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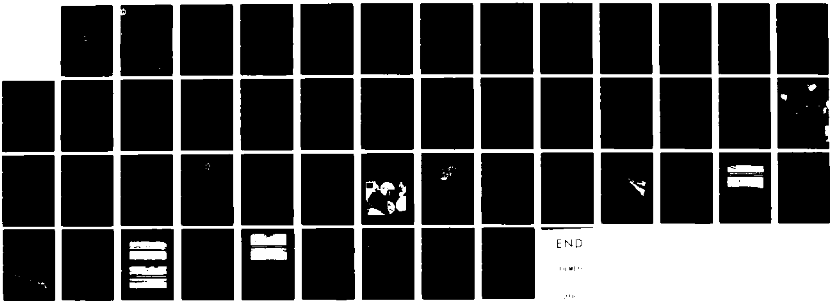

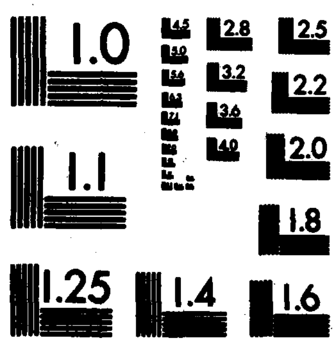
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MARINE PHYSICAL LABORATORY PROGRAM IN
ACOUSTICS AND THE OCEAN ENVIRONMENT

Final Report under Contract N00014-75-C-0704
Period from October 1, 1974 through October 31, 1980
Total Amount of Funding: $1,945,165

Principal Investigators(s)
F. N. Spiess and V. C. Anderson

Prepared for:
Office of Naval Research
Department of the Navy
Ocean Science and Technology Division
Code 480 (Now 420)
Arlington, Virginia 22217

Approved for public release; distribution unlimited.

MPL-U-43/82

September 1, 1982

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of the Scripps Institution of Oceanography
San Diego, California 92152

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sound absorption	Sea Beam	HEBBLE Expedition

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
Under the Office of Naval Research Contract N00014-75-C-0704, the Marine Physical Laboratory conducted a diverse program of investigations in the field of acoustics, both in the water and on the seafloor. The results have provided a better understanding of the effects of the ocean and its interfaces on the generation, propagation, and applications of acoustic energy, with specific application to problems of Navy interest. In addition, they have contributed toward increased knowledge in other aspects of marine

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) science; geology, biology, chemistry, and physical oceanography.

The research work carried out under this contract are listed in the following project summaries.

University of California, San Diego
Marine Physical Laboratory of the
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San Diego, California 92152

MARINE PHYSICAL LABORATORY PROGRAM IN ACOUSTICS AND THE OCEAN ENVIRONMENT

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MARINE PHYSICAL LABORATORY PROGRAM IN ACOUSTICS AND THE OCEAN ENVIRONMENT

Final Report

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INTRODUCTION

Under the Office of Naval Research Contract N00014-75-C-0704, the Marine Physical Laboratory conducted a diverse program of investigations in the field of acoustics, both in the water and on the seafloor. The results have provided a better understanding of the effects of the ocean and its interfaces on the generation, propagation, and applications of acoustic energy, with specific application to problems of Navy interest. In addition, they have contributed toward increased knowledge in other aspects of marine science: geology, biology, chemistry, and physical oceanography.

The research work ~~carried out under this contract~~ is are listed in ~~the following~~ project summaries.

Title of Project: Environmental Acoustics Research (UCSD 0058 and UCSD 0676)

NATOW Supplemental Support (UCSD 0192)

Principal Investigator: F. N. Spiess

Under this amendment funding was provided over a four year period for investigations of the 4 kHz acoustic properties of the sea floor. Much of the data were collected during NSF funded expeditions, although one major operation in the North Atlantic was funded by ONR (with broader geological objectives - our part of that multi-institutional operation was funded under Amendment 01) and is treated elsewhere in this report.

Results included descriptions of 4 kHz sound reflectivity and absorption in a variety of environments. Initially these funds supported the work of Robert Tyce as a graduate student resulting in his Ph.D. thesis (Tyce, 1977a) and related papers (Tyce, 1970, 1976, 1977b, 1981).

In its latter stages, proceeding from some implications of Tyce's work, the focus was on the properties of normal incidence returns from carbonate sediments. The apparent discrete layering was shown to result from interference effects due to small changes occurring pseudo-periodically with a wavelength corresponding to that of the incident 4 kHz signals. The results are reported in detail in the Ph.D. thesis of Dr. Larry Mayer (Mayer, 1979).

Title of Project: Environmental Seafloor Acoustics (UCSD 0347)

MPL Program in Environmental Acoustics (UCSD 0676)

Principal Investigator: F. N. Spiess

Precision transponder development was initiated in 1976 and was carried through the development of a new type of transponder, for which a patent was eventually obtained (U.S. Patent No. 4,214,314) (Spiess et al., 1980). Work on this project, which became oriented toward the goal of participation in the Munk and Spindel initial acoustic travel-time measurement sea experiments, was terminated prior to those operations because of schedule conflicts with other deep tow expeditions. Permission was given by the technical officer at ONR, Dr. Hugh Bezdek, to utilize these funds for general deep tow system maintenance and improvements.

Title of Project: Deep Tow Instrument System Improvement (UCSD 1549)

Principal Investigator: F. N. Spiess

Under this contract we carried out the initial stages of implementation of the swath mapping (side-looking sonar interferometer) capability. The subsequent contract provided additional funding for this work and it is anticipated that the system will be given a preliminary test at sea in January, 1981 on an NSF funded expedition in the Pacific. The target is full operation for the ONR funded HEBBLE expedition scheduled in May, 1981.

Title of Project: NATOW Supplemental Support (UCSD 0192)

Principal Investigator: P. F. Lonsdale

This amendment was primarily for partial support of the 1975 multi-disciplinary, multi-institutional NATOW Expedition in the North Atlantic. A summary report of this expedition and its results is attached in Appendix A. This report was sent to Dr. Tom Pyle, Program Manager, ONR Geology and Geophysics, in March of 1980.

Title of Project: A Submersible Program in Mexican Waters (UCSD 0954)

Principal Investigator: P. F. Lonsdale

Submersible diving programs were conducted with DSV SEACLIFF inside the Gulf of California and DSV TURTLE on seamounts at the mouth of the Gulf. Results of these operations are reported in the cruise report by Lonsdale (January, 1978); and three scientific papers, Lonsdale and Bischoff et al. (1980); Lonsdale and Batiza (1980); Lonsdale and Lawver (1980).

Title of Project: Supplementary Funding for the Deep Tow Studies in the North Atlantic (UCSD 1038)

Principal Investigator: P. F. Lonsdale

A CTD instrument was purchased from Neil Brown Inc. and adapted by our engineers for routine use as a sensor on the deep tow vehicle. It was successfully employed on the North Atlantic cruise of Expedition INDOMED, as noted in a cruise report (Lonsdale, December 1978). See Appendix B.

Title of Project: Measurements of Mixed Layer Velocity with a Range Gated Doppler Sonar (UCSD 0418)

Augmentation for Measurements of Mixed Layer Velocity with a Ranged Gated Doppler Sonar (UCSD 0626)

Principal Investigator: Robert Pinkel

Under the terms of this contract during the period 4 February 1976 through 31 January 1977, much of the pioneering research was done on Doppler sonar techniques. The work centered on adapting an 87.5 kHz depth sounder, borrowed from Dr. Fred Fisher of the Marine Physical Laboratory, for physical oceanography research. The work involved development of Doppler signal processing electronics, tests at Lake San Vicente and installation of the modified sonar on the research platform FLIP. This effort culminated in a successful data collection cruise during January 1977 off the California coast. The first successful remote sensing of the ocean velocity field was achieved on this cruise.

Work was initiated on the investigation of small-scale low energy features which were now resolvable by Doppler sonar techniques. The first power spectra of sonar velocity data were calculated during this period. Velocity spectra as a function of both frequency and wavenumber were produced. The results of this study led to the publication of a paper on Doppler sonar measurements (Pinkel, 1981).

Title of Project: Acoustics and the Ocean Environment
(UCSD 0956 and UCSD 1267)

Principal Investigator: Robert Pinkel

Following a successful January 1977 sea trip it was felt advantageous to develop a special purpose Doppler sonar transducer, rather than relying on the existing converted echosounder for future work. During late 1977 and early 1978 preliminary design studies were performed on individual transducers. Simulations of array performance were also made. During late 1978 the prototype sonar was fabricated. It would be operated at a peak power of 32 KW, an order of magnitude greater than the previous sonar. The first test of the new sonar was conducted from FLIP during January 1979. Measurements were achieved to a range of 1.6 km, depth 1.1 km; double the performance of the previous sonar. Following the first test, only minor modifications would be necessary to make the sonar operational.

In 1979 the necessary modifications to the new sonar were made. A second array was constructed under the Office of Naval Research Code 220 sponsorship. Under funds from this contract a controller was created to coordinate the operation of all of the sonars. A microprocessor which sends commands to the various components of the Doppler system is at the center of this controller. The time at which each power amplifier is enabled, the sonar which it drives, and the receiver circuit which listens to the echo are set by this controller. In addition, the prototype power amplifiers and prototype signal processing circuits were replicated. The work was conducted in preparation for a major data collection cruise planned for May 1980. The cruise subsequently proved to be tremendously successful.

Title of Project: Environmental Acoustics Research (UCSD 0058)

Environmental Seafloor Acoustics (UCSD 0347R)

Principal Investigator: George G. Shor, Jr.

The primary goal under this task was to determine whether there was a significant amount of energy propagated from near-surface sources to near-surface receivers in the very low frequency range via the various sub-paths within the "refracted path" through the ocean floor. Much of this energy probably travels by forward-scattering processes due to inhomogeneities in the seafloor, and so is not easily amenable to theoretical calculation. On the theoretical side, a study was made by Spudich on energy partition between the compressional and shear modes of transmission, and compared with previously obtained records in the area near Guadalupe Island, Mexico; this was published as a Ph.D. thesis (Spudich, 1979). Field observations were made with a high dynamic range digital recording system using shots fired in the Pacific Ocean west of San Diego. In these studies, it was shown that energy in the bottom-transmitted signals rises with decreasing frequency at a rate higher than the ambient noise spectra, down to the low-frequency cutoff of the shot sources (in this case, 6 Hz). The bottom-transmitted energy only becomes a significant portion of the total transmission at frequencies at this low-end cutoff. Attempts to build a long array (at low cost) adequate to determine the directionality of these arrivals were not successful; we could not maintain adequately low levels of self-noise and reliability of operation in such a long array at the necessary frequencies below 6 Hz.

Title of Project: Acoustics and the Ocean Environment (UCSD 1267)

Principal Investigator: F. H. Fisher

In order to measure the pressure dependence of sound absorption due to $MgSO_4$ and its relaxation frequency in seawater several parallel efforts have gone forward since this project commenced in February 1978.

Since the key to success for this work rests on stable temperature and pressure control within the 100 liter titanium spherical acoustic resonator (ballast tank for the ALVIN borrowed from Woods Hole) considerable effort has gone into assuring such stability. A temperature controlled room (10' x 20' x 14') has been built to house the temperature controlled vacuum chamber system for the resonator. An automatic pressure control system has been purchased from Hruska to keep the dead weight gage at constant pressure.

