U. S. Geological Survey.

Reports-Open file Series, no. 78-921.
1978.

UNITED STATES

DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Open-File Report

No. 78-921

Geologic Conditions in the Baltimore Canyon Trough Area: A Summary of U.S.G.S. Second-Year Environmental Studies

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Geologic Conditions in the Baltimore Canyon Trough Area:

A Summary of U.S.G.S. Second-Year Environmental Studies

by

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FOREWORD

This report is a summary of the principal objectives, results, and conclusions of the environmental studies conducted by the U.S. Geological Survey (USGS) in the Baltimore Canyon Trough area from October 1, 1976, to September 30, 1977. Environmental studies in the Baltimore Canyon Trough area were funded by the U.S. Bureau of Land Management (BLM) under an interagency Memorandum of Understanding (AA550-MU7-3). In accordance with this Memorandum of Understanding, the USGS submitted (in June 1978) a comprehensive Final Report to the BLM that set forth all the methods, techniques, equipment, analyses, and interpretations that were employed or generated in the fulfillment of the contract requirements. The Final Report currently is awaiting publication by the Virginia Institute of Marine Science, Gloucester Point, Virginia 23062.

The present report is a synopsis of the eight chapters and four Appendices that make up the Final Report. Duplicates of illustrations and tables used in the Final Report have not been reproduced here and many references have been deleted. For illustrative material and complete reference lists, the chapters in the Final Report must be consulted. The personnel who were responsible for the individual studies during 1976-77 under the Memorandum of Understanding and who produced the chapters and Appendices that make up the Final Report are listed in the section entitled "Roles of Key Participants". Liz Diamond typed the report, and Sally A. Wood prepared the index map.

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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 pollution 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 making 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.

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 the 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 sea bed 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 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 1). 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 1. 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.

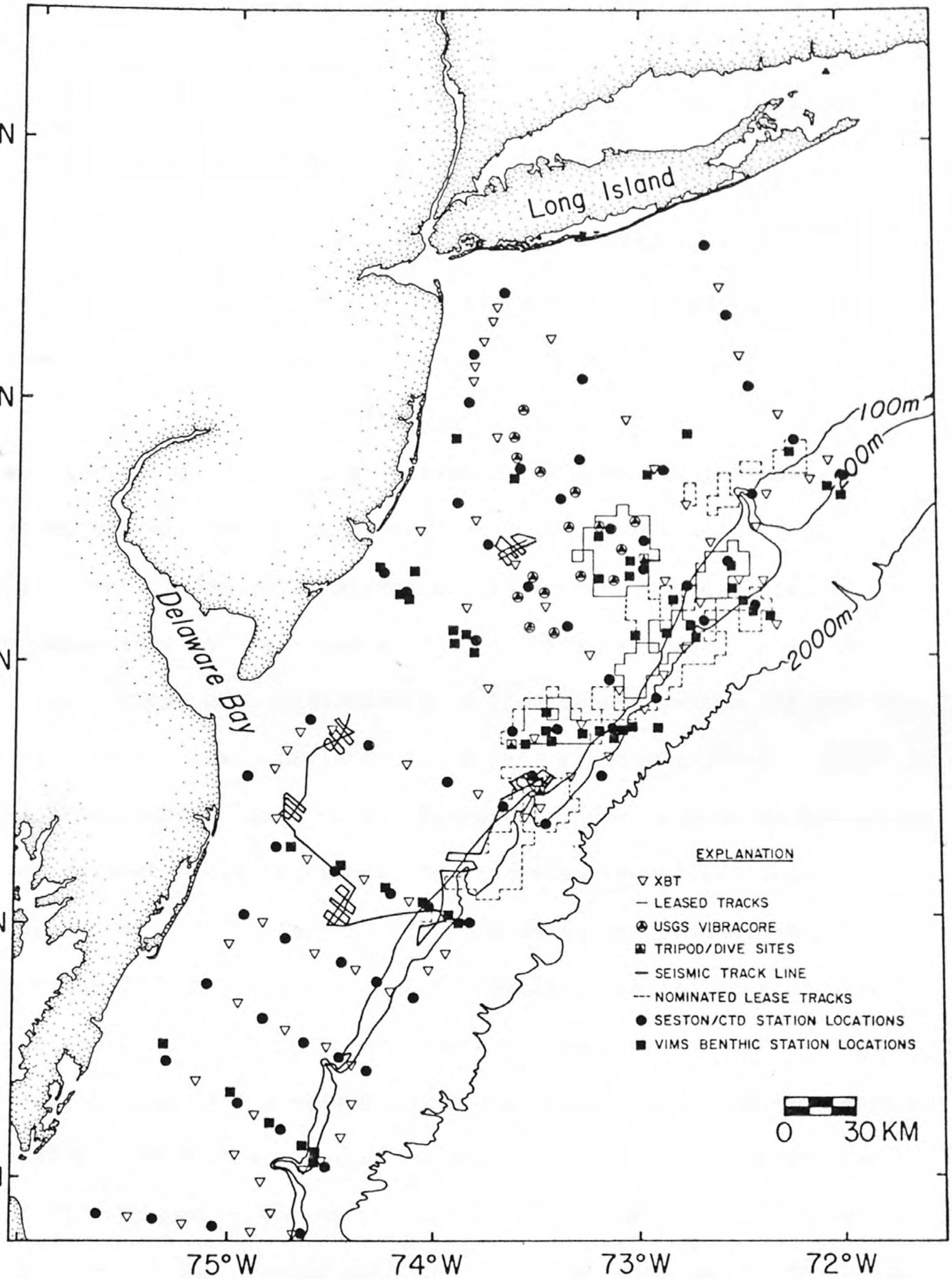
The equipment and devices that were used to collect the field data were quite varied. The tripod components included: Sea Data electronics and tape transport; Bendix Savonius rotor current meters; Paroscientific pressure sensors; Sea Data thermistors; Montedoro-Whitney transmissometer-nephelometers; 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[1/] 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[1/]

[1/] Any trade names in this publication are used for descriptive purposes only and do not constitute endorsement by the U.S. Geological Survey.

Table 1. 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 September77
R/V ANNANDALE	(AN-1-77)	18 September- 25 September77

Figure 1. Map showing locations of lease areas, geophysical tracklines, tripods, dive sites and other geologic and hydrographic stations.


41°N
40°N
39°N
38°N
37°N
75°W
74°W
73°W
72°W
Long Island
Delaware Bay
100m
200m
2000m
EXPLANATION
XBT
LEASED TRACKS
USGS VIBRACORE
TRIPOD/DIVE SITES
SEISMIC TRACK LINE
NOMINATED LEASE TRACKS
SESTON/CTD STATION LOCATIONS
VIMS BENTHIC STATION LOCATIONS
0 30 KM

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

LABORATORY ANALYSES AND PROCEDURES

Table 3 summarizes the kinds and numbers of analyses that were run on samples collected from the water column and from the bottom.

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

Table 2. Summary of observations and samples taken in the Middle Atlantic on USGS-related cruises.

CRUISE IDENTIFICATION		Instrument Deployment/Recovery	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 3. 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

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^{o}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 sediments 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 $\overline{R}$ 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 $\overline{R}$ 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 2). 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 interferred 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 interations 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 concentrations, 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 essential 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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