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SEDIMENTARY PROCESSES ON THE CONTINENTAL SLOPE OFF NEW ENGLAND

By

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Joseph MacIlvaine

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ABSTRACT

A detailed study of a small (5000 km^2) area of the continental slope south of Cape Cod, Massachusetts, was conducted. Bathymetry, 3.5 kHz profiles, seismic profiles, suspended sediment analysis, bottom photographs, television, laboratory flume experiments, studies of surface sediments, and piston cores were combined to form the basis for understanding the sedimentary processes which control transportation, deposition, and erosion of sediments, and the geomorphic features of the continental slope.

Gravitational processes (slumping, creep, and turbidity currents) are apparently the most effective erosional processes on the continental slope. Massive large-scale failure occurs where the slope steepens from a gradient of 1.5° to 7.6°, producing scarps hundreds of meters in height. Upslope propagation of slumping on the upper continental slope has formed steep-sided gullies with layers of disturbed residual material and hummocky floors. On the steep lower continental slope small slump scars on the order of 100 m in horizontal extent and several meters high are common. Material removed by slumping is emplaced at the foot of the continental slope as intact and disrupted blocks 1 to 100 m thick. Turbidity currents generated by slumping have apparently eroded V-shaped gullies in the lower continental slope.

Bottom currents are most influential at the shelf-break, where they produce sorting of surface sediments and suspension of fine material by erosion of the bottom. Internal waves may be a significant source of high velocity bottom currents and turbulence. Laboratory flume experiments and observation of the bottom indicate that the

sediments of most of the continental slope are not normally affected by bottom currents. Sediments at the foot of the continental slope on the upper continental rise are reworked by bottom currents.

Biological activity causes both roughening and smoothing of the sediment surface. Tracking of the bottom produces small-scale roughness, and reworking of the bottom reduces larger roughness elements. Biological production of fibrous structures helps render the sediment surface extremely resistant to erosion by bottom currents. Biological erosion of rock outcrops produces rubble slopes locally at the bases of scarps.

Conditions have varied markedly during the Pleistocene and Holocene. During glacial periods rapid deposition increased the activity of gravitational processes, while during interglacial periods of slow deposition biological and hydrodynamic processes became relatively more important.

ACKNOWLEDGEMENTS

This study was made possible by the unselfish help of many individuals. In particular I thank Dr. D.A. Ross for his continuous support and guidance. Drs. K.O. Emery and J.B. Southard served on my thesis committee, and added valuable insights. Dr. G.T. Rowe was especially helpful in providing me with the chance to dive on the continental slope in DSRV ALVIN.

The success of this study was in large part due to the efforts of the officers and crews of the research vessels GOSNOLD, ATLANTIS II, LULU, and ALCOA SEAPROBE, and the many individuals who participated on the cruises to the study area. In particular, Dr. D.A. Ross directed operations on ATLANTIS II cruise 72, and Mr. Scott Briggs aided in suspended sediment analysis.

This work was supported through several grants to the Woods Hole Oceanographic Institution. The Union Oil Company of California Foundation supported my first three years as a graduate student, and my last year, plus ship and laboratory expenses were supported by the Office of Naval Research contract CO-N-00014-66-0241. Ocean Search Incorporated supplied ship time for two cruises on the

ALCOA SEAPROBE, and the Ocean Industries Program of the Woods Hole Oceanographic Institution provided funds for shipboard operations on these cruises.

Drs. D.A. Ross, J.B. Southard, and K.O. Emery read the manuscript and made valuable suggestions for improvements.

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CHAPTER I

INTRODUCTION

STATEMENT OF THE PROBLEM

Two basic incentives towards understanding the sedimentary environment of the continental slope are: 1) The slope is a major physiographic feature of the ocean floor, and may be characterized by a combination of sedimentary processes unlike that of any other province in the deep ocean; 2) The continental slope occupies a prominent position in the worldwide sedimentary regime. Although the slope environment comprises only a small fraction of the ocean floor (less than 9%, based on Menard and Smith, 1966), all detrital material (excepting windborn material) entering the deep sea must pass over it. The continental slope is thus an important area for study, both in itself and as part of the larger oceanic sedimentary system.

The objective of this work is to determine:

a) which sedimentary processes are active on the continental slope;

b) how these processes combine to control deposition and erosion and thus the physiography and structure of the continental slope and the characteristics of continental slope deposits;

c) the ways in which processes acting on the continental slope have responded to changes in environment during the Pleistocene and Holocene.

A detailed study of a small portion of the continental slope off New England was made. The study area (Fig. 1) was small enough to allow detailed sampling and surveying by a wide variety of techniques, but large enough to include a submarine canyon and a representative section of open continental slope. Along the continental margin of the northeastern United States the continental slope is most easily defined as that section of ocean floor lying between the flat continental shelf and the gently sloping continental rise, and having a gradient exceeding 1:40 (Heezen, Tharp, and Ewing, 1959).