Experimental results have been obtaind by graduate student C. C. Hsu at atmospheric pressure in water, 0.02 molar $MgSO_4$ solutions with various amounts of NaCl. Results compare very well with prior experimentalists. Theoretical and experimental papers are being written for submission to Marine Chemistry, Journal of Solution Chemistry, and the Journal of the Acoustical Society of America

Funding limitations have delayed implementation of pressure system, but this was finished during the next fiscal year. The pressure work on seawater at 25° will be completed during the coming year 1 February 1980 to 31 January 1981.

Title of Project: Church Stroke 1 Data Analysis (UCSD 0878)

Principal Investigator: Gerald B. Morris

Analysis was performed on the Large Aperture Marine Basic Data Array (LAMBDA) during Exercise Church Stroke 1, to measure the instantaneous deviation from straightness and the front-to-back tilt. These measurements were performed using aircraft dropped SUS charges at ranges of approximately 2000 meters on either side of the array. Data from selected hydrophones were recorded for later processing. Time differences of arrival of the direct pulse between hydrophones distributed along the array were used to calculate the array shape via a least-mean-squares method.

The departure from straightness and array tilt were related to array signal gain degradation. These results are reported in Bucca et al. (1978).

Title of Project: Acoustics and the Ocean Environment (UCSD 0956)

Acoustic Delineations of Plankton Patchiness (UCSD 1258)

Principal Investigator: Paul R. Greenblatt

A large effort was made to assess the sources of acoustic reverberation from an 87.5 kHz sonar and to determine whether high frequency sonars can be used to measure plankton distributions.

During an October 1979 FLIP cruise, samples were simultaneously collected with a horizontally pointed 87.5 kHz sonar and a multiple opening-closing plankton net. The net was towed either parallel to or in the sonar beam. Over 300 zooplankton samples were collected.

Since the October 1979 cruise, a major effort has been made to analyze the data from the sea trip. As the analysis phase is completed, several conclusions can be reached. Based on three independent approaches, it was concluded that the major scatterers during the day were large copepods and small euphausiids. At night, the principal scatterers were small nekton (midwater fish and squid) and large euphausiids. The major scales of variability were larger than the sampling program could resolve (i.e., a red wavenumber spectrum). The scales of variability did not change from day to night or with animal size. However, the total variance of both volume scattering strength and zooplankton biomass was greater at night than during the day. Interesting migration patterns were observed and interpreted.

The details of the results are presented in Greenblatt (1980, 1981, 1982a, 1982b) and Greenblatt et al. (1982).

Title of Project: Multibeam Echo Sounder Investigations (UCSD 1467)

Principal Investigator: Robert C. Tyce

During the contract period of 1 April 1979 through 31 January 1980, a study was conducted by Dr. Robert Tyce regarding signal and data processing options related to multibeam echo sounders. In particular this study included the following efforts:

1. Extended discussions with the Harris division of General Instruments Corp., the builders of the SASS and Sea Beam multibeam echo sounder systems, at their production facility in Massachusetts.

2. Participation in noise measurement tests aboard the R/V CONRAD during the summer of 1979, for prediction of multibeam performance on this class of ship.

3. Discussions with the Navy research community regarding experience with multibeam echo sounders, including the BOATOSS development group, George Moss at NORDA, ARL Texas, and the Naval Oceanographic Office.

As a result of these investigations and discussions, it was concluded that the multibeam echo sounding system called Sea Beam would be a reasonable technology for installation aboard AGOR class research ships, provided additional bubble noise and interference tests were performed. Some of the sonar technology involved in this system was deemed in need of modernization, but adequate for the present, and with minimal alternatives other than custom construction. Bubble noise and interference tests were successfully conducted in a subsequent contract. Results of all these efforts were communicated directly to the program manager, Dr. Thomas Pyle, in advisory discussions concerning multibeam echo sounder implementation.

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APPENDIX A

SUMMARY REPORT: [illegible] APPENDIX A

EXPEDITION NASON (1975):

Expedition NASON (Knorr 51, legs 2 and 3) was a two-leg deep-tow operation on Woods Hole's R/V Knorr in the northeast Atlantic during the summer of 1975. [illegible] funding was principally from ONR Contract N00014-74-C-0262 with Woods Hole Oceanographic Institution. Field work was supported by:

a) NSF DES 74-0380, to F. N. Spiess and P. Lonsdale, for principal costs of deep-tow operations.

b) ONR N00014-74-C-0262, to C. D. Hollister, for coring and hydrography.

c) ONR N00014-[illegible]-C-0704 and -0749, to the Marine Physical Lab, as part of the Environmental Acoustics and Ocean Acoustics contracts.

d) ONR contract with [illegible], M.I.T., for her participation on the first leg.

Subsequent data analysis and interpretation has been supported by several NSF and ONR grants and contracts, most notably NSF DES 74-20396 and OCE 76-21592 ([illegible]), NSF DES [illegible] and OCE 76-[illegible] (to Hollister), ONR [illegible] and ONR N00014-75-C-0262 (with Hollister).

FIELD PROGRAM

The first leg ([illegible]), Ponta Delgada to Reykjavik, 9 July–2 August 1975 [illegible] surveys at three sites, and deployment of current meters for [illegible] on the second leg.

[illegible] we made a [illegible]-day survey around 52°44'N, [illegible] with a spreading axis and at [illegible]. The [illegible] sites were within an area [illegible] current meters had been [illegible]. We collected 7 short-term [illegible].

[illegible] survey centered at 56°24'N, 24°25'W, with [illegible] and one track across the [illegible].

[illegible] was crippled by failure of Knorr's aft cycloid [illegible] survey because maneuvering the [illegible]. The rather hazardous towing conditions also [illegible] photography. A zig-zag tow track was followed along the ridge until we were [illegible].

The second leg ([illegible]-03) was 31 days from Reykjavik to Glasgow.

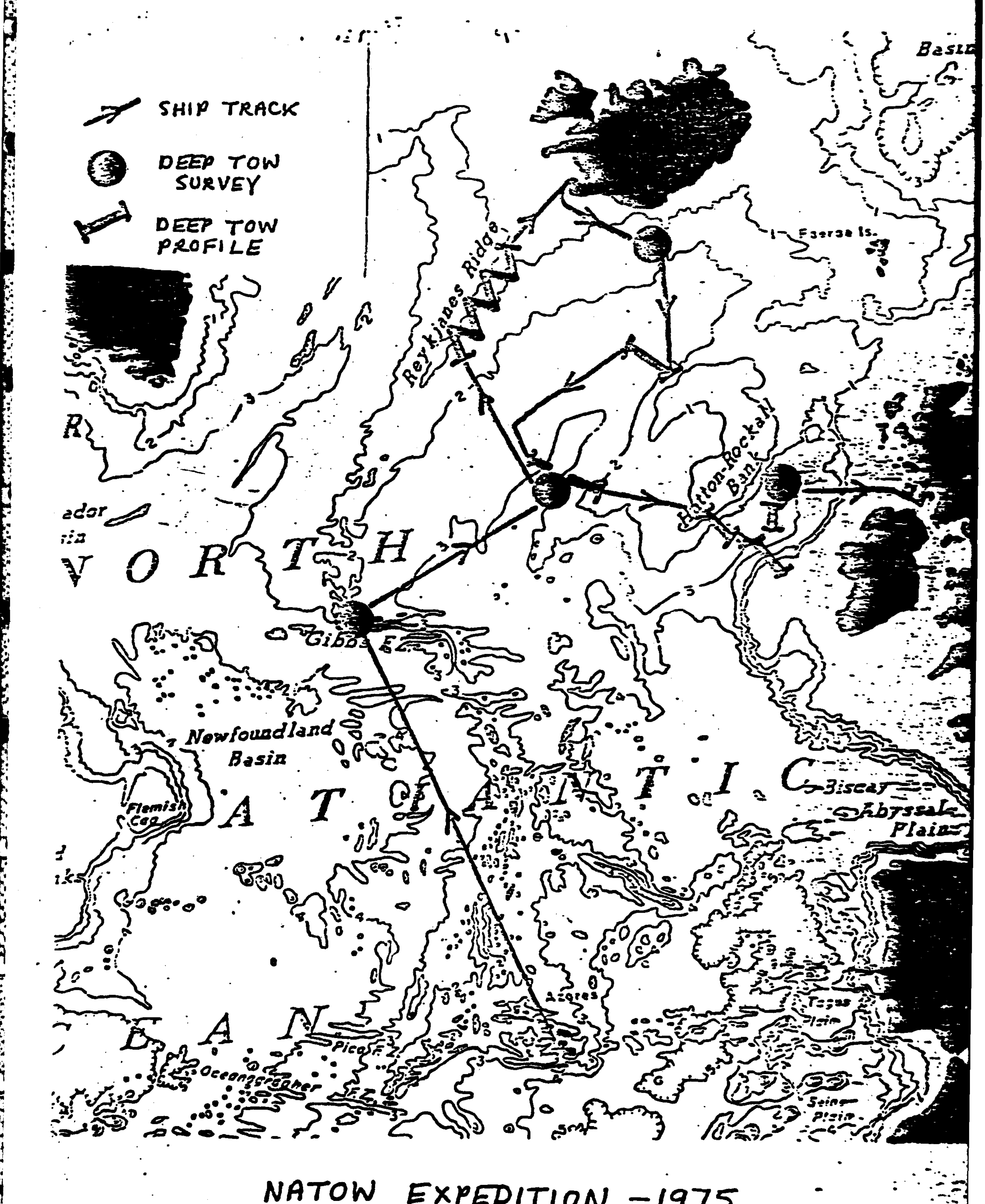
On the Icelandic [illegible] we made a 3-day survey of a meander in the [illegible] valley at 61°40'N, 20°40'W. During this operation the WHOI Giant Piston Corer, planned to be a major tool on this leg, was lost when the wire parted. Immediately after our work at this site, failure of Knorr's aft cycloid recurred, and the rest of the leg was steamed on the forward cycloid alone (maximum speed 3-5 knots); towing on straight tracks was dictated.

At [illegible] Channel we made a short transect of the upper channel and adjacent [illegible] near 59°[illegible]'N, [illegible]°00'W, and another short transect in the 56°24'N survey area. Current meters that had been deployed across Hatton and Gardar Drifts on the previous leg were recovered, though they had only a 50% success rate.

In Rockall Trough we made straight deep-tow transects of both the northwest (Rockall Plateau) and southeast (Irish continental slope) margins, and of the toe of a large debris flow on Feni Ridge. A 3-day period of unusually calm weather (when the ship could be manoeuvered on its forward cycloid) allowed a transponder-navigated deep-tow survey of another part of this flow. Time was also spent on towing a 3.5 kHz pinger-probe, and on coring with an improvised giant corer.

New deep-tow equipment employed on the expedition included an experimental MPL nephalometer (attached to the deep tow instrument during one lowering in Maury Channel), a filtering pump for sampling suspended particulates, a plankton net, and a dangling thermometer to search for hydrothermal emanations. Significant improvements to the side-scan sonar and 4 kHz systems also proved successful.

