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IDENTIFICATION OF GENERIC STUDY AREAS FOR THE DISPOSAL OF LOW LEVEL RADIOACTIVE WASTE:

WESTERN NORTH ATLANTIC OCEAN

by

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Prepared for the Sandia Laboratories.

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JULY 1979

TECHNICAL REPORT

Prepared for the Sandia Laboratories.

APPROVED FOR DISTRIBUTION John I. Ewing

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Dept. of Geology and Geophysics

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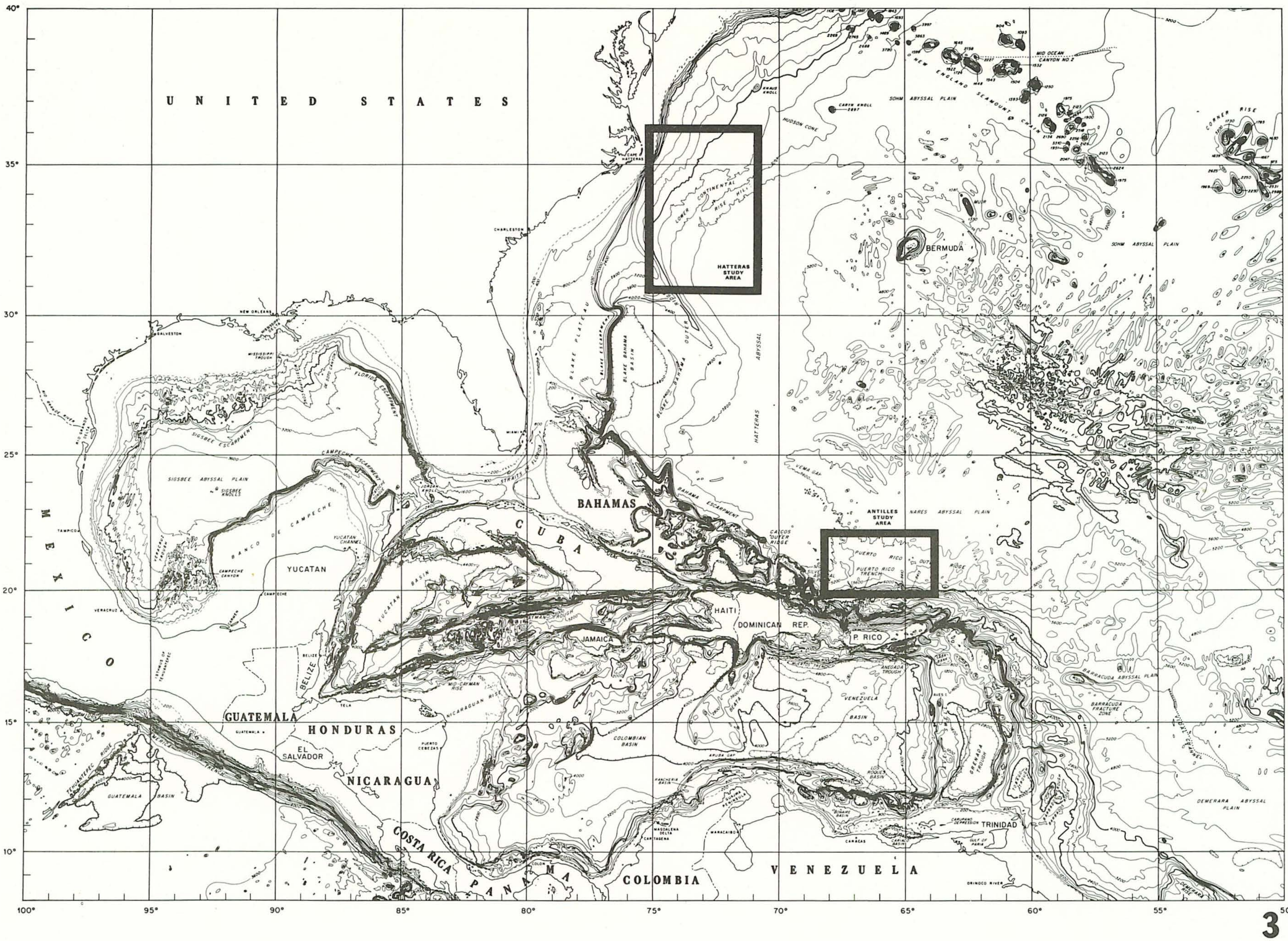


FIG. 1. Proposed generic study areas in relation to major physiographic features of the western North Atlantic. Contour interval: 400 m. (after Uchupi, 1978)

INTRODUCTION

There is a growing need to effectively dispose of the low level radioactive waste presently accumulating in the United States. It may be decided to "dump" radioactive contamination products onto the deep sea floor (within 200 miles of the U.S.) in accordance with present IAEA guidelines (see Appendix A) for ocean dumping of low level waste; in the event of such a decision suitable areas must be identified and carefully studied to determine the subsequent influence of the waste on the environment.

Using the site suitability criteria mentioned above we have identified two areas of possible use for low level waste disposal, one north of Puerto Rico and one east of Cape Hatteras, as deserving further study.

The following report describes the relevant physical and geological characteristics of these two areas that may be important in considering a dumping operation. We have also made some recommendations for confirmatory research.

The Hatteras Abyssal Plain, lying close to the 200 mile limit, appears to be a viable region for the focus of future research efforts.

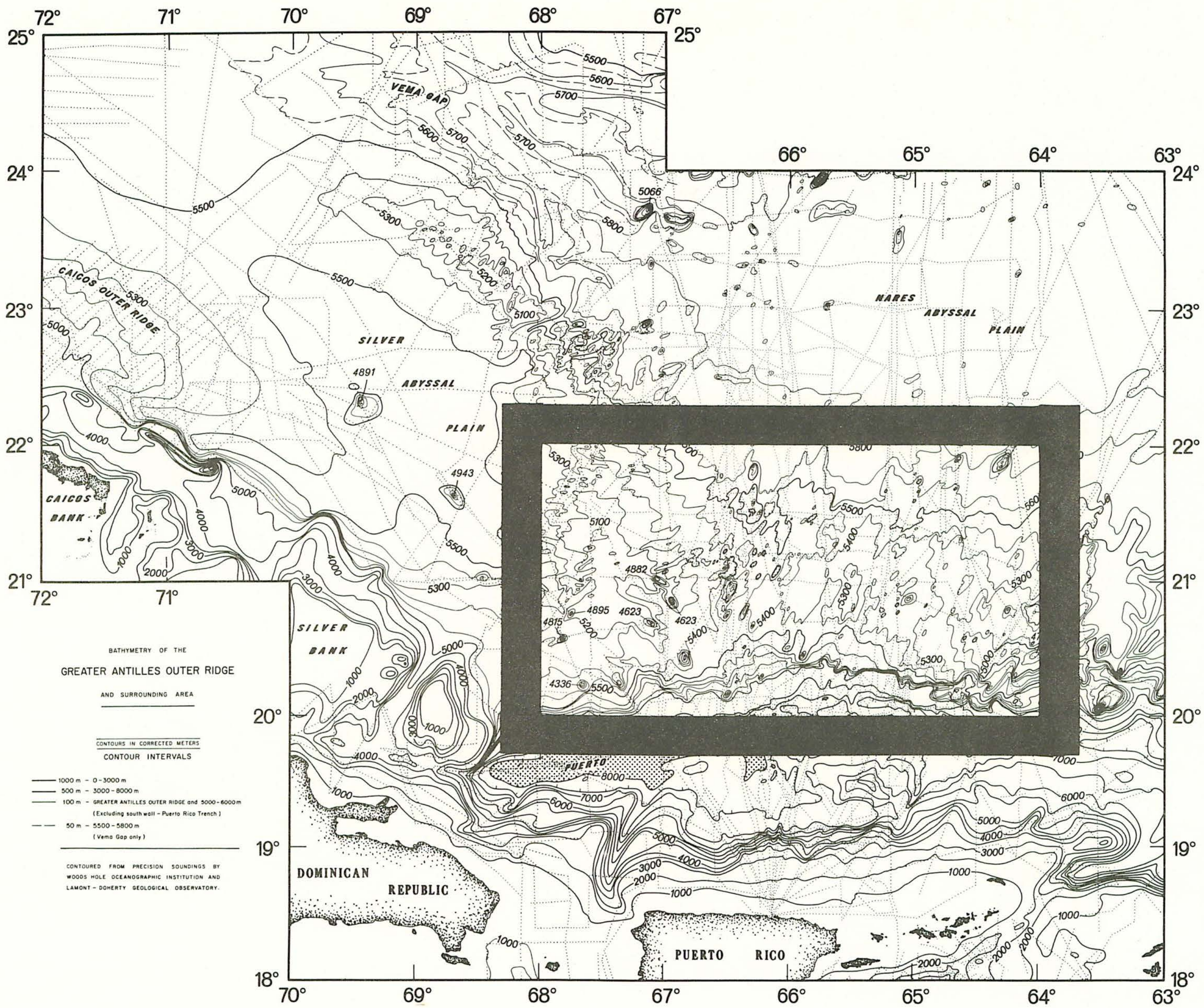


FIG. 2. General location of proposed Antilles Study Area. (after Tucholke, 1973)

ANTILLES AREA

This site, located north of Puerto Rico at 20-22^{o}N, 64-68^{o}W (Fig. 1, 2), has the following characteristics:

TOPOGRAPHY: (5000-6000 m depth) Most of the area is dominated by an undulating surface of regular to irregular small-scale sediment swells with spacing of 1-12 km and amplitudes of 10 to 140 m (Tucholke, 1973). Local slope gradients vary from 1:150 to 1:250, but become steeper (1:30) in the southern sector (north slope of Puerto Rico Trench).

SEISMICITY: The site is just north of the Puerto Rico Trench, where frequent seismic activity has been recorded. Some of this activity is associated with the Greater Antillean portion of the Trench; considerably more activity, however, is recorded toward both its western (Mona Passage, Hispaniola) and eastern (Lesser Antilles) termini (Bunce, et. al., 1974; Molnar and Sykes, 1969). Proximity to this area necessitates further study of epicenter locations; in-situ seismometer data are needed to fully assess localized earthquake activity.

VOLCANIC ACTIVITY: There is no evidence to suggest that vulcanism has occurred in this specific region since crustal formation; Eocene (about 50 million years ago) geosynclinal volcanic activity in the Lesser Antilles area (Weyl, 1968) is generally believed to be the source of ash layers found in the sediment. Recent eruptions in the island chain, however, suggest that volcanism is still very active near the study area.

DEPOSITIONAL CONDITIONS: The average Pleistocene/Holocene rate of sediment deposition is about 5 cm/1000 yr, with locally variant conditions in the northwestern and southern sectors (Tucholke and Ewing, 1974). North of the Antilles Outer Ridge crest (21^{o}N) existing core lithology indicates the rate is higher (up to 30 cm/1000 yr) due to current circulation and associated preferential deposition (see OCEAN CIRCULATION). Along the slope of the trench the rate is extremely low (less than 1 mm/1000 yr since Eocene time), suggesting this area has received sediment exclusively from normal pelagic sedimentation and occasional ash falls. These rates are not absolute, since they average over periods of erosion, nondeposition and unusually rapid sedimentation.

SEDIMENT CHARACTERISTICS: Sediments in this area typically consist of texturally homogeneous, terrigenous, low-carbonate content abyssal clay (less than 4 microns in mean grain size). Grain size is quite uniform and consists of an average of 80%

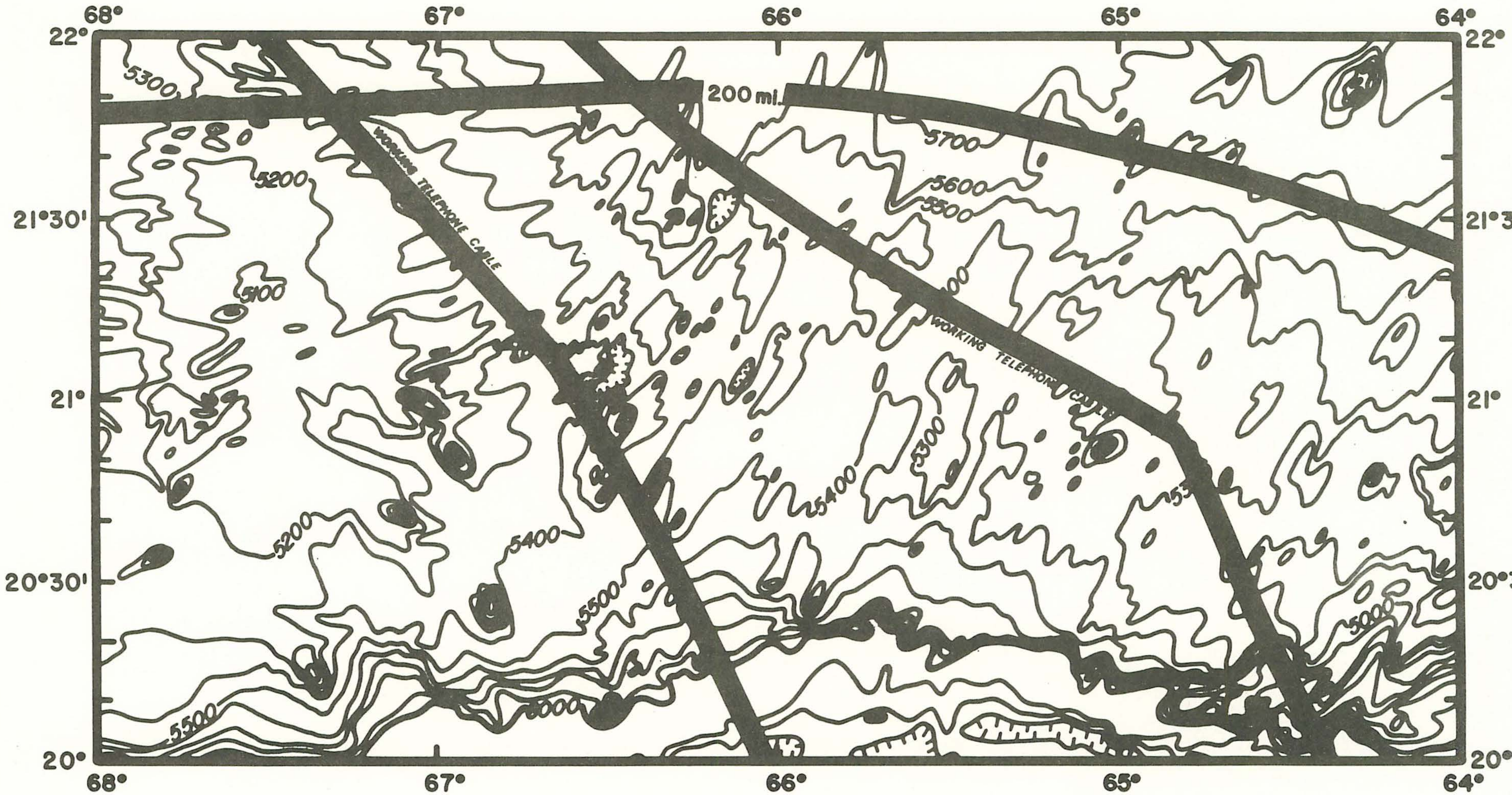


FIG. 3. Detailed bathymetry (100 m contours) of the Antilles Study Area, with 200-nautical mile limit and telephone cable locations. (after Tucholke, 1973)

