meiofauna abundance and no obvious seasonality was observed although at many stations total meiofauna abundance was greatest during spring. Ridge and swale topography did, however, have a significant effect on faunal composition. The organically richer, finer sediments in swales and at the shelf break were dominated by deposit feeding nematodes (Figure 20), by robust harpacticoid copepods, and also by clearly epipelic harpacticoids (Figure 21). The coarser sediment of ridge and terrace stations were characterized by epigrowth feeding nematodes, omnivore-predator nematodes, and by interstitial copepods. Although nematodes always outnumbered harpacticoid copepods, copepods were relatively more abundant at ridge and terrace stations, while nematodes were overwhelmingly dominant at swale and shelf-break stations. Harpacticoid copepod abundance was positively correlated with grain size, while nematode abundance was negatively correlated with grain size.

All components of the meiofauna had highly contagious distributions in 56 cm^2 and 6 cm^2 subsamples, but density appeared uniform over larger areas within similar habitats.

IV. Macrobenthos and Megabenthos. The macrobenthos (collected by grab and sieved through a 0.5 mm mesh) of the study area was dominated by small polychaetous annelids which usually comprised 40 to 60 percent and occasionally up to 90 percent of the individuals. Peracaridean crustaceans (primarily amphipods) were also abundant generally comprising 10 to 30 percent of the individuals. Molluscs and echinoderms (echinoids and ophiuroids) were also common. The megabenthos (collected by dredge or trawl with a 4 mm mesh bag) was dominated by decapod crustaceans (crabs and shrimp), echinoderms (asteroids and echinoids), and bivalve molluscs.

The macrobenthos and megabenthos demonstrated similar distribution patterns across the continental shelf and upper continental slope. Faunal changes were gradual rather than abrupt, but five faunal zones could be distinguished: inner shelf (to 30 m), central shelf (30-50 m), outer shelf (50-100 m), shelf break (100-200 m) and continental slope (> 200 m) (Figure 22). Inner and central shelf assemblages were relatively similar, and outer shelf assemblages contained both inshore and offshore species overlapping in distribution, but shelf break and slope assemblages were more discrete.

Species diversity of both macrobenthos and megabenthos generally increased with depth. Highest Shannon diversity and numerical species richness of macrobenthos was found on the shelf

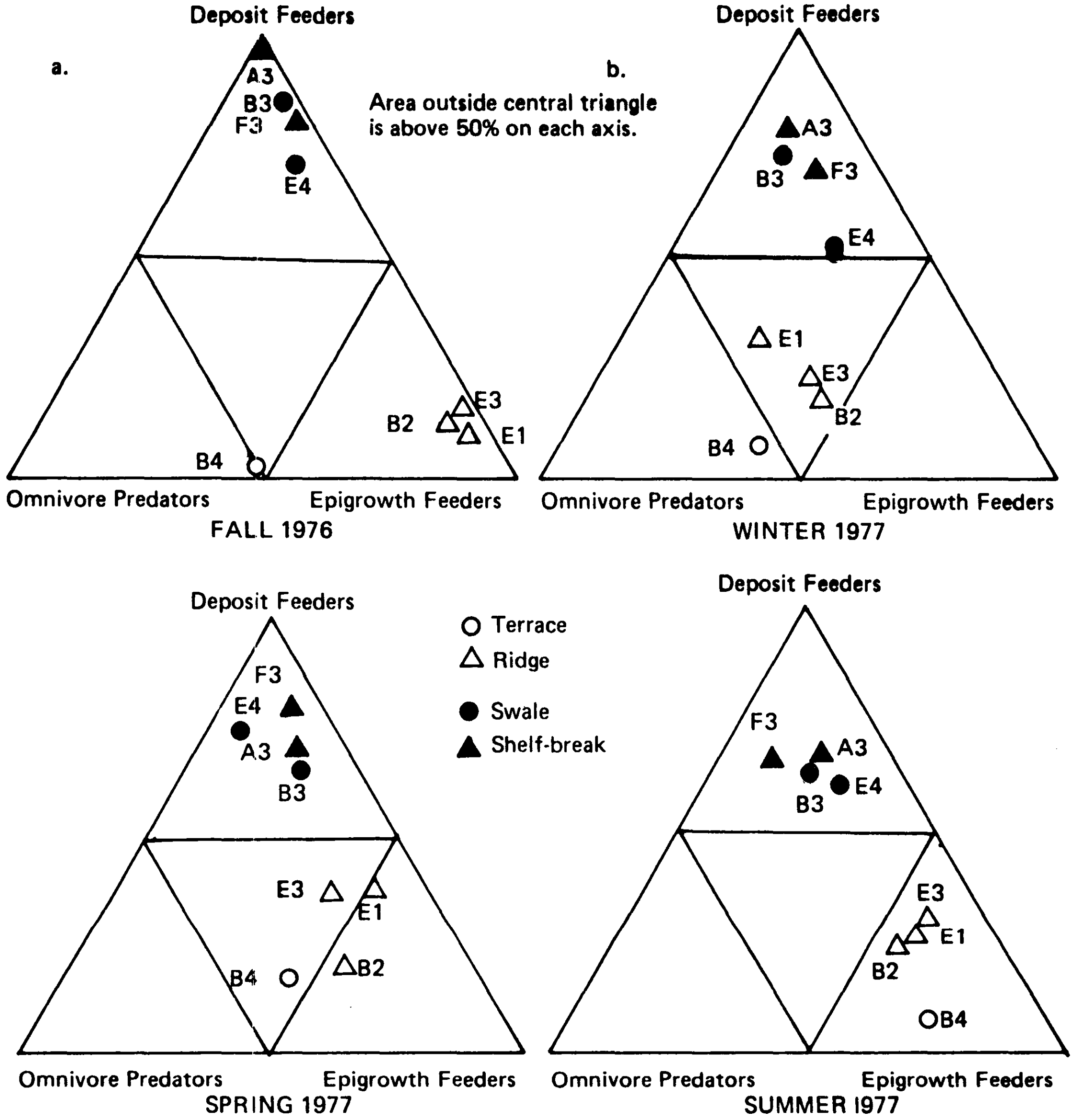
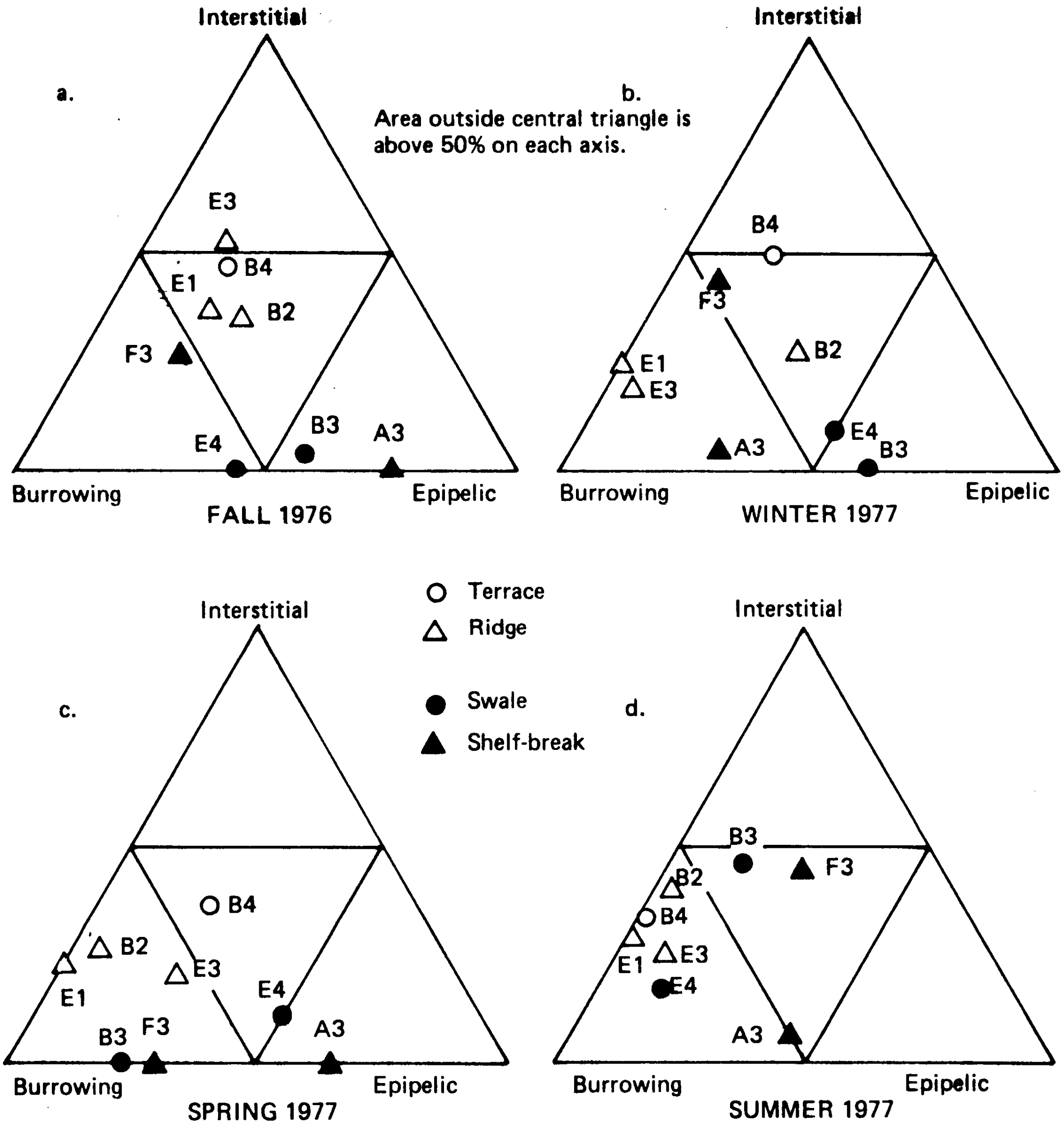


Figure 20. Proportional representation of nematode feeding types in collections by season.



Area outside central triangle is above 50% on each axis.

Figure 21. Proportional representation of harpacticoid body types in collections by season.

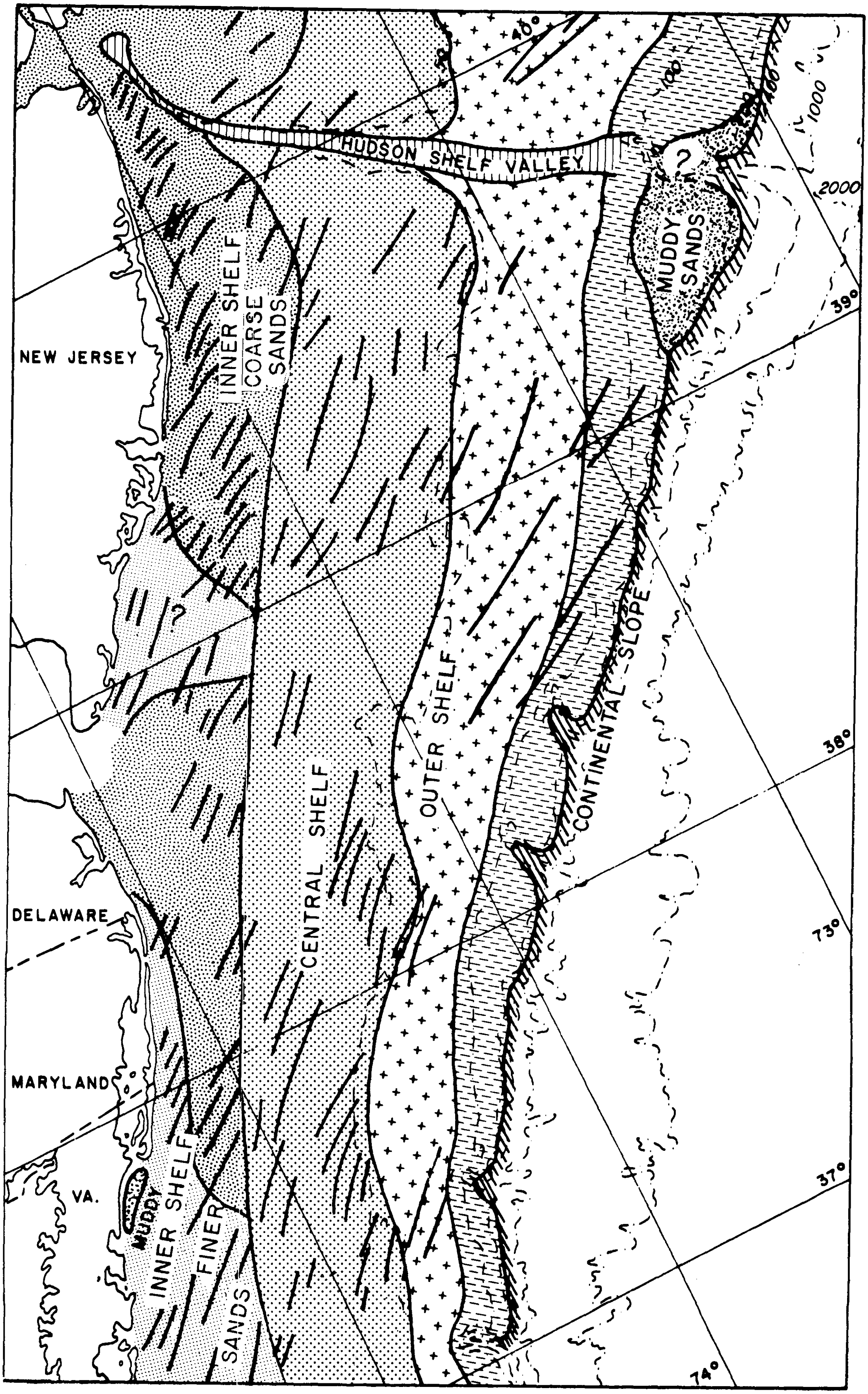


Figure 22. Schematic zonation of macrobenthic biotopes in the middle portion of the Middle Atlantic Bight. Major ridge fields are indicated.

break and slope, and lowest was found on the inner shelf.

Major faunal differences occurred over small distances within the broad scale patterns in relation to shelf topography and its effect on sediment distribution. The most pervasive of such topographic habitats are those related to ridge and swale topography. Swales generally have finer sediments containing higher carbon content than ridges or flanks. The benthos of swales is more abundant (Figure 23), has a greater biomass and species richness, and is composed of more deposit-feeding animals than the benthos of ridges or flanks (Figures 24 and 25). Results of the habitat delineation study confirm the hypothesis that benthic communities are highly predictable if depth and sediment characteristics are known. Thus, ridge and swale community composition based on stations sampled during the two year study period can be extrapolated to other regions of the shelf.

The results of two years of sampling the macrobenthos of the Middle Atlantic Bight revealed little evidence of seasonality, but rather that community composition and population density of dominant species is generally persistent. Size or life history stage varied with season, but the study was not designed to investigate this in detail. Gonadal maturation of selected invertebrates also varied seasonally.

The anoxic or hypoxic conditions that developed in bottom waters over a broad area of the inner shelf enabled study of the effects of catastrophic disturbance on the benthos. The oxygen stress resulted in mass mortalities of many species, especially crustaceans and echinoderms (Figure 26); however, some species of molluscs and annelids demonstrated no reduction in population density. Several opportunistic species not previously abundant proliferated following the perturbation, but their populations gradually declined with time (Figure 27). Species with a planktonic dispersal phase returned quickly after elimination (*E. parma*, Figure 26), but many species without a planktonic dispersal phase had not significantly recolonized one and one-half years following their elimination (Figure 26).

V. *Demersal Fishes*. Based on semiannual (fall, spring) NMFS cruises from 1967 through 1976, and seasonal VIMS cruises during 1968 and 1976/1977 fishes of the Middle Atlantic Bight may be placed in one of three categories based on their migratory habits.

1. Fishes that remain on the outer continental shelf or upper slope throughout the year. This group, dominated by silver hake, *Merluccius bilinearis*, squirrel hake, *Urophycis chuss*; and little skate, *Raja erinacea*, would be chronically exposed to any pollutant introduced on the shelf or upper slope.

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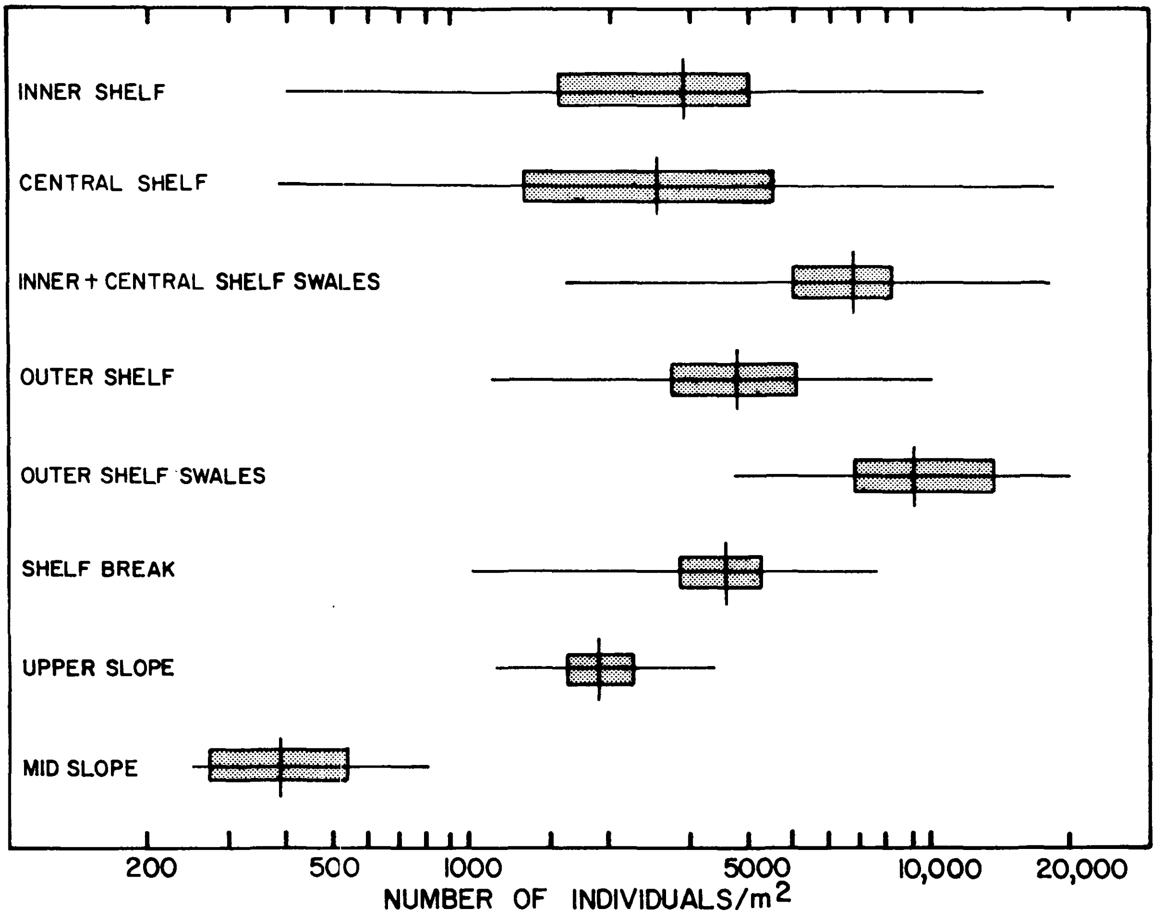
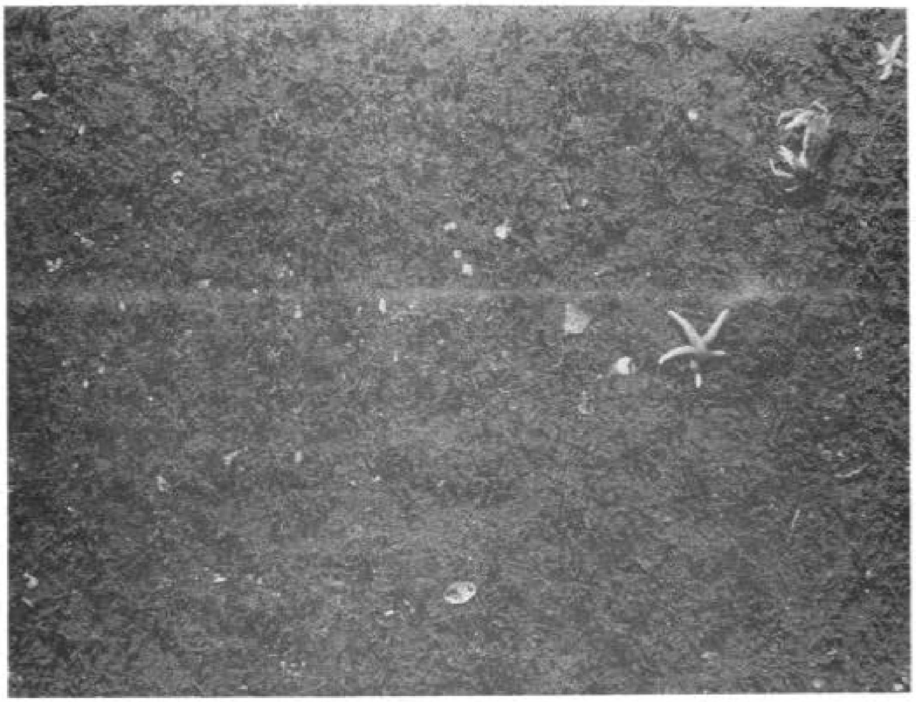


Figure 23. Distribution of total density of macrobenthos by major habitat. Horizontal lines represent ranges, bars represent the mid-ranges, and vertical lines represent medians.