The expedition was severely handicapped by failure of Knorr's aft cycloid, which reduced the planned deep tow work by about 50%, and dictated a change in the style of operation away from the most effective survey patterns. The other major disappointments were loss of the Giant Piston Core at its first lowering, and poor success rate of the S.I.O. current meters.



NATOW EXPEDITION -1975

PUBLICATIONS ON DEEP TOW RESULTS

Charlie-Gibbs Fracture Zone

1) Lonsdale, P., and Shor, A. N., "The oblique intersection of the Mid-Atlantic Ridge with Charlie-Gibbs Transform Fault", Tectonophysics, v. 54, p. 195-209, 1979.

2) Shor, A., Lonsdale, P., Hollister, C. and Spencer, D., "Charlie-Gibbs fracture zone: bottom water transport and its geological effects", Deep-Sea Research, v. 27A, in press (1980).

Reykjanes Ridge

3) Shih, J., Atwater, T. and McNutt, M., "A near-bottom geophysical traverse of the Reykjanes Ridge", Earth and Planetary Science Letters, v. 39, p. 75-83, 1978.

Maury Channel

4) Lonsdale, P., Hollister, C., and Mayer, L., "Erosion and deposition in interplain channels of the Maury Channel system, northeast Atlantic", Oceanologica Acta, v. 4, p. 185-201 (1981).

5) Lonsdale, P., "Abyssal analogs of Martian outflow channels", Icarus, submitted.

Hatton-Gardar Drifts

6) McCave, I., Lonsdale, P., Hollister, C., and Gardner, W., "Sediment transport over the Hatton and Gardar contourite drifts", Journal of Sedimentary Petrology, v. 50, p. 1049-1069 (1980).

7) Lonsdale, P., "The abyssal circulation of the northeast Atlantic: hydrographic and geologic inference, and direct measurement", (in prep.).

Icelandic insular rise

8) Lonsdale, P., and Hollister, C., "Cut-offs at an abyssal meander south of Iceland", Geology, v. 7, p. 597-601, 1979.

9) Lonsdale, P., and Hollister, C., "Geomorphologic effects of the interaction of thermohaline and turbidity currents south of Iceland", (in prep.).

Rockall Trough

10) Flood, R., Hollister, C., and Lonsdale, P., "Disruption of the Feni sediment drift by debris flows from Rockall Bank", Marine Geology, v. 32, p. 311-334, 1979.

11) Lonsdale, P., and Hollister, C., "A near-bottom traverse of Rockall Trough: hydrographic and geologic inferences", Oceanological Acta, v. 2, p. 91-105, 1979.

12) Tyce, R., "Acoustic reflectivity of the sea floor——a close 4 kHz look," Geophysics, submitted.

In addition there are papers reviewing larger areas that use substantial amounts of NATOW data, e.g.:

Lonsdale, P., and Spiess, F. N., "Abyssal bedforms explored with a deeply towed instrument package", Marine Geology, v. 23, p. 57-75, 1977.

Several other papers report data from ancillary programs conducted on NATOW, which included coring for mass physical properties studies (A. Silva) and isotope measurements (V. Bowen) and use of a WHOI pinger-probe (W. Dow and E. Laine).

DISSERTATIONS

Several of the Woods Hole/M.I.T. and Scripps students who took part in the cruise used NATOW deep tow data for substantial parts of their theses, e.g.:

K. Wishner (Scripps), "The biomass and ecology of the deep-sea benthopelagic (near-bottom) plankton, 1979.

K. Crane (Scripps), "Hydrothermal activity and near-axis structure at mid-ocean spreading centers", 1977.

R. Tyce (Scripps), "Near-bottom observations of sea floor acoustics", 1977.

J. Shih (WHOI/MIT), "The relationship between spreading rate, roughness and style of ocean floor relief, and the morphology of mid-ocean ridges from analysis of deep tow bathymetric profiles", 1980.

R. Flood (WHOI/MIT), 'Studies of deep-sea sedimentary microtopography in the North Atlantic Ocean", 1978.

The material in some of these dissertations is still being revised and submitted for publication.

APPENDIX B

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MARINE PHYSICAL LABORATORY
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BEDFORMS AND THE BENTHIC BOUNDARY LAYER IN THE NORTH ATLANTIC: A CRUISE REPORT OF INDOMED LEG 11

Peter Lonsdale

Sponsored by
Office of Naval Research
N00014-75-C-0704

29 December 1978

SIO REFERENCE 78-30

UNIVERSITY OF CALIFORNIA, SAN DIEGO
MARINE PHYSICAL LABORATORY OF THE
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LA JOLLA, CALIFORNIA 92093

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F. N. Spiess

F. N. SPIESS, DIRECTOR
MARINE PHYSICAL LABORATORY

MPL-U-71/78

BEDFORMS AND THE BENTHIC BOUNDARY LAYER IN THE NORTH ATLANTIC: A CRUISE REPORT OF INDOMED LEG 11

Peter Lonsdale

ABSTRACT

In August and September 1978, deep-tow surveys were conducted with R/V Melville at four sites in the North Atlantic: a field of mud waves on the Moroccan continental rise; a patch of hyperbolae-creating bedforms with interfingering debris flows on the Saharan continental rise; an area of abyssal furrows near the crest of Eastward Scarp on the Bermuda Rise; and a field of furrowed sediment waves on the southwest Bermuda Rise. In addition to near-bottom acoustic records, the deep-tow instrument collected stereo photos, CTD and nephelometer data, and samples of bottom water and suspended sediment. There were also current meter, hydrocast and coring stations. This report includes preliminary deep-tow maps of each site, locating photo runs and samples, and presents a few typical sections of data.

INTRODUCTION

The primary mission on Leg 11 of Scripps' 20-month Expedition INDOMED was to conduct near-bottom surveys of four sites in the North Atlantic where the shape of the deep sea floor has been affected by fast bottom currents. The principal survey tool was the Marine Physical Laboratory's deep-tow instrument system (Spiess and Tyce, 1973). We hoped that at some of the sites the currents responsible for such superficial geologic features as bedforms and erosional surfaces were still active, so that by measuring and correlating properties of the ocean's bottom layer and the sedimentary seabed we might disentangle and understand sediment-water interactions in the benthic boundary layer. However, direct hydrographic evidence for fast modern currents was lacking at all of the chosen sites, so an important part of our field program was to deploy arrays of near-bottom current meters. They monitored the speed and direction of prevailing bottom currents, albeit only for the 3-6 days available for each survey. Additional measurement of bottom water properties was carried out on samples collected by Niskin-bottle hydrocasts and by 9-litre bottles attached to the deep-tow instrument. This vehicle also carried a Neil Brown CTD, whose measurements were digitally logged at 1 to 10 second intervals, a filter pump for collecting suspended sediment, and, on one lowering, a Lamont long-term nephelometer which recorded near-bottom turbidity every 7.5 min. Several piston and gravity cores were collected from sites whose lithology, or lithologic diversity, had not been adequately established by previous bottom sampling.

In addition to personnel from the Scripps Institution of Oceanography, the scientific party aboard R/V Melville included investigators from Woods Hole Oceanographic Institution, the University of Rhode Island, and Lamont-Doherty Geological Observatory. Their involvement in the deep-tow research effort was separately funded by ONR contracts with those institutions. Part of the station time was also spent deploying a long-term current meter plus time-lapse camera (for M. Wimbush, U.R.I.), retrieving long-term current meters, nephelometers and sediment traps from the northeast Bermuda Rise (for E. Laine, U.R.I.; W. Gardner, Lamont; and M. Richardson, Woods Hole), and retrieving a long-term current meter from the southwest Bermuda Rise (for B. Tucholke, Lamont). No results of these ancillary operations will be presented in this cruise report. Its purpose is to present preliminary maps of the deep-tow surveys, locating sampling and camera stations; to describe the quality and probable usefulness of the deep-tow data at each site; and to show samples of deep-tow records, suggesting some of the questions they address.

Most of the investigators on INDOMED Leg 11 also participate in ONR's High Energy Benthic Boundary Layer Experiment, a long-term program on parts of the deep-sea floor swept by fast currents. Although the geographic focus of this efforts is the continental rise at the western boundary of the North Atlantic, our cruise has been designated, rather ex post facto, HEBBLE Cruise 2.

CRUISE NARRATIVE

R/V Melville departed Cadiz, Spain, on the evening of 11 August 1978, and arrived in St. George, Bermuda, 33 days later, on 13 September. A brief intermediate stop of 2 hours was made at Santa Cruz de Tenerife, Canary Islands, where we picked up needed scientific supplies and had a physician come aboard to treat our sick.

The overall disposition of time on the leg is shown on Fig. 1. During the long traverse of the North Atlantic we processed much of the data from the two eastern sites, and while underway mapped the structure of the surface mixed layer by taking XBTs at frequent (2 hour) intervals, as part of a global study of ocean surface temperatures by K. Kenyon, NORPAX. Magnetic and 3.5 kHz profiler data were collected along most of the track, except during the brief run from the last station into port, when all hands frantically disassembled and packed equipment in preparation for a complete off-load in Bermuda.

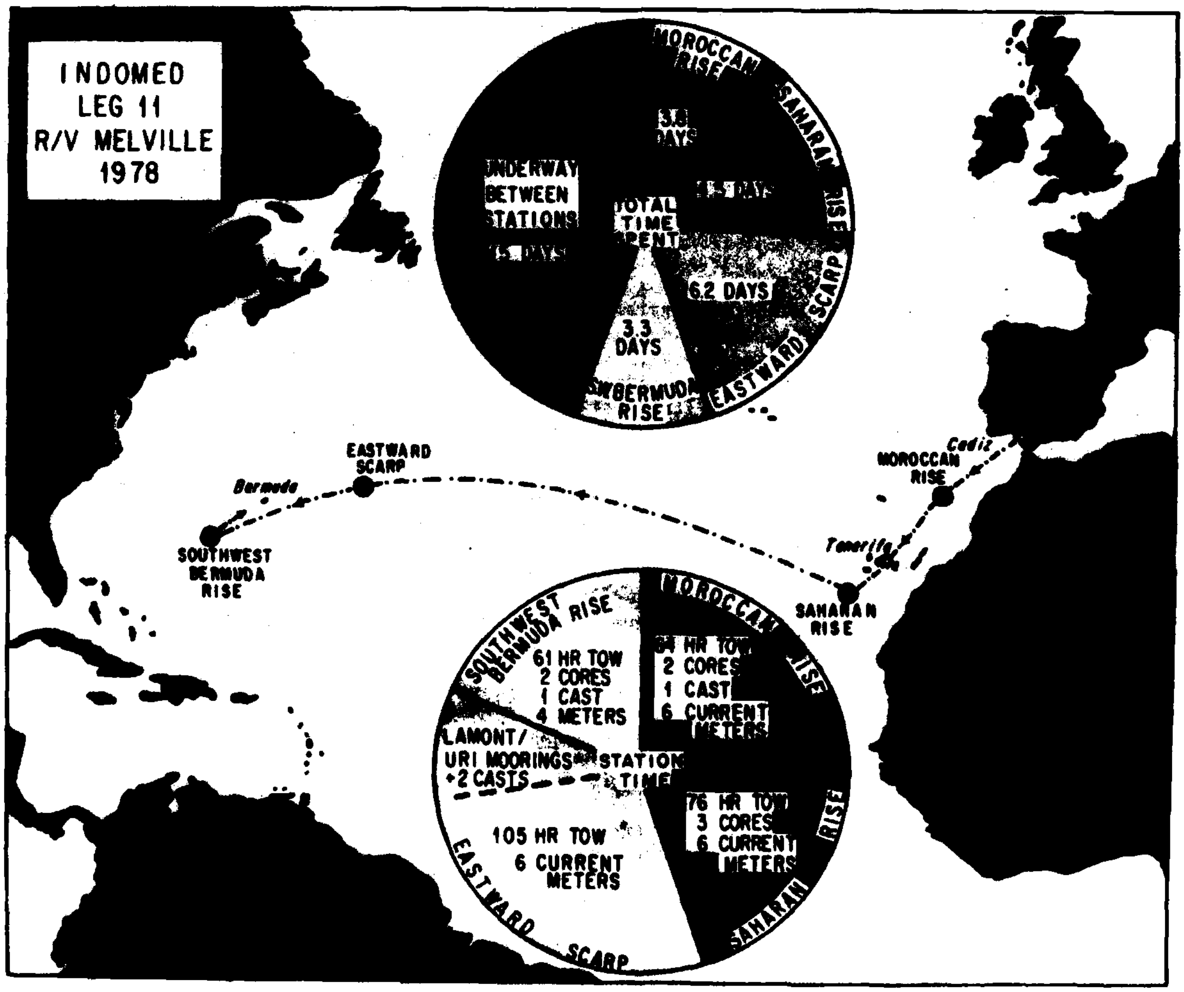

Fig. 1. Cruise track and time allocation, INDOMED Leg 11.