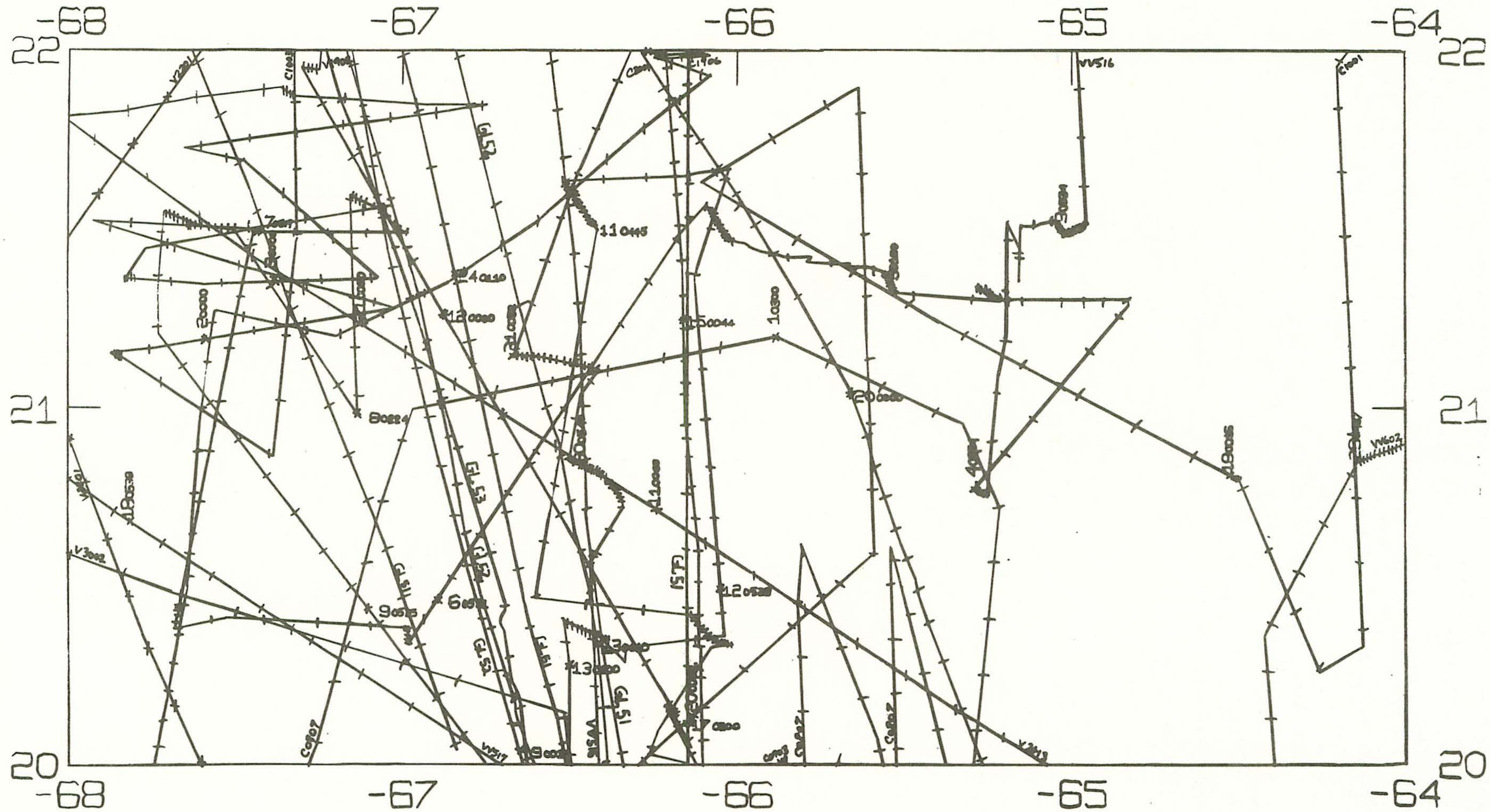


FIG. 4. Antilles Area ship tracks studied for this report.

clay and 20% silt (mean grain size 4 to 62 microns). The fine size of the sediments precludes detection of current-produced primary structures such as cross-bedding, especially south of the ridge crest. Cores obtained there show unfossiliferous silty clays which consist of clay minerals (e.g. illite, montmorillonite), quartz, feldspar, altered ash and rare zeolites. Sediment thickness ranges from a few hundred meters to a maximum of about 0.8 km above acoustic basement, and in places the basement outcrops through overlying stratified and transparent layers to reach heights of up to 500 m above the surrounding sea floor (Tucholke, 1973). Moisture content is high (e.g. 90-120% of dry wt.) on and north of the ridge crest; it is lower on the trench slope (e.g. 20-50%).

BENTHIC BIOLOGY: There are three phyla to which particular classes of fauna found at these depths belong. One is the phylum Annelida (worms), to which the class Polychaeta belongs. The Polychaeta species are either pelagic bottom crawlers, active burrowers or sedentary types that inhabit tubes and burrows. Arthropoda (crabs, etc.) is the second phylum, of which Isopoda and Amphipoda are members. Isopoda are characteristically found beneath the sediment surface, while Amphipoda are shallow "plowers" and scavengers. The last phylum is Chordata. Tunicates and Ascidians are subphyla of Chordata and are frequently found at abyssal depths. They are filter feeders and remain stationary once the adult stage of development is attained. The larvae, however, are free swimming. Groups of these animals attach themselves to any surface they can find, although in this study area solid purchases are few and far between (this situation would obviously change after a "dumping" operation).

The total number of invertebrates decreases with depth; the relative number of Tunicates in relation to the other invertebrates increases with depth to 4200 m and then decreases thereafter (Monniot, 1978). A representative biological survey taken by Sanders, et. al. (1965) revealed, in order of decreasing relative size, 66 Polychaetae (up to 26 mm long), 31 Crustacea (Isopods, 1.5-5 mm) and no Tunicates (500 microns-5 mm) inhabiting one square meter of the sediment surface.

OCEAN CIRCULATION: The two abyssal, contour-following water masses affecting sediment provenance and dispersal in this area are Antarctic Bottom Water (AABW) and the Western Boundary Undercurrent (WBUC). Current meter observations south of the ridge crest define the AABW as flowing westward through the Puerto Rico Trench, while the warmer and more saline WBUC enters the area from the northwest and proceeds in an easterly direction on both sides of the ridge crest (overlying the AABW in the trench). WBUC current velocities measured 15 m above the bottom ranged from 2-12 cm/sec, with an average of 9 cm/sec (Tucholke, 1973).

CABLE ROUTES: Two submarine telephone cables pass through the area, linking Florida and St. Thomas, Virgin Islands. Their location is shown in Fig. 3.

DETAILED TOPOGRAPHIC ANALYSIS-Antilles Area: The total area covered by the chart in Fig. 5 is roughly 99,000 km^2; that within the 200 mile limit is somewhat less. Ship tracks examined total 3700 km; track spacings vary from less than 9 to over 50 km with numerous crossings. Navigational control was Loran A (accuracy of + 2 km) for all tracks. All records are 12 kHz in frequency.

Topography along the ship tracks has been classified in 5 units, shown by the patterns in Fig. 5 and illustrated with photographs of characteristic records (Figs. 6-10). The patterns summarize the relative areas of the different topographies.

It is apparent that only a relatively small area of very smooth topography lies within the 200 mile limit: in the northwest corner, enclosed by latitude 21°20'N, the boundary, and longitudes 67° and 68°W (see box on Fig. 5). This is the sole candidate site that appears deserving of a detailed survey.

Discussion

This area was initially chosen because we knew, from previous studies, that it was one of the few primarily depositional areas within the 200 mile limit that fit the IAEA siting criteria (see Appendix A). Mindful that areas of least topographic complexity would be more easily surveyed and monitored we examined the slope characteristics of the precision (12 kHz) echograms and found that the local topography was considerably rougher than the regional contours would suggest (see Appendix B for other examples of published bathymetry). We feel that smooth and flat, sediment-covered areas that also comply with IAEA criteria will be most suitable for the dumping operations. Accordingly we have identified the sub-area outlined in Figure 5.

Recommendations

1) Determine political implications of 200 mile zone in relation to Puerto Rico; i.e. is this area politically viable for dumping operations?

2) If the answer to 1 is yes, then we suggest that the identified sub-area be mapped with multibeam high-frequency sonar to fully determine the distribution of microphysiographic elements. Navigational transponders should be deployed at the end of this survey in an appropriate nav-net for future precise sampling efforts.

3) Take a suite of large diameter gravity cores, precisely located topographically, to determine maximum variations in texture, mineralogy and geotechnical properties germane to the isolation (or dispersal?) of the waste.

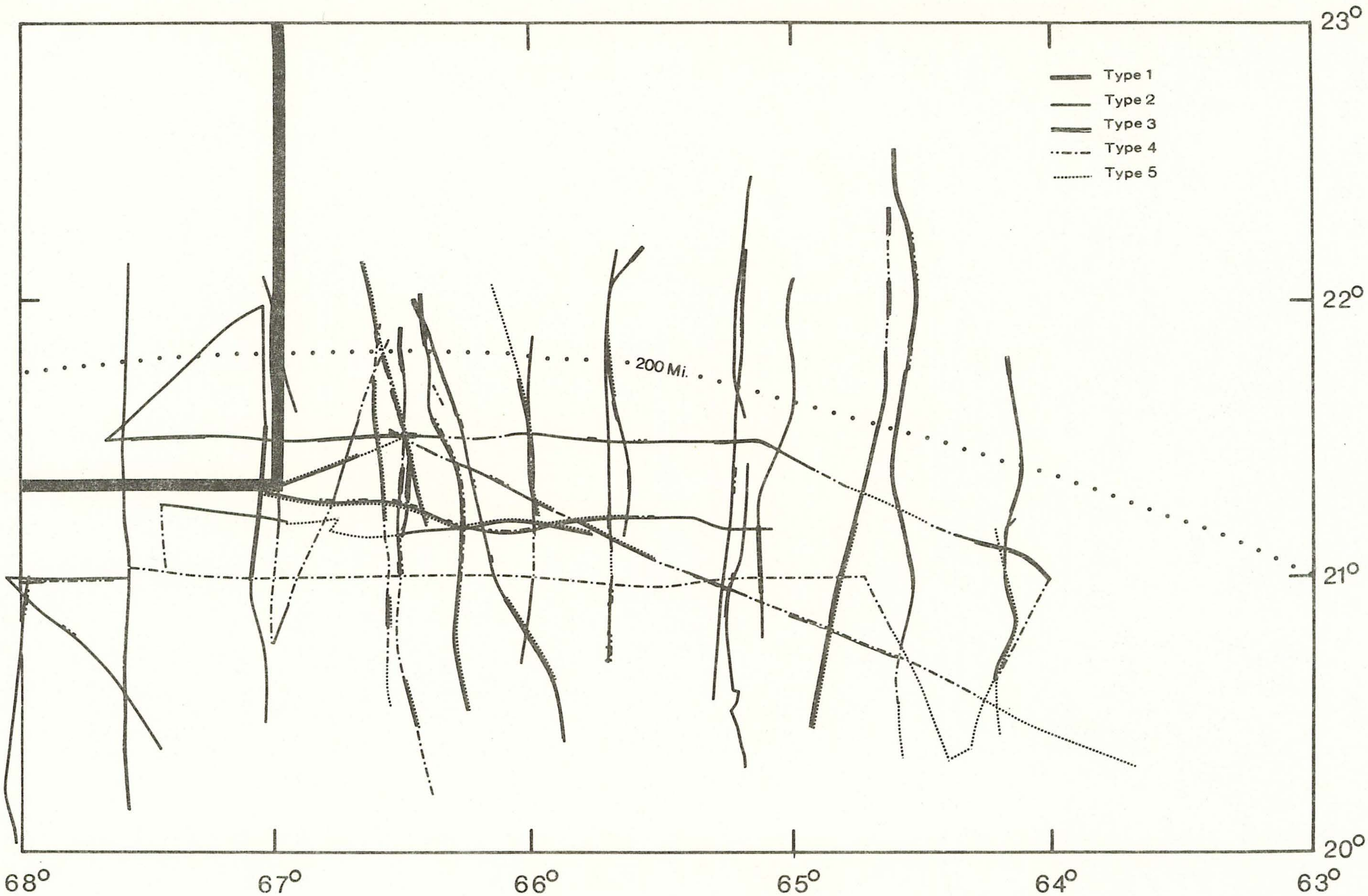


FIG. 5. Chart showing Antilles ship tracks. Patterns indicate seafloor (topographic) character; their numbers refer to the accompanying photographs. Box in upper left corner is the proposed detailed study site.

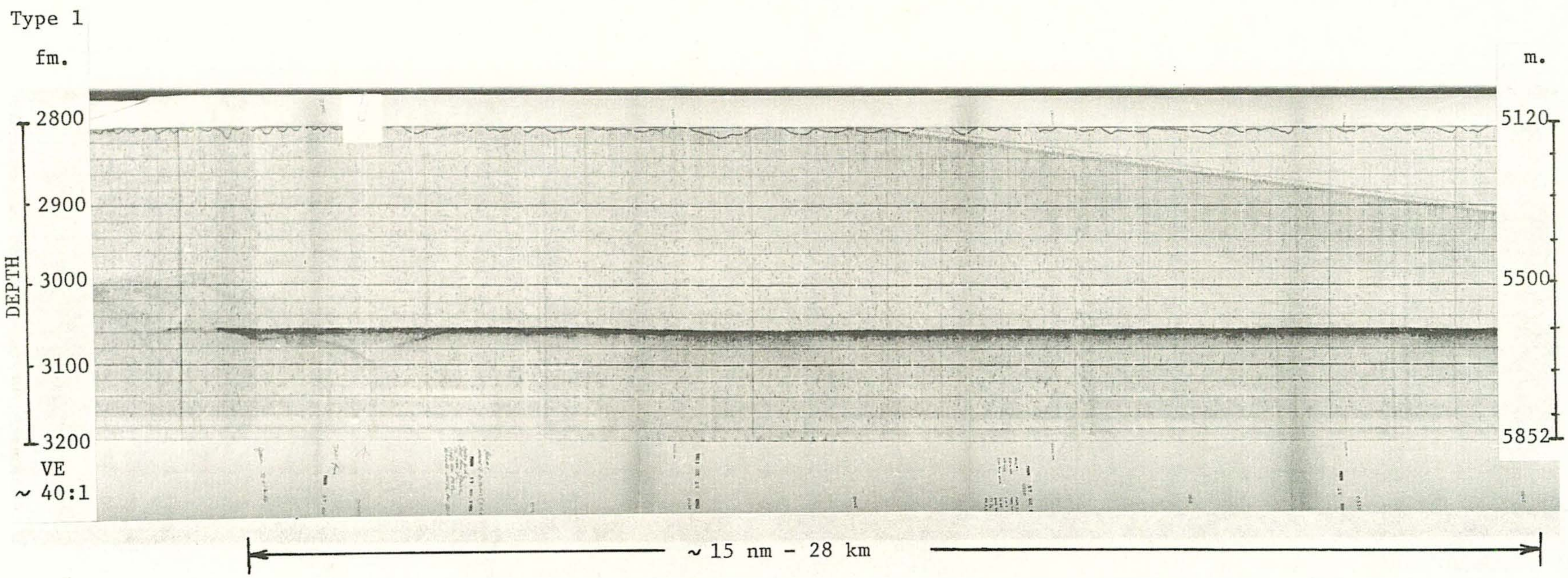


FIG. 6. Seafloor smooth, topography flat. VE is the vertical exaggeration.