GEOLOGICAL SETTING

The continental slope off New England represents the edge of the Atlantic Coastal Plain province of North America. Paleozoic metamorphic and crystalline rocks are overlain by a seaward-thickening section of Cretaceous and Cenozoic sediments. The basement off much of eastern North America has the form of basins separated by ridges which

Figure 1. Position of detailed study area (shaded) with respect to major features of the continental margin off Eastern North America.

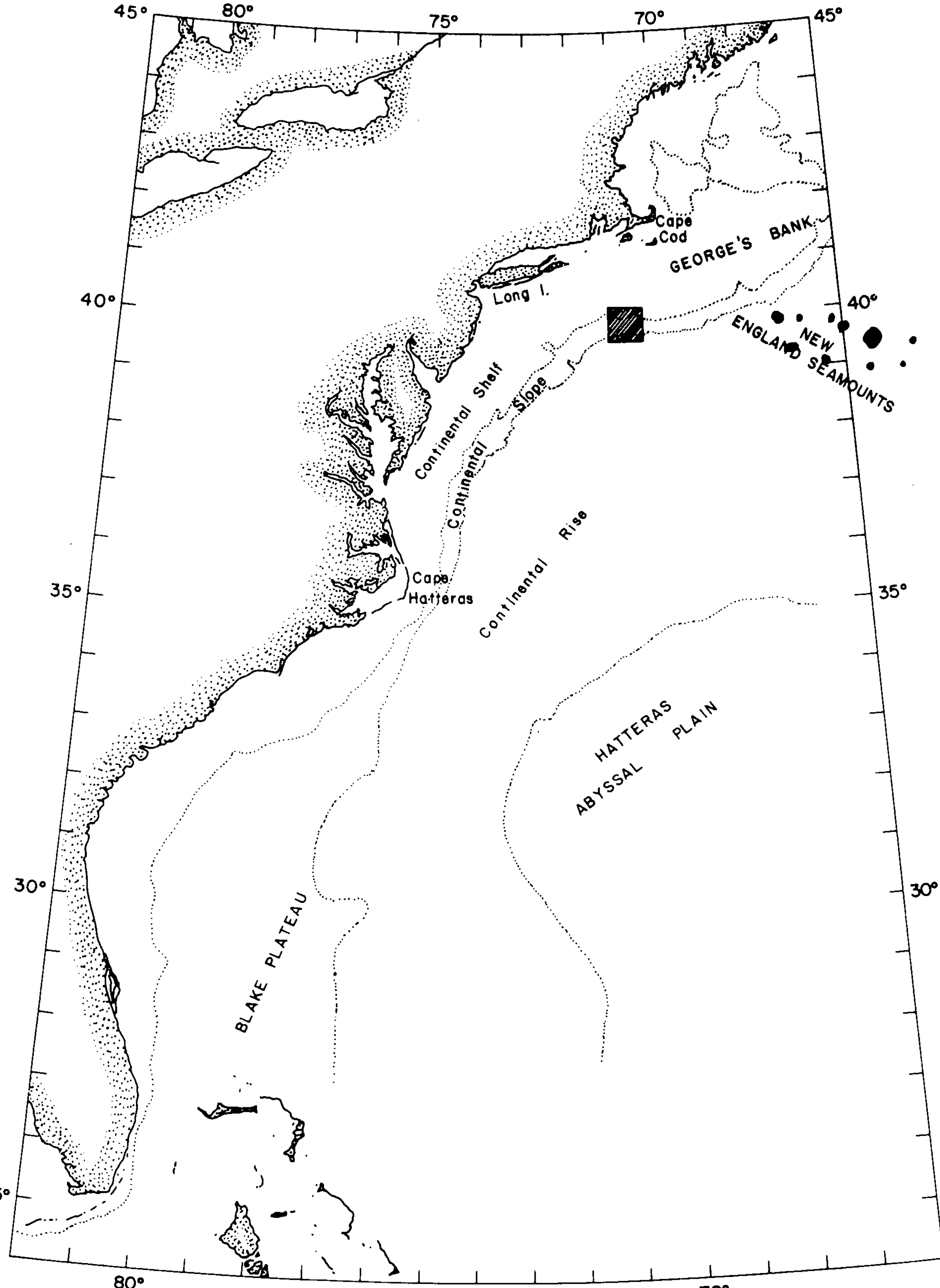
45°
80°
75°
70°
45°
Cape
Cod
GEORGE'S BANK
Long I.
40°
NEW
ENGLAND SEAMOUNTS
Continental Shelf
Slope
Continental
Continental Rise
Cape
Hatteras
35°
HATTERAS
ABYSSAL PLAIN
30°
BLAKE PLATEAU
25°
80°
75°
70°

Figure 1.

trend generally parallel to the trend of the continental slope. The basin-ridge structure is offset by the right-lateral Kelvin Fault, which apparently cuts across the continental margin from near New York and continues seaward along the New England Seamount Chain (Drake and others, 1968).