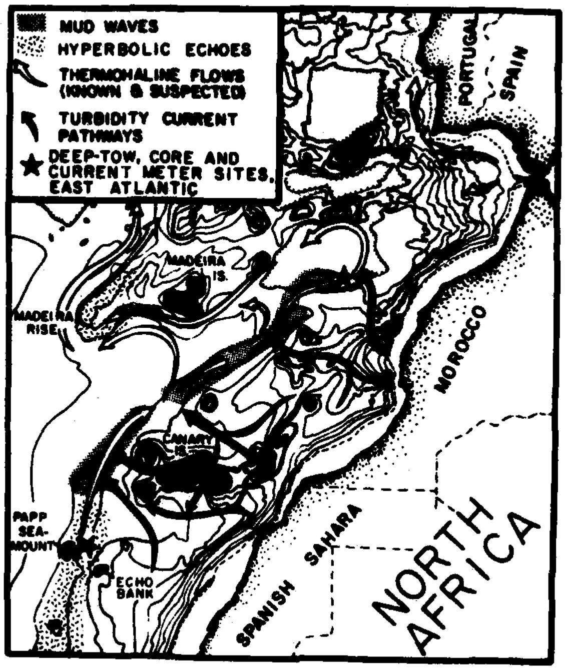

Fig. 2. Location of deep-tow sites on the Moroccan and Saharan continental rises, with a hypothetical pattern of bottom currents. Bedform distribution from Jacobi et al. (1975) and Embley et al. (1978).

Performance of the vessel and the deep-tow instrument was near-perfect, with minimal time loss because of mechanical or electronic breakdowns. Also noteworthy was the successful and prompt recovery of all 24 freevehicle packages launched during the leg, together with 3 arrays that had been deployed on earlier expeditions. Weather was fair throughout the leg, and never limited operations, though for a time it seemed that the work southwest of Bermuda might be threatened by a hurricane.

EASTERN ATLANTIC OPERATIONS

Justification

Surface-ship 3.5 kHz profiles across the continental rise of northwestern Africa indicated that there was a relatively narrow band of regular sedimentary bedforms at depths of 4000-4500 m on the lower rise. Off Morocco, Jacobi et al. (1975) mapped a 10-50 km-wide band of mud waves which were so large (0.5-2 km wavelength) that their orientation and some of their internal structure could sometimes be resolved on surface-ship profiles. They were reported to be parallel or "somewhat oblique" to the regional contours, and to have migrated upslope. These are properties of a large majority of the abyssal mud waves displayed on 3.5 kHz profiles from many parts of the ocean (Embley and Langseth, 1977). South of the Canary Islands, off Spanish Sahara, Embley et al. (1978) mapped a zone of hyperbolic echoes that they suggested might be created by abyssal furrows oriented along the slope of the rise.

We postulated that these bands of bedforms had been created by a bottom water boundary current that flowed northeast along the rise (Fig. 2). Because such a current might be expected to show less Pleistocene fluctuations than those (such as the Western Boundary Undercurrent) with a northern source, there was some hope that the bedforms beneath it might be in equilibrium with present flow conditions, rather than being relict. A possible scenario was that the bottom current might be erosional in the sediment-starved reach off the Sahara, but become depositional after receiving turbidity current injections from the Canary Islands and canyons on the Moroccan slope.

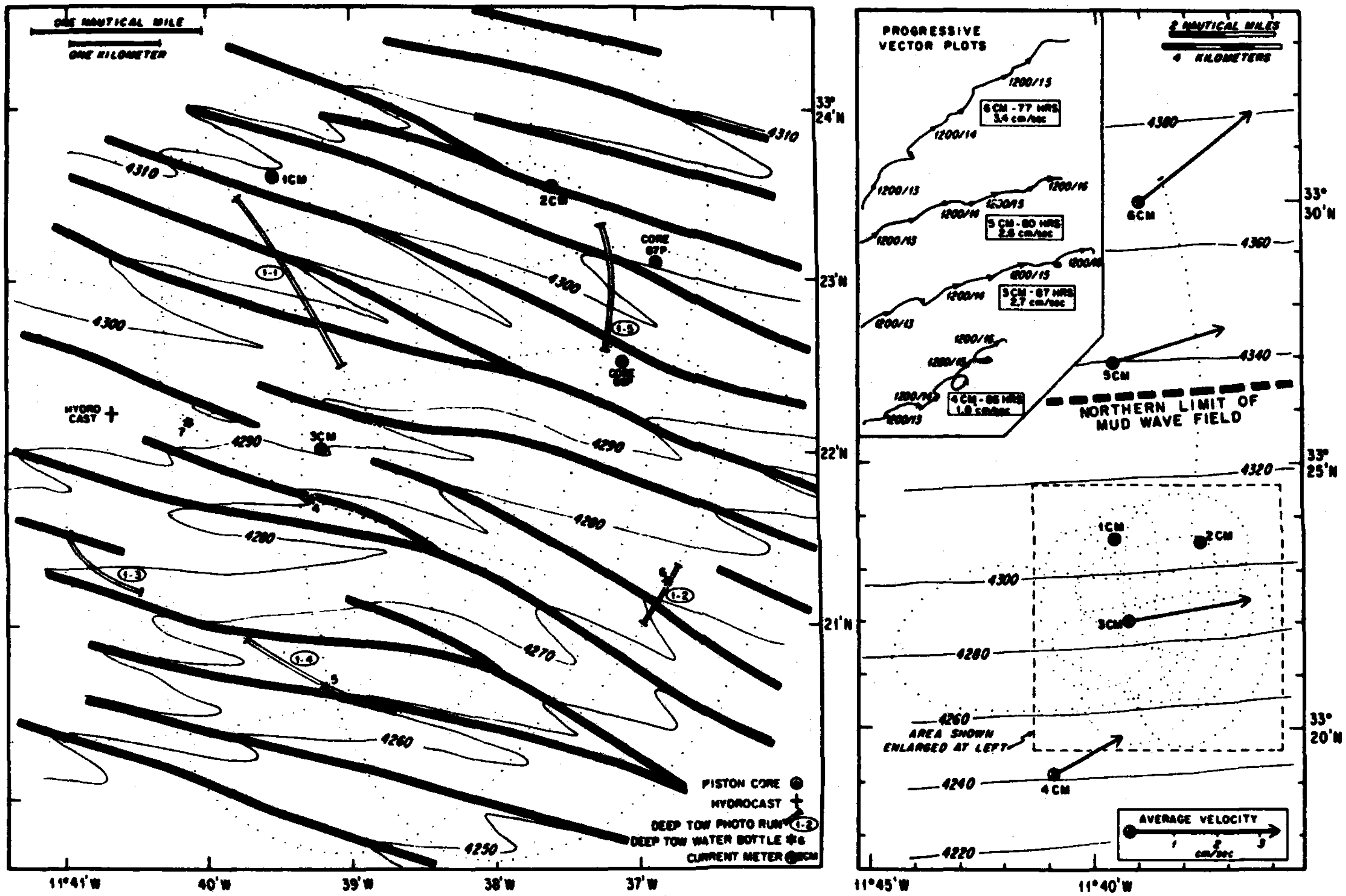

Fig. 3. The Moroccan Rise site; depths in corrected meters. Map at left shows pattern of mud wave crests (solid lines) within the area of detailed survey. Map at right shows generalized contours, and the current meter results.

The field program was designed primarily to test the presence of any eastern boundary current and to measure its properties; to resolve the morphology and internal structure of the mud waves and the bedforms responsible for hyperbolic echoes; and to establish whether the bedforms were erosional or depositional, whether they were in equilibrium, and if so whether relationships between properties of the flow and of the bedforms could be identified. In addition, we examined the morphology, structure and lithology of deposits from debris flows whose distal ends had entered a zone of well developed hyperbolae: debris flows are important agents of downslope sediment transport at this continental margin (Embley and Jacobi, 1977).

Moroccan Rise Survey

The site selected for our survey of Moroccan Rise mud waves is in the northeastern part of the field, where regional contours trend almost east-west. A line of current meters (attached to transponders and 50 m above the seabed) straddled the lower (northern) boundary of the mud wave zone; Meters 1CM and 2CM malfunctioned, and the others recorded slow net flows to the northeast (Fig. 3). The fastest current speed measured during the four days of operation was 9 cm/sec.

A deep-tow profile up the rise began on the gently sloping terrain near Meter 6CM, but most of the deep tow effort was concentrated in a 60 km^2 area between 4250 m and 4310 m. There is complete side-scan sonar coverage of most of this area, but the only distinct targets on our side-scan records are the free- vehicle packages that we had deployed. About 600 stereo photos show a lumpy, heavily burrowed mud bottom, with few superficial tracks and trails. Four samples of near-bottom water were collected by deep tow's bottles, but at least two of them were so turbid that they must have been contaminated with seabed sediment. A bottom hydrocast, with Niskin bottles for collecting suspended material, was successfully completed after stressful delays caused by problems with the hydrowinch.

The deep-tow bathymetric and 4 kHz profiles establish that these mud waves have an average wavelength of about 0.7 km, and are oriented 30° oblique to the regional contours and to the measured current which parallels the contours (at 3CM, in the survey area). The acoustic signature of the shallowest resolvable stratum changes across the crest of each wave, becoming thicker and showing internal reflectors on the nearly horizontal upslope face; this indicates that the processes maintaining the wave form and its upslope migration continued to be active as the upper 3-4 m of the sediment section were deposited. A pair of 6 m piston cores (86P and 87P) were collected from upslope and downslope faces of adjacent waves.