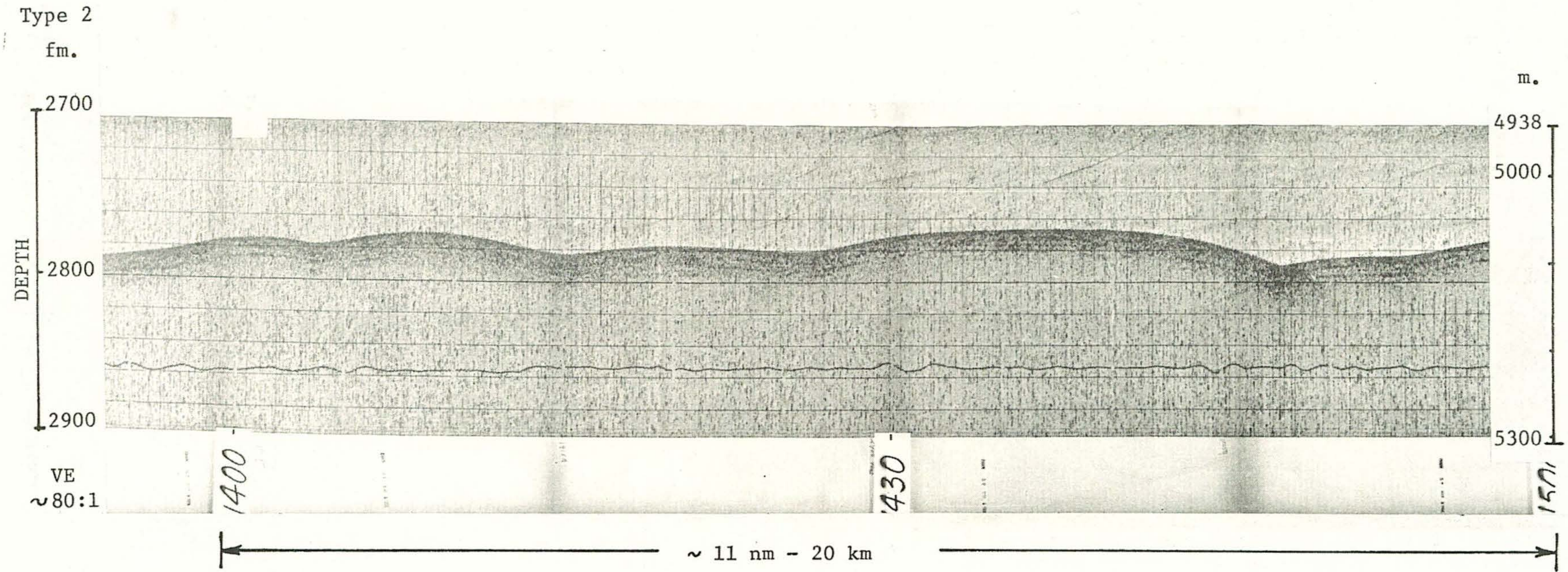


FIG. 7. Smoothly rolling topography, average depth constant.

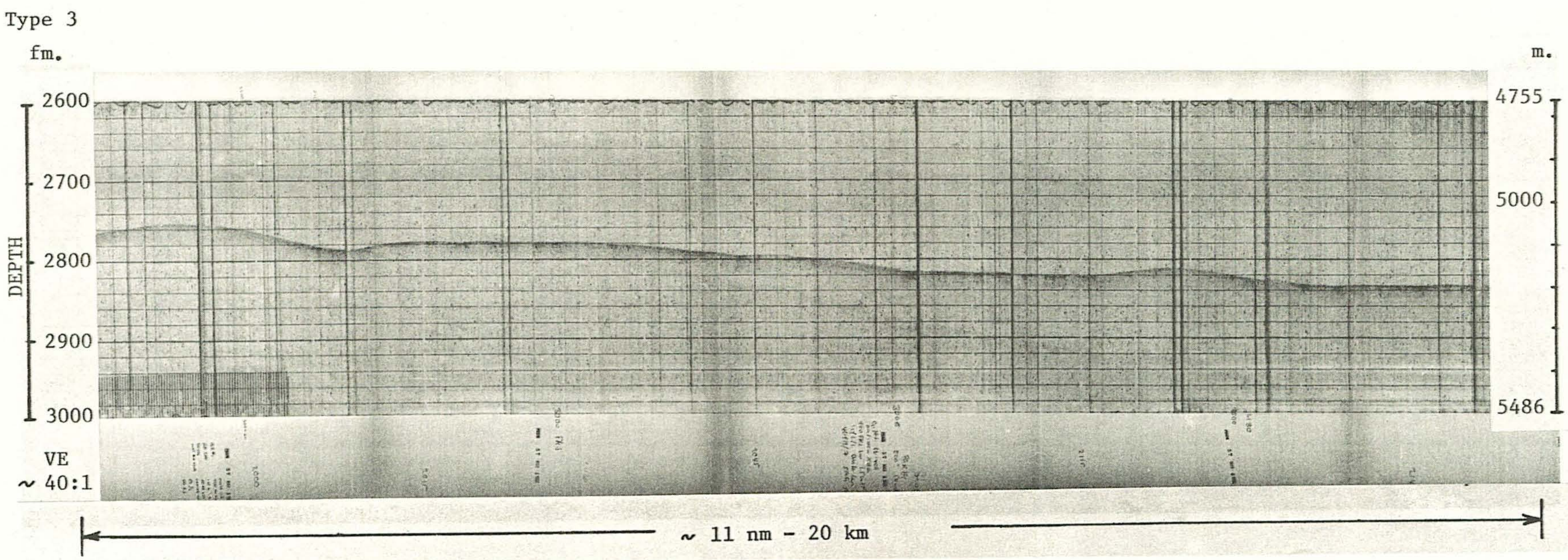


FIG. 8. As Type 2, but with overall depth changing slowly.

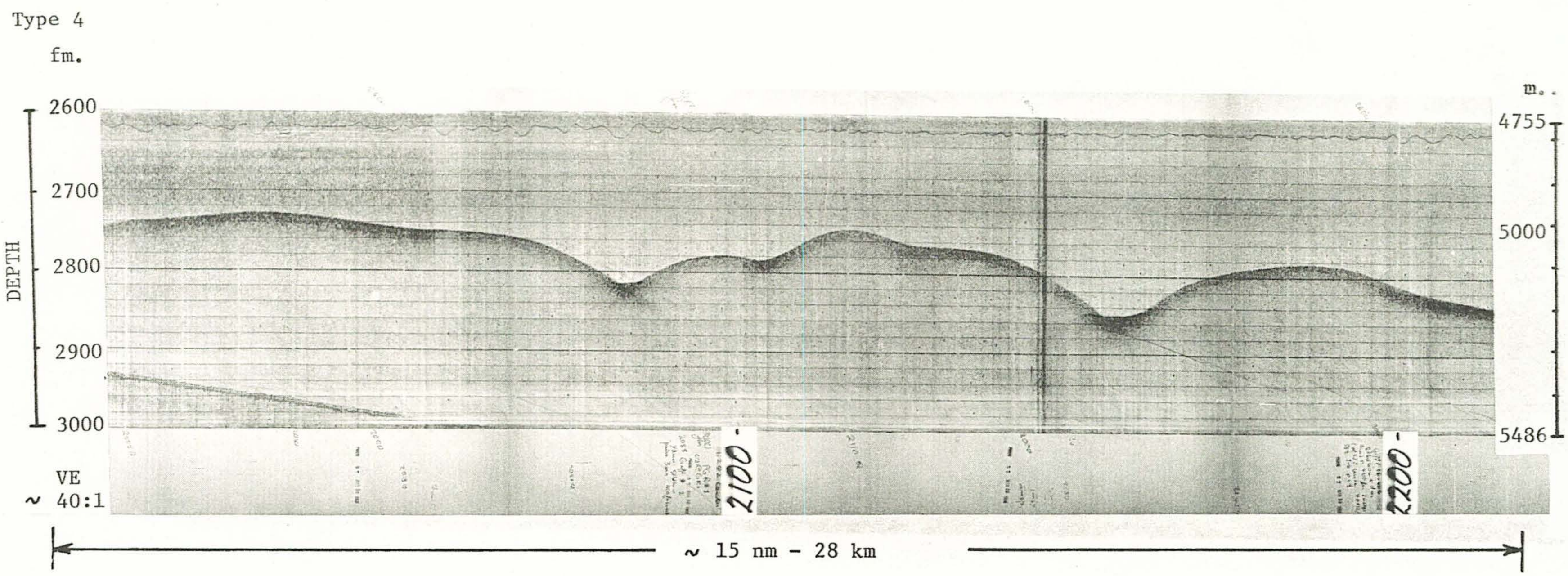


FIG. 9. Seafloor and topography both showing irregular changes; "lumpy".

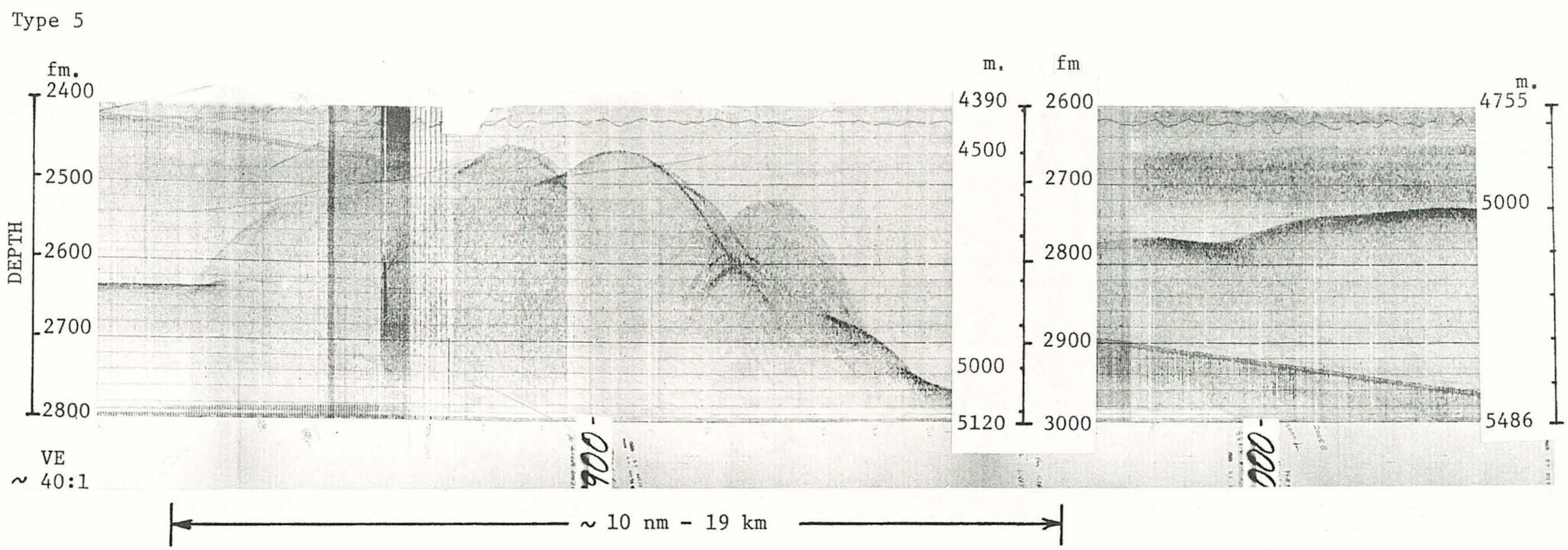


FIG. 10. Topography rough; depth changing abruptly.

HATTERAS AREA

This site, situated southeast of Cape Hatteras, North Carolina at 31-36^{o}N, 71-75^{o}W (Figs. 1, 11) has the following characteristics:

TOPOGRAPHY: (1000-5300 m depth) The region is comprised of three physiographic provinces: continental slope, continental rise and abyssal plain. Closest to land and striking roughly NNE is the slope, with an average gradient of 5^{o}. Its surface is cut by numerous submarine canyons, which are generally normal to the strike. Roughly parallel to the slope and directly adjacent is the continental rise; notably less dissected and displaying more subdued relief than the continental slope. Starting with a gradient of nearly 1^{o} at its landward edge, the rise gradually flattens (gradients are typically 1:250 to 1:750) until it merges with the Hatteras Abyssal Plain (gradients less than 1:1000) some 300-600 km from the slope (Emery, et. al., 1970). Heezen (1959) divides the continental rise province into upper (approx. 185 km wide) and lower (275 km) sections, the latter commonly displaying small mounds and low rolling hills, some of which are thought to be produced by strong bottom currents (see Fig. 11b). Occasionally submarine valleys may be found to extend across the entire rise.

SEISMICITY: There are no recorded earthquake epicenters within or in close proximity to the area.

VOLCANIC ACTIVITY: The closest active volcanoes to the Hatteras region are located in the Lesser Antilles island arc, 900 miles to the southeast. It is highly improbable that vulcanism at such a distance would seriously affect the study area; it is equally improbable that the area itself would be perturbed directly by a volcano.