Figure 24. Top. Station B4 shelf on the terrace above Tiger Scarp off central New Jersey, 40 m, on 6 August 1977 (0.6 m focal distance). Very dynamic sediments with medium-coarse sand and gravel. A small Cancer irroratus, Asterias forbesi, and the shrimp Dichelopandalus leptoceras can be seen in the upper right.
Bottom. Station B2, outer shelf ridge off central New Jersey, 62 m, on 6 August 1977 (0.6 m focal distance). Dynamic environment with medium sand. Numerous sand dollars, Echinarachnius parma, partially covered with sediment can be seen along with a single Asterias vulgaris (lower left) and A. forbesi (upper center).



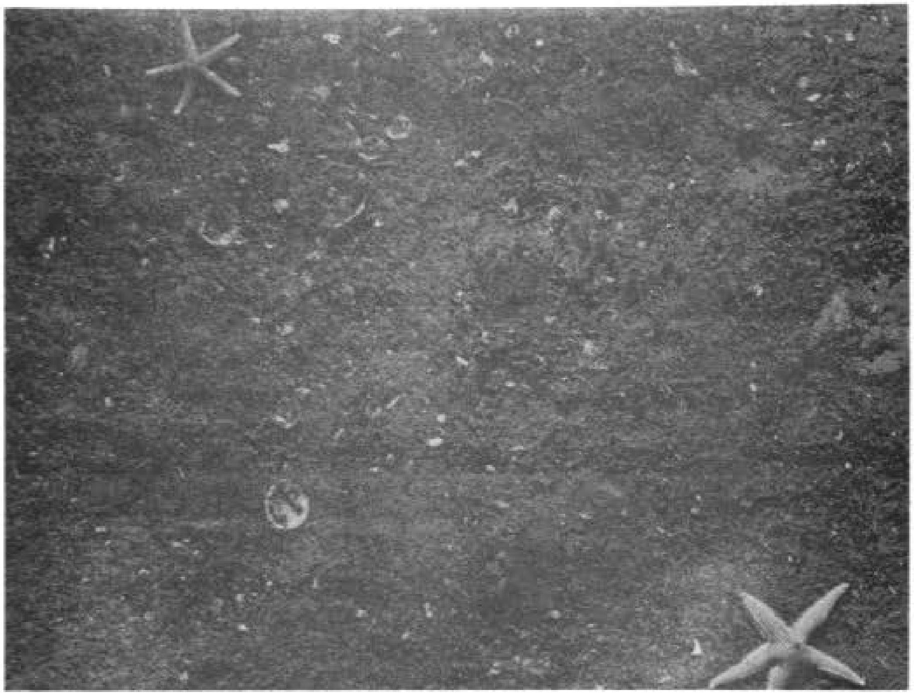


Figure 25. Top. Station B5, outer shelf swale off central New Jersey, 65 m, on 6 August 1977 (0.6 m focal distance). Medium sand bottom is covered by a dense mat of amphipod tubes, primarily Erichthonius rubricornis, but also Unciola irrorata and Ampelisca spp. Two Asterias vulgaris and one Cancer borealis can be seen. Bottom. Station B3, outer shelf swale off central New Jersey, 72 m, on 6 August 1977 (0.6 m focal distance). Sediments are slightly muddy fine sand. Dense mats of tubes of the amphipods Ampelisca agassizi and, to a lesser extent, Unciola irrorata, interspersed by mounds of reworked sediment around burrows, are apparent and Asterias vulgaris and Astropecten americanus are visible.

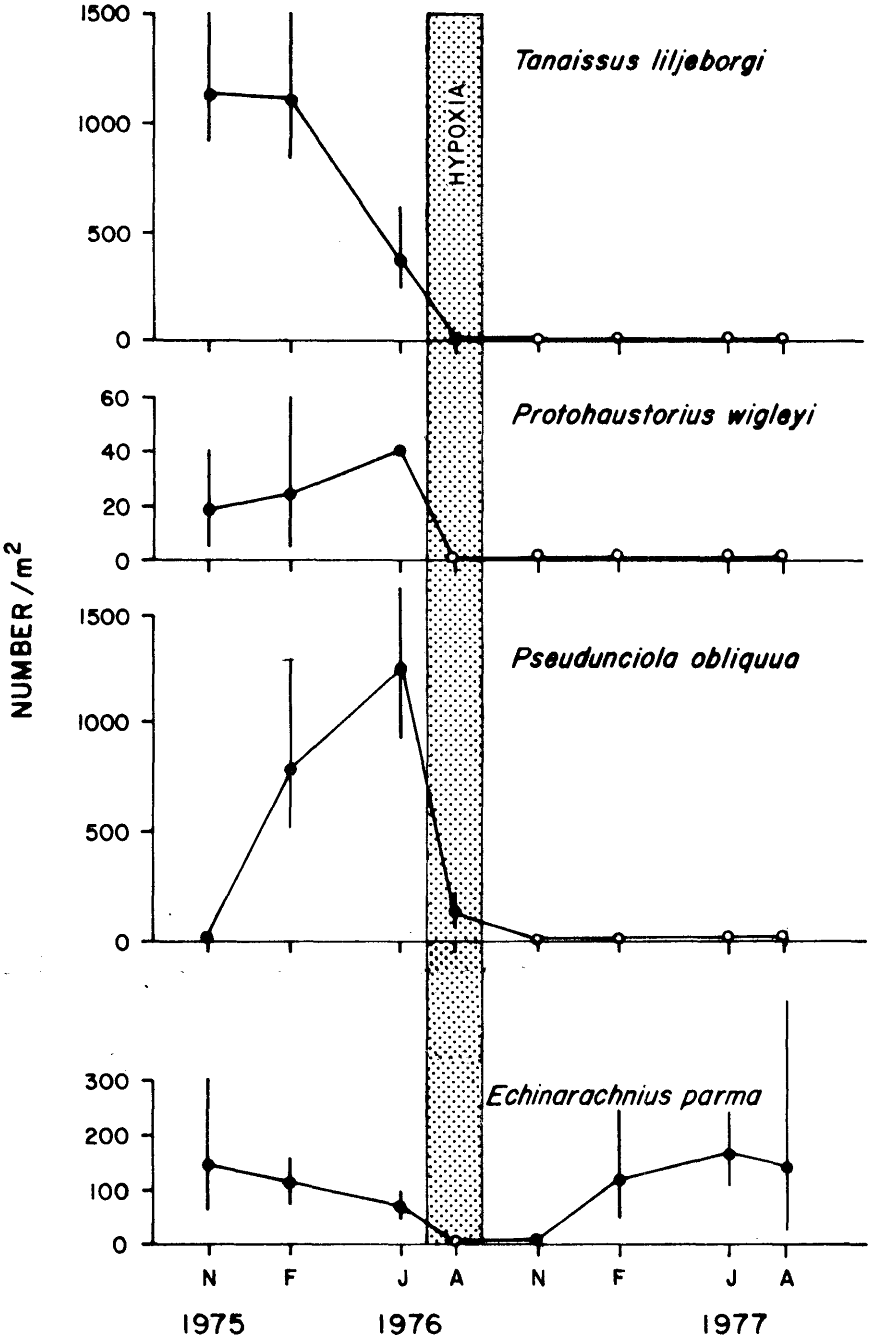


Figure 26. Temporal variations in population densities for dominant macrobenthic species at Station C2, which was affected by the hypoxia incident of the summer of 1976. Vertical lines are confidence limits ($\bar{x} \pm S_{\bar{x}}\, t_{.05}$) computed on log transformed values; levels connect geometric means. Open circles are zero estimates.

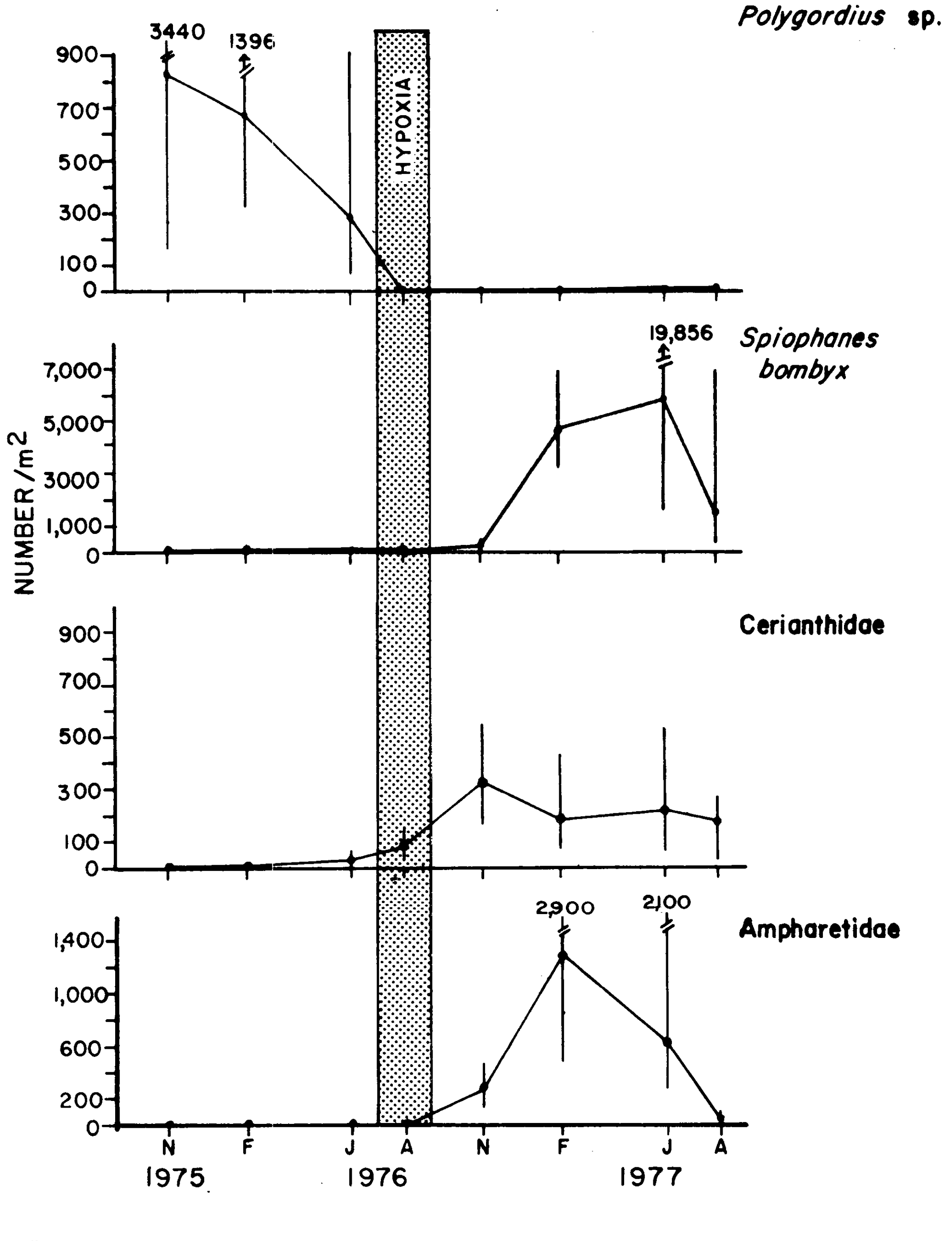


Figure 27. Temporal variations in population densities for dominant macrobenthic species at Station C4, which was affected by the hypoxia incident of the summer of 1976. Vertical lines are confidence limits ($\bar{x} \pm S_{\bar{x}}\, t_{.05}$) computed on log transformed values; levels connect geometric means. Open circles are zero estimates.

2. Fishes that are boreal (northerly) in their faunal affinity. Most species in this group, dominated by the yellowtail flounder, Limanda ferruginea, and the spiny dogfish, Squalus acanthias, migrate north and offshore in summer and south and inshore in winter.

3. Fishes that are warm-temperate (southerly) in their faunal affinity. Most species in this group, dominated by the butterfish Peprilus triacanthus, the sea robin, Prionotus carolinus and the scup, Stenotomus chrysops, migrate north and inshore in summer, and south and offshore in winter.

Temperature and depth are the most important factors controlling distribution of fishes on the shelf. Ridge and swale topography appears to have little influence on demersal fish distributions.

Fish food habit analysis indicates that demersal fishes prey heavily on benthic invertebrates, but not necessarily on the most abundant species. The more vulnerable crustaceans, especially amphipods, are consumed far out of proportion with their abundance, while the more abundant, but deep burrowing polychaete worms are only rarely consumed.

VI. Trace Metals in Benthos. Temporal or spatial trends of trace metal concentrations in benthic organisms were not observed. Within species variability was high due to differing size, age, and maturity, and evidence of sediment contamination was found, especially in sand dollars, a detrital feeder.

Significant correlations were found among metals in Mollusca (Fe-Zn-Cu), Arthopoda (Cr-Cd, Cu, Zn), Echinodermata (Fe-Zn and Cr), and Pisces (Cr-Ni, Cd-Cu and Pb).

VII. Hydrocarbons in Benthos. Hydrocarbon levels in benthic organisms were low, with no evidence of petroleum contamination. Fish (hakes) contained large amounts of pristane relative to other hydrocarbons.

There was no correlation between either aliphatic or aromatic hydrocarbons and trace metal concentration in benthic fauna.

Histopathological Studies. Twelve benthic invertebrate species were chosen for histopathological examination with emphasis on four aspects of their biology: 1) the distribution and range of each species; 2) reproductive activity; 3) normal histology of selected organs; and 4) the symbionts and/or lesions associated with the animals.

Many of the benthic crustacea, especially the shrimp *Dichelopandalus leptocerus* and the crab *Cancer irroratus*, appeared to be migratory. Young *D. leptocerus* were concentrated on the continental shelf and older shrimp on the slope. Immature *C. irroratus* were widely distributed on the shelf, but mature females were concentrated in the shallow water of the inner shelf. Mature males occurred widely over the shelf during spring and summer, but moved inshore during fall and winter.

Effects on reproductive biology may be among the more sensitive methods of assessing impact since some physiological processes may be interrupted even though mortality does not occur. Studies on the gonadal cycle of the selected invertebrates revealed that most of the animals spawned or extruded gametes during a particular season, usually spring or summer. Two exceptions, however, were the shrimp, *Crangon septemspinosa*, and the *Astarte* clams in which viable gametes were present throughout the year.

Symbiotic organisms were found on or in all twelve species examined, and ranged from harmless commensals to potentially destructive forms such as *Hematodinium*, the parasitic dinoflagellate found in the haemal spaces of the *Cancer* crabs. Host symbiont accommodation may also be a sensitive indicator of impact due to the delicate balance among host, symbiont, and the environment.

No correlations existed between trace metal or hydrocarbon concentrations in organisms and the presence of symbionts or lesions. One interesting trend, however, was the spring peak in zinc levels in the starfish, *Asterias vulgaris*, observed during both years of study. Since the synthesis and accumulation of gonadal products in this organism also peaked in spring, it is suggested that a significant portion of the zinc may be associated with gonadal products.

Special Studies

Petroleum and Chitin Degradation. Laboratory experiments demonstrated consistent and significant increases in viable counts of heterotrophs and petroleum-degrading bacteria from both surface water and sediments in response to crude oil addition. For surface water inocula, however, significant n-paraffin degradation occurred only in flasks enriched with inorganic nutrients. Inshore surface waters and swale sediments consistently exhibited the greatest degradation potential during all seasons compared with offshore waters or swales. Swale inocula always exhibited significantly greater degradation than ridge inocula (see Figure 28, ridge; Figure 29, swale). Degradation was always more extensive in enriched flasks.

Based on two years of study, bacterial degradation of n-paraffins was always greatest during fall, with spring, summer, and winter showing decreasing degradation capacity, respectively.

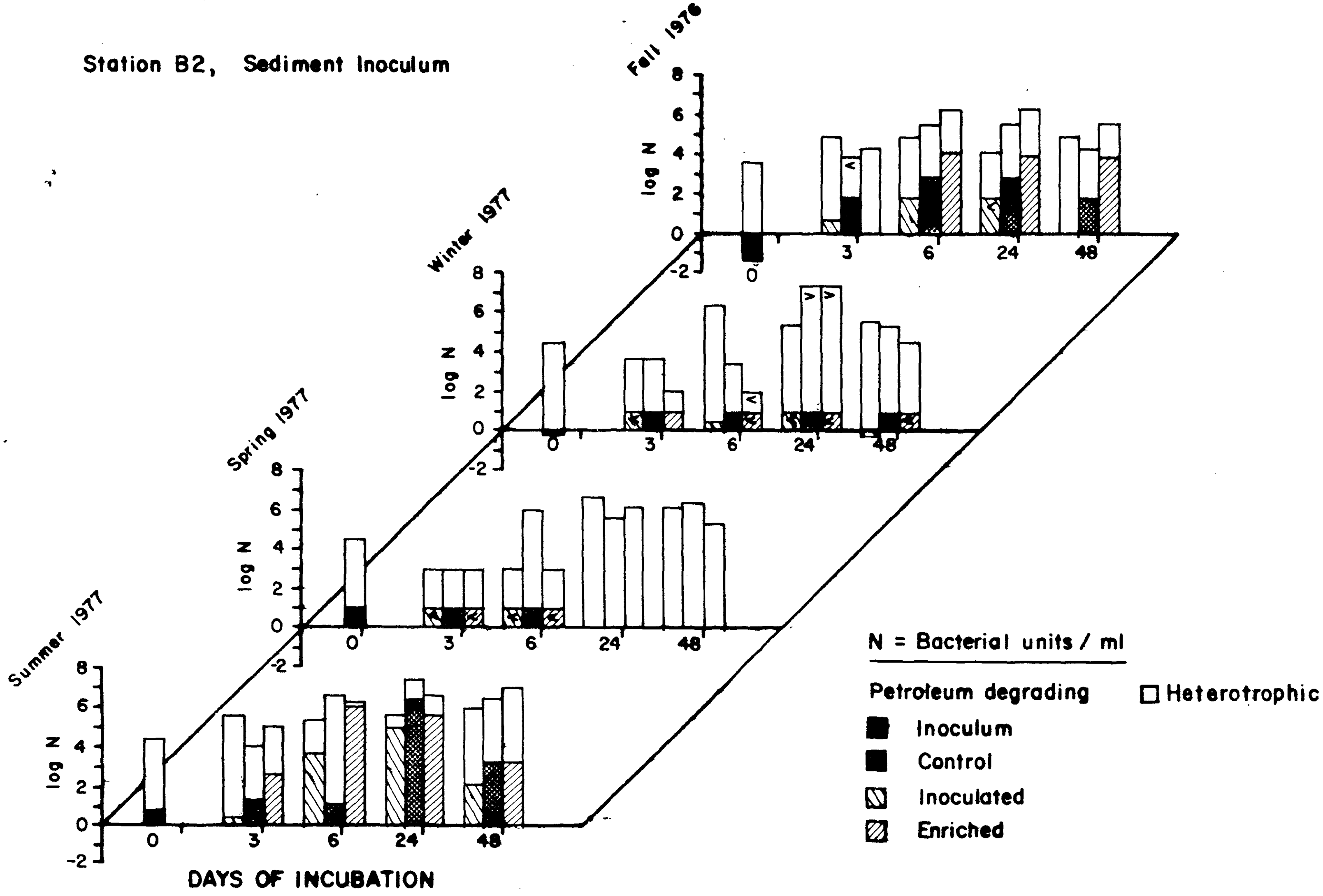


Figure 28. Viable counts of petroleum-degrading and heterotrophic marine bacteria during incubation in closed flasks treated as follows: control, sterile seawater + sediment homogenate inoculum; Inoculated, sterile seawater + sediment homogenate inoculum + petroleum; Enriched, sterile seawater + sediment homogenate inoculum + petroleum + inorganic nutrient amendment.

