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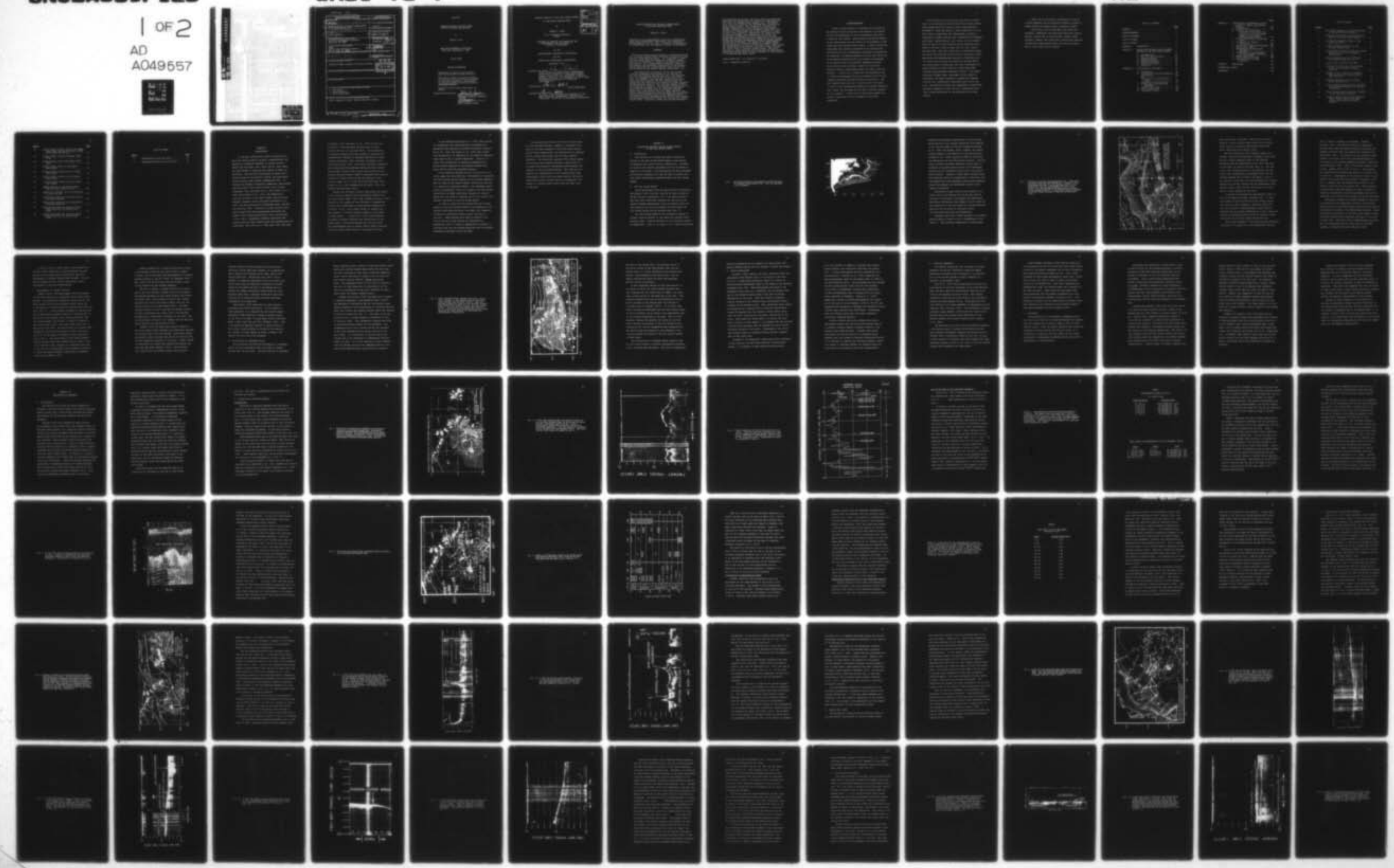

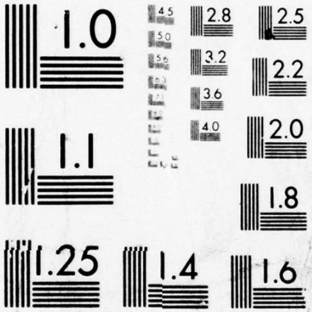

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GEOLOGICAL EFFECTS OF THE GULF STREAM SYSTEM IN THE NORTH AMERICAN BASIN

by

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GEOLOGIC EFFECTS OF THE GULF STREAM SYSTEM IN THE NORTH AMERICAN BASIN

by

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B.A., Wesleyan University
(1969)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
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Chairman, Joint Oceanography Committee in the Earth Sciences, Massachusetts Institute of Technology - Woods Hole Oceanographic Institution

GEOLOGIC EFFECTS OF THE GULF STREAM SYSTEM IN THE NORTH AMERICAN BASIN

Edward P. Laine

Submitted to the Massachusetts Institute of Technology-Woods Hole Oceanographic Institution Joint Program in Oceanography on July 20, 1977, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

ABSTRACT

The Gulf Stream System contains a clockwise rotating set of bottom currents which influence the sea bed in the northern North American Basin. It is possible to interpret the present-day and historical record of current activity in this basin in terms of the deep flow of the Gulf Stream. This interpretation provides a much mor satisfactory and consistent explanation of the geologic record than previous interpretations based strictly on the influence of the classic abyssal circulation.