DEPOSITIONAL CONDITIONS: Deposition in this region occurs largely as a result of the seaward migration of terrigenous material. Most sediments from inland sources have apparently bypassed the shelf and slope and have been carried beyond and deposited on the continental rise or abyssal plain. The resulting apron is thickest beneath the upper rise and thins seaward. It represents not only downslope transport but the concurrent accumulation of pelagic and hemipelagic matter at the base of an originally faulted continental slope (Stanley, 1970). The agents primarily responsible for this transport are

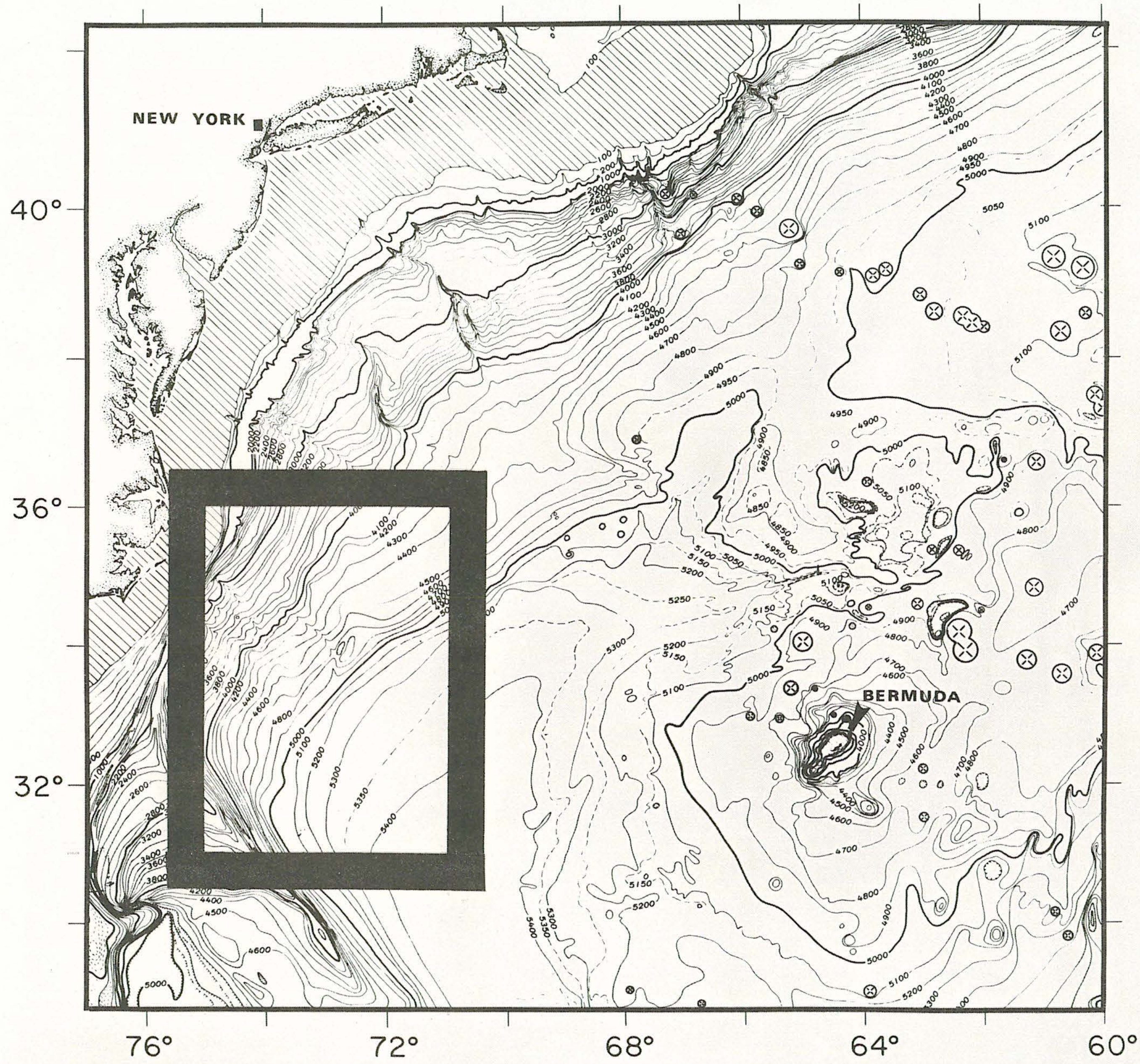


FIG. 11a. General location of proposed Hatteras Study Area. (after Pratt, 1963)

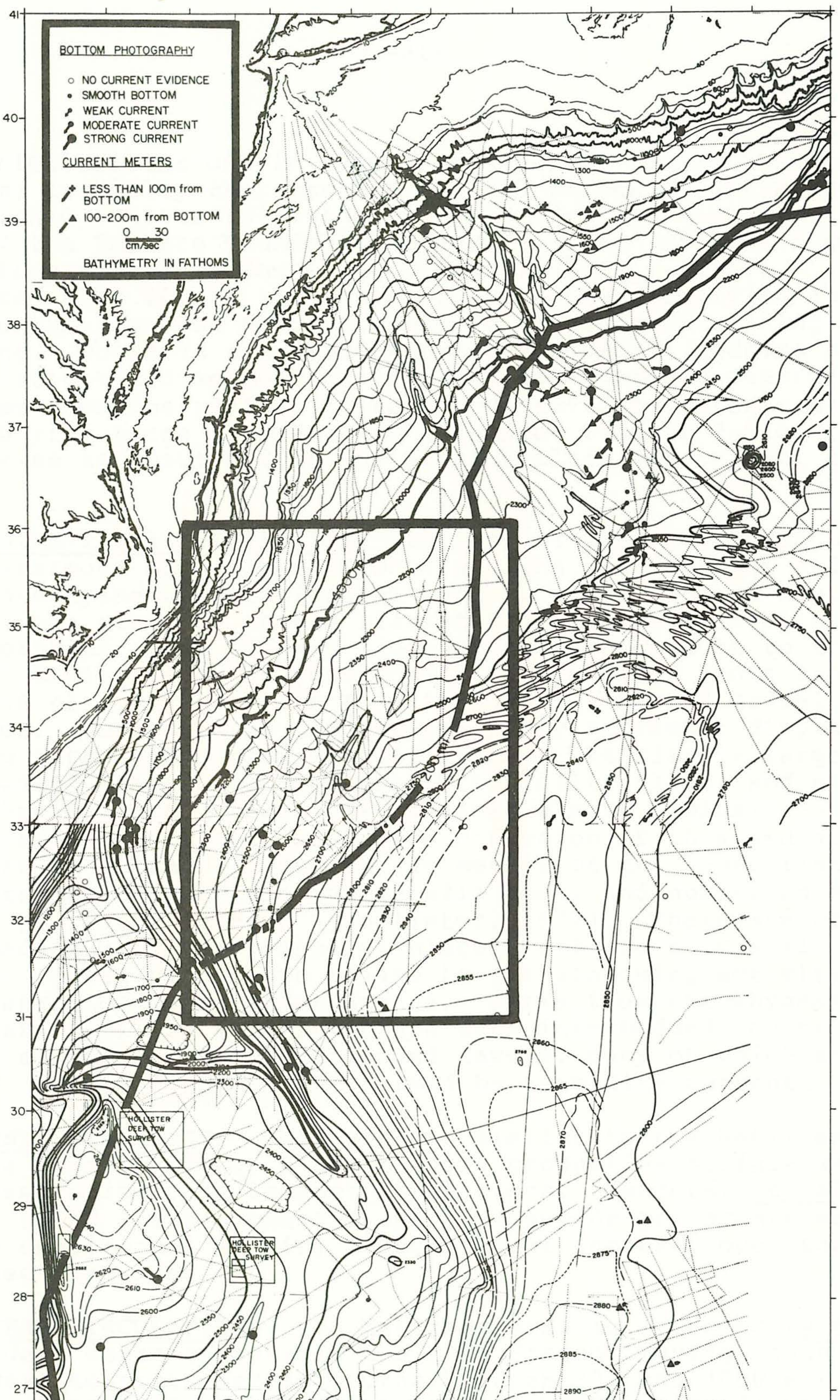


FIG. 11b. Current indications off the east coast of the U.S. from bottom current meters and photographs. Hatteras Study Area shown as box.

the periodic (last one in this area occurred during the last ice age) turbidity currents (up to 2500 cm/sec), continuous geostrophic contour-following currents (2-20 cm/sec) flowing as part of the Western Boundary Undercurrent, and massive slumps and slides that move downslope. Emery, et. al. (1970) estimated that 50% of the volume of sediment underlying the continental rise has been deformed by large scale sliding and slumping. There is a seaward convergence of all bedding planes and an abrubt sedimentologic and acoustic boundary separates the rise from the plain. Average sediment deposition rates (in cm/1000 yrs) range from 5-10 on the upper rise to 2-5 on the lower rise to about 2.0 on the abyssal plain (Emery, et. al., 1970).

SEDIMENT CHARACTERISTICS: Relict detrital (terrigenous) and calcareous biogenic sediments are the two dominant sediment types overlying the continental margin. According to Uchupi (1963), the slope is thinly blanketed by glauconitic silt and clay north of about 28° and biogenic calcareous ooze to the south. Sediments in canyons normal to the slope range from silt and clay on the walls to silty sand, sand and gravel along the axes. These coarse deposits probably represent displaced shallow water sediments (Uchupi, 1963). The rise is largely composed of homogenous fine gray-brown silty clays, and since these hemipelagic deposits are derived almost exclusively from the denudation of land, a seaward diffusion of this sediment type can be assumed. The top few meters of the lower rise are dominated by thin, clean quartz-silt beds, and number as many as ten per meter (Heezen & Hollister, 1971). These are often crossbedded with heavy mineral placers and are very well sorted. These structures relate to the winnowing activity of the Western Boundary Undercurrent. Cores from the abyssal plain are typified by brown clays with interbedded and often poorly sorted thick silt and sand layers, many of which are graded. These deposits are formed by turbidity currents.

BENTHIC BIOLOGY: This area is similar to the Antilles area in life forms present, although more productive surface water promotes an increase in most populations. Sanders, et. al. (1965) found 358 Polychaetae and 136 Isopods per square meter on the continental margin; a significant increase over the Antilles findings.

OCEAN CIRCULATION: The Hatteras area is affected by two major deep ocean currents: the Gulf Stream, moving roughly southwest to northeast in depths between 200 and 3000 meters, and the Western Boundary Undercurrent (WBUC) which flows

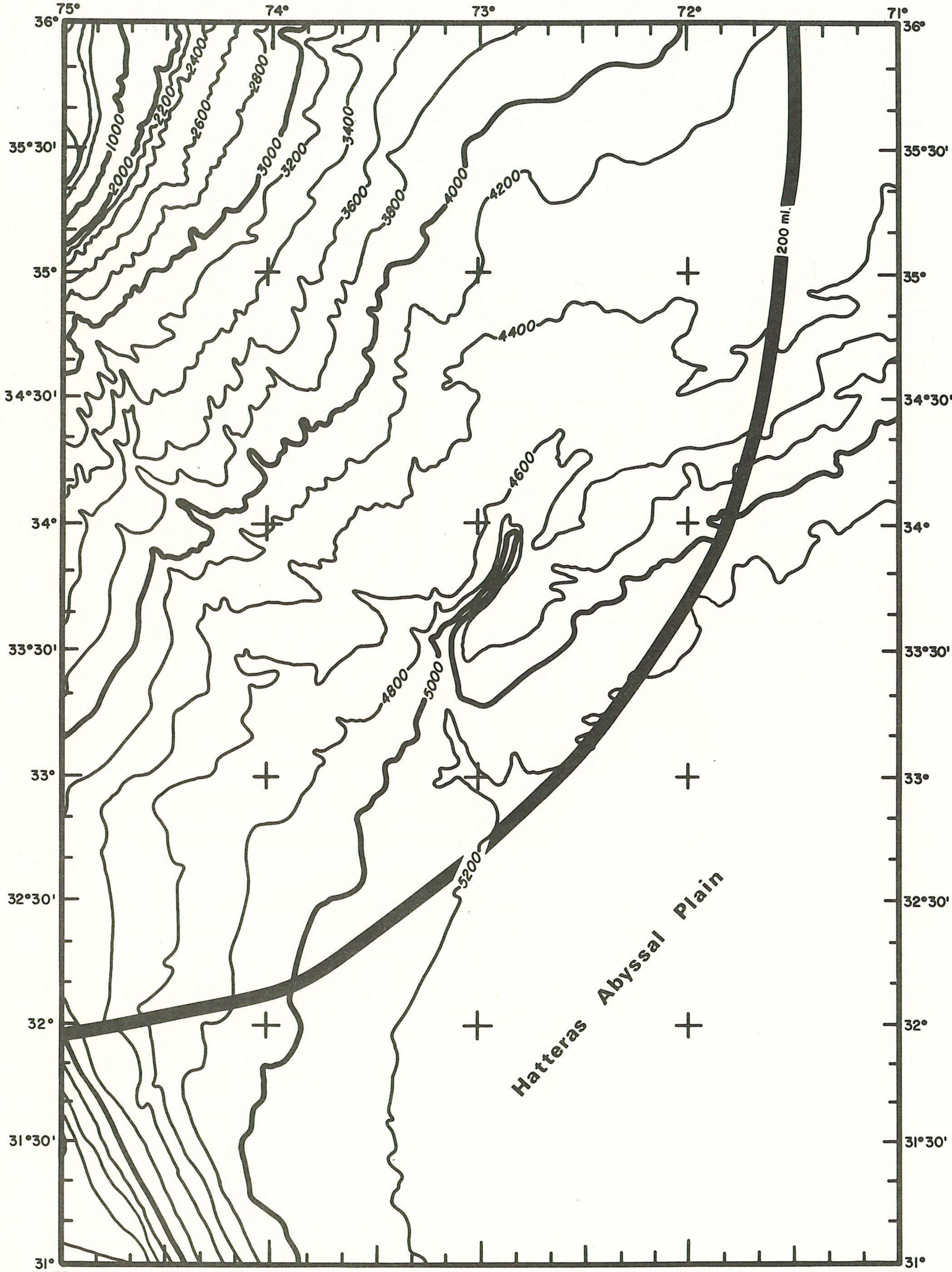


FIG. 12. Detailed bathymetry (200 m contours) of Hatteras Study Area, with 200-nautical mile limit. (after NAVOCEANO, 1977)