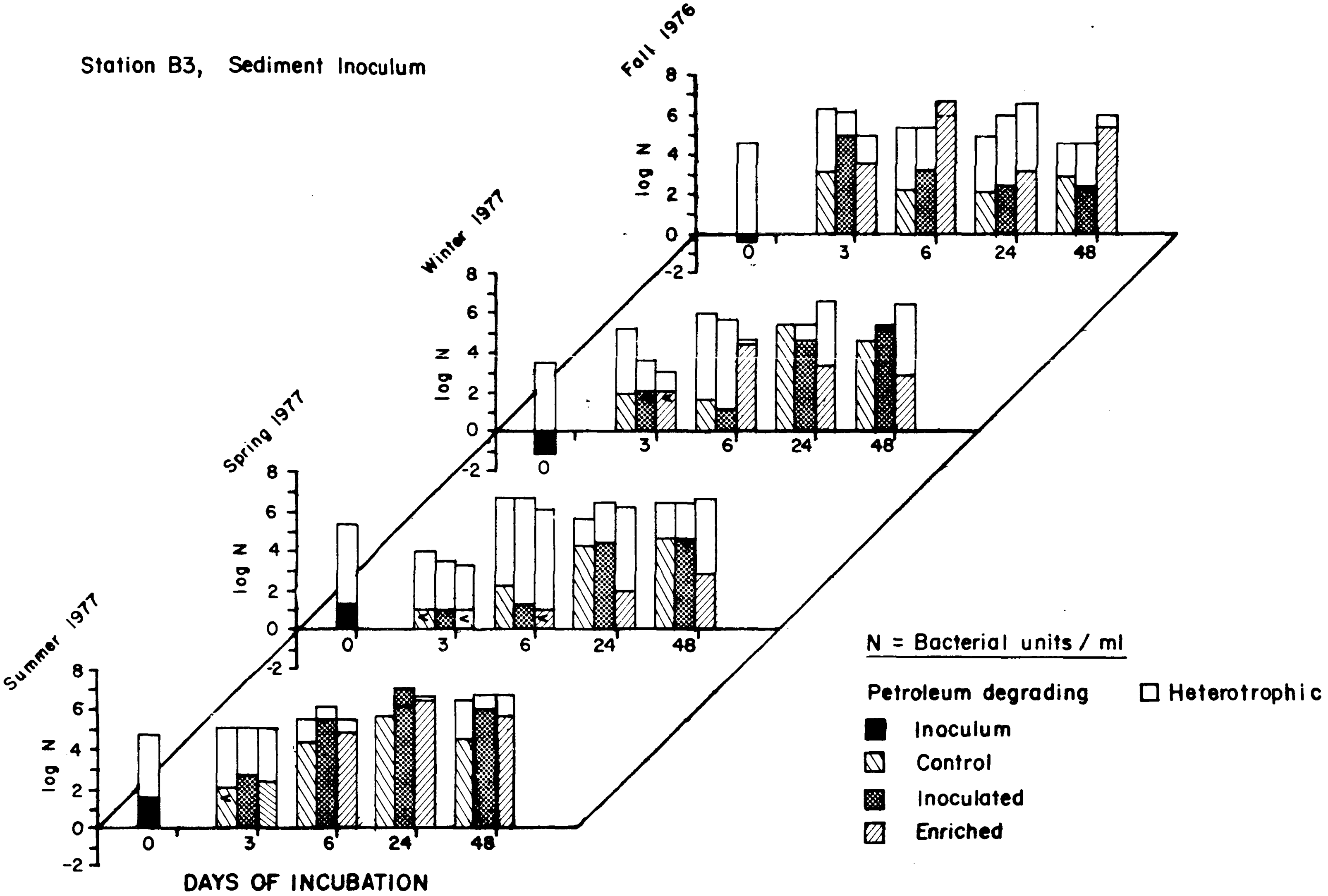


Figure 29. Viable counts of petroleum-degrading and heterotrophic marine bacteria during incubation in closed flasks treated as follows: control, sterile seawater + sediment homogenate inoculum; Inoculated, sterile seawater + sediment homogenate inoculum + petroleum; Enriched, sterile seawater + sediment homogenate inoculum + petroleum + inorganic nutrient amendment.

Neither South Louisiana crude oil nor its degradation products were toxic to chitinoclastic bacteria as measured by chitin degradation.

Results of growing pure cultures of bacteria in the presence of weathered and unweathered oil suggest that following an oil spill, the species composition of bacterial populations may change in response to the toxic effects of crude oil on susceptible bacteria, followed by enrichment of petroleum-degrading bacteria or other resistant strains.

Wave Climatology. Baltimore Canyon Trough Wave Climate Model Studies based on a second order depth grid with 0.25 nautical mile spacing show major areas of wave energy concentration in the northwest, southwest, and shelf-edge portions of the lease block area. The northwest region is affected by more wave directions and periods (for example, Figure 30 and 31); the other areas only by east or southeast waves with thirteen or fourteen second periods.

Results of sediment transport threshold studies indicate that large areas of the shelf are subject to sediment transport. Sediments finer than 1.0ϕ are capable of being moved throughout the area for at least one of the twelve wave conditions modeled (Figure 32). The threshold velocity for sand-size sediments between 1.0ϕ and -2.0ϕ is exceeded at many locations in the lease block area (Figure 33).

Synthesis

The following discussion will concentrate on synthesizing the major trends in physical, geological, chemical and biological parameters within a uniform frame of reference. The discussion is based on two years of seasonal data (1975-1977) and is non-quantitative in that trends are indicated in relative, rather than absolute, scalar terms. However, most of these trends have been demonstrated to be significant in the relevant disciplinary chapters of this report.

A commonality of many of the trends observed is the pattern across the continental shelf. Cross-shelf trends seem to be much more distinct than latitudinal trends, which for most parameters in the study area are of little or no consequence. Although the dominant trends seem to be related to water depth or distance from shore, these are often not of direct importance. Rather, many environmental factors covary with depth, and it is these other factors, such as seasonal temperature constancy, which are responsible for the observed chemical or biological trends.

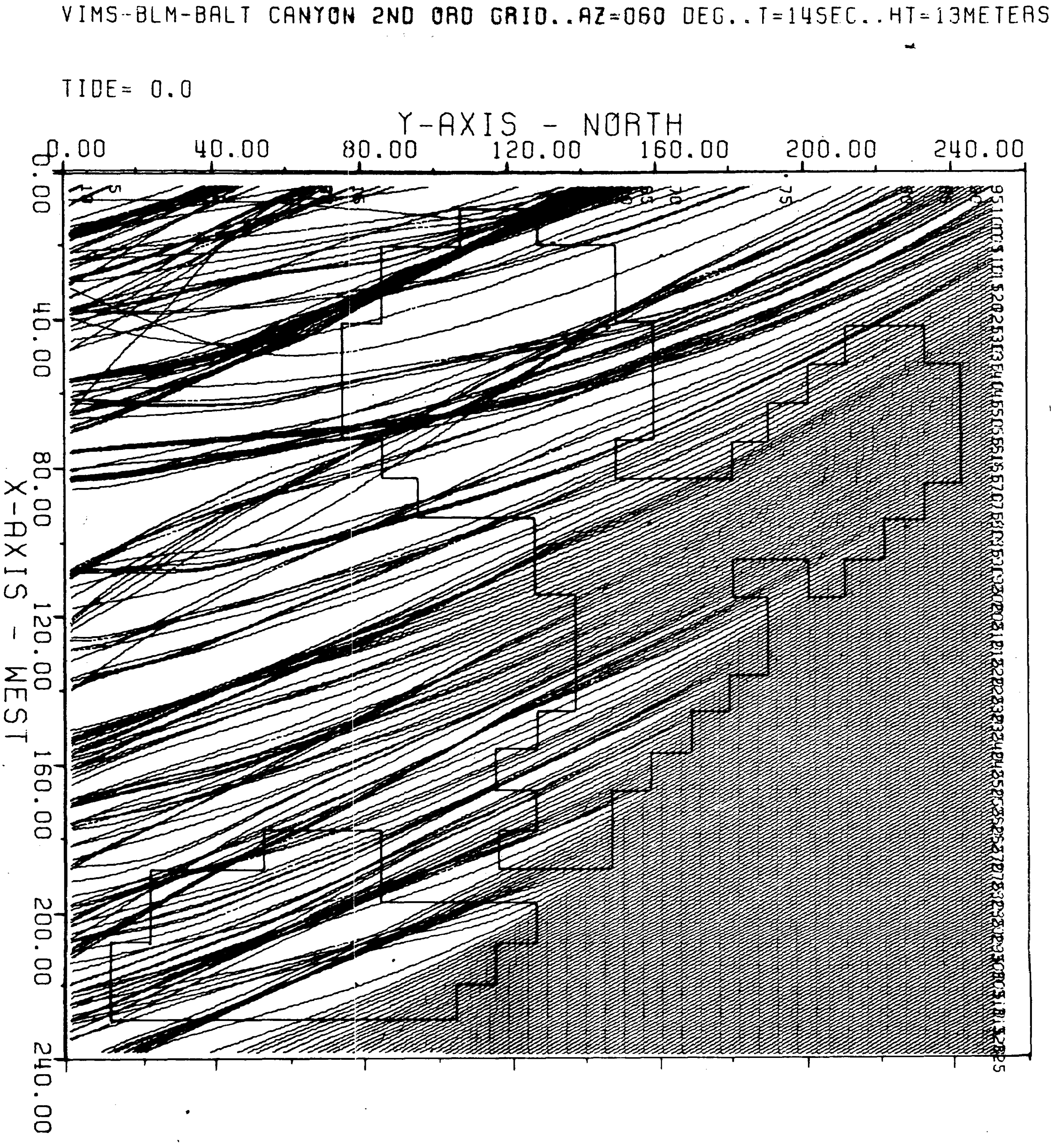


Figure 30. Second Order depth grid wave refraction diagram. Location indicated in Figures 15-1a and 15-1b.

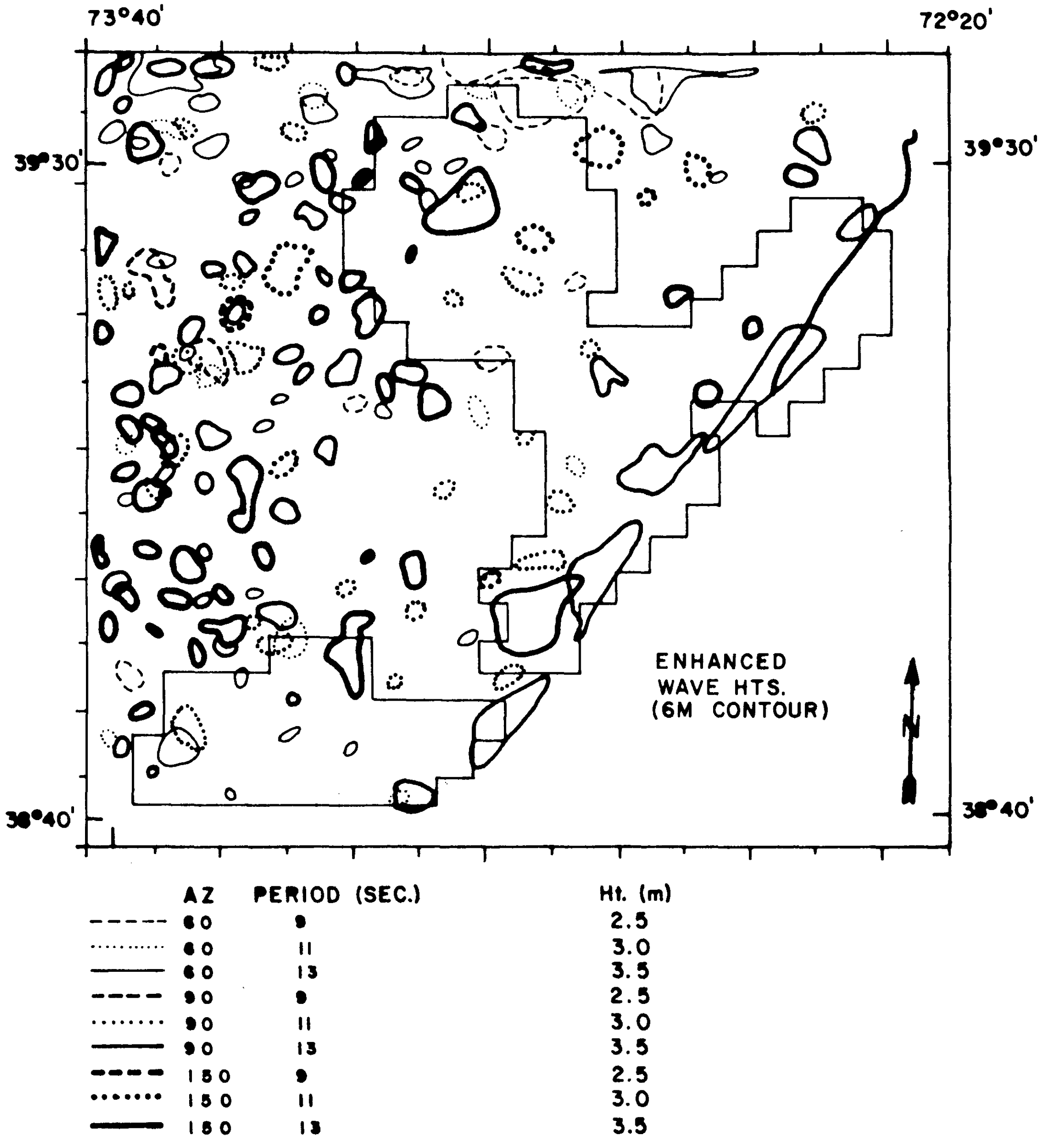


Figure 31. Summary of areas of "enhanced" wave heights (6 meter height contour) for 9 commonly occurring wave conditions with input height of 2.5 and 3.5 meters.

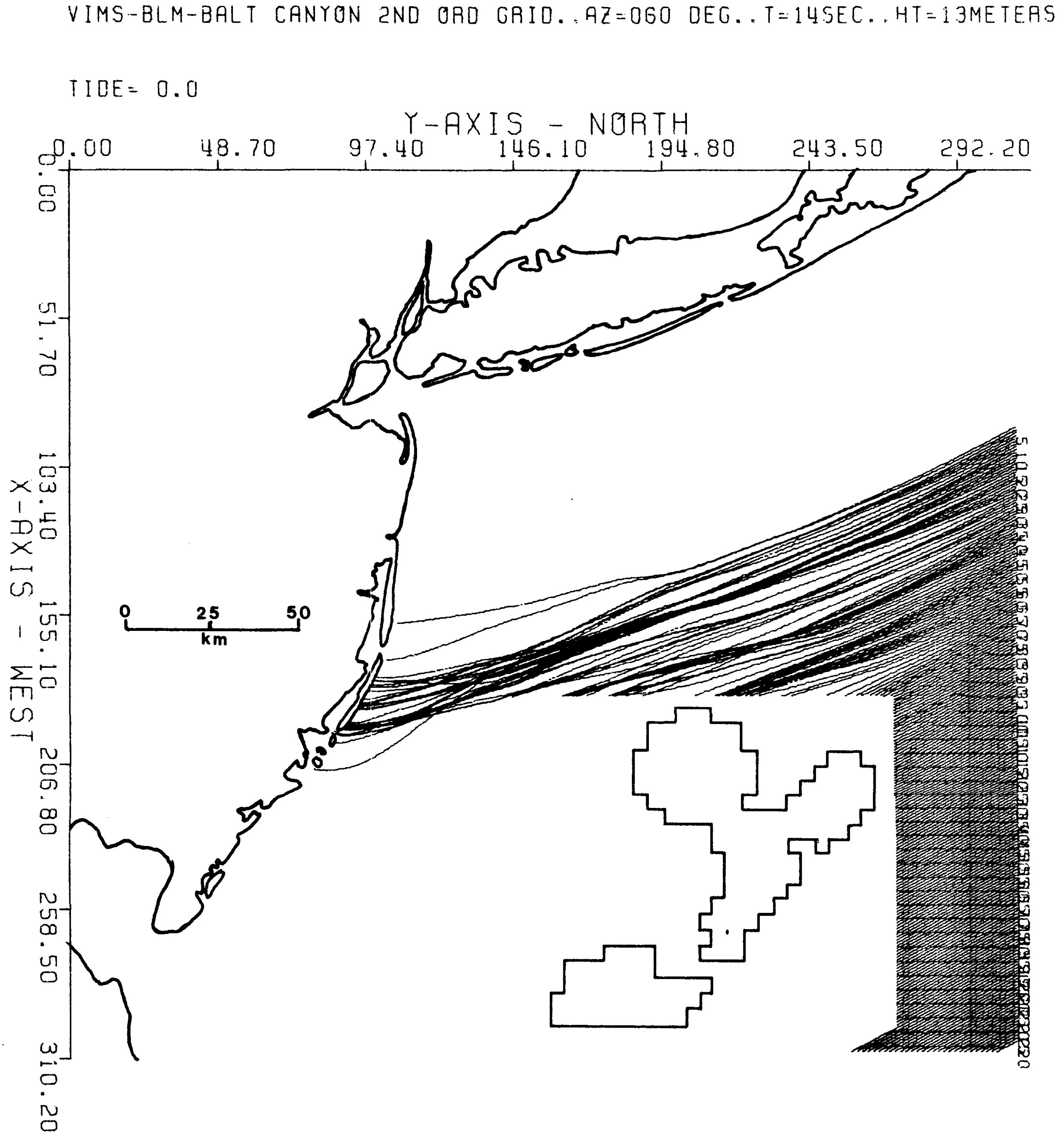


Figure 32. First Order Model modified to produce input for Second Order BLM grid.

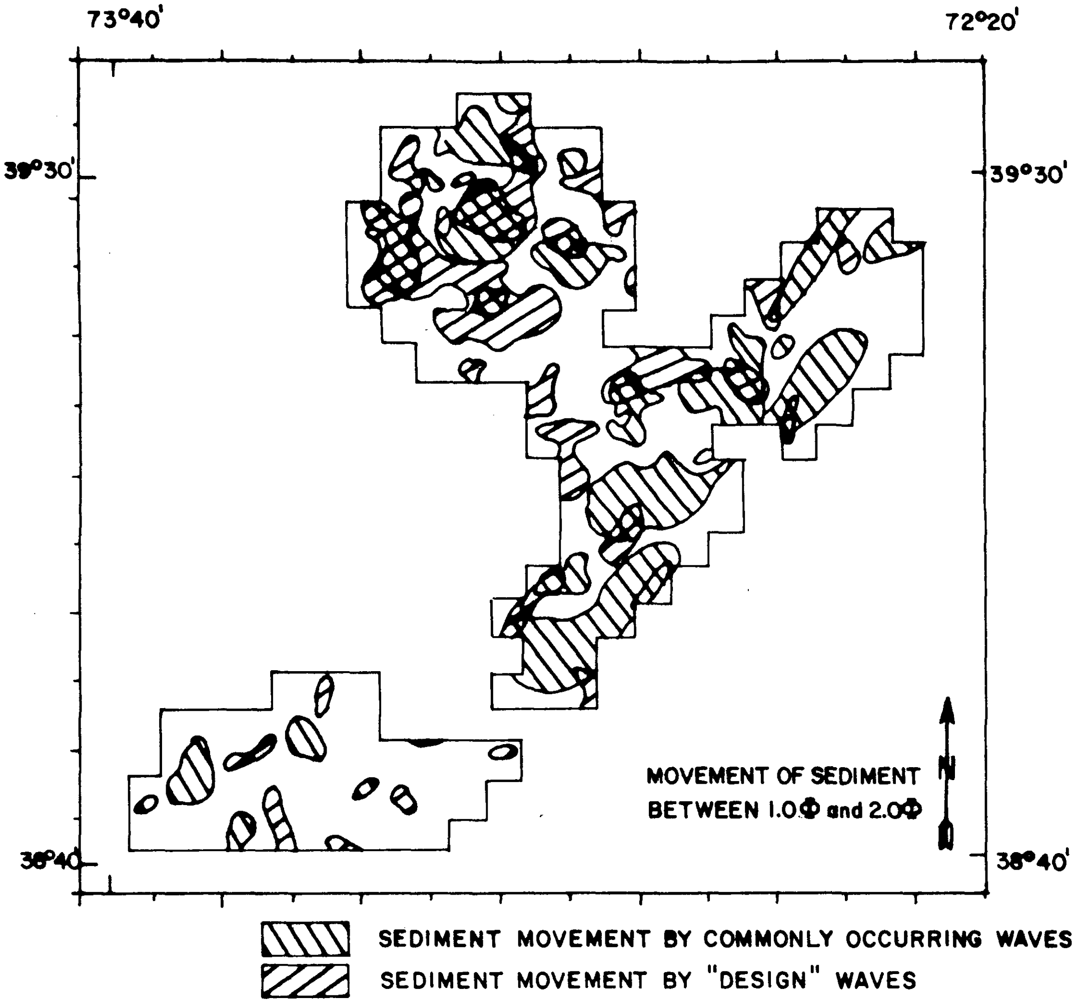


Figure 33. Areas of computed sediment movement within lease blocks indicated by twelve modeled wave conditions for sand grain size between 1.0ϕ and -2.0ϕ.