Further analysis of data from this site will include better definition of mud wave morphology by removing the regional 0.5° slope of the rise from the soundings; integration of core and 4 kHz profiler data for the study of wave asymmetry and migration rates; and careful analysis of the CTD data to see how the benthic boundary layer structure is affected by the presence of bed corrugations. A short section of CTD temperature data that has already been examined suggests that the bottom mixed layer (about 50 m thick over most of the survey area) is thinner and less distinct in the deeper part of the survey area, and water temperatures above the mixed layer show a spatial variation that is directly correlated with the bathymetry of the waves (while an inverse correlation would be expected if isotherms tend to parallel the seafloor).

Saharan Rise Survey

The site selected for our survey of eastern boundary hyperbolic echoes (Fig. 4) is near 26°N, 50 km northeast (downstream) of a 50 km gap between two seamounts (Echo Bank and Papp Seamount) that project through the thick sediments of the rise. Although it was possible that the nearby seamounts might complicate the flow pattern, this site had the advantages of well-developed hyperbolae, mapped by a thorough surface ship survey (Embley et al., 1978); well defined upper and lower limits to the hyperbolated zone (at about 3850 and 4040 m, respectively); and the impingement of tongues of debris flow deposits.

Near-bottom current meters were deployed in a line down the continental rise, straddling the 50 km-wide band of hyperbolae (Fig. 5). Two meters over the smooth seafloor of the upper rise recorded slow net currents, upslope (7CM) and to the south (8CM), with a large superimposed tidal componenet. Meters 11CM and 10CM, over the hyperbolated zone, recorded a northeast flow, parallel to the contours and to the highly elongate M_2 tidal ellipse; maximum speeds were 18 cm/sec. Unfortunately, there was a malfunction in Meter 9CM, over the smooth and almost horizontal seafloor below 4040 m, so we were unable to test whether the northeasterly current was restricted in width to the zone of bedforms.

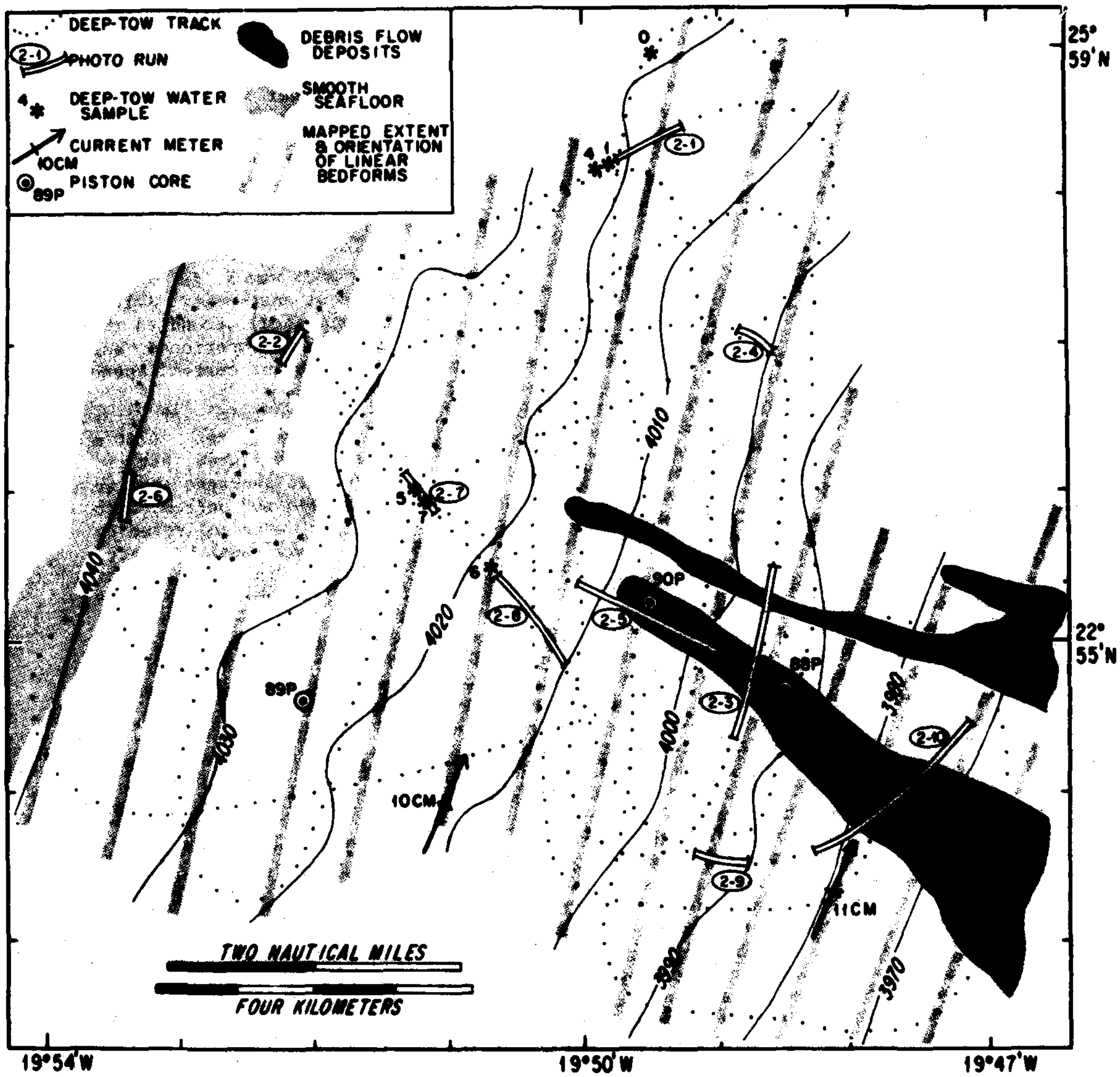

Fig. 4. The Saharan Rise site. Depths in corrected meters.

The deep-tow survey (Fig. 4) straddled the lower boundary of the hyperbolated zone. The linear corrugations responsible for the hyperbolae show up well on side-scan sonar records (Fig. 6), except where the tracks are nearly orthogonal to their trend and in the near field where the angle of incidence of sound waves is more than about 20°. We therefore acquired overlapping side-scan coverage, with approximately north-south tracks, of a large fraction of the survey area. Debris flow surfaces are also distinctive on the side scan records, because of their small scale roughness, especially near their edges and termini. About 1200 stereo pairs of bottom photos were taken on 10 photo runs, one across smooth, uncorrugated seafloor, 3 across debris flow tongues (showing a hummocky seabed with occasional free-standing moated clasts), and the remainder across the linear bedforms (which lack sharp breaks of slope, and are not well displayed on individual frames). A piston core (89P) sampled the calcareous sediment of the bedforms, and two others (88P and 90P) sampled both this material and the overlying 1-2 m thick debris flow deposit.

Analysis of the cores and 4 kHz profiles is required to determine whether the linear bedforms are erosional furrows or depositional mud waves. The bedform field is not a generally flat surface dissected by grooves, like the furrow fields in terrigenous sediment on Blake-Bahama Outer Ridge (Hollister et al., 1974) or Bermuda Rise (see below); the entire seafloor is corrugated with continuous slopes, and more closely resembles furrows in calcareous sediment near the Samoan Passage in the southwest Pacific (Lonsdale and Spiess, 1977). One hint that the features might be depositional is that subbottom reflectors seem to parallel the seafloor. We expect that analysis of the superposition of the bedforms and dateable debris flows will clarify the chronology of bedform development. Some of the debris flow surfaces are corrugated (Fig. 6), perhaps because thin debris flow deposits have maintained a fairly constant thickness over preexisting lineated relief, and at some debris flow margins secondary tongues of debris can be seen to extend along bedform troughs.

Bottom photos of scoured seabed prove the efficacy of modern currents for sediment redistribution at this site. Opportunities for explaining bedform characteristics by measured bottom water properties include relating their wavelength to the spatially changing thickness of the bottom mixed layer (monitored by the deep-tow CTD), and interpreting their unusual pattern of as a response to the reversing currents that were measured at current meters 10CM and 11CM. Most linear landforms on Earth have branches that open in the upstream direction, but those in the survey area have branches

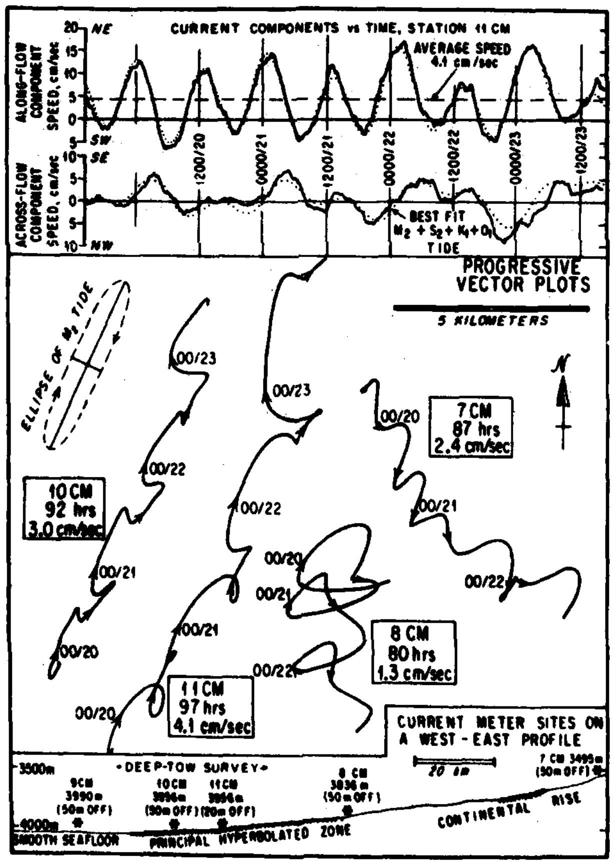

Fig. 5. Current meter results from the Saharan Rise. Progressive vector plots are shown for all successful meters, and components of the speed along and across the mean flow are shown for Station 11CM.