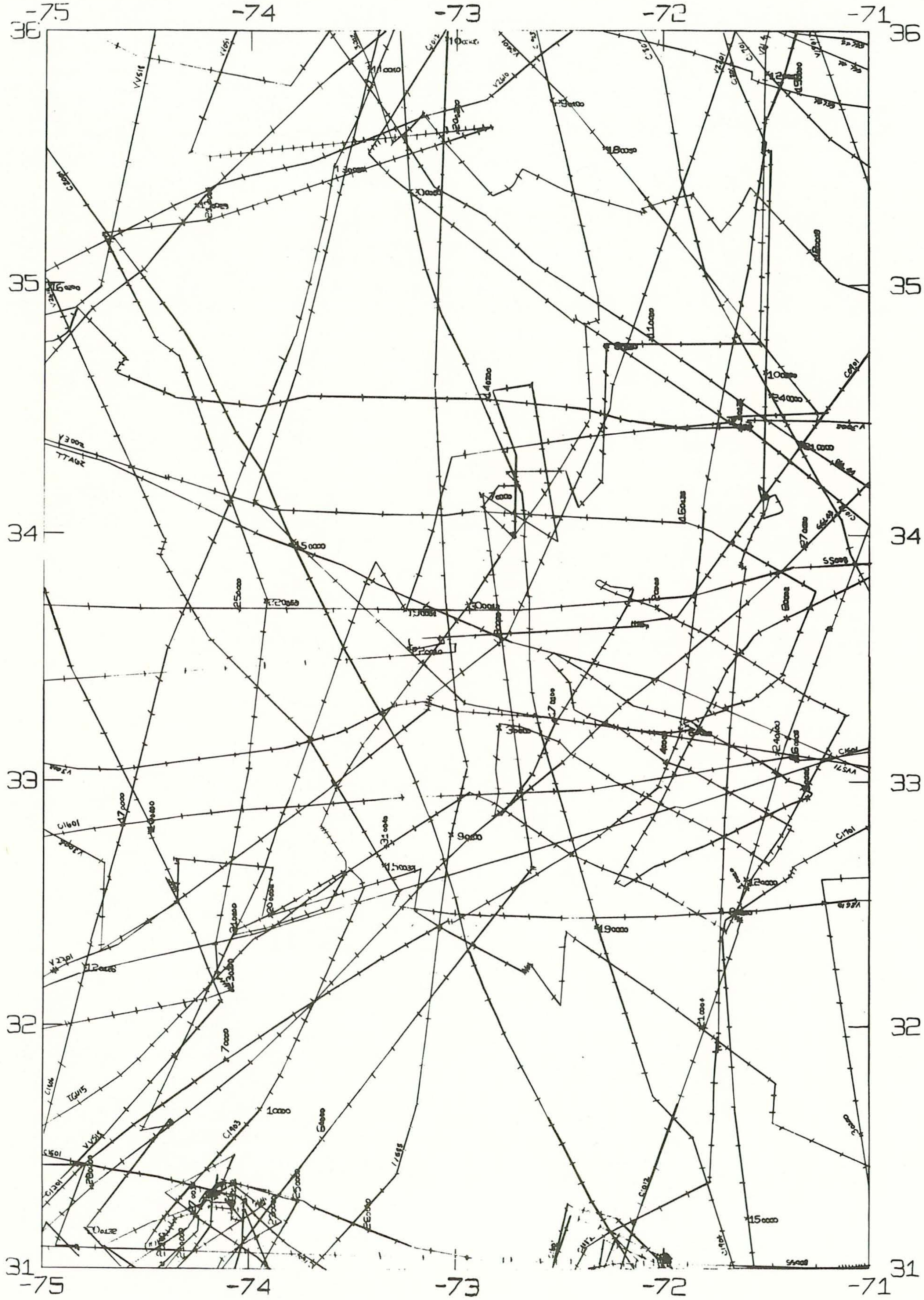


FIG. 13. Hatteras Area ship tracks studied for this report.

southward parallel to regional contours in depths over about 3500 meters. The Gulf Stream, originally thought to be solely a surface current, has been found to extend to the bottom over much of its course. Richardson and Knauss (1971) identified the average speed of the Stream's deepest 1000 meters as approximately 5 cm/sec, with localized variations evident. The WBUC, on the other hand, has a near-bottom velocity southeast of Cape Hatteras of up to 18 cm/sec, with a mean of about 10 cm/sec (Luyten, 1977). In the vicinity of 35°N, 74°30'W, the two moving water masses cross. According to Richardson (1976), the Gulf Stream narrows vertically so there is an 800-meter gap between its lower boundary and the bottom. Here the WBUC abandons its contoured path and assumes a jet-like characteristic as it flows seaward under the Stream at speeds of up to 24-44 cm/sec. It then resumes its southerly course and slower speed (about 15 cm/sec) as before, while the Stream starts out to sea to the northeast (at about 38°N). Cyclonic eddies of North Atlantic Deep Water called "cold rings" move southwestward through the area at 3 km/day; each has a diameter of 50 km and a depth of at least 4000 meters (in all probability they extend to the bottom). Lai and Richardson (1977) estimate that two eddies move through this particular area each year, and these could easily disturb or interrupt sediment deposition.

The WBUC (with some additional Antarctic Bottom Water) is clearly the most active of all near bottom current systems in this area, but very little quantitative work has been done toward defining its effects. Although velocity calculations consistently show a southwestward flow, the lack of data makes an accurate estimate of its effects difficult to determine. Swallow and Worthington (1961) calculated a $3\text{-}7 \times 10^6$ m^3/sec transport volume off Cape Hatteras, but there have been no verifying studies undertaken. Long term (several months) near-bottom current measurements at closely spaced intervals are essential to the prediction of flow velocity in this area.

<u>CABLE ROUTES</u>: To the best of our knowledge no commercial undersea cables pass through the study area; however certain Navy cables are thought to traverse at least the shallower areas of this region.

<u>DETAILED TOPOGRAPHIC ANALYSIS</u>-Hatteras Area: About 2900 km of track were examined in this area, the records being about equally divided between 3.5 kHz sub-bottom profiles and 12 kHz

precision echograms. Other data are available, but the preponderance of one type of topography would indicate that a further examination should be of small sub-areas identified by this study in preparation for subsequent cruises.

The majority of tracks generally run parallel to the slope/rise boundary, crossing contours at relatively low angles. This might be construed as the reason for the observation that the major topography is gently rolling to slightly rough (Types 2, 3) except that the tracks running perpendicular to contours show the same pattern. There is very little smooth, flat seafloor within the 200 mile line.

Another pertinent point is the appearance of stratified sediments over large portions of the tracks. Where not obviously stratified there is 'lumpy' topography (hyperbolic echoes) which is evidence for erosion of the strata by current action.

The illustration for Type 1 has been omitted since it is identical to the Antilles Type 1.

Discussion

The Hatteras Area is the deepest area within 200 miles of the east coast of the U.S. Depending on which set of contours used, the continental rise-abyssal plain boundary lies very close to a 200 mile limit near an R/V EASTWARD camera station taken at 33°N and 72°30'W (water depth about 5200 m). The importance of the rise-plain boundary is based on the need to avoid the circulating effects of strong bottom currents. As far as we can tell the rise is swept by bottom currents strong enough to resuspend sediment and the plain is tranquil. This inference is principally based on bottom photographs (Heezen and Hollister, 1971). However, there is not sufficient data to delineate exactly where the current-swept-tranquil boundary lies with respect to the precise contact of the continental rise and abyssal plain. A detailed topographic and bottom photographic survey using normal oceanographic ship capabilities (e.g. not multibeam swath mapping) could rapidly delineate the topographic plain-rise boundary as well as the hydrographic boundary between the current-swept areas and the tranquil region. It is quite conceivable that there is an area that is both flat (i.e. abyssal plain with gradients of less than 1:1000) and tranquil and of a size large enough for disposal operations. However, the lack of data and the closeness of these various boundaries simply require a dedicated field effort for verification.

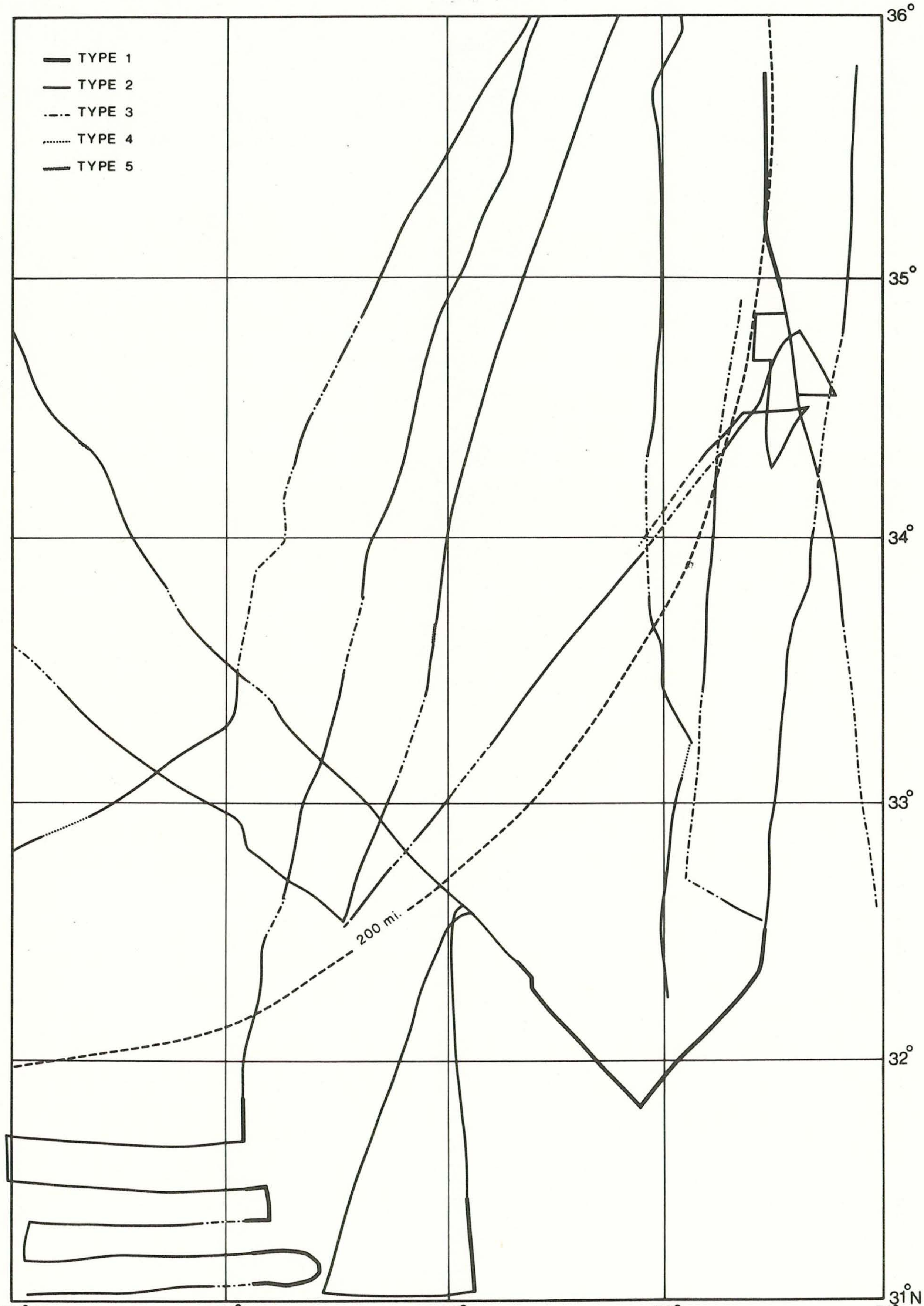


FIG. 14. Chart showing Hatteras ship tracks. Patterns indicate seafloor (topographic) character; their numbers refer to the accompanying photographs.

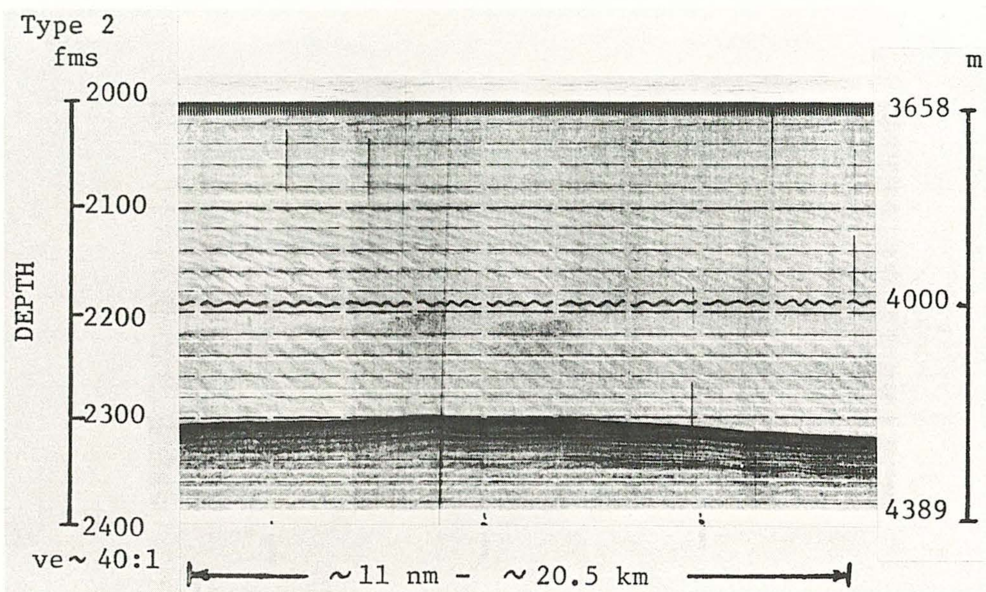


FIG. 15. Seafloor generally smooth; gently rolling topography. Sometimes stratified. See also left side of Type 5.

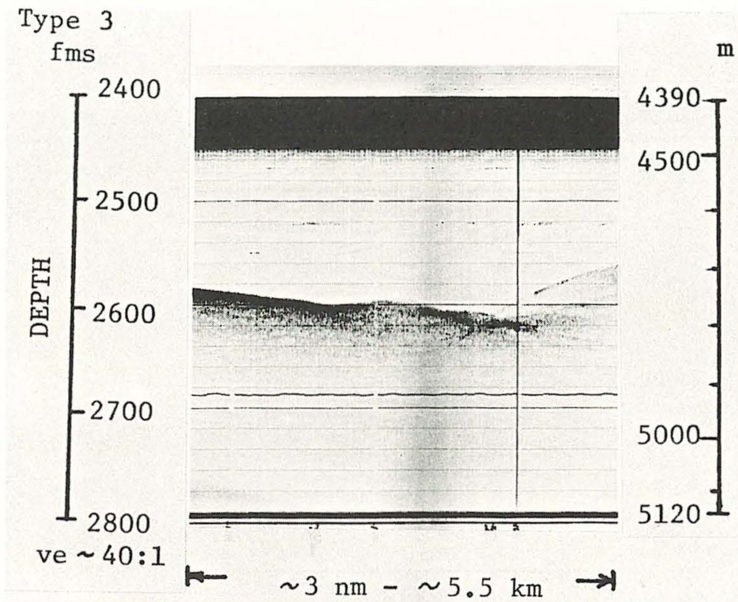


FIG. 16. Seafloor and topography both more irregular than Type 2; hyperbolic echoes. Some stratification.

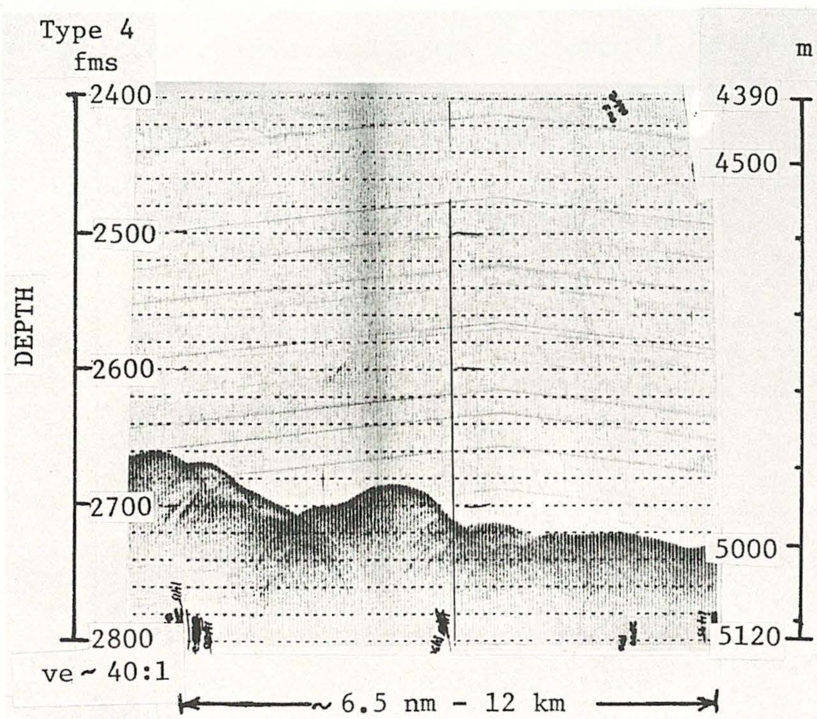


FIG. 17. Structure relatively rough; hyperbolic echoes.