Cross-Shelf Patterns in the Pelagic Realm

Figure 34 summarizes the cross shelf patterns of water column parameters measured during the program. The waters of the Middle Atlantic Bight are characterized by three hydrographic regimes, a coastal boundary layer, the mid-shelf regime, and the slope regime. The mid-shelf and slope regimes are clearly separated by a sudden transition in temperature and salinity called the shelf-slope front. The transition between the coastal boundary layer and the mid-shelf region is more subtle, frequently being expressed in the biological community structure before it is apparent in the physical hydrography. This set of indications implies longshore drift associated with the coastal boundary layer. Its physical expression is sometimes a salinity front to the south of fresh water sources, primarily the Connecticut, Hudson and Delaware rivers.

The three regimes are all affected by seasonal changes, and they respond by having two structures, one for the warming season and one for the cooling season. These seasons are separated by two short transition periods. The mid-shelf shows the clearest seasonal cycle, being vertically stratified in the summer, with warm water overlying cold water. The warm water receives the fresh input from the coastal rivers, and so it is fresher than the colder water. This combination of warm, fresh water over cold, salty water produces a strong pycnocline, which tends to inhibit turbulent exchange vertically and separate the lower water from the upper water. The temperature in the outer part of the lower layer remains low during the summer, particularly at the outer part of the mid-shelf region. The resulting pattern of isotherms forms a distinctive minimum attached to the bottom which is often called the cold pool. During the winter, the mid-shelf region is vertically mixed by the frequent occurrence of both high winds and cold temperatures. The resulting hydrographic patterns are typically vertical lines, with cold, fresh water near the coast and warm, salty water offshore. During lulls between storms, ocean water frequently intrudes along the bottom in a fashion which is similar to the pattern of estuarine circulation. These intrusions disappear as they are vertically mixed by the succeeding mixing event.

The coastal boundary layer appears during the winter as a relatively homogeneous region of low salinity water, the salinity being a minimum reached by the interplay between coastal runoff and coastal mixing processes. During the summer, the expression of the coastal boundary layer is an increase in the thickness of the pycnocline. This indication is frequently seen to have a nearly exponential structure decreasing away from the coast in the manner of a classical boundary layer. The characteristic length of the exponential function varies in our data between five and thirty kilometers.

The slope water region showed only the formation of a summer pycnocline above a depth of about 100 meters, which is the location of

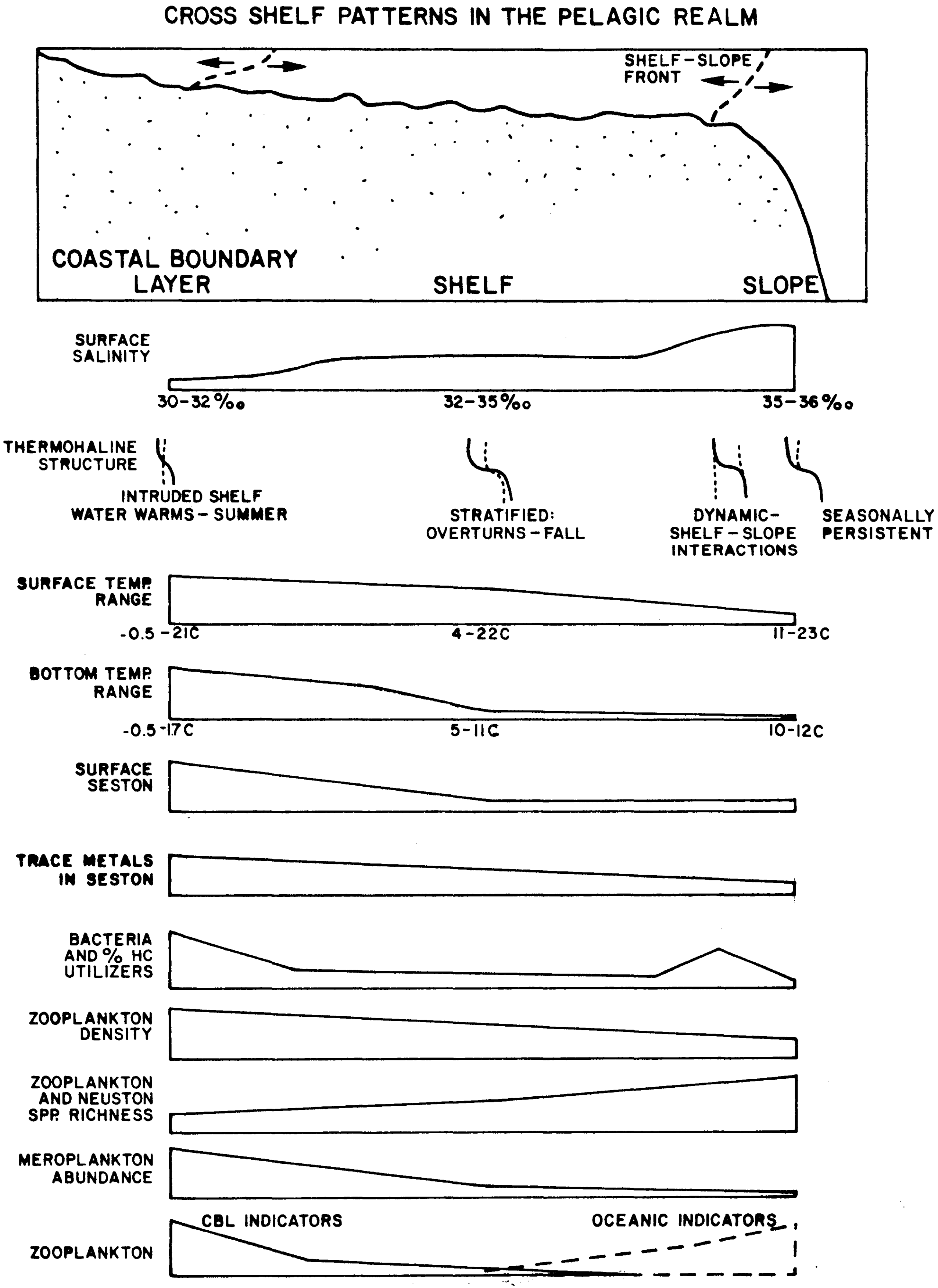


Figure 34. Cross shelf pelagic trends observed during fall 1975-summer 1976, BLM-sponsored OCS studies in the Middle Atlantic.

the upper slope water thermostad. The mixing across the shelf-slope front changes from the bottom water intrusions of the winter, which were observed to reach halfway across the shelf on occasion, to calving during the summer, which is evident in the sections as a small scale exchange of parcels of water at mid levels across the shelf-slope front.

The abiotic environment, particularly the temperature, changes substantially across the shelf as a result of this seasonal response of the various regimes. The most stable (constant) temperatures are found in and below the upper slope water thermostad. The cold pool, on the outer part of the shelf, maintains cold temperatures throughout the summer. In fact, the warmest part of the season in this region is immediately following the transition to the cooling season. The temperatures are most variable both on a regular seasonal basis and within weekly periods in the coastal boundary layer. The greatest variability in dissolved oxygen seems to be in the inner part of the mid-shelf region. Here, respiration rates are probably higher than in the colder water farther offshore, but replenishment is blocked from the sea by the cold pool structure and from above by the still strong pyncnocline. In the winter, the efficient vertical mixing raises these levels of oxygen to near saturation values.

Seston concentrations in the water column were locally variable. In particular, near bottom concentrations were affected by resuspension of bottom sediments. However, seston concentrations in surface waters showed a clear trend toward decreasing concentrations offshore. On the outer shelf and in slope waters, seston was primarily composed of phytoplankton (bioseston) whereas closer to shore mineral particles (abioseston) were more important. Trace metal concentration in both surface and near bottom seston generally decreased seaward across the shelf; however, during periods of storm-induced sediment resuspension at outer shelf stations, near bottom trace metal concentrations increased. No cross shelf patterns were observed for either dissolved or particulate hydrocarbon concentrations.

Heterotrophic bacteria were more concentrated in the coastal boundary layer than elsewhere. The increased populations were coincident with higher nutrient and dissolved organic carbon levels. A secondary peak occasionally occurred in waters over the shelf break, in the vicinity of the shelf-slope front. This may have been the result of observed nutrient enrichment in the frontal zone. The population density of hydrocarbon utilizing bacteria covaried with that of the total heterotrophs; however, hydrocarbon utilizing bacteria comprised a greater proportion of the total population in areas of high bacterial density than in low density areas. Thus, the percentage of the total bacterial community which could utilize petroleum hydrocarbons was also highest in the coastal boundary layer and at the shelf break.

Zooplankton densities were highly variable, but generally decreased in an offshore direction. The abundance of meroplankton (planktonic larvae of benthic or nektonic animals) showed an even sharper attenuation away from the inner shelf. The high meroplankton densities sometimes found in the coastal boundary layer included many larvae of coastal and estuarine animals, and occasionally larvae of some coastal species were found in neuston samples well out on the shelf, indicating offshore transport of surface waters. While density of zooplankton generally decreased offshore, the numbers of species in the subsurface zooplankton and neuston increased greatly. This was due to the collection of more species of the diverse oceanic fauna in addition to neritic forms on the outer shelf. Certain species of zooplankters were highly specific to the coastal boundary layer or oceanic (slope) water. These scarcely overlapped in the shelf water mass. Several species which were widespread across the shelf were most abundant on the central shelf where the "indicators" were scarce.

There are two principal sources of the zooplankton fauna observed in the Middle Atlantic Bight: offshore Gulf Stream and slope waters and the shelf waters of Georges Bank and southern New England. The offshore tropical and subtropical species are introduced to the shelf environment by the southwestward passage of anticyclonic eddies from the Gulf Stream, while the northern boreal zooplankton community is transported in the generally southward drift of Middle Atlantic Bight shelf waters. Observations in the past two years have led to the hypothesis that, while there is a continuous year-round source of these two very different communities, seasonal temperatures alternately limit their shelf distribution and survival. An additional feature of shelf circulation appears close to the coast in the form of a Coastal Boundary Layer that may concentrate and funnel species southward where they are seasonally added to the fauna of major estuaries such as Delaware and Chesapeake Bays. Boreal fauna, typified by *Calanus finmarchicus* and *Sagitta elegans*, survives its southward mixing along the shelf only in winter and spring of normal years; its relative annual abundance may depend both on the severity of winter and on strength of flow in the Coastal Boundary Layer. Subtropical species, limited to offshore waters, or to warm rings during winter and spring, survive mixing across the shelf in summer and fall, several species having been found limited to shelf-edge and slope stations in one season and to the Coastal Boundary Layer in the following season.

Cross-Shelf Patterns in the Benthic Realm

While hydrographic processes are the main abiotic factors responsible for the patterns described for the pelagic realm, substrate characteristics are of at least equal importance in effecting cross-shelf patterns in the benthic realm (Figure 35). The most important hydrographic factor on the Middle Atlantic Shelf is temperature. As described above, bottom temperatures were quite

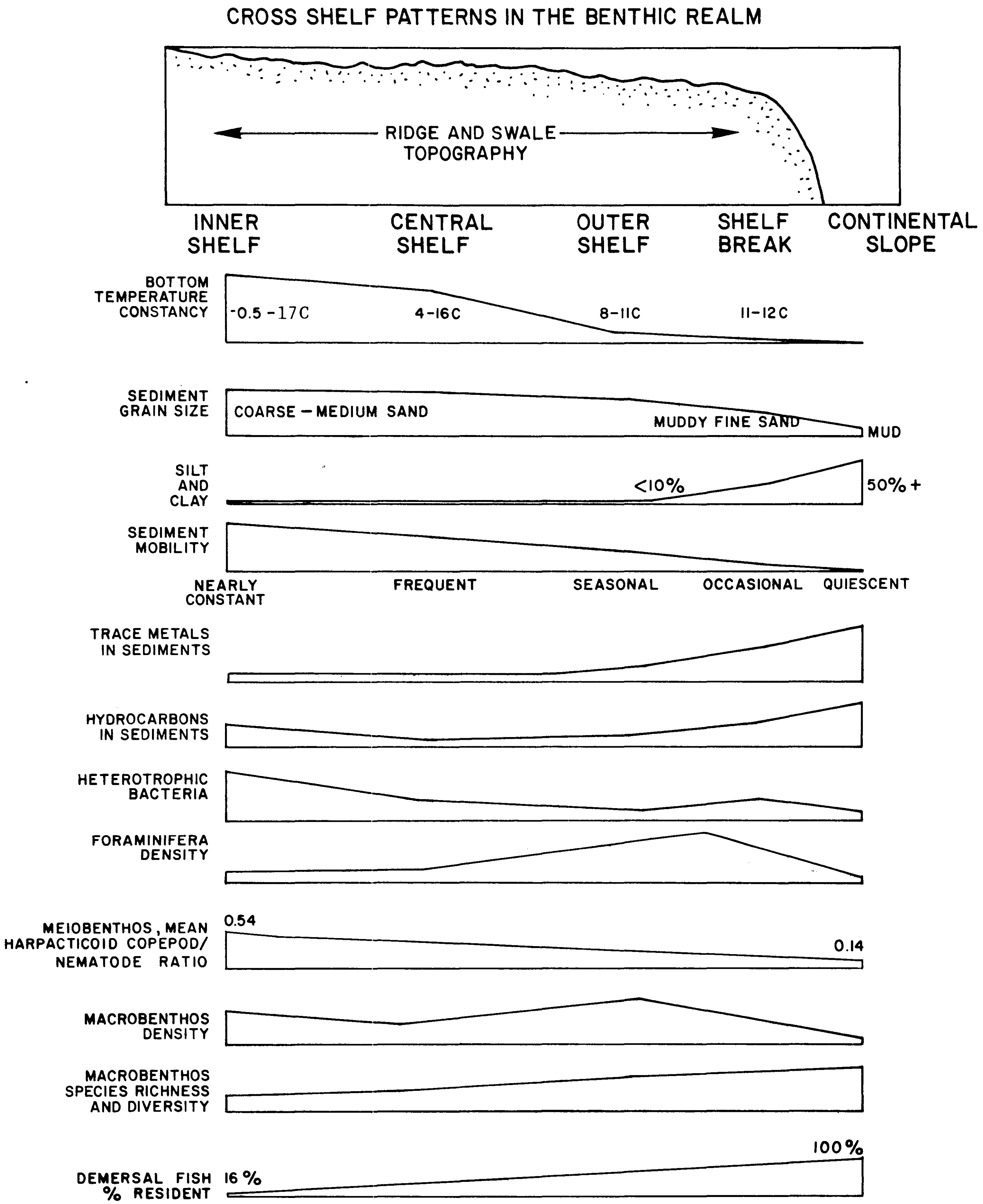


Figure 35. Cross shelf benthic trends observed during fall 1975-summer 1976, BLM-sponsored OCS studies in the Middle Atlantic.

variable over the inner and central shelf; however at depths greater than ca. 40 m, bottom temperature was notably constant throughout the year. The "cold pool" insulated the benthic boundary layer of the outer shelf from spring and summer warming. In the shelf break zone and on the continental slope, temperature was kept constant by the stable slope water pycnocline.

The Middle Atlantic continental shelf is characterized by complex topography. Dominant features of this topography are ridges and swales running somewhat obliquely to the shoreline and extending nearly to the shelf break (ca. 80 m). These features and others, such as terraces resulting from sea level stillstands and cross-shelf valleys, were formed during the Holocene transgression of the shoreface across the shelf and have since been modified by contemporary hydraulic processes (Milliman 1973). The influence of this complex topography on the distribution of sediments and benthic organisms is pervasive. These relationships will be discussed below in a separate section. The description of cross-shelf patterns in this section ignores patterns related to local topography.

Sediments on the Middle Atlantic shelf are characteristically very sandy. Little fine sediment currently reaches the shelf, as it is largely trapped in estuaries, however, most of that which does is winnowed from bottom sediments by waves and currents and is eventually deposited on the continental slope (Swift et al. 1972). The hydraulic grading of sediments on the shelf is such that sediments on the inner shelf are medium and coarse sands (although fine sands are found off Virginia), and those at the outermost shelf and shelf break are slightly muddy, fine sands. Shelf sands grade quickly to sediments which are predominantly silt and clay in water deeper than 300-400 m. A factor influencing the distribution of sediments and affecting the benthic communities occupying them is the frequency and severity of sediment movement by waves and current. This is obviously related to depth. Interpretation of bedforms evident in bottom photographs, as well as information resulting from USGS tripod deployments (see Volume III, USGS Report), indicates that sediment mobility on the inner shelf is very frequent but on the outer shelf sediment movement is episodic, generally resulting from winter storms. On the continental slope, surficial sediments are quite stable but may be rarely disturbed by down slumping or turbidity flows (see Volume III).

Trace metals and hydrocarbons tend to associate with fine sediment particles (clays and silts) because of the greater surface area for adsorption, and thus the distribution of these chemical constituents in sediments closely reflected the distribution of these fine sediments rather than a potential source of origin. Higher concentrations of both leachable trace metals and hydrocarbons were found in muddier sediments at the shelf break and on the slope; however, there was limited evidence of increased trace metal and hydrocarbon concentrations in sediments near-shore off New Jersey.

There was no evidence that this increased concentration was the result of anthropogenic input.

The densities of both heterotrophic and petroleum degrading bacteria were highest in near-shore sediments, but were also relatively abundant at the shelf break. This suggests that bacteria density is related to sediment silt-clay content which is greatest at the shelf break, but is also related to proximity to shore where sediment is medium coarse sand with essentially no silt-clay and little organic carbon. Higher sediment temperatures and greater concentrations of inorganic and organic nutrients were probably responsible for elevated populations in near-shore areas.

Foraminifera were variable in abundance and greatly affected by local topography. Greatest densities were found on the outer shelf and at the shelf break, and lowest densities on the central shelf and continental slope. Density and species diversity of total meiobenthos were uniform across the shelf; however, the percentage of nematodes increased across the shelf in response to an increase of silt and clay. Macrobenthos was most abundant on the outer shelf and least abundant on the continental slope. However, the species diversity and richness of macrobenthos showed an obvious offshore increase. Shelf break communities generally had the most species per unit area, but continental slope communities had more species for a given number of individuals collected.

Demersal fish communities on the inner and central shelf are boreal (northerly) in affinity during winter and temperate (southerly) in affinity during summer, with few resident species. On the outer shelf the percentage of species resident throughout the year increases and continental slope species are all permanent residents. The distribution of the boreal community is strongly influenced by the location of the cold pool.

Patterns Related to Local Topography

Local topography, notably the widespread presence of ridges and swales, exerts an influence on the distribution of sediments, their constituents and benthic biota which rivals that found across the shelf. Substantial changes in these properties can take place over a distance of a few kilometers and a depth change of 10 m or less.