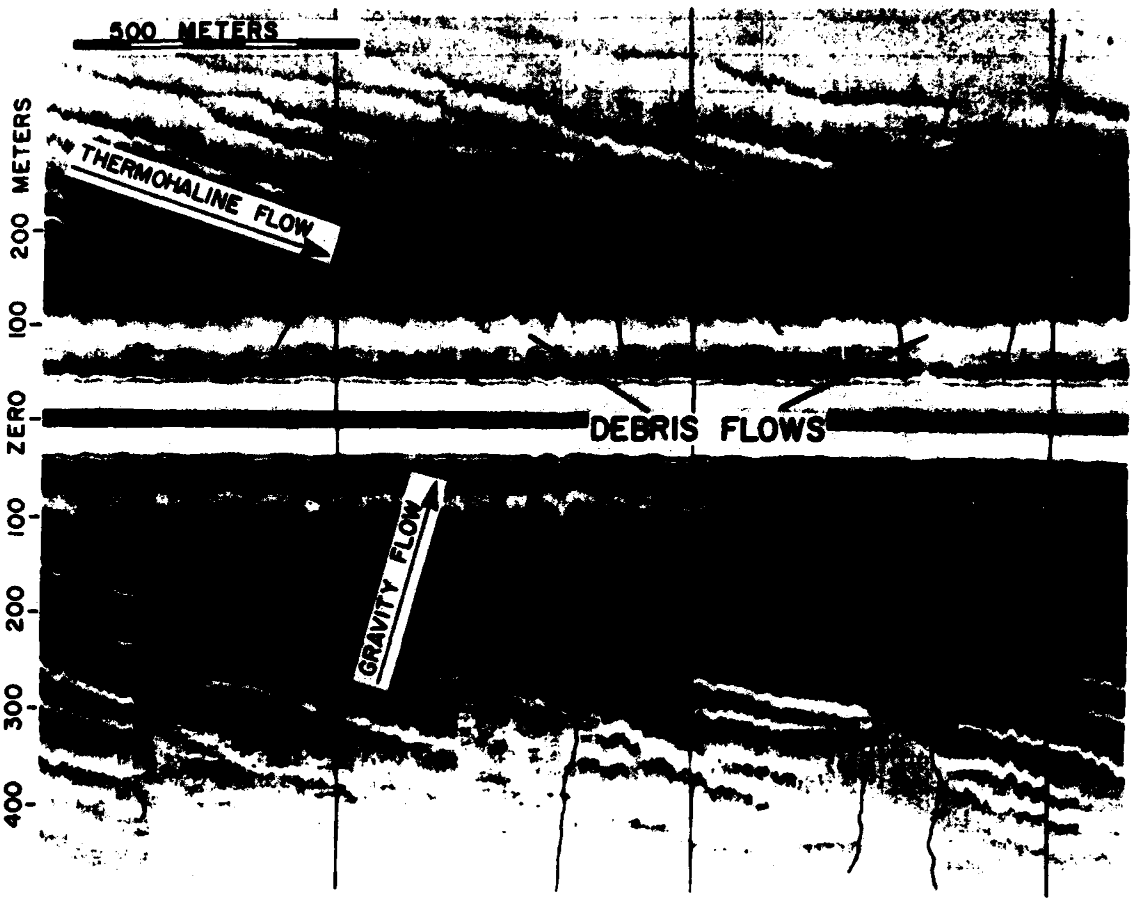

Fig. 6. A pair of side-scan records from the Saharan Rise, showing linear along-slope bedforms parallel to measured thermohaline currents, and cross cutting debris flows.

open to both the soutwest and northeast. Because the tidal currents are faster than the thermohaline flow, and have an elongate ellipse parallel to the latter, the bottom current regime is one of alternating northeast and southwest flows, and this may explain the bimodal branching direction. The dominant role of the tides for moving bottom water, and presumably sediment, helps explain why we find such well developed linear bedforms at a site with quite slow predicted, and measured, thermohaline currents.

BERMUDA RISE OPERATIONS

Justification

The Bermuda Rise has thick deposits of terrigenous sediment far removed from terrestrial sources. Thermohaline currents have been responsible for transporting sediment from the North American margin to this mid-ocean site of deposition; in places these currents have also caused erosion of the rapidly deposited sediment. The return flow of the deep Gulf Stream is thought to be the principal supplier (Laine, 1978). After flowing southwest across the Sohm Abyssal Plain it encounters the northeastern Bermuda Rise at a steep slope known as Eastward Scarp. Since the exploratory photography and coring of R/V Eastward, this region has been the focus of intensive seismic profiling, which established the acoustic stratigraphy, identified outcrops of erosionally truncated strata on the scarp, and mapped zones of hyperbolae-causing bottom roughness. There had also been more coring, including the collection of long cores for geotechnical studies (Silva et al., 1976), and a hydrocast transect by R/V Endeavor which found high concentrations of suspended sediment in bottom water beside the scarp. A few months before our INDOMED 11 survey, a pair of moorings that included nephelometers and sediment traps, as well as the first deep current meters in this area, had been tethered near the top and bottom of the scarp. Our objectives during the six days spent at the northeastern Bermuda Rise were to retrieve these moorings and take bottom hydrocasts alongside them, and to complement the large amount of surface-ship data with deep-tow observations and measurements of the near-bottom currents.

The southwestern Bermuda Rise is thought to be swept by northward-flowing Antarctic Bottom Water (e.g., Heezen et al., 1966; Tucholke et al., 1973). Regional profiler and coring surveys by Lamont had identified areas of seafloor, in both extensive patches and strips a few kilometers wide, that returned very "fuzzy" or hyperbolic echoes indicative of regular roughness. The objectives of our near-bottom survey there were to enhance interpretation of the surface ship data by identifying and describing the roughness elements, which were presumed to be bedforms, and to measure properties of the bottom water that might explain their form, distribution and genesis. We also recovered a bottom current meter mooring that had been deployed a few months earlier, by Lamont, about 90 km north of the site chosen for the deep-tow survey.

Eastward Scarp Survey

Deep-tow effort was concentrated in a transponder-navigated survey near the crest of Eastward Scarp, straddling a hyperbolated section of the acoustically laminated sediment that blankets the plateau, the erosionally truncated edge of this section at the plateau rim, and part of the outcrop of the underlying "acoustically transparent" section. The hyperbolae on surface ship records were found to be caused by linear erosional furrows, similar to those discovered by deep-tow on the Blake-Bahama Ridge in 1973 (Hollister et al., 1974). The survey area was at the corner of the plateau rim, in the angle between Eastward Scarp and the side of an orthogonal fracture zone valley, one of several deep reentrants in the scarp. We did make one long deep-tow profile that began on the gently undulating plateau surface 10 km from the survey area, and extended down Eastward Scarp to the Sohm Abyssal Plain (Fig. 6). Except at the steep foot of the scarp from 5100 m to 5500 m, where the seafloor truncates gently dipping "acoustically transparent" strata, this entire slope has furrows of varying size and spacing developed in acoustically laminated sediment. Photographs were taken at frequent intervals down the irregular slope (Fig. 6). At the end of each photo run we made a vertical excursion of 100-200 m to collect CTD profiles: changes in mixed layer thickness can be related to changes in bedform spacing, and the CTD data can complement the results of the Endeavor hydrocast transect. A single photo run was made during our short tow across the edge of the smooth, unfurrowed Sohm Abyssal Plain.

The transponder-navigated survey (Fig. 7) is the most complete mapping of an abyssal furrow field. Overlapping side-scan sonar coverage was obtained for most of the survey area, so that furrow trend, continuity and branching frequency is well determined. The furrows bend smoothly around the corner of the plateau, from a southeasterly orientation (parallel to the fracture valley) in the northern part of the survey to a southwesterly orientation (parallel to Eastward Scarp) in the south. The direction of furrow bifurcation, from which the sense of flow can be inferred, is very consistent (Fig. 8). Three meters (15, 17 and 18CM) 100 m above the furrow field recorded average flows of 7.5 to 10.3 cm/sec, in each case exactly parallel to adjacent furrows; the remarkable feature of the records is the extreme steadiness in direction, though the speed has a tidal fluctuation of about 4 cm/sec. About 700 stereo photos were taken in the furrow field; on those photo runs in the southwestern part of the survey some details of the bed are obscured by murky bottom water, but elsewhere water is clear enough for good photography. Some furrow walls have oblique ripples, similar to those on some Blake Outer Ridge furrows (Hollister et al., 1974).

We expect to learn much about the dynamic geomorphology of erosional furrows by analysis of 'he deep tow data — which includes continuous near-bottom CTD measurements — from this field. An advantage for understanding furrow genesis is that the northern part of the survey includes the beginning of many of the furrows, so that we can see how they start in a spatial sense. In the northeastern part of the survey we also mapped, for the first time, the ends of large furrows, which end abruptly with "birds-foot terminations" (Fig. 9) formed by the splaying of short distributaries. Since the near-bottom currents are parallel to furrow trends, we can use the patterns mapped by side-scan to infer streamlines (Figs. 6, 7); these show, for example, that the water in the branch of thermohaline current that flows southeast along the contours of the fracture valley changes depth by over 150 m as it negotiates the corner of the plateau.

The outcrop of the "acoustically transparent" section in the eastern part of our survey area was found to have a smoothly streamlined surface that lacks furrows but has some small-scale bedforms (showing up in our photographs) that include transverse ripples. The fastest current we measured (average velocity of 13.7 cm/sec at 14CM) was over this eroded outcrop; another meter (16CM) over the "transparent" section (which on our near-bottom 4 kHz profiles shows distinct subbottom reflectors) monitored a steady southeasterly current, but the speed recorder failed to work. A free-vehicle package that has current meters and a time-lapse camera was deployed by M. Wimbush at 32°52'N, 57°29.0'W, near the position of 16CM; it will be recovered in 1979 after several months' operation. The erosionally truncated "transparent layer" outcrop at the foot of our long profile of Eastward Scarp (Fig. 6) had a streamlined surface with crag-and-tail and moated nodules and rock fragments, all indicative of fast currents; current meter 13CM, higher up the lower slope on furrowed terrain, measured an average flow of only 4.0 cm/sec.

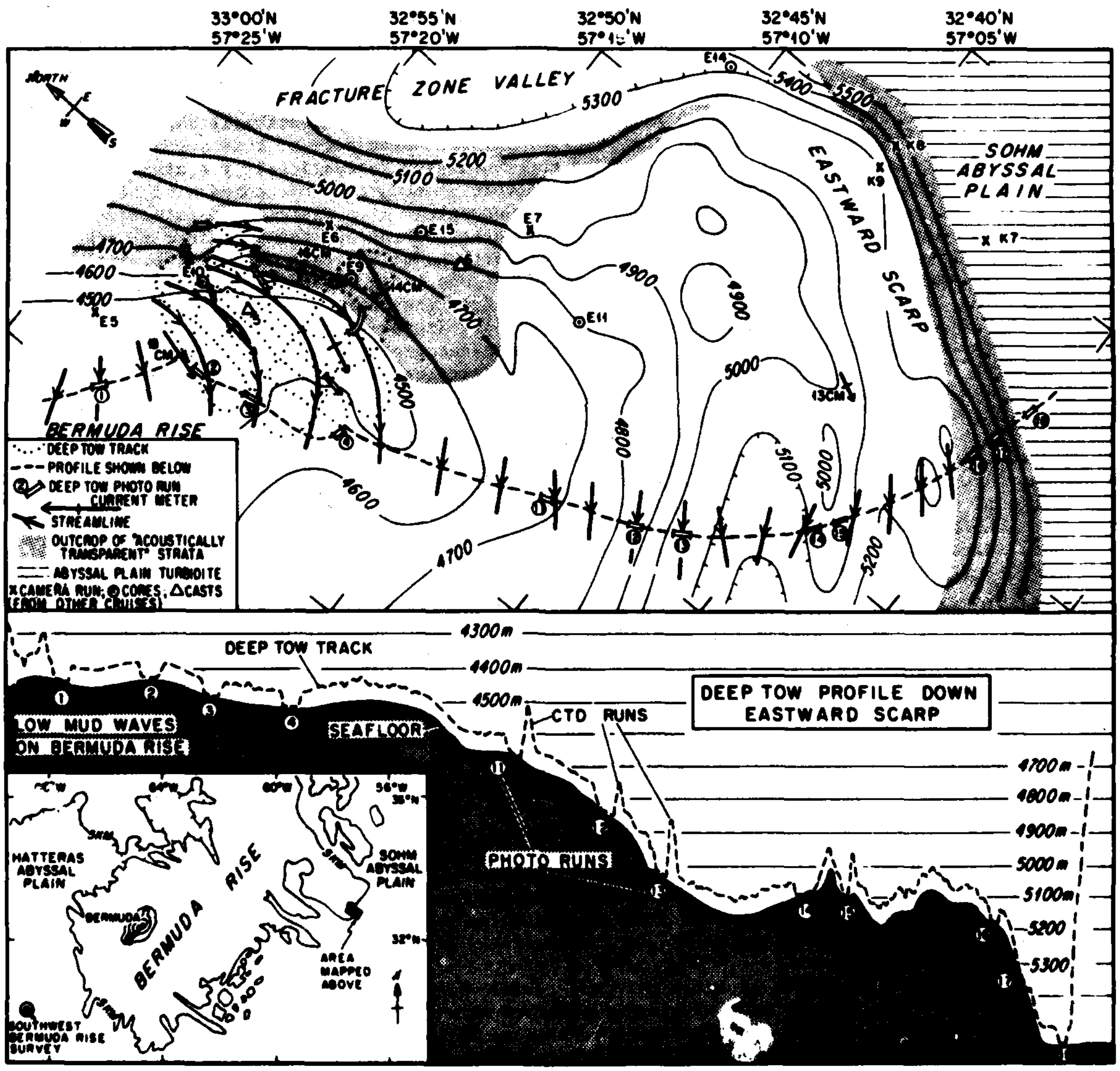

Fig. 7. The deep-tow survey site and long traverse at Eastward Scarp, Bermuda Rise. Inferred streamlines for the bottom current are drawn parallel to mapped furrows in the seafloor. Inset shows location of this site and the one on the southwestern Bermuda Rise.