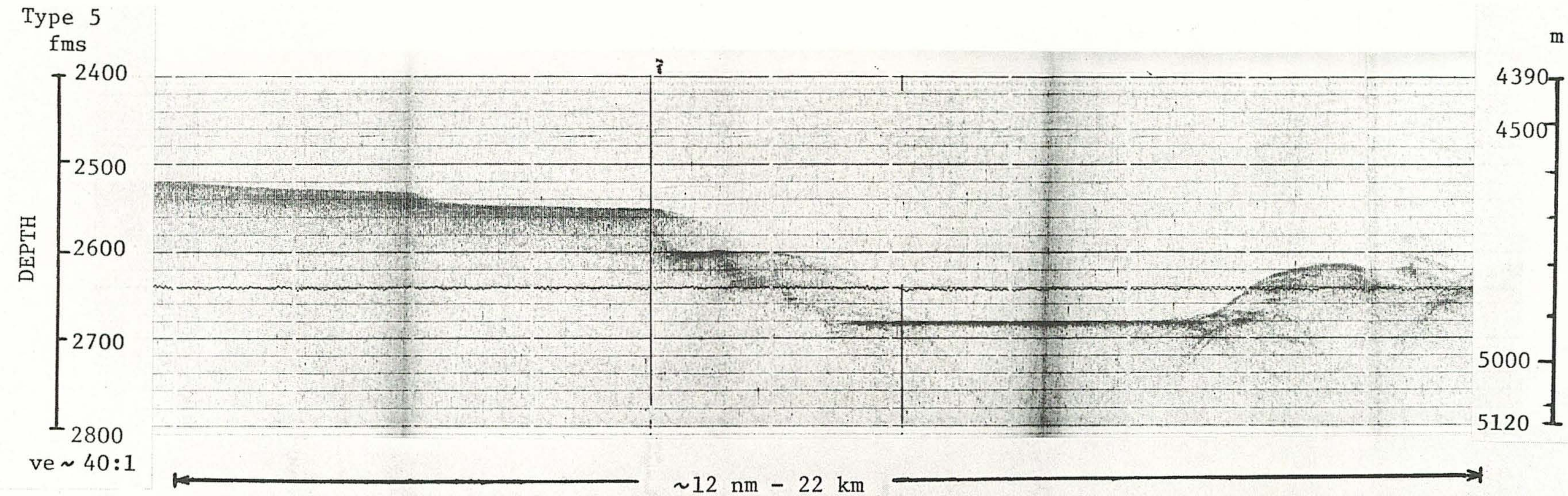


FIG. 18. Canyon structure. Note differing character of side walls: left as Type 2, right as Types 3,4. Floor of canyon is flat, smooth.

Recommendations

1) Obtain precise 200 mile economic zone boundary as determined by the U.S. Dept. of State for the area.

2) Mount a 2-3 week (in area) cruise (starting at 33°N, 72° 30'W and extending, like a spiral, from this point) on a research vessel that is equipped with precision echo sounder (12-16 kHz), a 3.5 kHz sub-bottom profiler, precise navigation (e.g. Loran C and Satellite), and a bottom bounce, low-angle oblique deep-sea (and very close-up) camera system.

3) Determine the precise boundary of the abyssal plain and continental rise with 12 and 3.5 kHz systems. This task would probably require about 30 to 50 crossings of the boundary extending from about 32°N to about 34°N.

4) Determine precise boundary of the tranquil vs. the current-swept areas with a close-up (the water may contain high concentrations of suspensates) bottom camera. This task could be done with 50 to 75 camera stations transecting the rise-plain boundary.

5) Establish where the sub-areas are that fit the criteria and then, on a separate cruise, deploy a navigational net of transponders and sample, with a large diameter gravity core, the substrate in order to determine texture, mineralogy, and geotechnical properties that pertain to the dumping operation.

6) This latter effort should be combined with a CTD profiler and current meter deployment that would establish the thickness and variability of the bottom mixed layer and the mean velocity through the area.

7) The above data could then be fed into the "oceanographic model" for determination of rates and flow direction likely to occur from a point source.

8) A biological/biomass determination should be done at some point prior to site selection in order to establish the unperturbed "background" census. However, it is important to keep in mind that the presence of the waste objects themselves will perturb the environment. Any biological modeling using the "background" can lead to false conclusions concerning biological aspects of that part of the pathway closest to the source; examples of these conclusions include a) acceptable radiation effects on biota and b) acceptable hazard to man.

APPENDIX A

IAEA Site Suitability Criteria

From INFCIRC/205/Add. 1/Rev. 1, dated August 1978, as modified by C. Hollister, C. Detrick and R. Heath. References are to the IAEA submission to the London dumping convention.

1. Sites should be between 50° North and 50° South latitude.
   This criterion is designed to avoid the sources of bottom water and the high biological productivity of the polar regions. Ice rafting is also a concern in the polar areas. (Section C. 2.1.(2))

2. Depth at the site should be 4000 meters or greater.
   This criterion is derived from the fact that the topographical, chemical, and biological gradients tend to flatten below 4000 m, bottom water circulation is slower and organic carbon in the sediment generally is low. This criterion is also motivated by the desire to be clear of continental margins.

3. Sites should be remote from continental margins.
   This criterion is based on avoiding the regions of high biological productivity, increased likelihood of resource exploration and exploitation and greater unpredictability and instability associated with the continental slope, rise, and associated alluvial fans. (Section C. 2.1.(3))

4. Sites should be away from areas of potential seabed resources.
   This criterion is designed to minimize the likelihood of future disturbances which might shorten pathways to man and to avoid possible conflicts in "land" uses. (Section C. 2.1. (5))

5. Sites should be away from cables in use.
   This criterion is intended to avoid disturbances and conflicts in uses. (Section C. 2.1. (4))

6. Sites should be away from areas containing active geologic phenomena such as volcanoes, which would be unsuitable.
   This criterion is designed to reduce the likelihood of unpredicted disturbances which might shorten pathways to man. (Section C. 2.1. (3))

7. The area of a site should be defined by precise coordinates, with an area as small as practicable, but no larger than $10^4 km^2$.

   This criterion appears to be motivated by a desire to limit the affected area. (Section C. 2.2)

8. Sites should preferably be in areas covered by navigational aids.

   This criterion is intended to assist in location of the sites for monitoring and future observation or research. (Section C. 2.1. (7))

9. Sites should be away from areas, such as submarine canyons, which have a high rate of exchange of the deep waters with surface layers of any adjacent continental shelf.

   This criterion is intended to avoid shortening of pathways to man. (Section 2.8.3 of Appendix)

10. Sites should be chosen for convenient conduct of operations and to avoid, so far as possible, the risk of collision with other traffic and undue navigational difficulties.

    This criterion is specified to minimize hazards to navigation and safe operations at the site. (Section C. 2.1. (7)).

11. Bottom current shear stress should not exceed critical erosional shear stress.

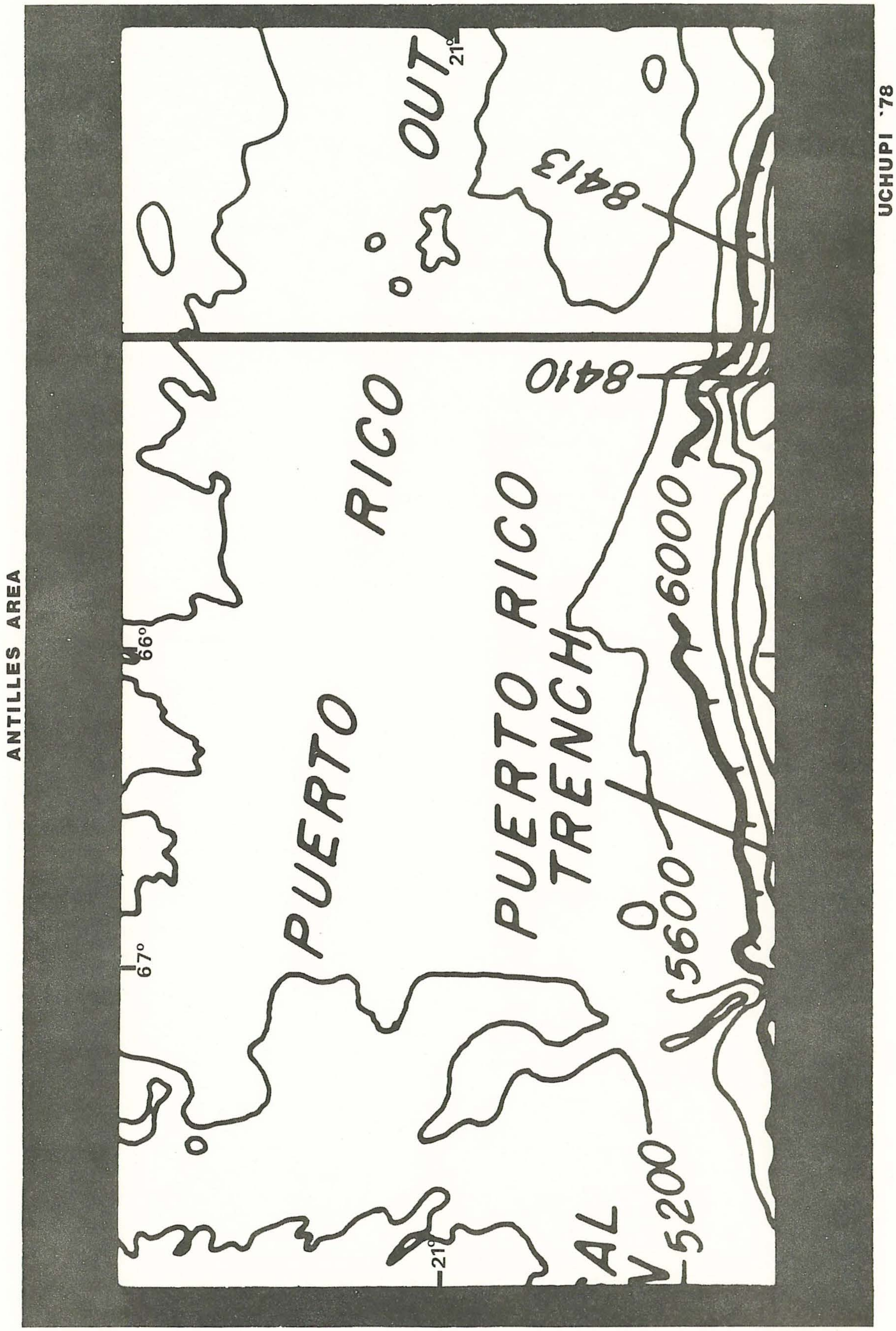
    This is desired to prevent high rates of resuspension of sediments at the site and so to prevent rapid movement of material.

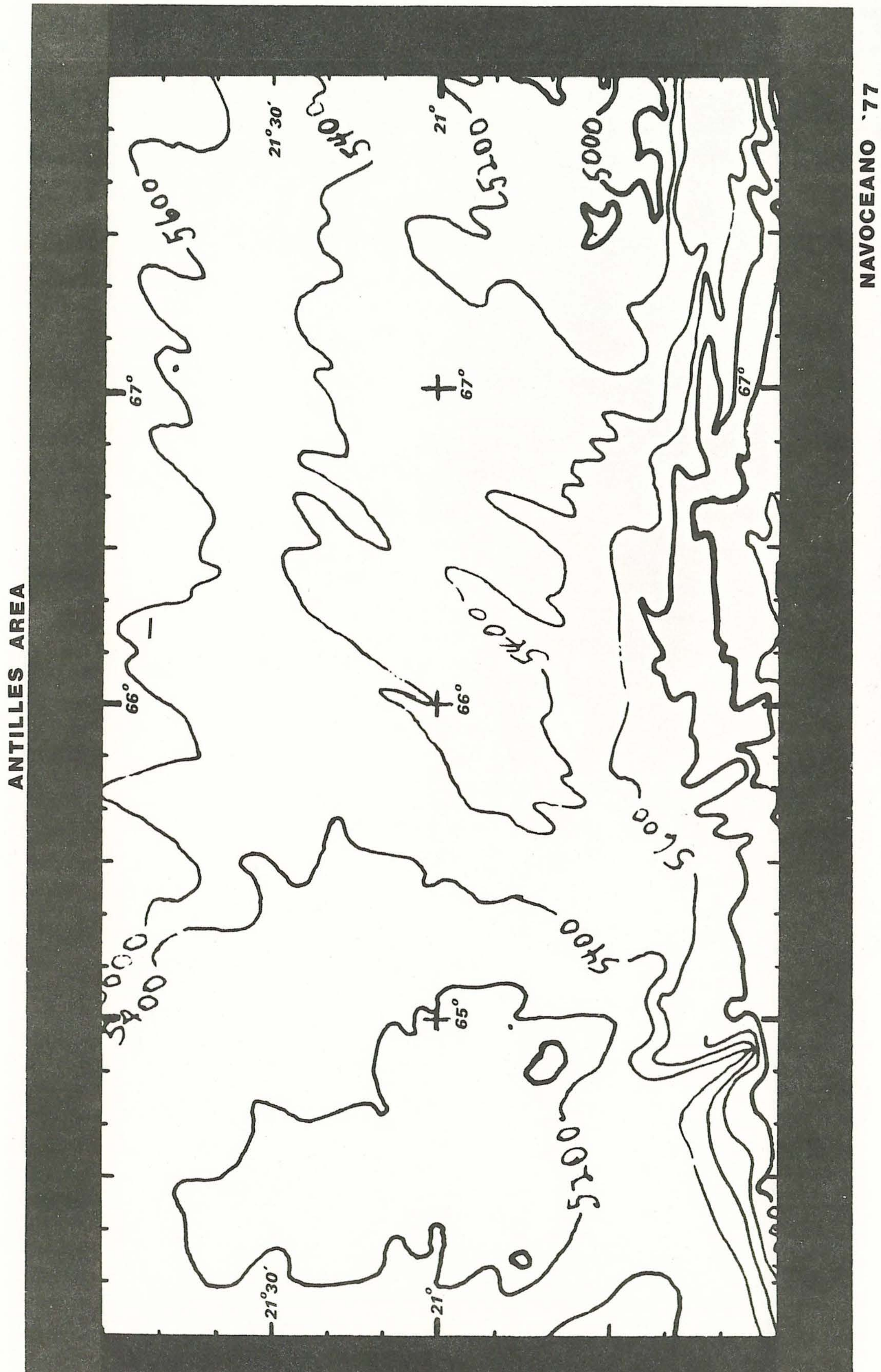
12. Sites should be away from areas of intense mesoscale eddy activity.