Cretaceous and Cenozoic shallow-marine sediments of several kilometers thickness lie atop the Paleozoic basement. The upper portions of this sequence thicken and dip seaward from exposures in New Jersey and on Martha's Vineyard and crop out locally on the continental slope (Stetson, 1949; Murray, 1961; Northrop and Heezen, 1951; Gibson and others, 1968).

The continental rise is a thick prism of sediments lying at the base of the continental slope. Horizon A, a prominent reflection sequence of upper Cretaceous to Eocene age present throughout much of the western North Atlantic ocean (Ewing and others, 1969), underlies the continental rise. Horizon A forms a flat, nearly horizontal surface upon which up to three kilometers of sediment having weak and distorted internal reflectors has been deposited (Emery and others, 1971).

The continental slope thus lies between the continental shelf, which has been gradually built upwards to compensate for downwarping and seaward tilting, and the continental rise, which has been deposited at the base of the continental slope, burying the lower portions of the continental slope.

During the late Pliocene and Pleistocene, continental glaciation lowered sea level, exposing much of the continental shelf. The minimum extent of Pleistocene glaciers is marked by terminal or recessional moraines on Long Island, Block Island, Martha's Vineyard, and Nantucket, but glaciers may have reached nearly to the shelf edge south of Martha's Vineyard and Block Island (Emery and Uchupi, 1972). On Georges Bank at least five erosional surfaces are recognized in the upper 100 meters of sediment (Knott and Hoskins, 1968). Five deltaic sequences separated by well developed unconformities have been recognized off New Jersey and New York (Ewing and others, 1963; Knott and Hoskins, 1968).

The surface sediments of the continental margin from Long Island to Georges Bank range from the sands of the continental shelf to the sandy silty clays of the continental rise. The continental shelf sands are generally regarded as relict glacial and fluvial deposits which were reworked by the last transgression of the shoreline across the shelf, and which have been little altered since that time except for the gradual addition of calcareous skeletal material (Garrison and McMaster, 1966; Milliman and others, 1972). An anomalous area of fine-grained sediment occupies the outer shelf south of Cape Cod. Its origin remains in doubt, but most workers agree that it is post-transgressional in age (Stetson, 1936; McMaster and Garrison, 1966; Trumbull, 1972).

The continental slope is blanketed by a nearly continuous layer of Pleistocene and Holocene sediments ranging in texture from sands to silty clays, but generally falling in the clayey silt and sandy silt classes of Shepard (1954). This general decrease in grain size from the shelf onto the slope continues onto the continental rise, where the bulk of Pleistocene and Recent deposits are silty clays interbedded with sharply defined layers of sand (Ericson and others, 1961).

PREVIOUS WORK

Most of the previous work done in the vicinity of this study area has been in the form of large-scale studies of a regional nature (good examples are: Uchupi and Emery, 1967; Hoskins, 1967; Milliman and others, 1972).

More detailed studies within the area of this investigation include investigations of short cores for sediment characteristics (Stetson, 1949) and Foraminifera faunas (Phleger, 1939, 1942); description of Eocene rocks recovered from the continental slope (Stetson, 1949; Northrop and Heezen, 1951); a detailed seismic-reflection survey of a large-scale slump feature on the lower portions of the continental slope (Uchupi, 1967); several bottom photographs (Owen and Emery, 1967); and a detailed survey of a small portion of the continental slope adjacent to Alvin Canyon by submersible (Emery and Ross, 1968).

PRESENT WORK

The present study is based primarily on data and samples gathered on cruises of the Woods Hole Oceanographic Institution during 1971 and 1972 (Table 1). These included operations aboard R/V GOSNOLD; R/V ATLANTIS II; two cruises aboard ALCOA SEAPROBE utilizing an instrument pod equiped with closed circuit television, bottom cameras, and side looking sonar; and dives in the research submersible ALVIN

TABLE 1

Field Work Conducted in the Study Area

Cruise	Dates	Operations
GOSNOLD 177	28 May - 5 June, 1971	12 kHz echosounding, bottom photography.
GOSNOLD 183	23-28 August, 1971	3.5 kHz echosounding, gravity coring, bottom photography.
GOSNOLD 189	15-24 May, 1972	3.5 kHz echosounding.
GOSNOLD 191	7-16 June, 1972	3.5 kHz echosounding, bottom photography.
ALCOA SEAPROBE 1	17-26 July, 1972	Bottom observation, STD casts, surface sediment sampling.
ALCOA SEAPROBE 2	28 July - 7 August, 1972	Bottom observation and photography.
LULU 66	9-18 August, 1972	Bottom observation, box coring, photography.
ATLANTIS II 72	21 October - 7 November, 1972	Piston coring, seismic reflection profiling, water sampling, 3.5 kHz echosounding, bottom photography.

for direct observation of the bottom on the lower continental slope.

In addition to the field work, samples which were collected during the cooperative U. S. Geological Survey - Woods Hole Oceanographic Institution continental margin study of 1962-1970 were analyzed and incorporated in this study.