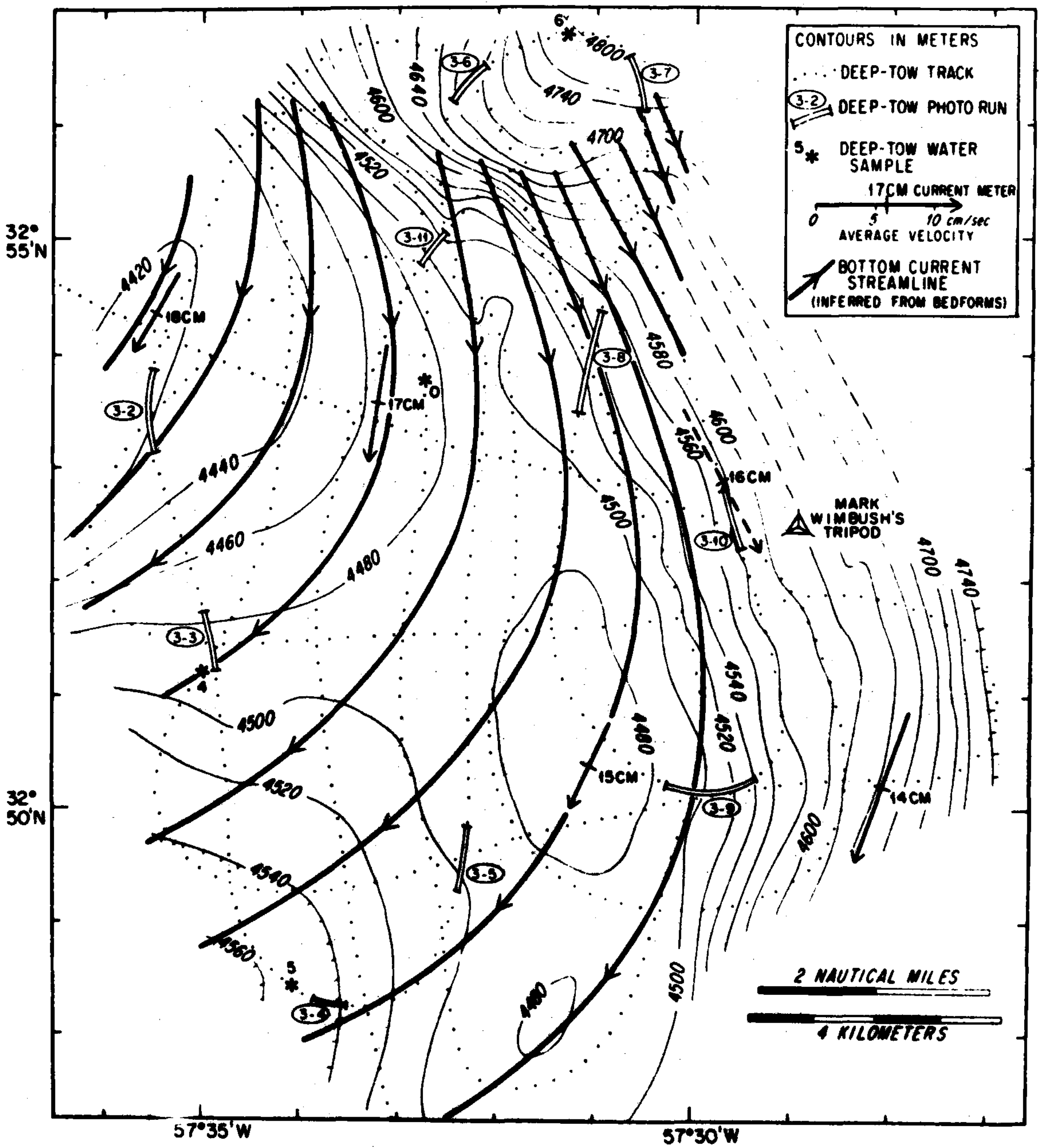

Fig. 8. The detailed survey area near the crest of Eastward Scarp. Depths in corrected meters.

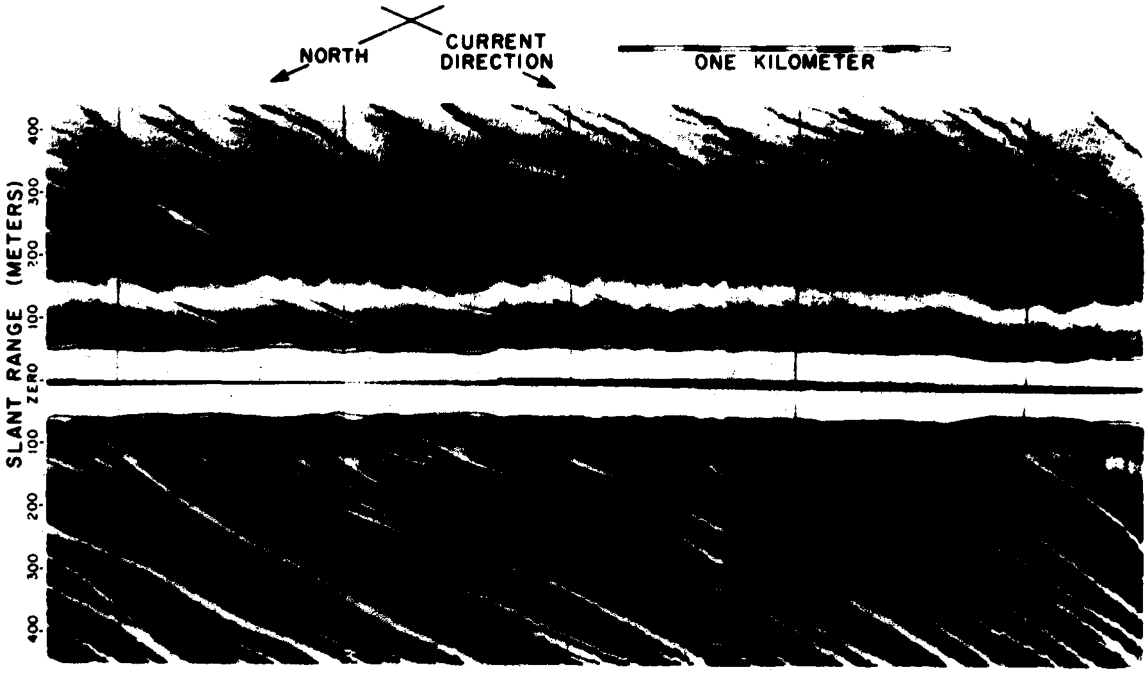

Fig. 9. Side-scan sonar record of a typical pattern of furrows on the northeast Bermuda Rise (southwest of Meter 17CM in Fig. 8).

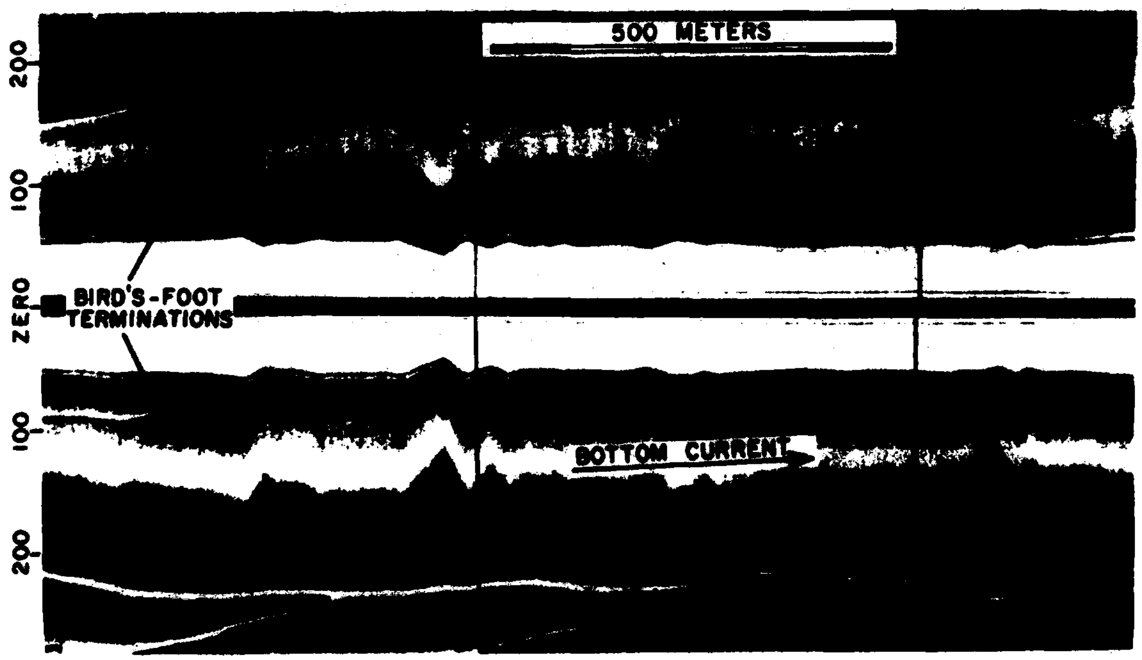

Fig. 10. Side-scan sonar record of bedforms near the western margin of the furrowed region (northeast of Meter 16CM in Fig. 8), showing distinctive shape of their downstream terminations.

Because enough cores had been collected on earlier cruises, we took no bottom samples at this site. The only hydrocasts taken were at the long term moorings we retrieved, about 16 km northwest and 60 km east of the deep-tow survey.