    This is intended to avoid areas of enhanced eddy diffusivity which could shorten pathways to man.

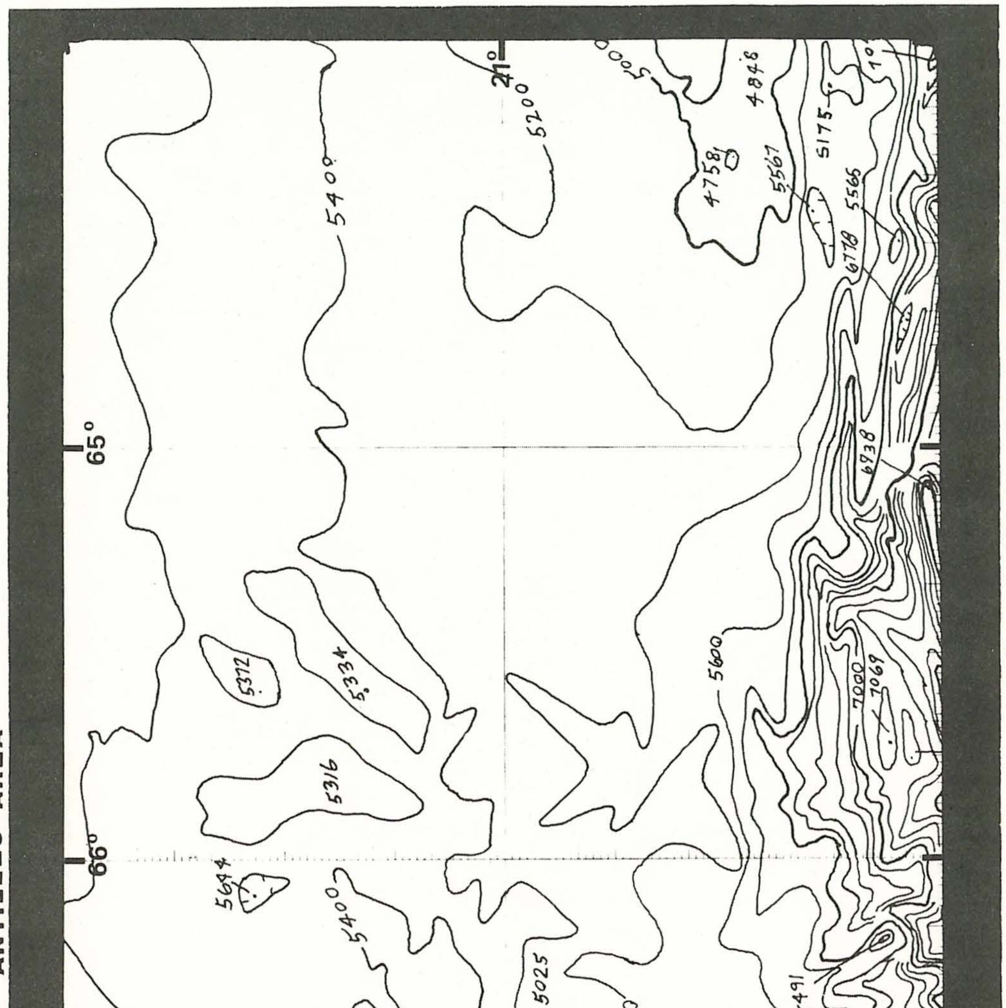
APPENDIX B

The following figures are additional examples of bathymetric contour charts for the proposed study areas. The purpose of reproducing these is to illustrate the wide diversity of interpretations as to what the regional topography is. The only way to resolve the issue as to precise topography, a critical factor in site selection, is to perform a precisely navigated swath map exercise using narrow, high-frequency multibeam sonars such as the SEABEAM or SASS. See Appendix C for illustrations of scales of features vs. systems that can be used for their identification.