Laboratory investigations included analysis of sediment samples and experimental erosion of "undisturbed" continental-slope sediment.

CHAPTER II

DATA

BATHYMETRY

Echosoundings were made on five cruises to the study area (Fig. 2). The resolution was limited by the precision of navigation and the width of the sound source beam. Navigation was based primarily on Loran-A readings taken at an average interval of twenty minutes. Loran-A positions are considered to be reproducible to about 1 km at best. On the steeper portions of the continental slope a 1 km offset could produce a depth change of 200 meters. Actual line crossings had an average discrepancy of 20 meters on the lower continental slope; the largest discrepancy observed was 71 meters, suggesting that the relative positions within the study area are accurate to closer than 1 km.

The second limit to detail in the bathymetric survey was the wide beam of the sound sources (a 60° cone), which in areas of deep water and high relief produce hyperbolic reflections rather than a true profile of the bottom. In 1500 meters water depth, reflections from a circular area with a diameter of more than 1 km are received, and steep-

Figure 2. Bathymetric control. Points indicate the soundings read from analog depth recordings taken during the cruises in Table 1 which were used to construct the bathymetric base chart for this study.

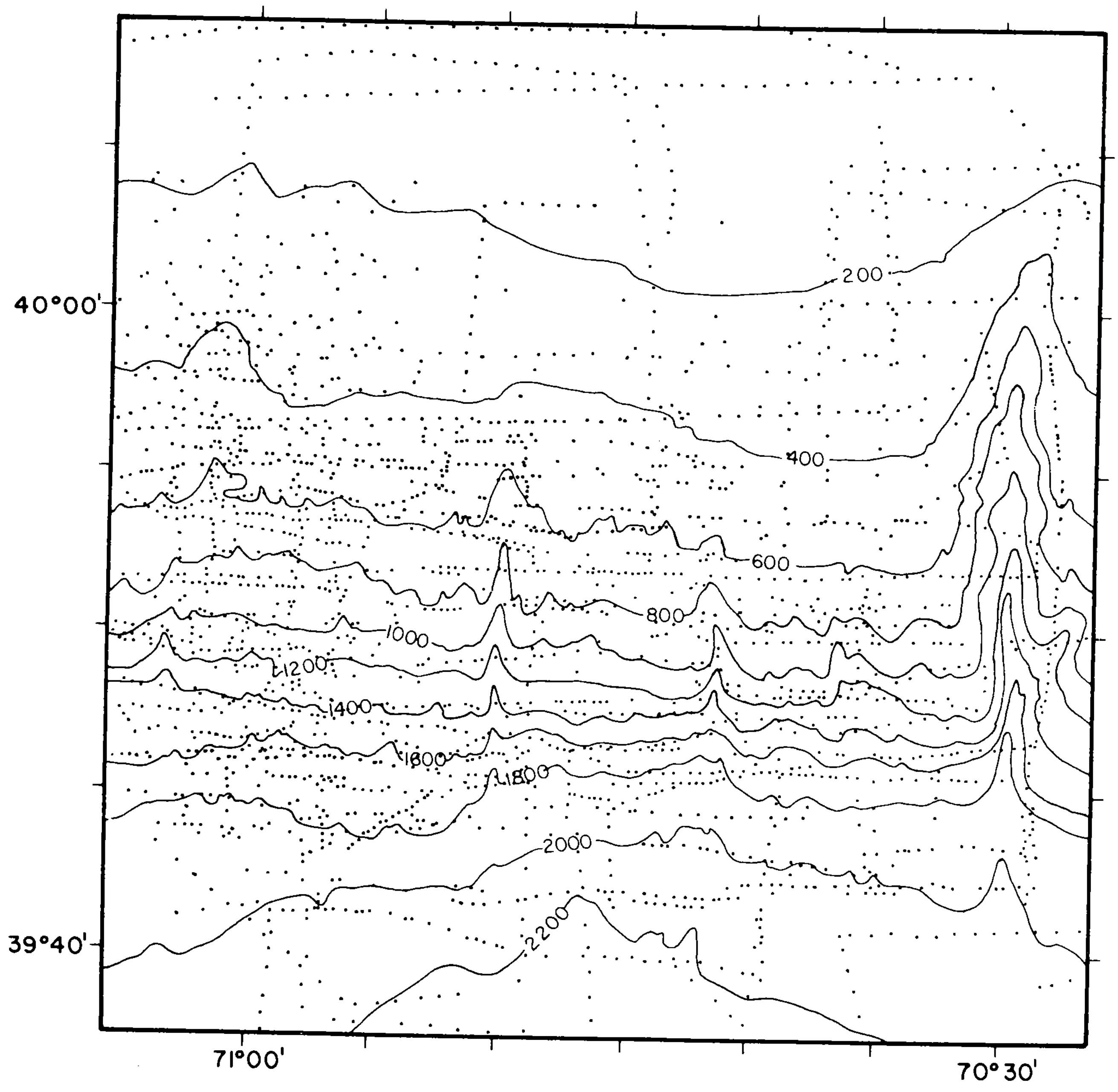
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
40°00'
39°40'
71°00'
70°30'

Figure 2.

sided features smaller than about 1/2 km are not properly resolved. Within these limitations, Figure 3 is an accurate representation of the shape of the continental slope surface.