Figure 36 summarizes patterns found for central and outer shelf ridge and swale systems off New Jersey. Ridges were characterized by coarser sediments, typically coarse-skewed medium sands. This graded to fine-skewed medium sands or fine sands in the swales. Concomittant with the shift in sand size was an increase in the silt and clay content. This was very low except on deeper flanks and swales where it comprised up to 6% of the sediment. Inferences can be made regarding important sedimentary processes responsible for the observed

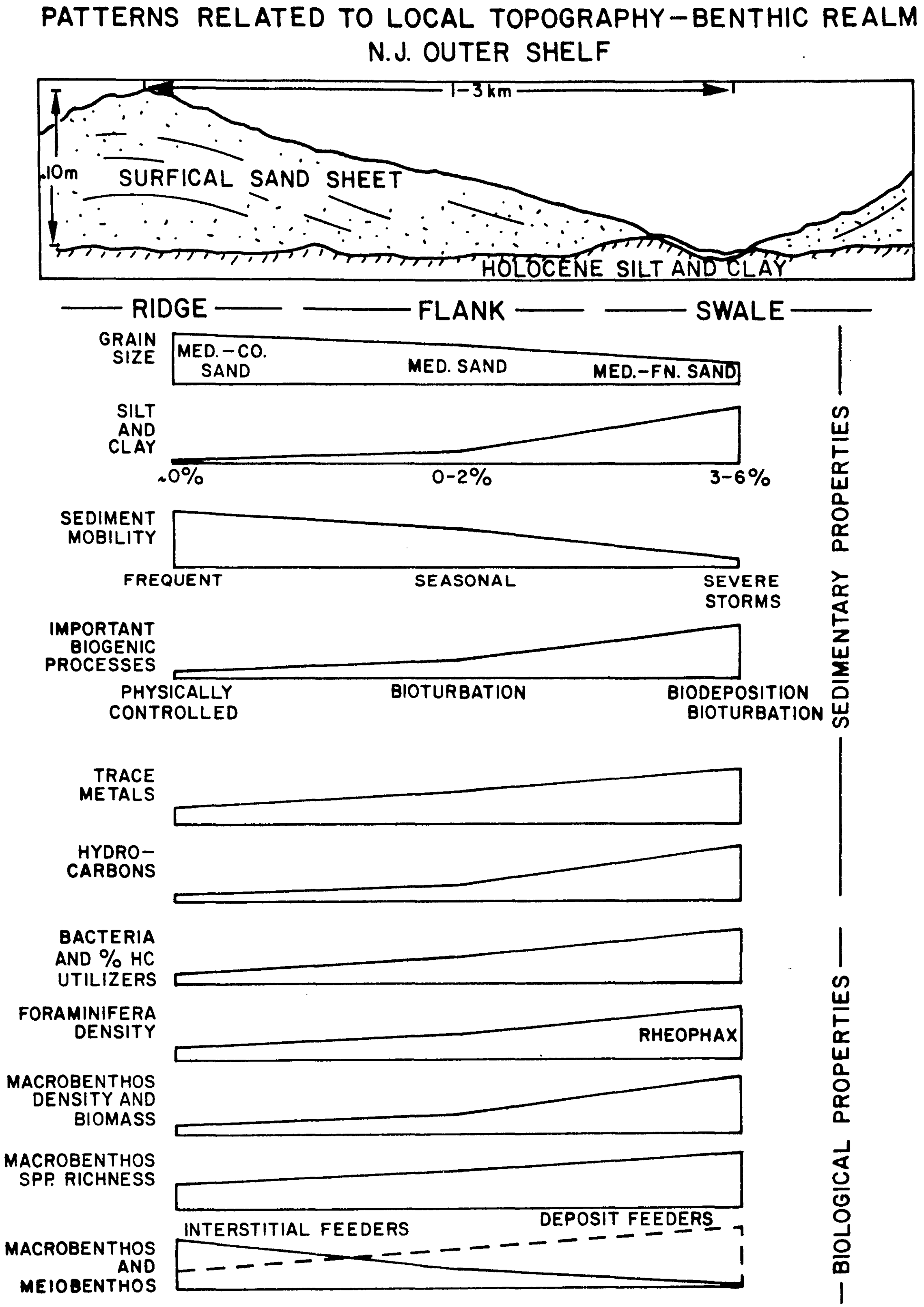


Figure 36. Benthic trends related to local topography observed during fall 1975-summer 1976, BLM-sponsored OCS studies in the Middle Atlantic.

distribution of sediments based on bottom photographs, benthic community distribution, USGS sediment mobility studies, the VIMS wave climate model, and the literature. Sediment movement is more frequent on ridges and exposed topographic highs. These sediments are more likely to be moved by oscillatory currents caused by surface waves and as a result commonly show symmetrical ripple marks. In topographic depressions, sediment movement is less frequent, and bottom sediments may be disturbed only during severe storms, where storm-generated currents may course through swales, locally eroding the substrate. Benthic organisms may play a role in sedimentary processes on the flanks and swales, but their effects are insignificant compared to those of physical processes on the exposed ridges. On less exposed bottoms, signs of bioturbation (the mixing of sediment by the activities of organisms) were commonly apparent in bottom photographs. In swale environments, benthic organisms may even play a more active role in sedimentation by removing fine material from the water and binding it in the form of fecal pellets, tube structures, and foraminifera tests (biodeposition). Biodeposition and erosion of underlying silt-clay deposits are probably the primary sources of fine sediments in swales.

Trace metal, hydrocarbon, organic nitrogen, and organic carbon concentrations are closely related to the silt and clay content of sediments. Therefore, highest levels were found in swales and other topographic depressions. This indicates that should contamination of the shelf benthic environment result from oil and gas development, such topographic depressions are the most likely sites of deposition.

Both the populations of total heterotrophic bacteria and the proportion of those populations which can utilize hydrocarbons as a substrate increased from ridges to swales probably in response to increased organic carbon content. The relative increase in hydrocarbon utilizers reflects the increase in hydrocarbons along the same gradient.

For the benthic fauna, increases in density from ridge to swale were characteristic for foraminifera and macrobenthos, but not for meiobenthos. The increase in foraminiferal densities in swales was largely attributable to great increases in one species, Reophax atlantica. While total number of meiobenthos did not change, the percentage of nematodes did increase and meiobenthic populations in swales were overwhelmingly dominated by this group. The macrobenthos of swales had greater species richness, greater biomass, and greater density. Both meiobenthic and macrobenthic animals which feed on bottom deposits were more prevalent in swales, where increased organic carbon concentrations make this feeding mode advantageous. Conversely, meiobenthic or macrobenthic animals which browse among sand grains in search of interstitial prey were only abundant in coarser sediments found on ridges and more exposed flanks. These coarser sediments have larger intersticies than the finer, slightly muddy sands of the swales.

Ridge and swale topography appeared to have little effect on distribution of the highly mobile demersal fishes.

Biotic Interactions

The biological components of the Middle Atlantic Outer Continental Shelf investigated during this study (bacteria, zooplankton, meiobenthos, macrobenthos, fishes) interact in many ways. Although many of the potential modes of interaction were not directly studied, it is obvious that detrimental impact on any one component will ultimately affect all other components.

The nearly exclusive source of organic matter in the outer shelf beyond the region of direct coastal influence is protophyte production. While primary production by benthic protophytes undoubtedly occurs on the inner and central shelf, the basis of both pelagic and benthic food webs is believed to be production by phytoplankton. Herbivorous zooplankton feed on phytoplankton, and in turn are preyed upon by larger zooplankters. Larval fishes and juveniles of some species feed exclusively on macrozooplankton and even some adult fishes rely heavily on plankton for food (Figure 37). The benthic invertebrate communities are deposit-feeder dominated, and it is unlikely that suspension feeding on near bottom living plankton is quantitatively important in the flux of carbon through the benthos. Rather, planktonic detritus probably serves as the primary input to the dominant surface deposit feeders and suspension feeders which filter the rich surface flux. While microbial metabolic rates might be expected to respond to seasonal particulate detritus inputs following phytoplankton blooms, and meiobenthos investigations suggest that micrometazoans may have population increases in response to seasonal enrichment, the macrobenthos shows no such pattern. The macrobenthos must either be unable to respond because of life history constraints (long generation time, etc.) or their populations may be controlled by factors other than food availability (e.g. predation).

The fishes and benthic invertebrates are also linked with the plankton by being temporary inhabits of it during some stage of their life cycles. Eggs and/or larvae of most fishes on the shelf are planktonic, and it appears that the majority of macrobenthos species have planktonic larval dispersal or are temporarily pelagic as adults.

Predator-prey relationships within the benthic community, especially between meiobenthic and macrobenthic components, are speculative, but results of predator exclosure during recolonization experiments provide evidence that outer shelf communities are, in part, predator controlled. Populations of several species were denser in sediments screened from predators than in unscreened sediments exposed for an equivalent time period.

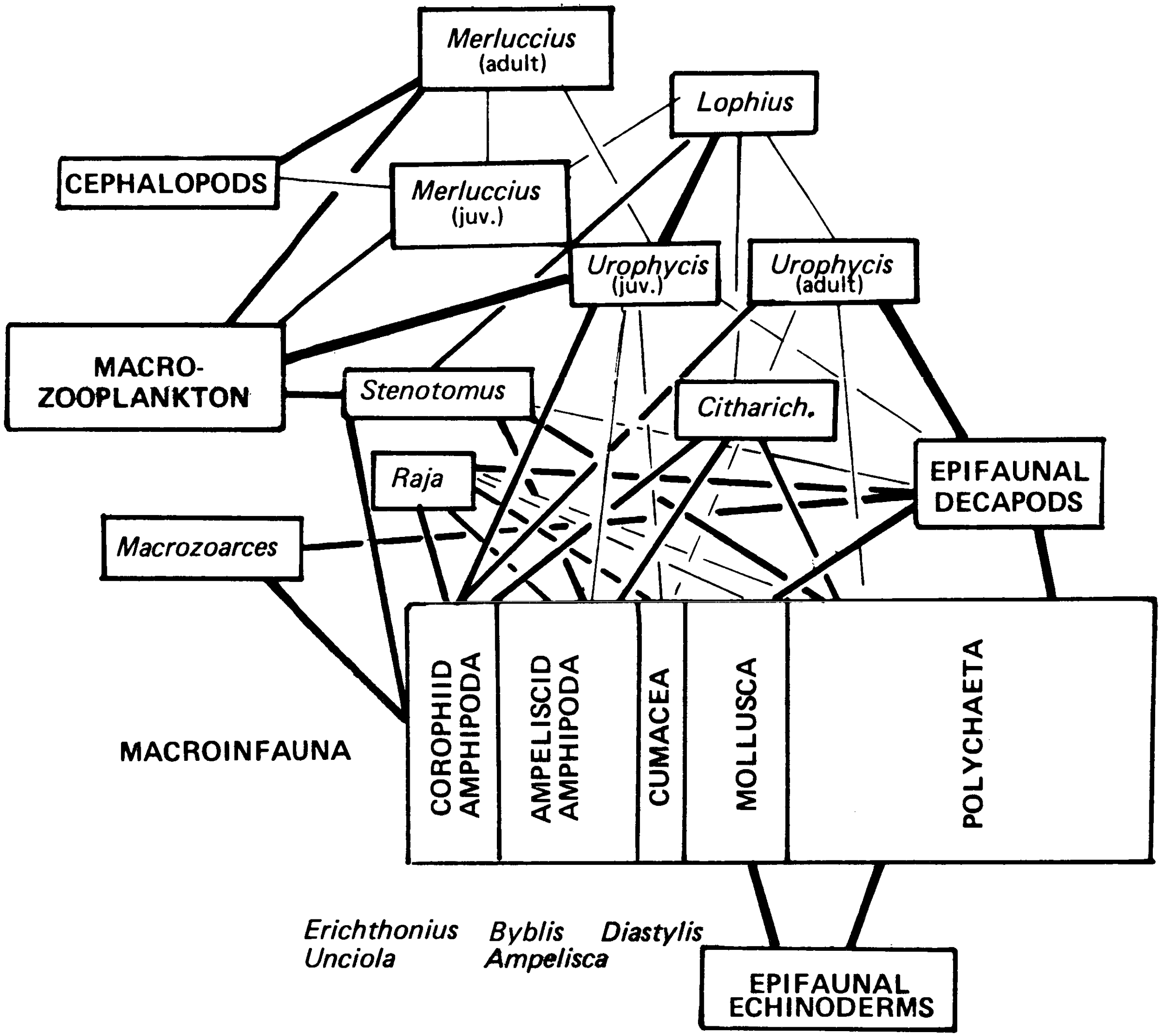


Figure 37. Schematic food web connecting macrobenthos and dominant bottom feeding fishes on the outer shelf. Macroinfauna partitioned approximate to the relative abundance of major taxa to emphasize disproportionate predation on Amphipods. Wide lines indicate major prey items, narrow lines indicate subordinate prey.

There is a diverse array of epibenthic predators on the outer continental shelf including invertebrates such as crabs (Cancer spp.), caridean shrimps, gastropods, and asteroids (starfishes) and demersal fishes such as hakes, skates, scup, and various species of flounder. While the food habits of the invertebrate predators remain unknown, investigations of fish food habits have yielded much insight into the predation pressures exerted by fishes on the macrobenthos. Fish predation does not impact the benthos uniformily. Decapod and peracaridean crustaceans are the most important food items of bottom feeding fishes on the outer shelf, whereas the numerically dominant polychaetes are not heavily consumed. The disproportionate predation on the peracaridean crustacean (particularly amphipod) component of the infauna is depicted in Figure 37 which illustrates the basic trophic structure of the higher consumers on the shelf. Amphipods, particularly corophids, are consumed far out of proportion with their numbers in the infauna, and it is this group which was favored by protection during recolonization studies indicating that predation does control population levels of certain species.

Implications for Resource Managers

The two year benchmark sampling program in the Middle Atlantic outer continental shelf region resulted in the general characterization of the biological, geological, chemical, and physical nature of the environment. In many cases controlling factors responsible for the observed temporal and/or spatial variation of parameters were elucidated which allowed a greater degree of confidence in conclusions drawn from the data. A discussion of those findings which are most important to resource managers for either future studies, impact assessment, or environmental protection is given below.

Physical Oceanography

The physical oceanographic studies were designed primarily to provide supplementary data for interpreting biological results, and thus were not exhaustive, synoptic analyses of physical processes. Even with these limitations, however, measurements taken document the hydrographic complexity of the region and the importance of a coastal boundary layer, Gulf stream eddies, frontal systems, upwelling, mid-level intrusions, submarine canyons, and winter storms. However, before questions concerning transport and dispersion of pollutants can be answered, a more intensive study is needed. Seasonal surface and subsurface current patterns are not well documented for the region, and interactions among the hydrographic features mentioned above and their influence on transport and mixing need additional investigation.

Studies conducted to date have also documented the relationship between potential contaminants (hydrocarbons and trace metals) and fine particles in the sediment. However, the role of particulate matter, both naturally occurring and those released by OCS activities, in the actual transport of contaminants is not well understood and may ultimately be more important than hydrodynamics alone.

Zooplankton/Neuston

The surface layer is of critical importance to shelf decapod crustaceans (crabs and shrimp) and fishes because it serves as a nursery area for eggs and/or larvae of many commercially, recreationally, or ecologically important species (see list on page 73). Any widespread degradation of the surface environment during peak reproductive periods (usually spring-summer, but also winter for some species) could have a serious effect on survival and recruitment of those species which depend on the surface layer for development of early life history stages. Large oil spills like the one resulting from the Argo Merchant grounding or the Ekofisk blowout could conceivably devastate a large percentage of a species' annual reproductive products; however, the effects of floating oil on individual species is still too sparse to permit a realistic assessment of the economic impact of oil spills. The varying effects of oil on eggs of two closely related fish species observed during the Argo Merchant study (Grose and Mattson 1977) demonstrates that all species may not be equally affected by oil, but obviously much more research needs to be conducted on the effects of oil on fish eggs and larvae.

Demersal Fishes

By dividing the Middle Atlantic continental shelf into 12 areas based on latitude and depth (Figure 38), the fish assemblage at any location during any season can be characterized. For any area on Figure 38, dominant fishes by season are listed in Table 14. Commercial or recreational importance of these species and pertinent biological characteristics are listed in Table 15. Common names are listed in Table 16. The fish fauna at lease sites on or adjacent to one of the geographic boundary lines on Figure 38, will probably include dominant species listed for both bathymetric zones adjacent to the lines. Migration of fishes occurs mostly during spring (April-June) and fall (October-November), and faunal composition at any location will be more favorable from year to year during those months than during summer (July-September) or winter (January-March).

Ridge and Swale Topography

Major benthic faunal differences occur over small distances in relation to shelf topography and its effect on sediment distribution. The most pervasive of such topographic habitats are those related to ridge and swale topography. Swales have finer sediments containing

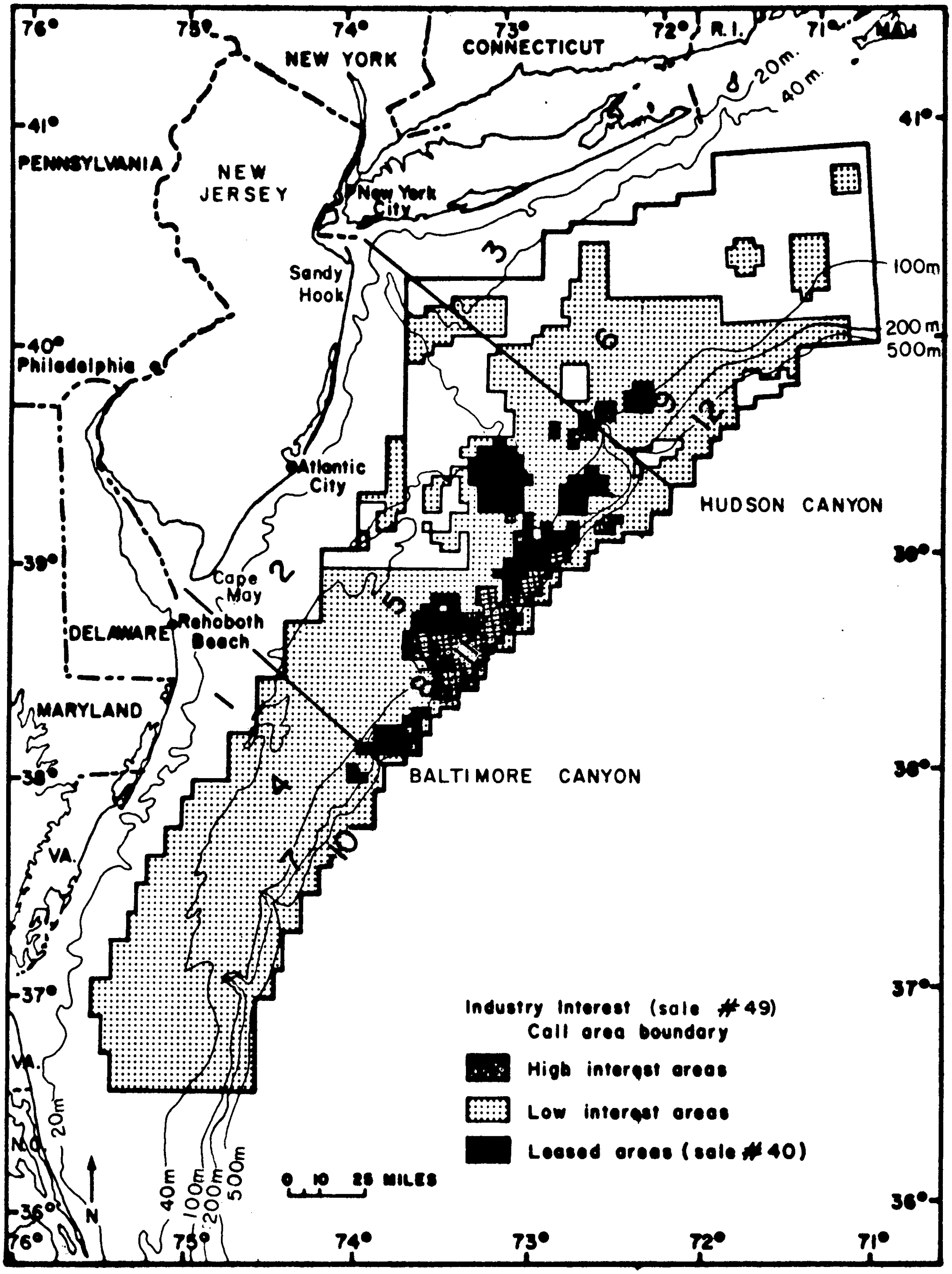


Figure 38. Chart of Middle Atlantic continental shelf lease areas divided into 12 zones to permit seasonal characterization of fish assemblages found therein. Zones 1-3 are inshore (20-40 m depth), zones 4-6 are middle continental shelf (40-100 m), zones 7-9 are outer continental shelf (100-200 m), and zones 10-12 are upper continental slope (200-500 m).

Table 14. Seasonal distribution of fishes among geographic and bathymetric zones on the Middle Atlantic outer continental shelf. Sp = Spring, Su = Summer, Fl = Fall, Wi = Winter.