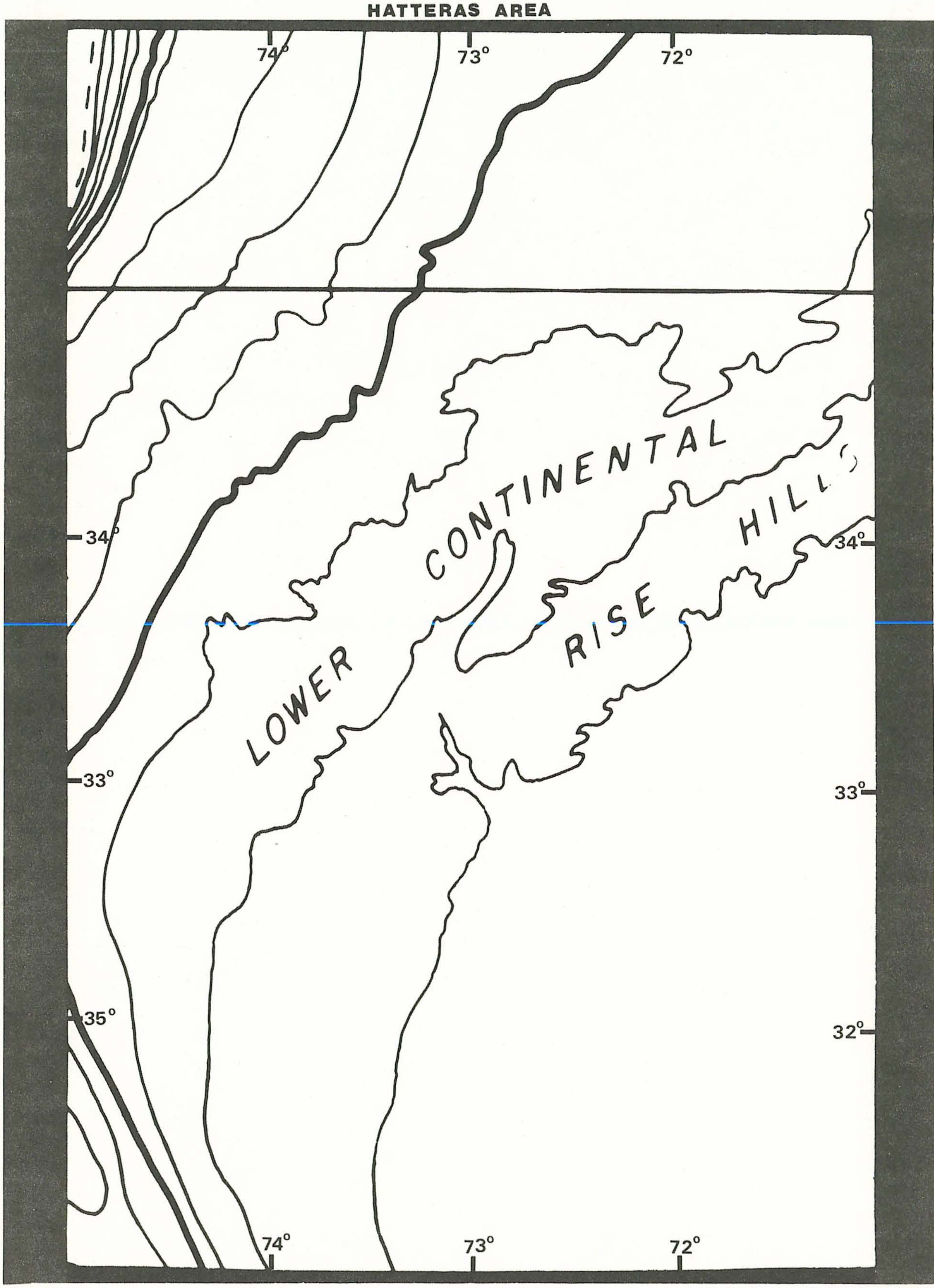

ANTILLES AREA
UCHUPI '78
PUERTO RICO
PUERTO RICO TRENCH
OUT
8413
8410
6000
5600
5200
AL
66°
67°
21°
21°


ANTILLES AREA
NAVOCEANO '77
21°30'
21°
67°
66°
65°
5600
5400
5200
5000
5100

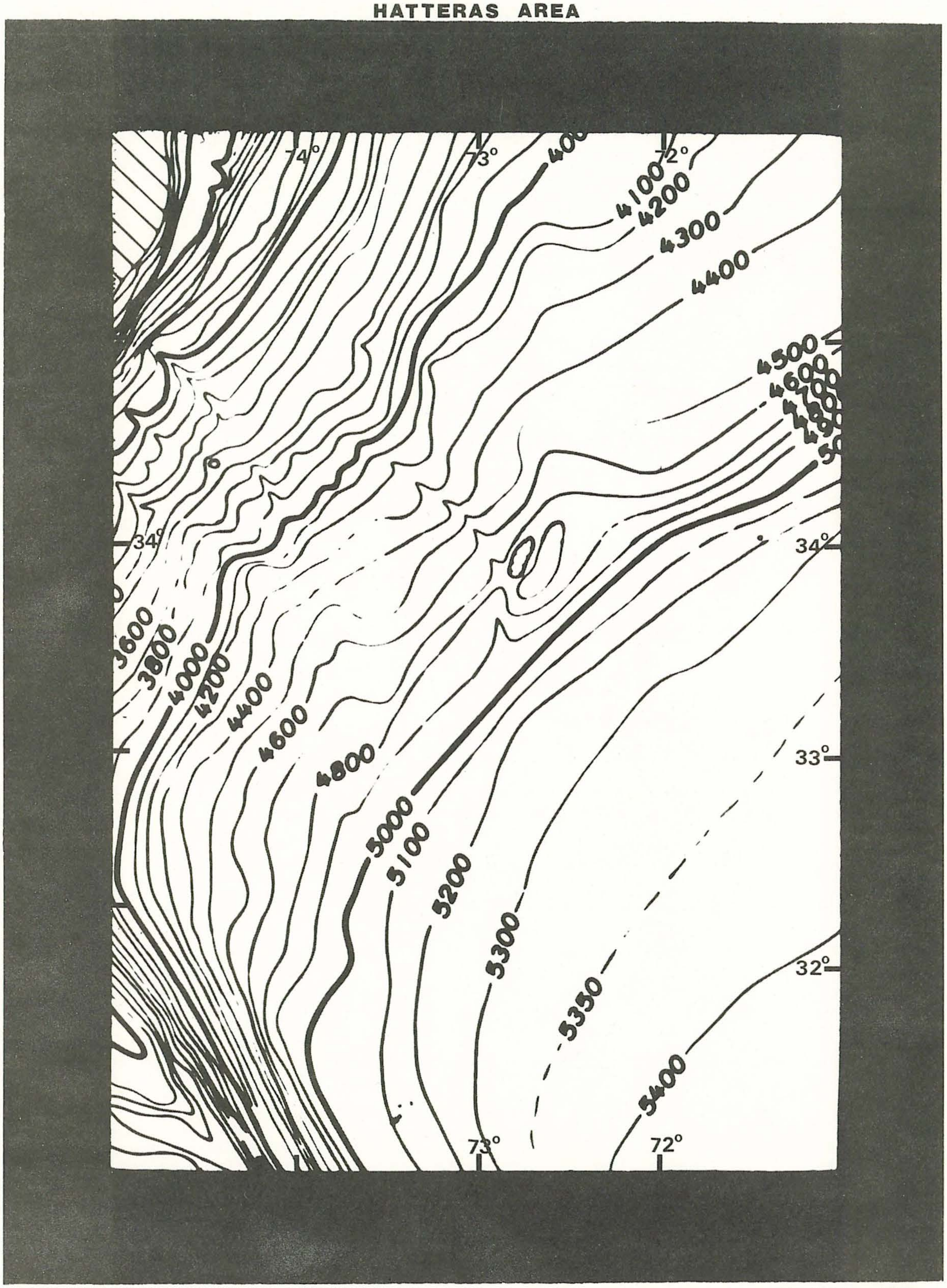
ANTILLES AREA



USGS '75

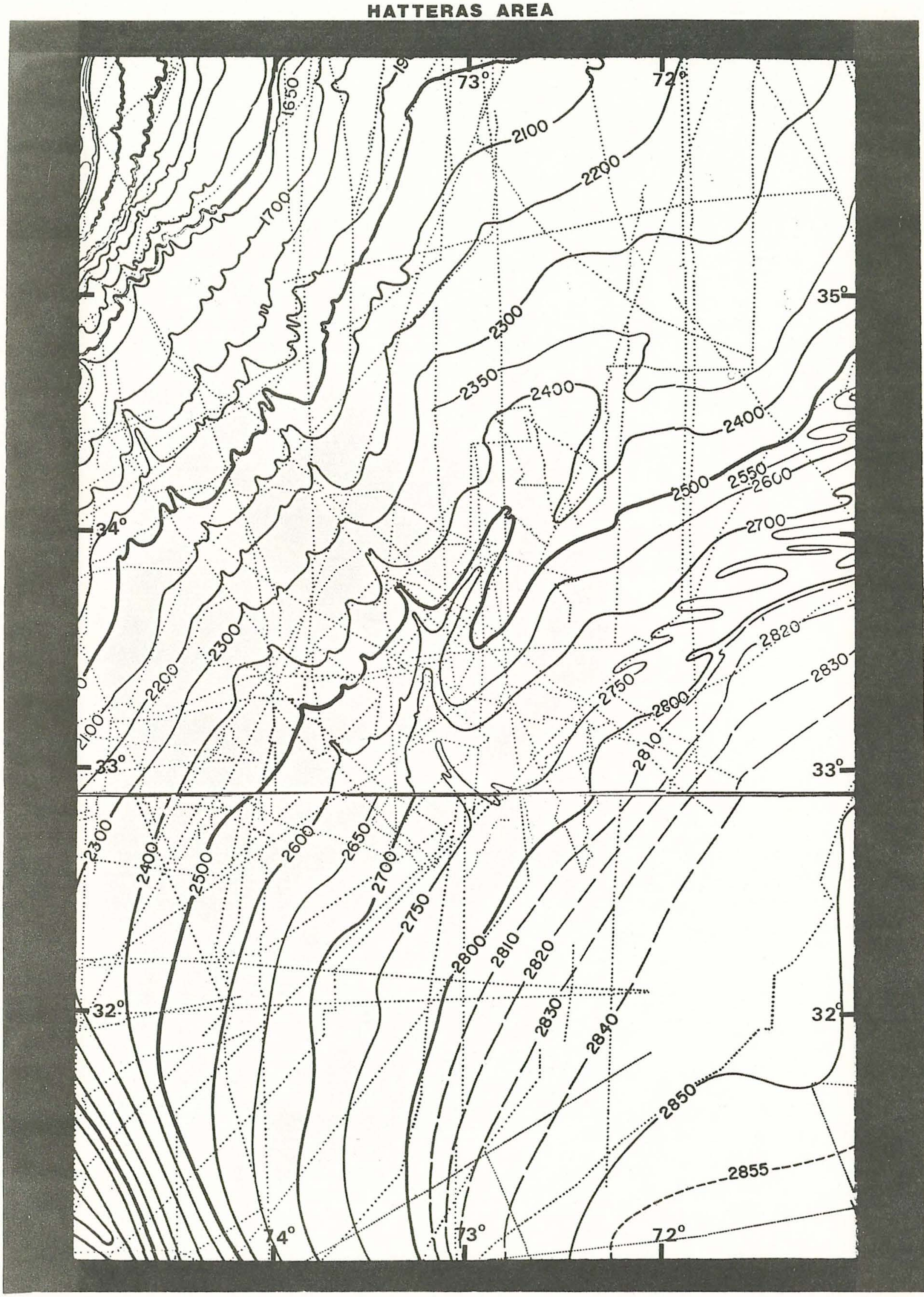

HATTERAS AREA
74°
73°
72°
UCHUPI '78
34°
33°
35°
34°
33°
32°
LOWER CONTINENTAL RISE HILLS
74°
73°
72°

HATTERAS AREA



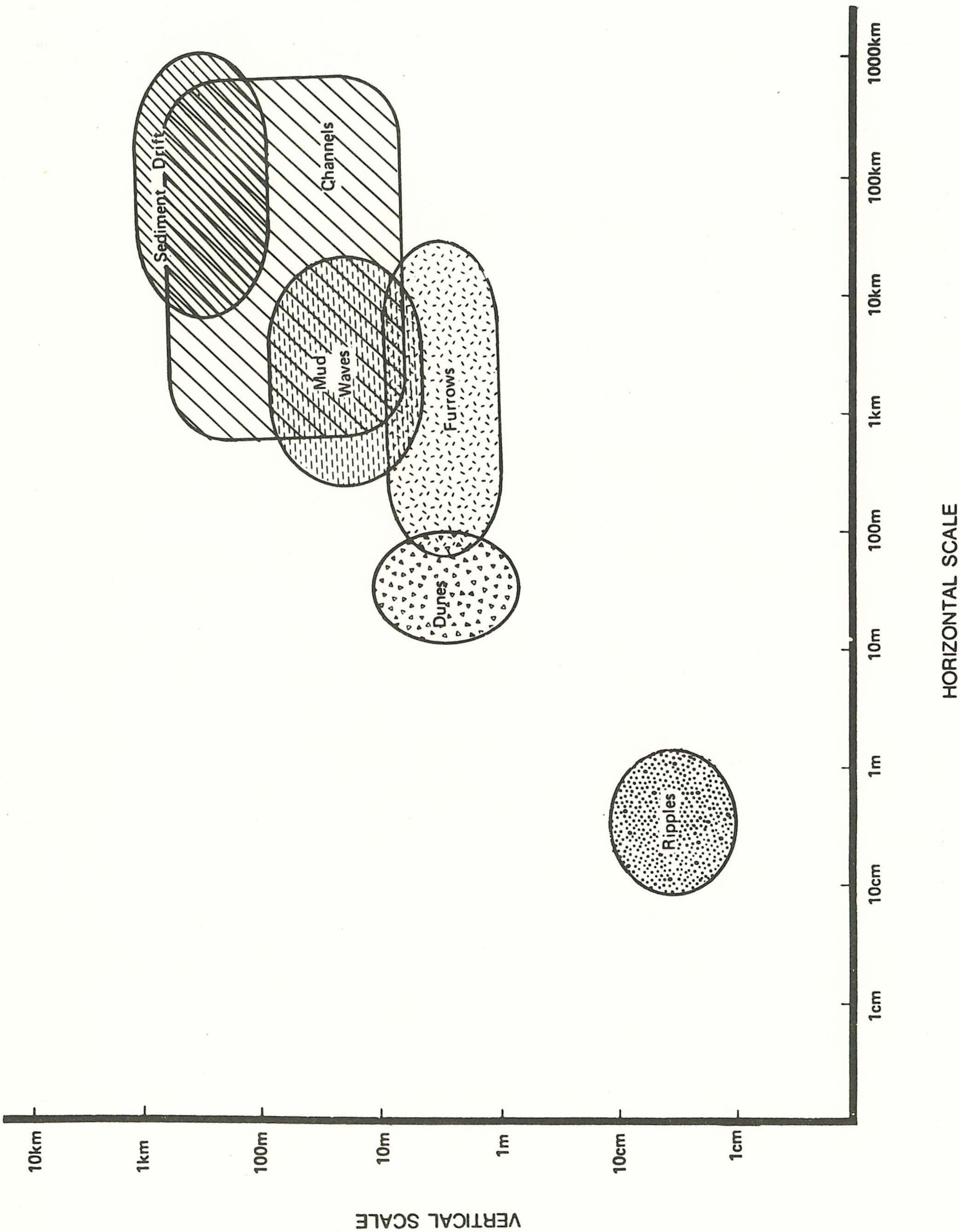
PRATT `63

HATTERAS AREA

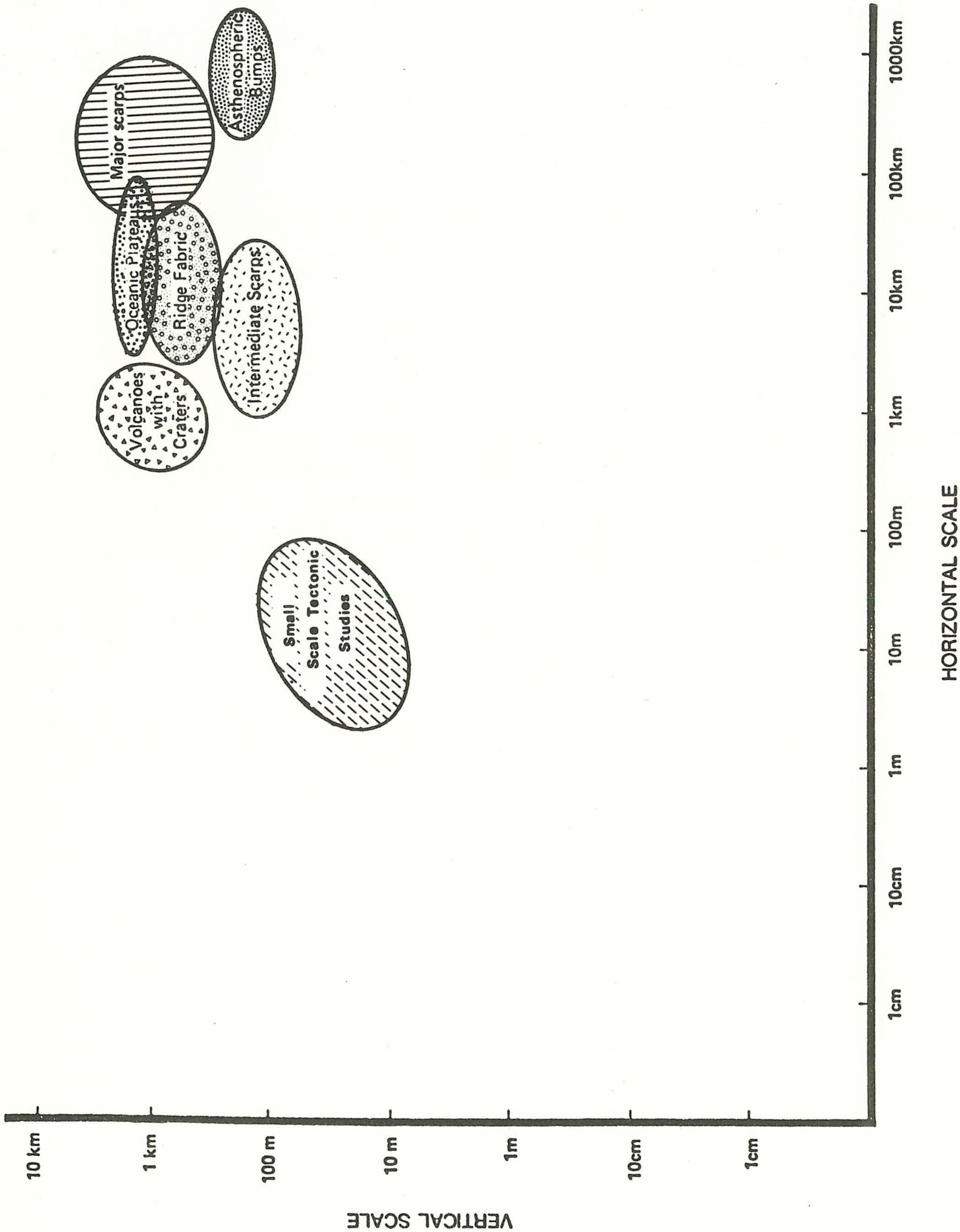


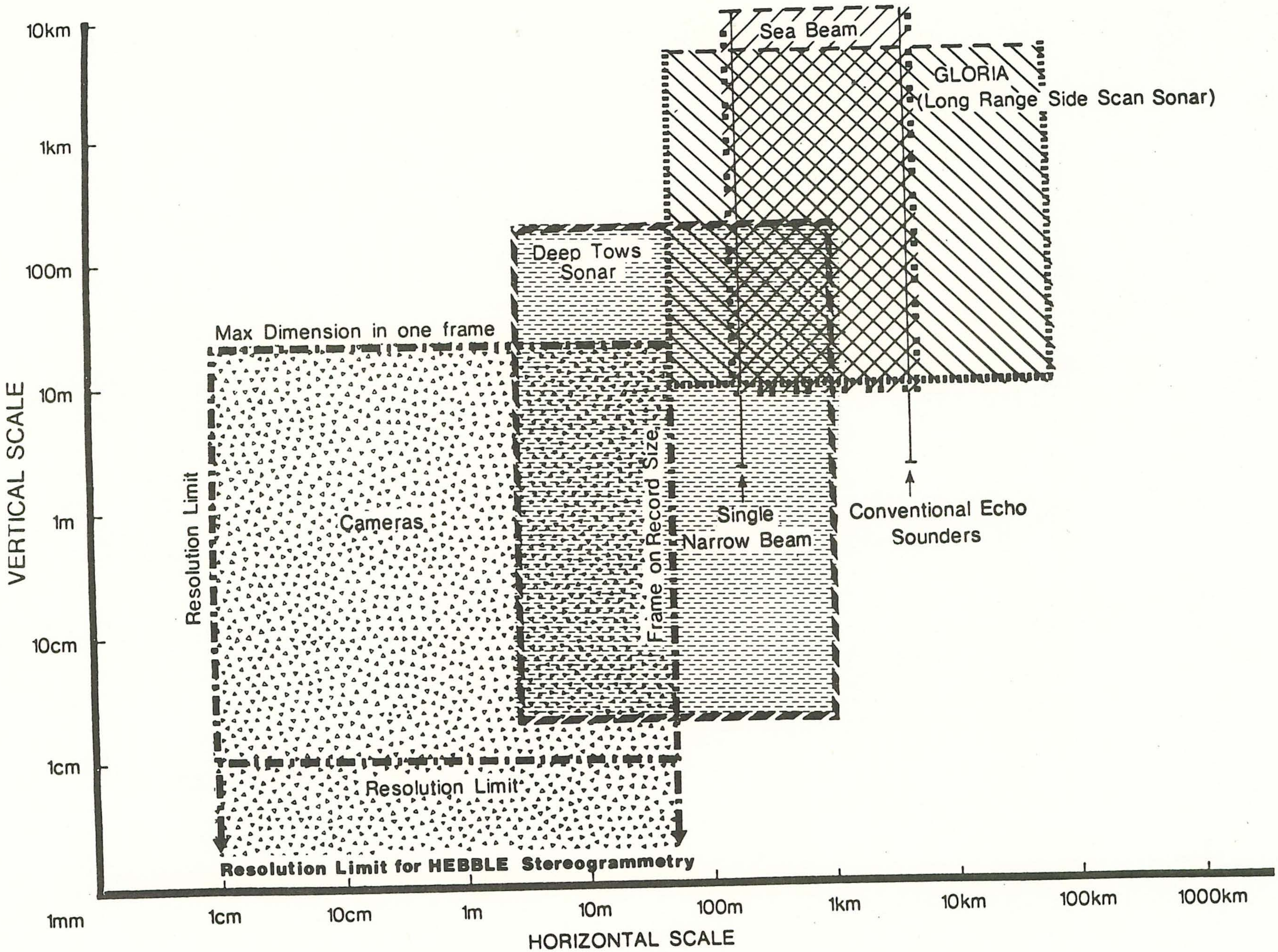
APPENDIX C

Illustrations of scales of some ocean bottom features and the systems that have to be employed for their identification.



Sediment Drift
Channels
Mud Waves
Furrows
Dunes
Ripples
HORIZONTAL SCALE
1cm
10cm
1m
10m
100m
1km
10km
100km
1000km
VERTICAL SCALE
10km
1km
100m
10m
1m
10cm
1cm


Major scarps
Asthenospheric Bumps
Oceanic Plateaus
Ridge Fabric
Intermediate Scarps
Volcanoes with Craters
Small Scale Tectonic Studies
1cm
10cm
1m
10m
100m
1km
10km
100km
1000km
HORIZONTAL SCALE
10 km
1 km
100 m
10 m
1m
10cm
1cm
VERTICAL SCALE


Sea Beam
GLORIA
(Long Range Side Scan Sonar)
Deep Tows
Sonar
Max Dimension in one frame
Cameras
Resolution Limit
Frame on Record Size
Single
Narrow Beam
Conventional Echo
Sounders
Resolution Limit
Resolution Limit for HEBBLE Stereogrammetry
VERTICAL SCALE
10km
1km
100m
10m
1m
10cm
1cm
1mm
1cm
10cm
1m
10m
100m
1km
10km
100km
1000km
HORIZONTAL SCALE

Acknowledgements

The authors wish to thank Heidi Hilgartner for her assistance in preparing the benthic biology sections of this report. We also thank Mary Berry and Cynthia Brown who have good naturedly typed and edited the draft, plus Pamela Hindley and Helen Hays for their drafting work.

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BIBLIOGRAPHIC DATA SHEET	1. Report No. WHOI-79-82	2.	3. Recipient's Accession No.
4. Title and Subtitle IDENTIFICATION OF GENERIC STUDY AREAS FOR THE DISPOSAL OF LOW LEVEL RADIOACTIVE WASTE: WESTERN NORTH ATLANTIC OCEAN			5. Report Date July 1979
			6.
7. Author(s) Charles D. Hollister, Elizabeth T. Bunce and Richard Chandler			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Woods Hole Oceanographic Institution Woods Hole, MA 02543			10. Project/Task/Work Unit No.
			11. Contract/Grant No.
12. Sponsoring Organization Name and Address Sandia Laboratories			13. Type of Report & Period Covered Technical
			14.

15. Supplementary Notes

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17. Key Words and Document Analysis. 17a. Descriptors

1. Radioactive waste
2. Ocean disposal
3. Low level

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 48
	20. Security Class (This Page UNCLASSIFIED	22. Price

FORM NTIS-35 (REV. 3-72) USCOMM-DC 14952-P72

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