The most striking topographic feature in this area is Alvin Submarine Canyon at 70°30' (Emery and Ross, 1968). The canyon is steep-sided, with average slopes of 10-15° on the side walls, and is cut to a depth of up to 600 meters below the adjacent slope.

Outside the canyon the area can be described in terms of outer continental shelf, shelf break, upper continental slope, lower continental slope, and upper continental rise (Fig. 4). The shelf break occurs at 125 to 150 meters, and is slightly shallower near the head of Alvin Canyon. No sharp topographic boundary separates the shelf from the upper continental slope, but a transition takes place over several kilometers from a nearly horizontal surface to the gentle (1.4°) inclination of the upper continental slope. This transition zone will be referred to as the shelf-break. Between about 750 meters and 1800 meters the continental slope steepens to an average 7.6°. At the base of this steep section the bottom decreases in gradient. At

Figure 3. Bathymetry of the study area. Contours in meters below sea level, corrected for variations of the speed of sound in sea water (Matthews, 1939).

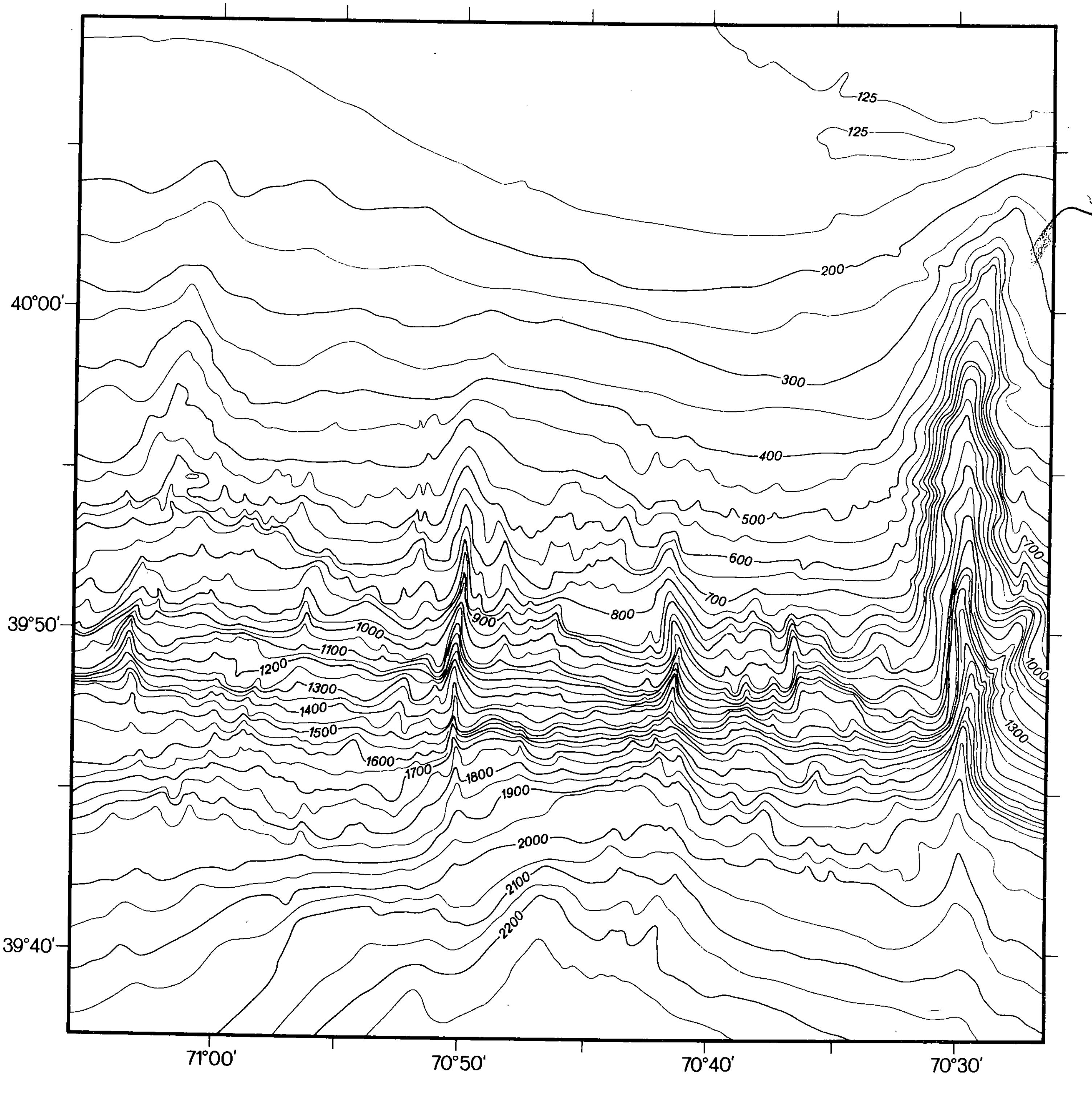
125
125
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
700
1000
1300
40°00′
39°50′
39°40′
71°00′
70°50′
70°40′
70°30′

Figure 3.