Species	Zone 1				Zone 2				Zone 3				Zone 4				Zone 5				Zone 6				Zone 7				Zone 8				Zone 9				Zone 10				Zone 11				Zone 12			
	Sp	Su	Fl	Wi	Sp	Su	Fl	Wi	Sp	Su	Fl	Wi	Sp	Su	Fl	Wi	Sp	Su	Fl	Wi	Sp	Su	Fl	Wi	Sp	Su	Fl	Wi	Sp	Su	Fl	Wi	Sp	Su	Fl	Wi	Sp	Su	Fl	Wi	Sp	Su	Fl	Wi	Sp	Su	Fl	Wi
Scomber scombrus	+			+		+				+			+			+		+				+																										
Clupea harengus harengus	+			+				+				+								+				+																								
Alosa aestivalis	+												+																																			
Alosa pseudoharengus	+			+	+			+	+			+	+			+	+			+	+			+																								
Brevoortia tyrannus	+	+				+				+																																						
Pomatomus saltatrix	+	+	+		+	+	+		+	+	+			+				+																														
Raja eglanteria	+	+	+								+				+																																	
Ammodytes dubius	+				+				+																																							
Gadus morhua				+				+				+																																				
Pseudopleuronectes americanus	+		+	+		+	+	+		+		+	+	+				+	+			+																										
Myoxocephalus octodecemspinosus				+								+				+				+				+																								
Scophthalmus aquosus	+	+	+	+	+	+	+	+	+	+	+	+			+	+			+	+		+	+	+																								
Raja erinacea	+	+	+	+	+		+	+	+			+	+		+	+	+	+	+	+			+	+																								
Limanda ferruginea				+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+																								
Macrozoarces americanus				+	+			+	+			+	+			+	+	+	+	+	+	+	+	+																								
Prionotus carolinus	+	+	+				+				+		+		+	+	+		+	+	+		+				+	+			+	+				+												
Stenotomus chrysops	+	+	+				+				+		+		+	+	+		+		+		+					+				+																
Paralichthys dentatus			+				+				+		+		+	+			+	+	+							+				+																
Centropristis striata	+		+										+		+	+			+	+					+		+	+			+																	
Cynoscion regalis		+	+																																													
Micropogon undulatus		+	+																																													
Mustelus canis	+		+												+																																	
Peprilus triacanthus	+	+	+	+		+				+			+		+	+	+	+	+			+	+		+	+	+	+	+	+	+	+	+	+	+	+												
Squalus acanthias	+		+	+	+		+	+	+	+			+	+	+	+	+	+	+	+	+	+	+	+	+		+	+	+		+	+	+			+												
Merluccius bilinearis	+		+	+	+	+	+	+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+												
Urophycis chuss				+	+	+			+	+			+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+												
Hippoglossina oblonga													+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Citharichthys arctifrons													+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Lophius americanus													+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Urophycis regius	+	+	+											+	+	+		+	+						+	+	+	+		+	+																	
Lepophidium cervinum																	+	+	+		+	+	+		+	+	+	+	+	+	+	+	+	+	+	+												
Glyptocephalus cynoglossus													+				+				+				+				+				+				+	+	+	+	+	+	+	+	+	+	+	+
Urophycis tenuis																																													+	+	+	+
Peristedion miniatum																																					+	+	+	+	+	+	+	+	+	+	+	+
Ophichthus cruentifer																									+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Maurolicus muelleri																									+	+	+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Myctophidae																									+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Helicolenus dactylopterus																									+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Chlorophthalmus agassizi																									+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Merluccius albidus																									+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Phycis chesteri																																					+	+	+	+	+	+	+	+	+	+	+	+
Coelorinchus c. carminatus																																					+	+	+	+	+	+	+	+	+	+	+	+
Lycenchelys verrilli																																					+	+	+	+	+	+	+	+	+	+	+	+
Myxine glutinosa																																					+	+	+	+	+	+	+	+	+	+	+	+
Nezumia bairdi																																					+				+	+	+	+	+	+	+	+

Table 15. Pertinent characteristics of dominant fishes of the Middle Atlantic Outer Continental Shelf.

Species	Faunal Affinity	Commercial Importance	Recreational Importance	Trophic Role	Life Style	Early Life History	Spawning Season	Spawning Importance in OCS
Alosa aestivalis	A	I	M	1	P,E	A	Sp	U
Alosa pseudoharengus	A	I	U	1	P,E	A	Sp	U
Ammodytes dubius	B	U	U	1	E	B/P	Wi	I
Brevoortia tyrannus	W.T.	I	U	1	P	P	Fl,Sp	M
Centropristis striata	W.T.	I	I	2	E	P	Su	I
Chlorophthalmus agassizi	R	U	U	1	B	P	?	I
Citharichthys arctifrons	R	U	U	1	B	P	Sp,Su	I
Clupea harengus harengus	B	I	U	1	P	B/P	Fl	M
Coelorinchus c. carminatus	R	U	U	1	E	P	?	?
Cynoscion regalis	W.T.	I	I	2,3	E,P	P	Sp,Su	I
Glyptocephalus cynoglossus	B.R.	I	U	1	B	P	Sp,Su	U
Gadus morhua	B	I	I	2,3	E	P	Wi,Sp	I
Helicolenus dactylopterus	R	U	U	1	B	A?/P	?	I
Hippoglossina oblonga	R	P	U	1,2	B	P	Sp,Su	I
Lepophidium cervinum	R	U	U	1	B	P	Su	I
Limanda ferruginea	B	I	U	1	B	P	Sp,Su	I
Lophius americanus	R	M	U	2,3	B	P	Sp	I
Lycenchelys verrilli	R	U	U	1	B	B/?	Su	I
Macrozoarces americanus	B	M	U	1	B	B	Fl	I
Maurolicus muelleri	R	U	U	1	P	P	Su	I
Merluccius albidus	R	I	U	2,1	E,P	P	Sp,Su	I
Merluccius bilinearis	B	I	I	2,1	E,P	P	Sp,Su	I
Micropogon undulatus	W.T.	I	I	1	E	P	Fl,Wi	I
Mustelus canis	W.T.	P	M	1,2	E	L	Sp,Su	I
Myctophidae	R	U	U	1	P	P	A	I
Myoxocephalus octodecemspinosus	B	U	U	1	B	B/P	Fl,Wi	M
Myxine glutinosa	R	U	U	1	B	B	A	I
Nezumia bairdi	R	U	U	1	E	P	Su	U
Ophichthus cruentifer	R	U	U	1	B	P	Su	I
Paralichthys dentatus	W.T.	I	I	2,1	B	P	Fl	I
Peprilus triacanthus	W.T.	I	U	1	E,P	P	Sp,Su	I
Peristedion miniatum	R	U	U	1	B	P	?	I
Phycis chesteri	R	P	U	1,2	E	P	Fl,Wi	I
Pomatomus saltatrix	W.T.	I	I	2,3	P	P	Sp,Su	I
Prionotus carolinus	W.T.	P	U	1	B	P	Su	I
Pseudopleuronectes americanus	B	I	I	1	B	B/P	Wi,Sp	U
Raja eglanteria	W.T.	P	U	1	B	B	Sp	I
Raja erinacea	B	P	U	1	B	B	A	I
Scomber scombrus	B	I	I	1	P,E	P	Sp,Su	I
Scophthalmus aquosus	O	U	U	1,2	B	P	Wi,Sp	I
Squalus acanthias	B	P	M	2	E	L	A,Wi	I
Stenotomus chrysops	W.T.	I	I	1	E	P	Sp	I
Urophycis chuss	B	I	I	1	E	P	Su	I
Urophycis regius	W.T.	P	U	1,2	E	P	Fl,Wi	I
Urophycis tenuis	B	M	U	1,2	E	P	Fl,Wi	U

Key to Symbols:

Faunal Affinity: A = Anadromous, B = Boreal, W.T. = Warm-temperate, R = Resident, O = Other

Commercial or Recreational Importance: I = Important, M = Marginally Important, U = Unimportant, P = Potentially Important

Trophic Role: 1 = Primary Predator, 2 = Secondary Predator, 3 = Tertiary Predator

Life Style: P = Pelagic, E - Engybenthic, B = Benthic

Early Life History: A = Anadromous, B = Benthic Eggs and Larvae; B/P = Benthic Eggs/Pelagic Larvae, P = Pelagic Eggs and Larvae, L = Live Bearer

Spawning Season: Sp = Spring, Su = Summer, Fl = Fall, Wi = Winter, A = All Year (aseasonal)

Importance of OCS as Spawning Area: I = Important, M = Marginally Important, U = Unimportant

Table 16. Common names of fish species cited in Tables 14 and 15.

Species	Common Names
Alosa aestivalis	blueback herring
Alosa pseudoharengus	alewife
Ammodytes dubius	northern sandlance
Brevoortia tyrannus	menhaden
Centropristis striata	black seabass
Chloropthalmus agassizi	shortnose greeneye
Citharichthys arctifrons	Gulf Stream flounder
Clupea harengus	Atlantic herring
Coelorhinchus c. carminatus	longnose grenadier
Cynoscion regalis	weakfish
Glyptocephalus cynoglossus	witch flounder
Gadus morhua	Atlantic cod
Helicolenus dactylopterus	blackbelly rosefish
Hippoglossina oblonga	fourspot flounder
Lepophidium cervinum	fawn cusk-eel
Limanda ferruginea	yellowtail flounder
Lophius americanus	goosefish
Lycenchelys verrilli	wolf eelpout
Macrozoarces americanus	ocean pout
Maurolicus muelleri	pearlsides
Merluccius albidus	offshore hake
Merluccius bilinearis	silver hake
Micropogon undulatus	Atlantic croaker
Mustelus canis	smooth dogfish
Myoxocephalus octodecemspinosus	longhorn sculpin
Myxine glutinosa	hagfish
Nezumia bairdi	marlin-spike
Ophicthus cruentifer	snake eel
Paralichthys dentatus	summer flounder
Peprilus triacanthus	butterfish
Peristedion miniatum	armored searobin
Phycis chesteri	longfin hake
Pomatomus saltatrix	bluefish
Prionotus carolinus	northern searobin
Pseudopleuronectes americanus	winter flounder
Raja eglantaria	clearnose skate
Raja erinacea	little skate
Scomber scombrus	Atlantic mackerel
Scophthalmus aquosus	window pane
Squalus acanthias	spiny dogfish
Stenotomus chrysops	scup
Urophycis chuss	red hake
Urophycis regius	spotted hake
Urophycis tenuis	white hake

higher carbon content than ridges or flanks. The benthos of swales is more abundant, has greater biomass and species richness and is composed of more deposit feeding animals. Bacterial populations are numerically larger in swales. Concentrations of trace metals and hydrocarbons due to their association with fine particles are also greatest in swales. This indicates that should contamination of the benthic environment occur as a result of oil and gas development, such topographic depressions are the most likely sites of deposition. Within each of two outer shelf areas containing many of the tracts currently leased for oil and gas development, at least five topographic habitats and associated faunal assemblages can be recognized (Figures 39 and 40). The lease tract overlay illustrates those tracts which contain swales and also shows that tracts are by no means homogeneous. Any one tract often contains many different habitats. Because of the relative richness of the benthic biota and the deposition of fine sediments along with introduced contaminants in topographic depressions such as swales, these environments must be regarded as relatively more valuable and susceptible shelf habitats.

Seasonality and Persistence of the Benthos

A major difficulty in establishing biological "baseline" conditions is the determination of temporal patterns of variability against which changes can be measured. Highly variable and dynamic communities present a particular problem because it often becomes impossible to determine if changes in community structure are the result of man's activities or natural variations. The two years of sampling on the Middle Atlantic outer shelf have shown that the benthic communities have seasonally persistent structure and density and, furthermore, community persistence tends to increase with depth. If these communities are truly persistent in the long term, then confidence in impact detection will be high. Furthermore, this persistence implies that baseline monitoring need not entail extensive multi-year sampling because after a few years the information gained to cost ratio will decline drastically.

Of course, environmental impact assessment strategies must take into account the effects of ridge and swale topography on benthic community structure. Relocation errors of the order of scores of meters can place the sampler in a different habitat than previously sampled and the faunal differences observed may be due to spatial rather than temporal variation.

Recolonization Following Catastrophic Disturbance

The observations made following the hypoxia incident on the inner shelf and during the recolonization experiment on the outer shelf (see Significant Findings of Chapter 6) have some very important implications both in predicting the severity of man's activities and

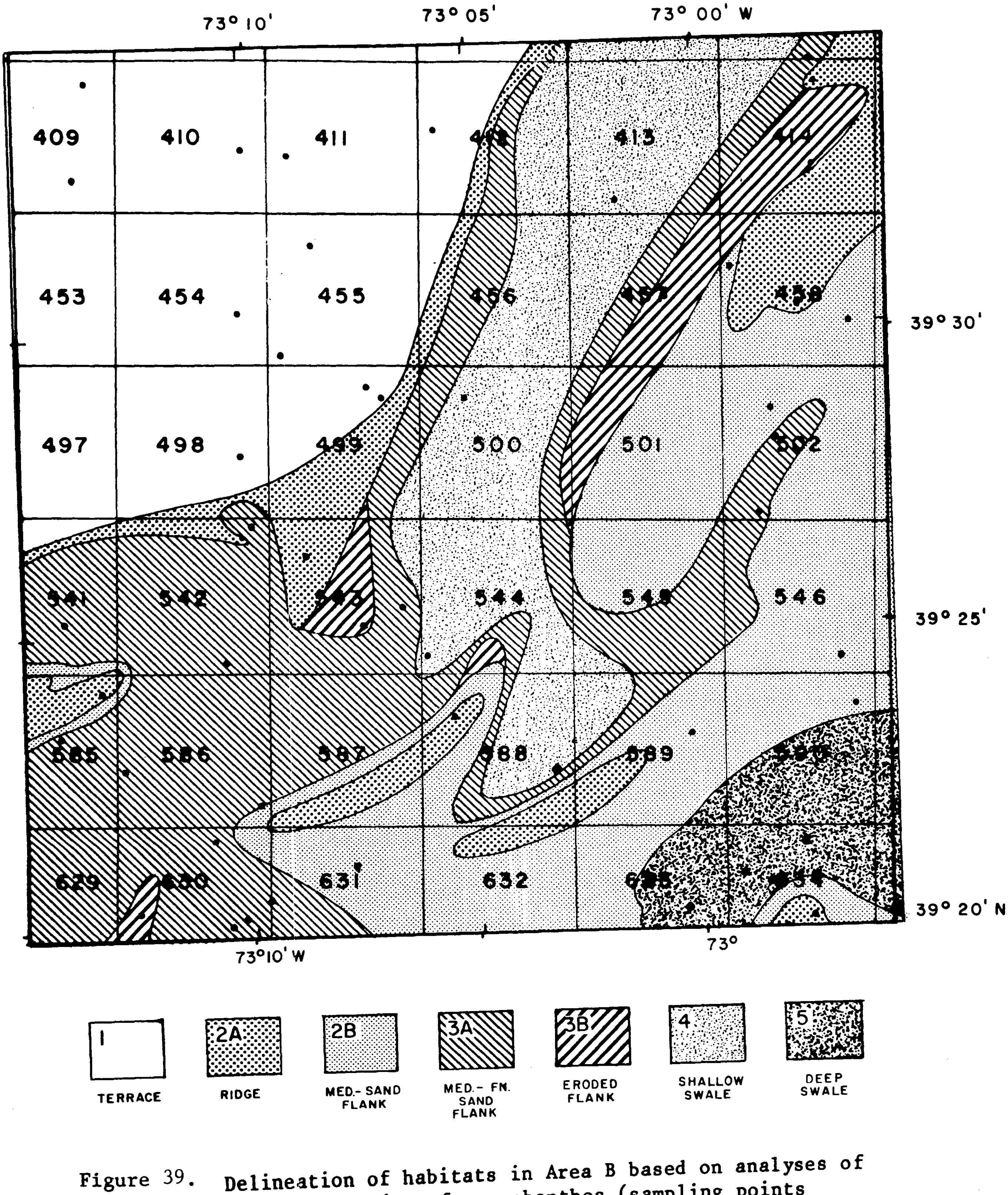


Figure 39. Delineation of habitats in Area B based on analyses of the distribution of macrobenthos (sampling points indicated) and sediments.

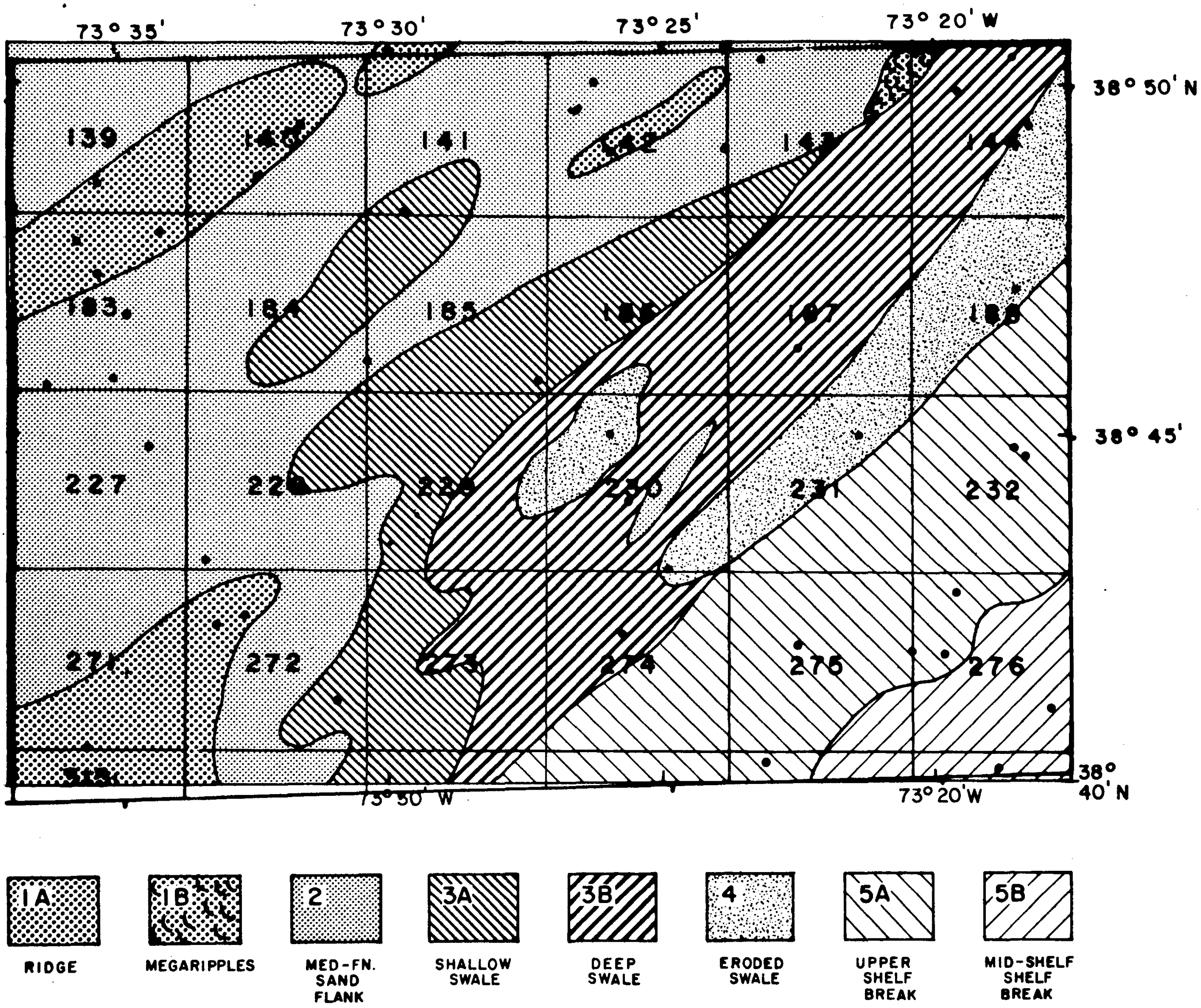


Figure 40. Delineation of habitats in Area E based on analyses of the distribution of macrobenthos (sampling points indicated) and sediments.

in detecting these impacts in the environment. The results demonstrate the inappropriateness of applying simple models based on maturation time or longevity to assess time for community recovery following catastrophe, such as those applied by the Offshore Oil Task Group, Massachusetts Institute of Technology, and others in environmental impact statements. When catastrophic disturbance occurs, species other than those originally present may appear and there may be a considerable period of time before the original occupants return. Species life histories vary; complex biotic interactions occur. Different scales and modes of disturbance may produce different recolonization patterns.