<u>Southwest Bermuda Rise Survey</u>

Profiles across a large area of the rise near its southwestern margin with Hatteras Abyssal Plain show patches of hyperbolated seafloor 1-100 km across. We chose to study a small region where a Lamont profiler survey had established the regional pattern of these patches: around 29°50'N, 68°50'W, roughened seafloor occurs in 1-2 km wide strips that extend south-south-west from a much broader patch of hyperbolae (in which a Lamont long-term current meter was deployed). The profiler records show that the roughened areas, with low sea-bed reflectivity, are on the western faces of 20-30 m high mud waves.

The deep-tow survey (Fig. 10) was centered on the crest of a mud wave that bifurcates in the northern part of the survey area. The roughness elements are found to be large slots or furrows up to 15 m deep and 30 m wide. They are similar in scale and their steep-sided morphology to the large erosional furrows mapped by deep tow near the boundary of the Bahama Outer Ridge and Abyssal Plain (Hollister et al., 1974), but are more closely spaced (Fig. 11). Individual furrows seldom branch, and extend for several kilometers, obliquely across the mud wave's west face. This side of the asymmetric, westward migrating wave has a thickened superficial stratum, evidently caused by more rapid sediment accumulation there (Fig. 12). The deep-tow survey encompasses the next wave to the east, whose western face has a similarly thickened but undissected sediment lens, and the furrowed crest of the next wave to the west. At the end of the survey, the tow was extended east to the furrowed face of another wave (beginning about 2.5 km east of Photo Run 4-10, mapped in Fig. 10).

The entire area of seafloor between the clearly furrowed strips, including mud waves' eastern faces and troughs, seems to be covered with subtle lineations whose amplitudes are so small that they have no obvious effect on surface-ship records. These bedforms were recorded by our near-bottom side-scan sonars only under optimum conditions

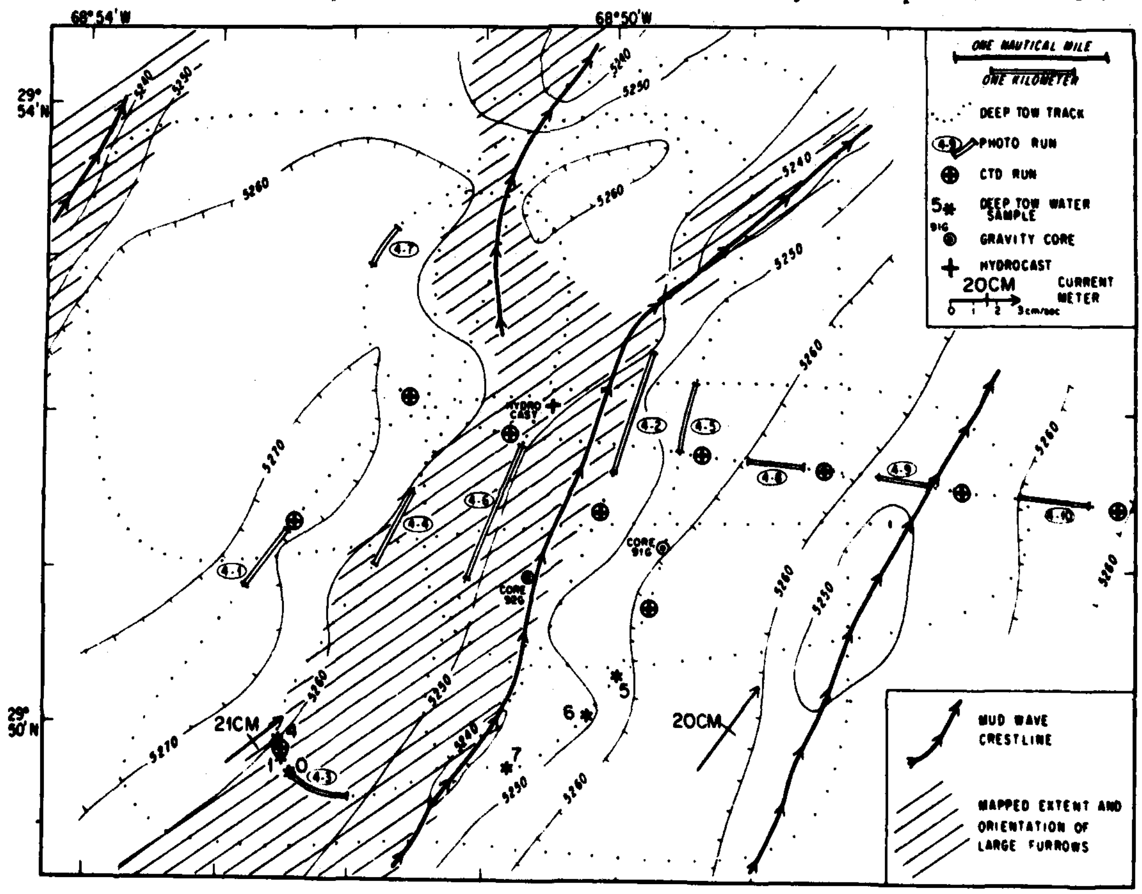

Fig. 11. The Southwest Bermuda Rise deep tow site. Depths in corrected meters.

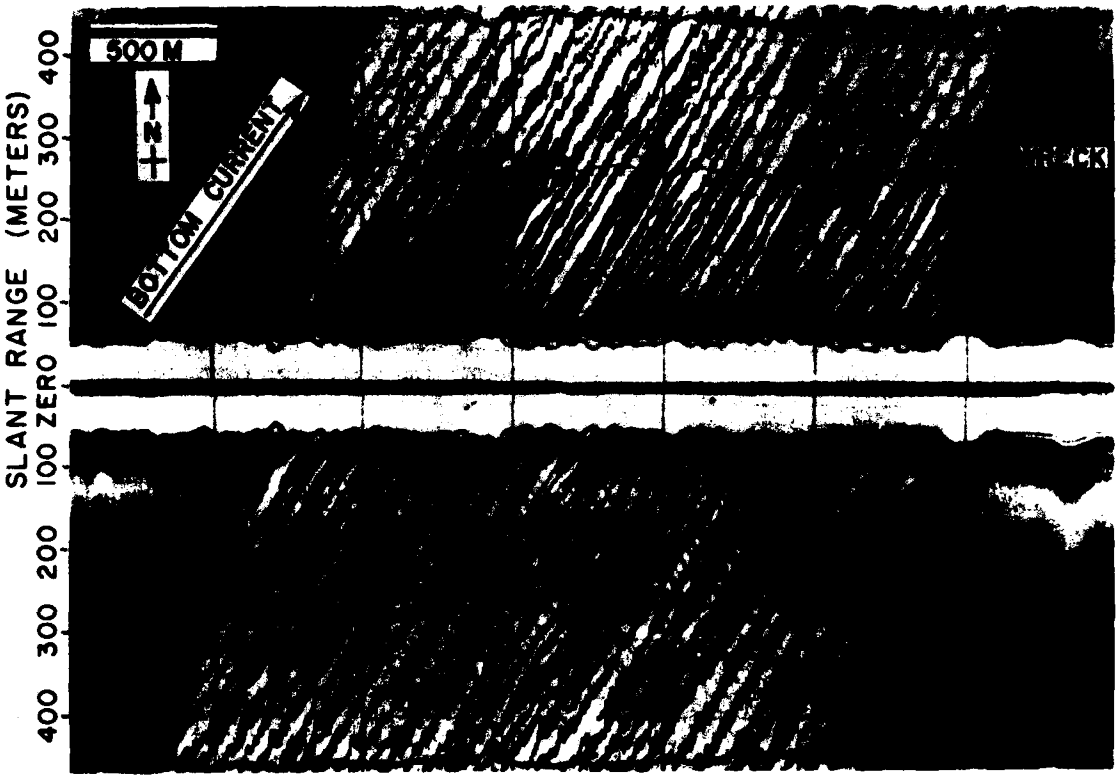

Fig. 12. A pair of side-scan sonar records from the Southwest Bermuda Rise, near the center of the area mapped in Fig. 11. The "striped" region of acoustic shadows and highlights is the furrowed face of a sediment wave; the wave's crest is 100-200 m west of the eastern edge of the furrowed area. The "wreck" is the remains of a small ship or airplane on the seafloor.

of low angle of sound wave incidence on tracks nearly parallel to the lineations. They are parallel to the large furrows, and merge into them at mud wave crests and near the foot of the west faces. Seven deep-tow photo runs were taken in these "unfurrowed" areas (Fig. 10), and many of the photos show shallow linear depressions with gently sloping unrippled walls. Stereoscopic examination will be required for proper interpretation of these photos, and of those from three photo runs in the area of large furrows, which show abrupt breaks of slope and local patches of transverse "ripples".

Two meters 100 m above a mud wave trough (20CM) and western face (21CM, at the margin of a furrowed strip) recorded slow but steady northeasterly currents; average velocities for the 2.7 days were 4.2 cm/sec and 3.0 cm/sec, respectively. Two other meters, one over the furrowed crest of a wave and the other over a trough, did not produce good records. The measured northeasterly flow direction is readily predictable from the mapped geomorphology: the current is 30° oblique to the mud waves (as at the Moroccan Rise), and parallel to the superimposed furrows (as at Eastward Scarp).

More effort than at our three other sites was expended in collecting deep-tow CTD data over these furrowed mud waves. We made frequent "CTD runs", involving vertical excursions of about 200 m through the bottom mixed layer, in an attempt to map bottom water structure. One reason for this emphasis is that we had attached a Lamont nephelometer, retrieved from one of the moorings on the Bermuda Rise, to the deep-tow vehicle, and it successfully measured water clarity every 7.5 minutes during the tow. Water samples collected for suspended sediment filtration by deep-tow bottles and a Niskin cast should complement these nephelometer data.

A preliminary interpretation of this site is that the upstream faces of mud waves oriented 30° oblique to the measured currents have suffered preferential erosion by incision of furrows parallel to the current. Profiler records show that the dissected slopes were once areas of preferential deposition. To test whether the pattern of erosion could be explained by different erodibility of different lithologies on the two faces of a mud wave, we collected a pair of wide-diameter gravity cores (91G and 92G). A comparison of the sediment from two faces of the same mud wave will add to a regional study of the lithologic difference between hyperbolated and smooth parts of the southwest Bermuda Rise that is being carried out at Lamont.

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The field program of INDOMED Leg 11 was conducted by the scientific party listed in the appendix, with the enthusiastic support of the officers and crew of R/V Melville (A. Phinney, captain). C. Hollister (Woods Hole Oceanographic Institution) and B. Tucholke (Lamont-Doherty Geological Observatory) were instrumental in planning the cruise, though they were unable to participate in the work at sea. L. Mayer, S. Miller and R. Lawhead helped directly in the preparation of this report.

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In August and September 1978, deep-tow surveys were conducted with R/V Melville at four sites in the North Atlantic: a field of mud waves on the Moroccan continental rise; a patch of hyperbolae-creating bedforms with interfingering debris flows on the Saharan continental rise; an area of abyssal furrows near the crest of Eastward Scarp on the Bermuda Rise; and a field of furrowed sediment waves on the southwest Bermuda Rise. In addition to near-bottom acoustic records, the deep-tow instrument collected stereo

20. Abstract (Continued)

photos, CTD and nephelometer data, and samples of bottom water and suspended sediment. There were also current meter, hydrocast and coring stations. This report includes preliminary deep-tow maps of each site, locating photo runs and samples, and presents a few typical sections of data.