Figure 4. Bathymetric profiles of the continental slope showing shelf break area, upper continental slope, lower continental slope, and upper continental rise. Vertical exageration is about 4.2:1. Actual inclinations and corresponding gradients are given for the exaggerated slopes shown by the angles above representative portions of the profiles.

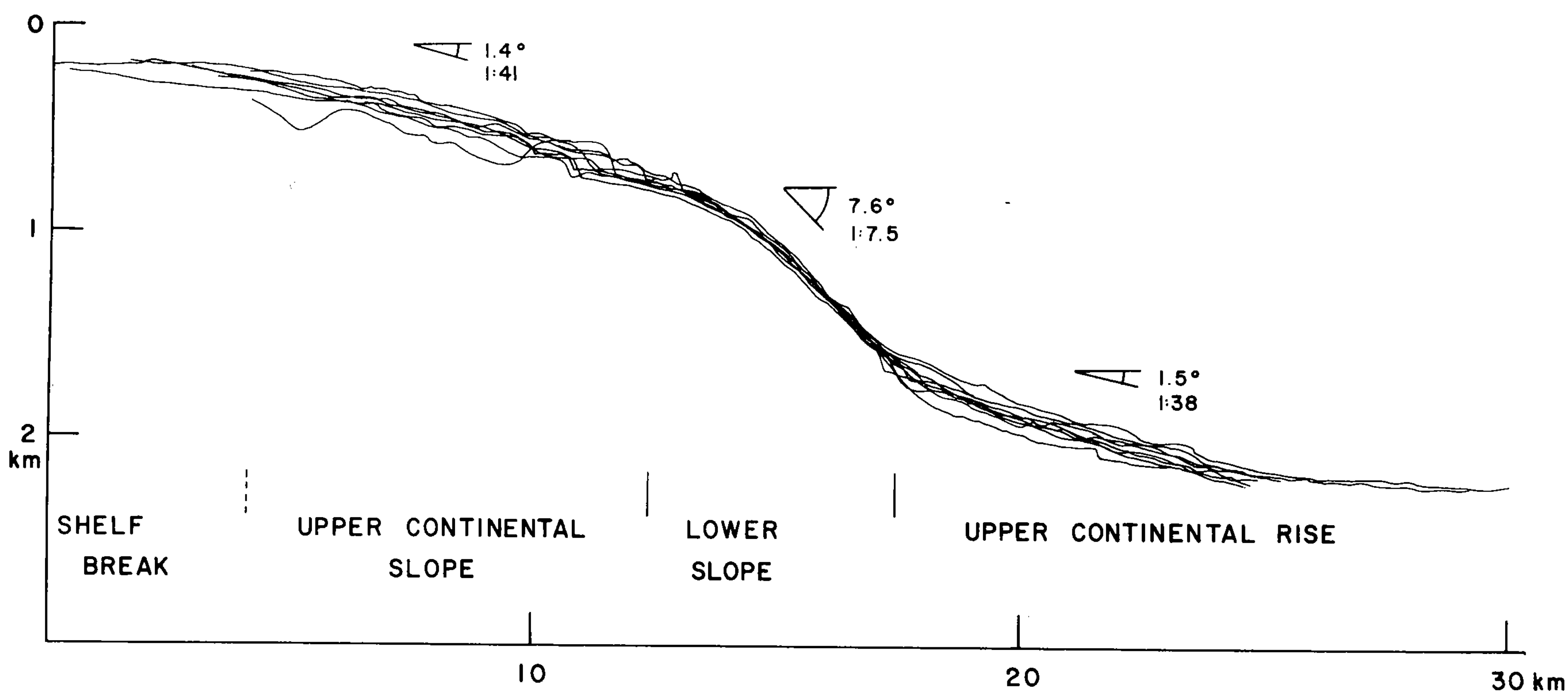
0
1
2
km
1.4°
1:41
7.6°
1:7.5
1.5°
1:38
SHELF
BREAK
UPPER CONTINENTAL
SLOPE
LOWER
SLOPE
UPPER CONTINENTAL RISE
10
20
30 km

Figure 4.

2000 meters the gradient is 1.5°.

Numerous gullies incise the surface of the continental slope. These range in size from large gullies approaching canyon size (as at 70°50'W in Fig. 3) to very small gullies at the limits of resolution of the echosounder. Gullies are most abundant on the steep lower continental slope, and generally trend downslope.