It is impossible to definitely conclude that a certain period of time is required for community "recovery". The criterion of recovery is, of course, debatable. However, by any reasonable criteria, the inner shelf communities had not recovered 18 months (February 1978) after the hypoxia, and the outer shelf communities in sediment boxes had not "recovered" 43 weeks after defaunation.

More encouraging are the implications these results have regarding detection of environmental impact. Disturbed communities were clearly different from unaffected communities for a considerable period of time after the disturbance. Such differences should be statistically detectable by properly designed survey or monitoring, especially on the biotically predictable outer continental shelf.

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GEOLOGIC STUDIES
EXECUTIVE SUMMARY REPORT

Harley J. Knebel[1]

INTRODUCTION

Geologic studies of the Outer Continental Shelf off the Middle Atlantic States (Baltimore Canyon Trough Area) have been carried out for two years to assess conditions and hazards which might cause or distribute oil spills and other potential pollutants associated with petroleum exploration and development. These detailed investigations were requested and funded by the Bureau of Land Management to carry out its responsibility under the Outer Continental Shelf (OCS) Lands Act (67 Stat 462) of 1953 and the National Environmental Policy Act of 1969. Because of the energy crisis, these studies had to be mounted quickly so that a substantial body of data would be available for input into decisions concerning environmental constraints on potential lease tracts. Indeed, pertinent data were available prior to Lease Sale #40 in the Middle Atlantic in August 1976. This was in part due to the alacrity of BLM's Environmental Division management, and in part due to the depth of USGS' experience in the area. For example, geophysical data and bottom samples had been collected since 1962 as part of the Geological Survey's role to "conduct geological and geophysical exploration in the Outer Continental Shelf" (43 U.S.C. 1340). At the advent of the energy crisis, the Atlantic-Gulf Coast Branch focused in-house resources and environmental assessment efforts on the Middle Atlantic OCS area. Thus, considerable information was available to guide the needed detailed studies.

SCOPE

Prior to the initiation of USGS studies, an assessment of potential geologic hazards in the area was made. The hazards were, in order of priority: (1) sediment mobility due to waves and currents, slumps, earthquakes, or inherent characteristics of bottom materials; (2) currents and waves that might distribute pollutants widely along the heavily populated coasts of New Jersey, Delaware, Maryland, and Virginia; and (3) faults that might cause earthquakes, or possibly serve as conduits through which gas or oil might escape to the surface during drilling or production operations.

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To assess these three potential hazards, the USGS conducted the following studies during the first year: (1) a study of bottom sediment transport by means of epibenthic tripods that monitored (for 2-3 months) current speed and direction, temperature, wave spectra, turbidity, and bottom-sediment movement (via bottom photographs); (2) a study of the surface and near-surface sedimentary characteristics by means of manned submersible dives, vibracores, grab samples, and detailed seismic-reflection surveys; (3) a study of the effects of meteorological forcing on the flow within the water column by means of analyses of wind and wave data that had been collected by a BLM/NOAA environmental buoy; (4) a study of the natural particle (seston) flux by means of suspended-matter samples and turbidity measurements from the water column; and (5) a study of the distribution of faults and of earthquake hazards by means of a regional high-resolution seismic-reflection survey along with a historical review of the seismicity of the area.

The first year studies also involved the acquisition of baseline information. Baseline studies included trace metal, hydrocarbon, and textural analyses of samples that had been collected by the benchmark contractor, the Virginia Institute of Marine Science (VIMS).

The first year studies did not reveal geologic hazards of sufficient magnitude to warrant the withdrawal of any lease tracts. However, the attendant report (U. S. Geological Survey 1977) did recommend several areas for continued study. First, the report stated that stresses due to waves and currents associated with major storms may be enhanced by the mobility and the low bearing capacity of the sea floor. Thus, further work was essential to document the rates of sediment movement and the engineering characteristics of the bottom and subbottom. Second, suspended sediments were found to be widely dispersed by waves and currents during major storms. As a result, the report recommended the collection of additional data on suspended solids to resolve the natural paths and sinks of sediments and to provide data to predict the distribution of pollutants from any point source. Finally, the report recommended the continued monitoring of the geochemical constituents of the sediments. This monitoring would establish reliable baselines against which future pollution could be accurately assessed.

In response to these recommendations, a Memorandum of Understanding (AA550-MU7-31) between the BLM and USGS was issued for a second year of studies of the Middle Atlantic OCS. The general objectives of the research program were to: (1) measure the rate of sediment mobility over the seabed and monitor resultant changes in bottom morphology and texture; (2) evaluate the geotechnical properties of bottom and subbottom sediments and their potential hazard to oil and gas development; (3) determine the concentration, distribution, and flux of suspended particulate matter in the water column; and (4) determine the nature and distribution of high molecular weight hydrocarbons in the near-surface sediments at selected locations. These objectives, in addition to being important in their own right, also were in support of the benchmark contractor (VIMS) by helping to synthesize and interpret the geological data as it pertains to the physical, biological, or chemical processes on the shelf.

RELATION TO THE BENCHMARK CONTRACTOR

The Virginia Institute of Marine Science has been responsible mainly for the acquisition of baseline information concerning the geochemistry, biology, and physical oceanography of the area. Baseline stations, which had been selected jointly by VIMS, BLM, and USGS prior to the first-year studies, were reoccupied and sampled on a seasonal basis during the second year. Samples, which were collected at these stations, have been analyzed at VIMS for various chemical and biologic parameters. These long-term measurements provide estimates of the natural variability of parameters which can be used to identify and assess subsequent changes.

Some samples for analysis by the USGS also were collected on the VIMS cruises. A representative from the USGS participated in each seasonal cruise and collected a suite of samples for hydrocarbon analysis at Reston, Virginia. Transmissometer traces and suspended matter samples also were acquired on each cruise; they then were sent to the USGS at Woods Hole, Massachusetts, for analysis. A representative of the USGS participated in the spring and summer cruises to aid in the collection of the seston data.

GEOLOGIC SETTING

The lease areas of the Middle Atlantic OCS lie atop an elongate northeast-trending structural basin called the Baltimore Canyon Trough. The Baltimore Canyon Trough is separated from the Georges Bank Basin to the north by the Long Island Platform; it extends southwestward from New York to Chesapeake Bay and underlies much of the Continental Shelf. Sediments within the Baltimore Canyon Trough have accumulated (since the Triassic continental breakup) to an aggregate thickness of almost 14 km (Schlee et al. 1976; Grow and Schlee 1976; Grow et al. 1978). No physiographic expression of the underlying basin is apparent on the smooth, gently-dipping (1.5 m/km) plain that forms the Continental Shelf. It is, thus, a normal open-marine shelf.

The morphology of the Continental Shelf in the Baltimore Canyon Trough area has been well studied (Veatch and Smith 1939; Uchupi 1968; Emery and Uchupi 1972; Swift et al. 1972; Stanley and Swift 1976). Typically, the bottom is covered by paired linear ridges and depressions that are 2-18 km wide and 2-40 km long. The origin of these bedforms has been attributed to barrier beach-lagoon complex formation during the Pleistocene lowered sea levels (Veatch and Smith 1939; Sanders 1962; Shepard 1963; McClennen 1973) and to modern storm-generated waves and currents (Moody 1964; Uchupi 1968). The ridge and trough topography in turn is superimposed on a framework of higher-order morphological elements (such as shoals, shelf-transverse valleys, and banks) that are of both constructional and erosional origin (Swift et al. 1972).

Previous textural studies by Donahue et al. (1966), Frank and Friedman (1973), Hollister (1973), McClennen (1973), Knebel (1975), Stubblefield et al. (1975) and Knebel and Twichell (1978) have shown that the surface sediments in the Baltimore Canyon Trough area are primarily medium sands (1-2ϕ) that have been, or are still being, reworked and sorted. However, large patches of fine sand do extend across the shelf off both northern and southern New Jersey, over the middle to outer shelf off Maryland, and along the entire shelf break. Coarse sand and gravel occur in scattered (smaller) patches across the shelf off New Jersey and Delaware. Although the grain size of the sand generally is uniform, the local variability may be relatively great due to detailed changes in the bathymetry.

The shallow subbottom stratigraphy in the area has been defined by data from reconnaissance and detailed seismic-reflection surveys and from long sediment cores. Early work by Knott and Hoskins (1968) revealed several prominent subbottom reflectors interpreted to be unconformities in the Tertiary and Pleistocene strata. Recent rotary drilling in the area as part of the USGS AMCOR project has shown that most of the sediments to a depth of about 80 m are either of Holocene or Pleistocene age (Hathaway et al. 1976). Knebel and Spiker (1977), in a detailed study of two relatively-large subareas on the outer shelf, found two near-surface sedimentary units, a surficial sand unit and an underlying muddy unit. The sand unit has a thickness that ranges from 1 to 20 m and is related closely to the bottom morphology; it is of Holocene age. The muddy unit, on the other hand, is texturally diverse, has an unknown thickness, and is of late Pleistocene age. Similarly, studies on the adjacent inner Continental Shelf have shown that the surficial sand sheet varies in thickness, is of Holocene age, and overlies a nearly horizontal surface of older Holocene or Pleistocene strata that can be traced acoustically for relatively great distances (Duane et al. 1972; Swift et al. 1973; Sheridan et al. 1974; Stahl et al. 1974). McClennen (1973) and Twichell et al. (1977) have traced the buried ancestral channels of the Great Egg and Delaware Rivers across the shelf near the central part of the area.

Shallow faulting apparently is sparse, and the seismic activity is low within the Baltimore Canyon Trough area. A reconnaissance seismic-reflection survey across the entire area failed to identify any faults in the upper 50-80 m of the sediments (U. S. Geological

Survey 1977). However, a more detailed survey in the northeastern part of the area did identify several faults that displace Pleistocene strata about 1.5 m, only 7 m below the sea floor (Sheridan and Knebel 1976). A few other small faults have been identified from closely-spaced seismic lines that were run in the same area for the USGS Conservation Division. Concerning earthquakes, only five epicenters have been located offshore near the area since 1900; all are close to the shelf edge on the upper slope (U. S. Geological Survey 1977). The seismotectonic map of the eastern U. S. classifies the inner coastal plain from New Jersey to Virginia at level 2 of seismicity and the adjacent offshore area at level 1, the lowest seismic activity level.

Slumping and slump deposits appear to be common at the shelf break and on the upper Continental Slope in this area. Analyses of 24 high-resolution seismic-reflection profiles that were collected during local and regional surveys show that small-scale slump deposits are ubiquitous in the intercanyon areas of the Continental Slope (Knebel and Carson 1978). These deposits involve the upper 10 to 90 m of sediments, extend downslope for 1.8 to 7.2 km, and may be either relict or modern. Large-scale slumps also have been identified on the upper Continental Slope northeast of Wilmington Canyon (McGregor and Bennett 1977) and southwest of Baltimore Canyon (Embley and Jacobi 1977).

Bottom flow and, thus, bottom sediment transport is temporally variable in the Baltimore Canyon Trough area. Early studies involving seabed drifters (Bumpus 1973) showed that the mean southerly bottom flow generally was onshore to a water depth of 80 m, and offshore at greater depths. Superimposed on this mean flow are tidal currents, low-period fluctuating currents associated with meteorological forcing, and other currents associated with forcing from the deep ocean (Beardsley and Butman 1973; Schmitz 1974; Boicourt and Hacker 1975; Scott and Csanady 1976). Bottom currents on the outer shelf that were measured during three winter storms exceeded 30 cm/sec and, during one, reached 43 cm/sec (U. S. Geological Survey 1977). The major flow axes at these times were oriented NE-SW or generally parallel to the shelf edge. In contrast, the bottom currents that were measured during the summer were low; current speeds generally did not exceed 20 cm/sec (U. S. Geological Survey 1977).

Limited information is available on the distribution of suspended matter within the water column over the area (Manheim et al. 1970; Meade et al. 1970, 1975; U. S. Geological Survey 1977). The concentrations of suspended matter generally are less than 2 mg/l, with the highest values nearshore and the lowest values offshore. Surface and mid-depth samples tend to be similar, but near-bottom concentrations tend to be higher over the middle and outer shelf. Biogenic debris accounts for most of the suspended matter in the upper part of the water column, whereas inorganic particles are relatively abundant near the bottom. The well-developed summer thermocline inhibits the settling of some surface suspended sediments and may contribute to their widespread dispersal.

FIELD WORK

Eight cruises were conducted by the U. S. Geological Survey under BLM funding to carry out the second-year investigations of the geologic characteristics of the area (Table 17). Other data were collected aboard the DSRV NEKTON GAMMA and the R/V ATLANTIC TWIN. These cruises were supported by funding from other sources.

The locations of the sampling stations, geophysical tracklines, and submersible dive sites for the second-year study are shown in Figure 41. During the BLM-funded cruises, navigational control for all station locations and tracklines was provided by Loran-C. On the R/V ATLANTIC TWIN (submersible) cruise, Loran A was used.

The equipment and devices that were used to collect the field data were quite varied. The tripod components included: Sea Data electronics and tape transport; Bendix Savonius roto current meters; Paroscientific pressure sensors; Sea Data thermistors; Montedoro-Whitney transmissometer-nephelometers; Benthos bottom cameras; AMF releases; Oceanic Industries pressure cases; Electro-Oceanics penetrators and connectors; and Miami Marine Research anti-fouling devices. Water samples for suspended matter, particulate organic carbon, organic nitrogen and chlorophyll were collected with Niskin bottles that were mounted on a rosette sampler. Aliquots for suspended matter were filtered through Millipore® filters, whereas aliquots for the other variables were filtered through glass fibre filters. Temperature and salinity profiles for use in the suspended-matter studies were obtained with a Plessey CTD system and conventional XBT's. An Ocean Research Equipment, Inc. integrated seabed survey system, which was composed of a 97 kHz side-scan sonar and a variable frequency high-resolution subbottom profiler, was used during the geophysical surveys. A Uniboom® system also was operated, except when it was ineffective due to rough seas. A Smith-McIntyre grab was used to collect samples for hydrocarbon analyses on the VIMS seasonal cruises. The vibracores were obtained with an Alpine system.

Table 18 summarizes the observations and samples that were taken in the Baltimore Canyon Trough area on USGS-related cruises.

LABORATORY ANALYSES AND PROCEDURES

Table 19 summarizes the kinds and numbers of analyses that were run on samples collected from the water column and from the bottom.

Table 17. Cruises conducted by USGS.

Cruise Identification		Dates
R/V WHITEFOOT	(10/76)	26 October - 31 October 76
R/V OCEANUS	(017)	3 December - 10 December 76
R/V WHITEFOOT	(77-01)	8 March - 17 April 77
R/V SUB SIG II	(4/77)	19 April - 2 May 77
R/V OCEANUS	(027)	8 June - 14 June 77
R/V OCEANUS	(029)	6 July - 13 July 77
R/V ADVANCE II	(9/77)	7 September - 23 September 77
R/V ANNANDALE	(AN-1-77)	18 September - 25 September 77

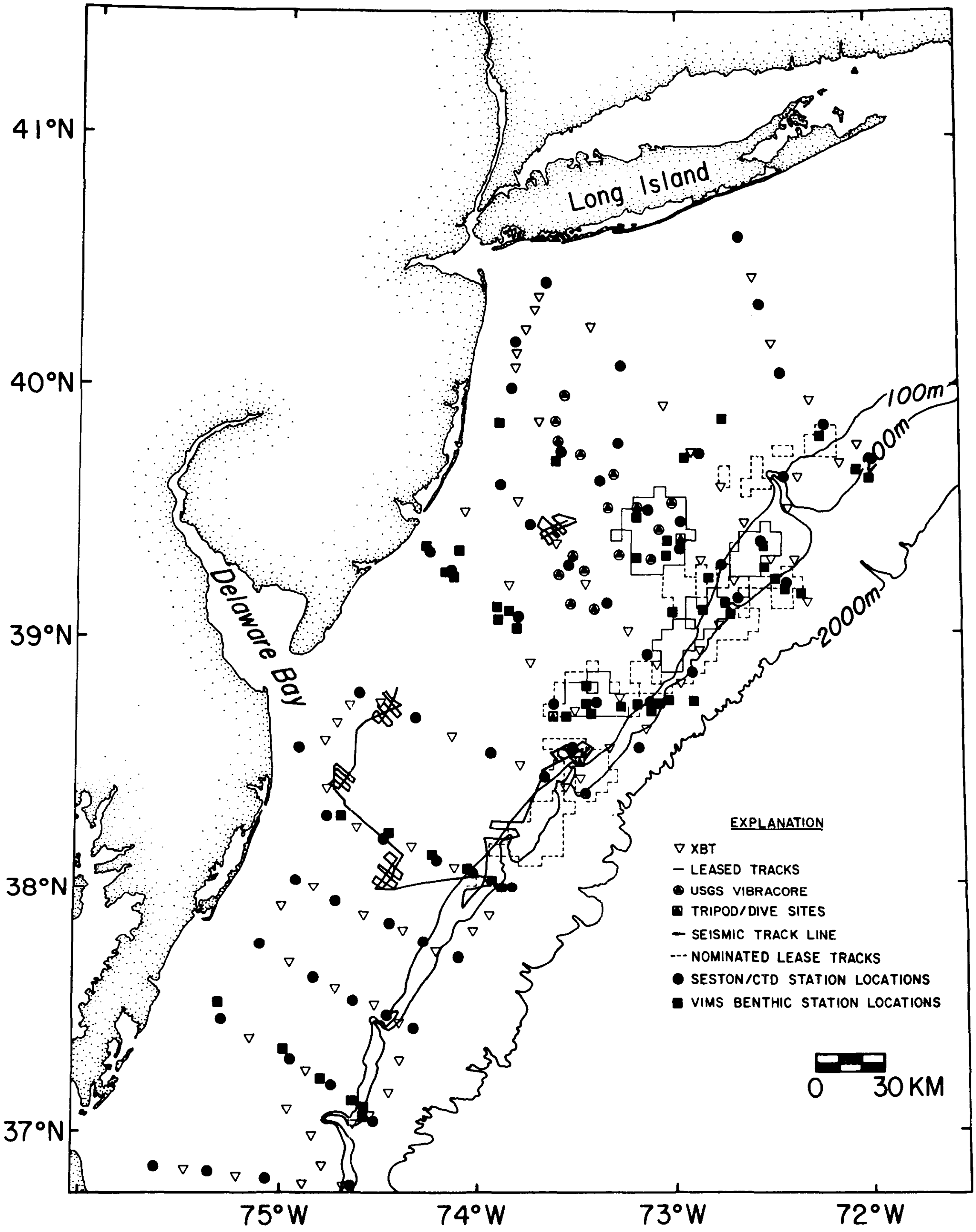

Figure 41. Locations of the sampling stations, geophysical tracklines, and submersible dive sites for the second-year study.

Table 18. Summary of observations and samples taken in the Middle Atlantic on USGS-related cruises.

CRUISE IDENTIFICATION	Instrument Deployment/Receovery	XBT	CTD Casts	Nephelometer/Transmissometer Casts	Suspended Matter Samples	Seismic Reflection/ Side-Scan Sonar (km)	Vibracores	Grab Samples
WHITEFOOT (10/76)	1	21						
OCEANUS (017)	2	33		4	12			
WHITEFOOT (77-01)	2	41						
SUB SIG II (4/77)		89	65	80	306			
OCEANUS (027)						788		
OCEANUS (029)	4	50	28					
ADVANCE II (9/77)	4	36	17					
ANNANDALE (AN-1-77)							20	
VIMS-05B (Fall)		24	31	25	18			20
VIMS-06B (Winter)		115	46	46	51			41
VIMS-07B (Spring)		59	33	28	65			20
VIMS-08B (Summer)		104	45	45	129			41
TOTALS	13	572	265	228	581	788	20	122

Table 19. Summary of analyses on samples collected from the water column and from the bottom.