3.5 kHz ECHOSOUNDING

3.5 kHz echosounding was performed on four cruises in the study area (Table 1); the most complete and evenly spaced lines were chosen for detailed study (Fig. 5). Bottom and sub-bottom reflections were traced directly from the records, reduced photostatically using a Xerox 1860 printer, adjusted to constant vertical exaggeration and combined into a three-dimensional drawing (Fig. 6). In addition, portions of the records were photographed directly.

The provinces defined on the basis of physiography (shelf break, upper continental slope, lower continental slope, and upper continental rise) have distinct characteristics revealed by 3.5 kHz profiles.

The shelf break zone is smooth on a scale of several

Figure 5. Positions of 3.5 kHz profiles. Portions marked by wide lines and letters were photographed directly and are reproduced as figures 7 through 15.

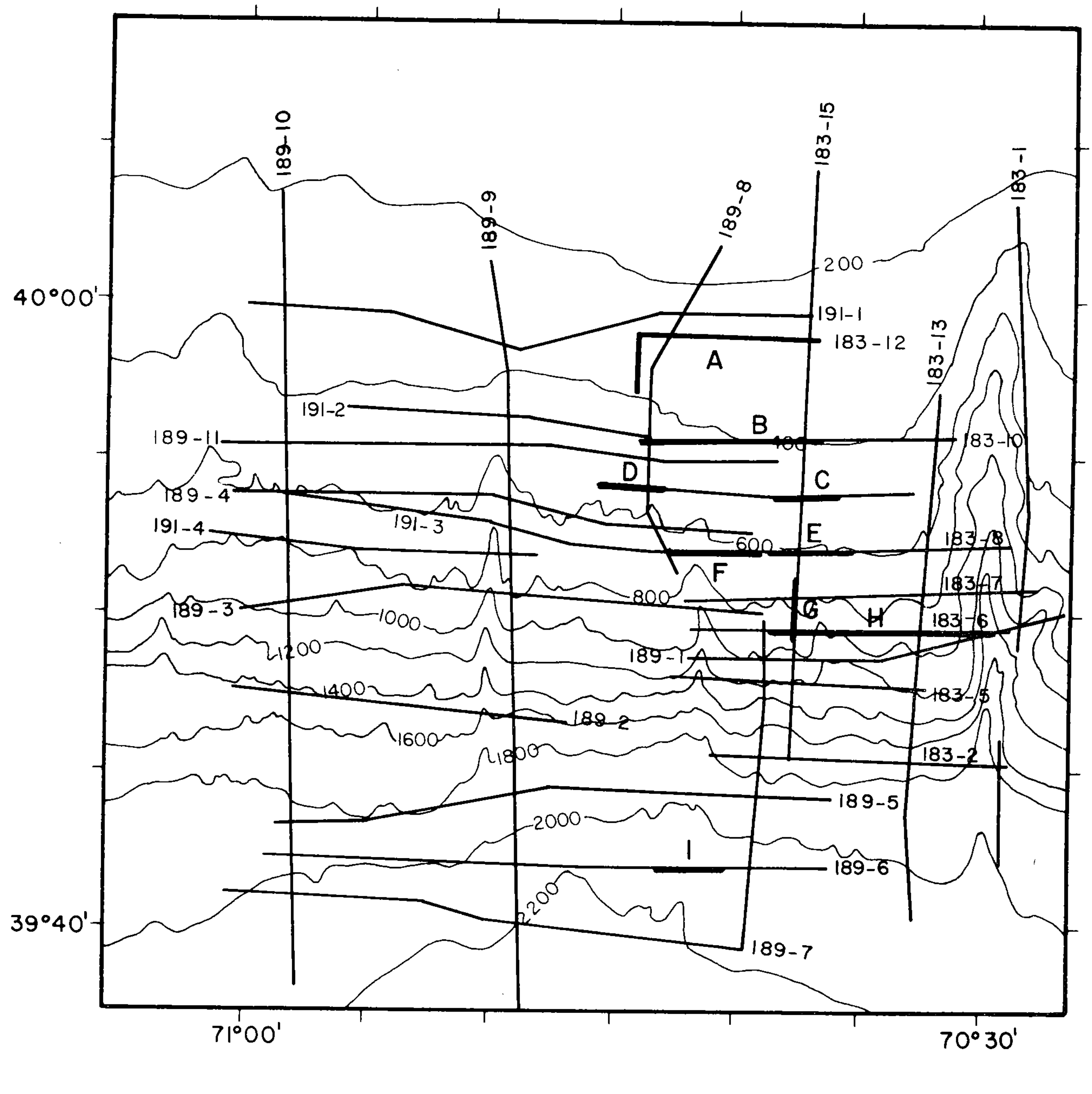
189-10
189-9
189-8
183-15
183-1
183-13
200
40°00'
191-1
183-12
A
191-2
B
189-11
183-10
D
C
189-4
191-3
191-4
600
E
183-8
F
183-7
800
189-3
1000
G
H
183-6
1200
189-1
1400
183-5
189-2
1600
1800
183-2
189-5
2000
I
189-6
2200
39°40'
189-7
71°00'
70°30'

Figure 5.

kilometers, having no large-scale relief (Fig. 6). The surface is not completely smooth, however, but has the form of rounded crests separated by V-shaped depressions with a relief of five to ten meters (Fig. 7). The track spacing was too large to detect linearity, but the features are more pronounced in east-west profiles than in north-south profiles, suggesting that they may be small gullies trending predominantly downslope. The evidence for this interpretation is not decisive. It is possible that the features are not linear, but have the form of isolated highs and lows. The spacing of crests is not strikingly regular, but the surface has this rough form over a large area of the outer continental shelf and upper continental slope (Fig. 6) suggesting that the process responsible for producing the relief may be active uniformly over the entire area.

Seaward of the shelf break sub-bottom reflections gradually become apparent (Fig. 8). These reflectors are generally parallel to the sediment surface and appear to continue uninterrupted upslope into the shelf break area, where they fade out, perhaps because they are masked by a strong surface reflection. The sub-bottom reflection sur-

Figure 6. Three-dimensional drawing of 3.5 kHz profiles. The base of the drawing is 2500 meters below sea level. Vertical-scale lines are at 1000 and 2000 meters. Vertical exaggeration is approximately 9 to 1.

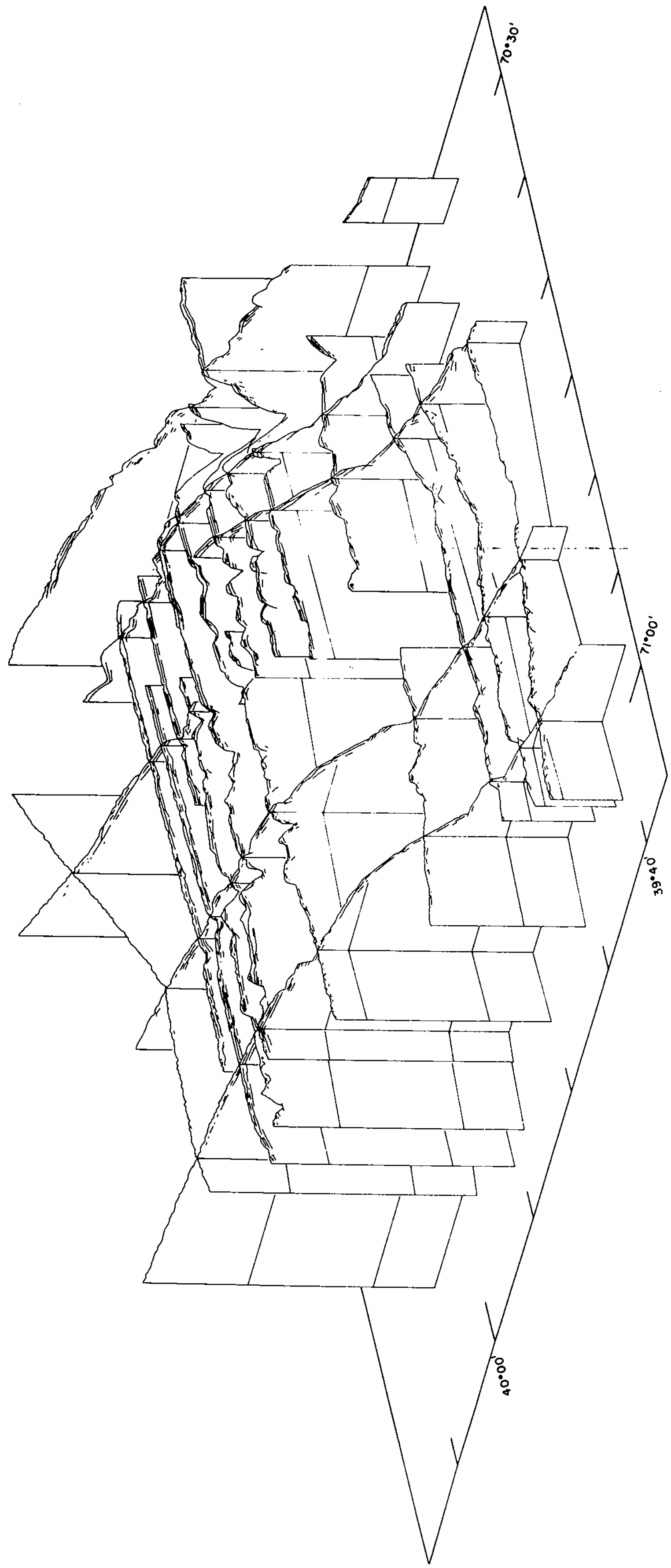

Figure 6.

Figure 7. Portion A (Fig. 5) of 3.5 kHz profile of the shelf break area, showing strong surface reflector, lack of sub-bottom reflections, and irregular surface. Vertical exaggeration is approximately 44 to 1.