Suspended Matter	Hydrocarbons	Geotechnical Properties								
		Bulk Unit Weight	Water Contents	Atterberg Limits (Liquid)	Atterberg Limits (Plastic)	Specific Gravity of Solids	Size Analysis	Consolidation Tests (One-Dimensional)	Consolidation Tests (Three-Dimensional)	Triaxial Compression
391	138	131	160	60	60	70	120	32	10	12

Tripods

Data recovered from the tripod instruments include: bottom photographs, current speed and direction, light transmission, pressure, and temperature. About 750 photos are taken during a deployment. The picture-taking rate is selected at 2 to 5 hours depending on deployment length. The photos are processed in a flow camera system and the "8 x 10" positive prints are reviewed for ripple crest migration, number of organisms, turbidity, and other features. For winter deployments, samples of current speed, pressure, temperature, and light transmission are obtained every 7.5 minutes. For summer deployments, samples are obtained every 3.75 minutes in order to resolve internal wave processes. Centered within the sampling interval are 12 samples of current speed, current direction, and pressure which are taken over a 4-sec sample period. These data are recorded on magnetic tape cassettes in the Sea Data Recording System. Cassette data are copied onto a 9-track tape with a HP computer and decoded with a Sigma 7 computer into physical variables such as cm/sec, millibars, degrees Celsius, and volts (for light transmission). For an initial look at data quality, the interval and average quantities calculated from the burst are plotted. These data are edited and stored on 9-track tape, ready for display analysis and scientific computation.

Seston

The rinsed and frozen samples were air-dried and weighed in the laboratory, and the total seston concentrations in the water were calculated. The filters then were split, and one half was used for optical or scanning electronic microscopic (100 to 800 X) study. For some samples, the major elements in some unidentified particles were analyzed with backscattering X-ray fluorescence. Transmissometer tapes were played back in the Montedoro-Whitney deck read-out, and the extinction coefficients were calculated at the depths at which the suspended matter samples were taken.

Geophysics

The high-resolution seismic-reflection profiles and the side-scan sonar records were reduced by means of a flow camera system. The photographic copies then were examined for significant bottom and subbottom acoustic characteristics. After examination, the characteristics were depicted in profiles and on plan-view maps.

Hydrocarbons

Approximately 100-300 g of sediment were freeze-dried, transferred to a pre-extracted paper Soxhlet thimble, and then

Soxhlet-extracted for 100 hours with a toluene:methanol azeotrope. Saponification was carried out by heating the sample with a 1:1:1 mixture of 0.5 N KOH in a methanol:toluene:water mixture at 100°C. The saponification mixture then was partitioned with a saturated NaCl solution and extracted at least three times with n-hexane for column chromatography, gas chromatography and mass spectrometry.

Geotechnical Properties

The sediment in the vibracores were kept refrigerated at 2-4°C and the following tests were performed: bulk unit weight; water content; Atterberg limits-liquid limit; Atterberg limits-plastic limit; specific gravity of solids, textural analysis; one-dimensional consolidation test; three-dimensional consolidation test; and consolidated undrained triaxial compression. The test methods followed the recommendations of the American Society for Testing and Materials (ASTM), whenever these were available. This was the case for all but the three-dimensional consolidation tests and the $\bar{R}$ triaxial compression tests. The three-dimensional consolidation tests were done in conventional triaxial cells on specimens 7.1 cm in diameter and 8 cm high. The specimens were backpressure saturated under 392 kPa and then isotropically consolidated in eight loading increments. The $\bar{R}$ tests were done on specimens 7.1 cm in diameter and 16 cm high. The specimens were backpressure saturated under at least 392 kPa, and undrained tests were performed by using a rate of strain of about 0.04% per minute.

ROLES OF KEY PARTICIPANTS

The personnel who were responsible for the elements of work during 1976-77 under MOU AA550-MU7-31 and who produced the written reports that make up the Final Report are listed below. Studies of bottom currents and bottom sediment mobility were headed by Dr. B. Butman, M. Noble, and Dr. D. W. Folger who, in turn, were assisted by a group directed by D. Hosom of the Woods Hole Oceanographic Institution (WHOI), by W. Hill of Sea Data Corporation, and by the USGS technical staff. Seston studies were carried out by Dr. J. D. Milliman of WHOI and his staff and by Dr. M. H. Bothner and C. M. Parmenter of the USGS. Dr. M. H. Bothner and his staff processed the Nephelometer/Transmissometer data. S. A. Wood and Dr. D. W. Folger processed and synthesized the data gathered during the manned submersible dives. D. C. Twichell conducted the seismic studies and interpreted the data. Samples for hydrocarbon content were collected aboard VIMS seasonal cruises and were processed and analyzed by Dr. R. H. Miller, Dr. D. M. Schultz, H. Lerch, D. Ligon, D. Doyle, and C. Gary at the USGS in Reston, Virginia. Dr. D. A. Sangrey and Dr. H. J. Knebel collected the vibracores and interpreted the geotechnical property measurements of the sediments that were made by Geotechnical

Engineers, Inc. Many other USGS professional and technical staff members supported the cruises that collected the physical oceanographic, sedimentary, and geophysical data or assisted in the preparation of the report. Dr. H. J. Knebel wrote the Introduction and Executive Summary parts of the Final Report, put the Final Report together, and served as Program Manager throughout the year.

SIGNIFICANT FINDINGS AND INTERPRETATIONS

This summary of the principal results and conclusions is based on the eight chapters included in the Final Report. Duplicates of illustrations and tables are not reproduced here and no references are included. Thus, for illustrative material and complete reference lists, the chapters in the Final Report must be consulted.

Bottom Currents and Bottom Sediment Mobility

(Chapter 2, Butman and Noble; Chapter 8, Butman and Folger)

The bottom tripod systems that have been developed by the USGS are designed to investigate processes that cause sediment mobility on the OCS. A second-year field program was necessary to augment those data on bottom currents and bottom sediment transport that had been obtained during the first-year effort. In particular, the second-year objectives were to: (1) investigate the seasonal variability of the bottom currents, the bottom sediment motion, and the bottom sediment transport at one representative (long-term) location; (2) investigate further the importance of internal waves on bottom sediment movement during the summer; (3) investigate the importance of the deeper ocean circulation and of the movements of the shelf-slope water front on sediment transport processes; and (4) investigate the relationship of the near-bottom tripod observations to the general shelf circulation, particularly to the various coastal and oceanic water masses.

To meet these objectives, the following strategy was employed. One tripod was maintained continuously (at 60 m water depth) near the BLM-NOAA meteorological buoy (EB41) so that long-term observations could be correlated with measurements of wind speed, wind direction, atmospheric pressure, sea surface temperature and surface wave observations. Shorter-term (2-4 months) measurements of the cross-shelf and alongshelf variability of bottom sediment transport processes were made by means of a second tripod system at some distance away from the long-term station. Limited studies of the near-bottom currents and the regional circulation also were conducted by means of conventional instruments where additional observations were needed. Finally, hydrographic observations were made on each instrument deployment and recovery cruise in order to determine the position of a particular tripod with respect to the various coastal and oceanic water masses.

Most of the observations during the second year were made during the relatively calm (spring and summer) months, although tripods were deployed at two of the "short-term" stations during the winter. The winter observations generally were consistent with studies made during the winter of the previous year which showed that: (1) bottom sediments frequently were resuspended by large surface waves and storm-generated currents; (2) the net bottom flow on the OCS generally is toward the southwest; and (3) small-scale bedforms rapidly formed in response to the wind-driven flow during large storms. However, anomalous mean northward currents (>30 cm/sec) were observed during one storm having strong winds that blew toward the northeast. This event clearly showed the kind of variability that can be expected during the winter season.

The bottom conditions during the spring and summer generally were tranquil (current speeds <20 cm/sec), although a variety of sedimentary processes were in operation over the OCS. During the time of summer stratification, internal wave packets were observed to move across the area. The current speeds of individual waves within a packet were typically 15 cm/sec or less with a period of 5 to 20 minutes. Although the magnitudes of these waves were individually not large enough to resuspend bottom sediments, some resuspension was observed when internal wave packets propagated through the area and their currents were reinforced by tidal currents. Over the outer shelf, the ambient suspended-sediment concentrations in the water column are partially determined by the position of the front between the shelf and slope water masses. The slope water, which was observed on the shelf for significant periods of time, contained lower suspended-matter concentrations than the shelf water. Because little mixing occurs across the interface, shelf sediments that might be within the slope water may be transported off the shelf as the front periodically moves eastwards. Finally, the data suggest that trawlers also may resuspend the bottom sediment. This process is relatively important only during periods of tranquil current conditions.

Seston (Suspended Matter) Distribution in the Water Column

(Chapter 3, Milliman, Bothner, and Parmenter)

The general purpose of this part of the second-year program was to document and interpret the temporal and spatial distribution and the composition of suspended particulates over the Middle Atlantic OCS. More specifically, the seston data could provide some insight into problems such as: (1) the sources for the particulates; (2) the role that bottom resuspension plays in the particulate load in the water column: (3) the influx of anthropogenic particles; and (4) the seasonal variability of the suspended sediment distribution and processes.

Samples to define the concentrations and composition of the suspended sediments were collected throughout the year on six cruises (Table 18). Four of the cruises were those conducted seasonally by VIMS; the remaining two were completed by the USGS during December 1976 and April to May 1977. Generally, the cruises were completed within a week or ten days, thus giving a quasi-synoptic view of the seston and hydrographic characteristics during the cruise period.

The annual variation in the seston regime over the Middle Atlantic OCS can be ascertained, in general, from the year-round collection of samples. During the winter, suspended particulates in the surface waters are low in combustibles (biogenic) percentages due to relatively low productivity and are high in non-combustible (lithogenic) material due to the resuspension and upward transport of bottom sediments. The seasonal impact of winter is less apparent on the suspended sediments near the bottom; in fact, the total and non-combustible fractions were lower during February than during other months. In spring, the total suspended particulates and the combustible fraction increased in both the surface and near-bottom waters as a result of plankton blooms. The non-combustible particulates decreased accordingly, but they remained relatively abundant near the bottom. In the well stratified summer waters, the disparity between the contents of surface and near-bottom seston was the greatest. Surface particulates were dominated by organic particles, whereas the near-bottom waters were dominated by terrigenous particles. In the fall, the decrease in productivity and the onset of mixing and resuspension by storms increased the non-combustible component throughout the water column. Resuspension of sediments greatly increased the total particulate concentrations in the bottom waters relative to those during the summer.

In addition to the annual cycle, several other trends concerning the suspended sediments were found during the second-year study. First, seston concentrations across the area were low, seldom exceeding 1 mg/l. Second, with the exception of nearshore areas, bottom waters on the outer shelf have the highest particulate concentrations, undoubtedly due to the resuspension of bottom sediments. Third, samples, which were obtained at a 20-hour station near the shelf edge, show that internal tides or groups of internal waves may resuspend sediments periodically. Fourth, the surface waters off Delaware Bay contain relatively high concentrations of suspended particulates, suggesting that the influx of terrigenous sediments from estuaries may cause significant local perturbations in the suspended-sediment distribution. Finally, in contrast to the first-year data, the samples that were collected during the second year contained far fewer indications of anthropogenic pollutants.

Submersible Observations

(Chapter 4, Wood and Folger)

Submersible dives were conducted on the OCS (water depths - 60-80 m) east and northeast of Delaware Bay during July 1976. The purposes of the dives were to assess the geologic, biologic, and hydrologic characteristics of the bottom and to observe the in situ operation of two tripods.

During the dives, photographs of the bottom were taken with a 35mm camera and any direct observations were recorded on magnetic tape. Poor weather limited the diving activities to only two of the five days that had been allocated.

The observations and photographs during the dives revealed that: (1) the bottom-water circulation during the summer generally is slow (<10 cm/sec); (2) the bottom consisted of small hummocks and depressions that were covered by a brown flocky layer; (3) fish and eel pouts interfered with the current-meter rotors and the sediment traps on the tripods; and (4) no appreciable deposition or scour had occurred near one tripod mooring anchor that had been on the bottom for almost a year.

Medium-Scale Bed Forms

(Chapter 5, Twichell)

Seven areas of the Middle Atlantic Continental Shelf were surveyed for sand waves to define their distribution, magnitude, and potential for sediment transport. Five of the survey areas were selected on the basis of sand-wave-like forms that were crossed during a geophysical survey of the entire shelf during the first-year study. Because sand waves had been found around the head of Wilmington Canyon, brief surveys also were conducted around the heads of Baltimore and Hudson Canyons.

The surveys revealed that, for this part of the shelf, genuine sand waves exist only around the head of Wilmington Canyon. This classification is based on their internal (acoustic) characteristics as well as their ordered distribution, orientation, amplitude and asymmetry. On the basis of their structure, these sand waves are interpreted to be of relict origin, probably having developed during the initial stages of the Holocene. Under the present hydraulic regime of the Middle Atlantic shelf, no net migration of these sand waves could be discerned, yet their surface sediments presently are being reworked and are systematically redistributed. The megaripples, current lineations, and subbottom outcrops that were found in the sand wave area probably were developed or are maintained during storm-generated flow. Because of their static nature, the sand waves around Wilmington Canyon are not a geologic hazard.

Hydrocarbon Baseline Studies
(Chapter 6, Miller, Schultz, Lerch, Ligon, Doyle, and Gary)

Hydrocarbon analyses were completed on samples of bottom sediments taken at selected stations across the Middle Atlantic Continental Shelf. The objectives of this study were: (1) to determine (qualitatively and quantitatively) the hydrocarbons at particular stations to allow comparisons to be made throughout the biological seasons; (2) to establish the statistical deviations that may occur in the concentrations and types of hydrocarbons at a given location; (3) to provide data points to define a "natural variability" curve for the entire Middle Atlantic Shelf; and (4) to document baseline levels of hydrocarbons that could be used subsequently to assess the impact of petroleum exploration in the area.

The sample stations for this study were those that were occupied during the first-year effort. Six cluster stations were sampled during each season, whereas 23 additional (isolated) stations were sampled only during the summer and winter. At each station, a composite-blend sample was collected by taking approximately 150-200 g of sediment from each of six grabs.

From the second-year study, several general statements can be made concerning the hydrocarbon geochemistry of the Middle Atlantic shelf sediments. First, the concentration levels of the n-alkanes in the sediments is very low, being less than 1.0 μg/g. Second, the concentrations of the resolved aromatic hydrocarbons also are low, being less than 1.0 μg/g. Third, the resolved n-alkane fraction in many samples contained an anomalous series of peaks in the n-C_{20} to n-C_{21} range that may be due to an unsaturated, branched C_{25} with cyclic structure. Fourth, seasonal changes were found for the resolved n-alkane fractions, the pristane/n-C_{17} ratios, and the pristane/phytane ratios, but the concentrations of the resolved aromatic hydrocarbons remained nearly constant throughout the year. Fifth, hydrocarbons that can be attributed to coal or other fossil fuels were found in low concentrations at only a few stations. Finally, the natural variability of the hydrocarbons in the area may be affected by (a) bottom sediment transport, (b) chemical and biological degradation, (c) the residence time of hydrocarbons in the water column, (d) the interactions of humic and fulvic substances with hydrocarbons, and (e) the input from anthropogenic sources.

Geotechnical Engineering Studies
(Chapter 7, Sangrey and Knebel)

Vibracores were taken within a representative transect across the Middle Atlantic Continental Shelf in order to evaluate the engineering characteristics of the near-surface sediments. These characteristics, in turn, can be used to evaluate geologic hazards relative to facility siting on the shelf surface, to understand the geologic history of the sediments, and to provide a regional data base for engineers who are contemplating projects in the area.

The engineering-properties data that were derived from this study are primarily for the clayey sediments that underlie the surficial sand sheet of the Middle Atlantic shelf. Because of the vibracoring method, all of the sandy sediments that were collected during this study were disturbed.

The majority of the clayey sediments that were tested were heavily overconsolidated, with adequate shearing resistance and low compressibility. Thus, they present no unusual hazard to facility siting. There are, however, local deposits of weak and more compressible sediments whose engineering properties may pose some small stability problems in applications such as bearing-capacity support for temporary or permanent structures. Consequently, site-specific studies are appropriate for structures that may be vulnerable to this condition.

The majority of the clayey sediments also are dilative. Under undrained cyclic loading, there should be no unusual hazard associated with these sediments. In addition, only a modest strength reduction under cyclic loading with drainage should be anticipated.

SYNTHESIS OF SEDIMENT MOVEMENT

From the data that have been developed during the first two years, we can make some preliminary estimates of the processes, the magnitude, and the effects of sediment movement on the Middle Atlantic OCS. Concerning processes, large fall and winter storms as well as hurricanes provide large surface waves and wind-driven currents that can resuspend and transport the dominantly well-sorted, fine-to-coarse sands that cover this part of the shelf. The current direction during storms may be oriented either to the northeast or southwest parallel to the shelf edge; the rather weak circular tidal currents are masked by the storm-driven currents. The bottom flow during storms rapidly forms small-scale bedforms (such as ripples) and may scour the sediments around objects on the sea floor. After a storm, the small bedforms rapidly disappear, apparently degraded by low-energy current flow or bioturbation. During the spring and summer, on the other hand, the bottom flow is rather tranquil; current speeds generally are not much greater than the background levels due to tidal flow. However, several varied processes (acting either independently or in conjunction with tidal currents) may cause limited resuspension and transportation of sediments. These processes include: (1) internal waves; (2) movement of the front between the shelf and slope water masses; (3) bottom trawling; and (4) biogenic activity.

The magnitude of the near-bottom sediment transport also varies seasonally. Water particle displacements in a 30-day period have been estimated from the available current records at three tripod locations (see Chapter 2). During the spring and summer, these displacements range from about 30 to 70 km, whereas during the fall and winter the displacements range from 32 to 130 km. Moreover, during periods of large winter storms, the short-term excursions of water particles may be considerably greater than the displacements suggested by the 30-day mean. Estimates of storm-related excursions range from 15 to 23 km for a 5-day period or from 3 to 5 km per day.

From the estimates of the sediment transport and the suspended matter concentations, it is possible to make some preliminary estimates of the flux of seston (at a particular location) in the near-bottom waters. During the spring and summer, for example, the total particulate concentrations in the bottom waters typically range from 250 to 500 μg/l. By putting these data together with the limits of the residual flow, the calculations show that the particle flux may range from 250 to 1,150 g/m^2/day. During the fall and winter, however, the flux variability is much greater. Using a range of 250 to 1,000 μg/l for the total particulates in the bottom waters, the flux may vary from 267 g/m^2/day for relatively quiet periods to as much as 5,000 g/m^2/day during large storms. These estimates of seston flux, however, assume that: (1) the suspended sediments act like water particles during transportation; (2) there has been no change in the total particulates due to (organic) production or predation; and (3) there has been no change in concentrations due to either the resuspension or the settling of sediments. The latter assumption must be viewed critically because measurements of the seston levels were not made during periods of storms.

The bottom-water mobility affects not only the distribution and flux of the suspended sediments, but it also produces changes in the bottom sediments as well. First, the continued resuspension and reworking of the bottom sediments prevents the accumulation of fine-grained particles over much of the outer shelf. This winnowing away of the finer material causes changes not only in the sediment texture (e.g., better sorting), but it also controls, to a great degree, the distributions of trace metals, hydrocarbons, and anthropogenic pollutants. Second, the thickness of the sand sheet as well as the maintenance or degradation of shelf bed forms depends, in part, on the strength and variability of the bottom flow. The large sand waves around Wilmington Canyon, for example, probably are of relict origin, yet they are maintained, and their surface sediments are being reworked, by the present current regime. Finally, the shifting and sorting of the surficial sands may cause changes in the engineering properties of the sediments. Bottom scour is directly related to the strength of the bottom flow, whereas the liquefaction potential for sands is related to the grain-size distribution and the degree of sorting.

SUMMARY

In summary, none of the hydrologic and geologic conditions that have been observed thus far on the Middle Atlantic OCS warrant the withdrawal of lease tracts or preclude petroleum exploration or development. However, the probability of structural failures will be the greatest during major winter storms or hurricanes. During these times, the current speeds, the sediment resuspension, and the bottom scour are the greatest. In this area, continued in situ observations of the currents and bottom conditions are esssential to: (1) define the seasonal and yearly variations in sediment transport processes; (2) monitor changes during catastrophic events; (3) investigate the possibilities of resuspension by currents associated with the shelf-slope water mass front; and (4) assess the importance of shelf-edge exchange mechanisms that may transport pollutants off the shelf. Moreover, further data needs to be gathered on the kinds and amounts of suspended matter in the water column in order to: (1) document long-term changes in the particulate distribution; (2) refine the estimates of seston flux; and (3) resolve the natural paths and sinks of sediments. The rates and depths of bottom sediment mixing also needs to be determined as an aid to predicting the fates of spilled hydrocarbons, drilling fluids, and drill cuttings. Finally, additional data on the shallow subbottom structure and stratigraphy should be collected to: (1) determine potential geologic hazards on the inner and middle shelf; and (2) identify and map areas of slumping and potential slump hazards on the upper Continental Slope.

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