The present-day circulation of the Gulf Stream actively resuspends large quantities of sediment on and near the northern Bermuda Rise and it is suggested that this resuspension may be due to the eddy field which is embedded in the westward flowing return flow. During the late Cenozoic the Gulf Stream System was responsible for depositing and shaping the major acoustic/sedimentological units on the relatively smooth surface of the Horizon A complex. Fine grained, montmorillionite-rich sediments derived from the chemically weathered saprolites of the Hudson and St. Lawrence drainage basins were injected into the deep ocean basins by turbidity currents during the late Paleogene and the Neogene. Fine-grained turbidites from the St. Lawrence spread southward down the Southeastern Sohm Abyssal Plain across the eastward-flowing Gulf Stream and its westward flowing return flows. Portions of these fine-grained sediments were entrained by the main and return flows and deposited downstream as acoustically non-laminated accumulations on the Corner and Bermuda Rises respectively. The Hudson River input was injected into the deep basin through the Hudson Canyon System. The interaction of these fine-grained turbidites with the southward flowing Western Boundary Undercurrent and the northward flowing deep flow of the Gulf Stream System led to the formation of a pair of outer ridge deposits; respectively the Hudson and Gulf Stream Outer Ridges, here defined for the first time. During the late Neogene or early Pleistocene the Gulf Stream Outer Ridge was partially eroded by the Gulf Stream System and portions subsequently covered by coarse-grained Pleistocene turbidites. The Hudson Outer Ridge dammed a similar series of turbidites behind its landward flank. The coarse-grained illite-rich turbidites that flowed across the southeastern Sohm Abyssal Plain also crossed the main and return flows of the Gulf Stream System. The finer portions of these sediments were entrained and deposited as Pleistocene acoustically laminated sediments on the plateaus of the Bermuda and Corner Rises.

Thesis Supervisor: Dr. Charles D. Hollister

Title: Associate Scientist

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Alan Driscoll and coring group deserves much thanks, since it was through his efforts that the key Giant Piston cores around which this thesis is built were obtained. Elizabeth T. Bunce and Sidney T. Knott helped me at a very early stage to appreciate the difficulties involved in interpreting seismic profiles and I greatefully acknowledge their help. Whitey Witzell, Earl Young, and Jack Connell bore the brunt of cruise preparation and technical assistance at sea and I wish to thank them for their uncomplaining help. This work could have not been done without the aid of the excellent seismic profile libraries at both Woods Hole and Lamont-Doherty Geological Observatory and so I would like to praise the efforts of William Dunkle and Grace Witzell at Woods Hole and their counterparts at Lamont-Doherty for their efforts to efficiently make available well-preserved scientific records. Lois Toner, Catherine Offinger Sheer, Christopher Peters, Mary Jo Richardson, and Pamela Hindley all helped with sediment analysis and I greatefully acknowledge their skills and help. The excellent Graphic Arts Department at Woods Hole has been a pleasure to work with and I especially would like to thank Mike Mello for the drafting of the final figures.

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CHAPTER I

INTRODUCTION

In the past fifteen years since the beginning of the first serious study of erosion, transportation, and deposition of deep-sea sediments by bottom currents (Heezen and Hollister, 1963, 1964 a and b), much effort has been devoted to exploring the effects of these circulations. This work has concentrated on those circulations driven by the cooling, sinking, and equatorward spread of polar water masses, thermohaline flow. In studying the abyssal circulations themselves, measurements have been made of the velocity field of the currents (Zimmerman, 1971; Hollister et al., 1974; Betzer et al., 1974; and Tucholke et al., 1973); the temperature-salinity structure of the water column, from which geostrophic transport can be calculated (Tucholke et al., 1973); and the distribution of suspended matter (Biscaye and Eittreim, 1976). Patterns of current activity have been inferred from bottom photographs (Hollister and Heezen, 1963; Heezen and Hollister, 1971; and Tucholke et al., 1973). Sedimentary bedforms associated with current flow have been studied using echo-sounding profiles (Hollister, 1976; Fox et al., 1968; Rona, 1969; Hollister and Heezen, 1972; Hollister et al., 1974) and the distribution of echo-character has been used to infer current activity on a regional basis. The petrography of deep-sea sediments has been studied to establish the characteristic features of sediments deposited by these currents (Hollister, 1967; Hollister and Heezen, 1972, Klasik and Pilkey, 1975). The shape, lithologic character, and distribution of sedimentary bodies has been studied using seismic profiles and in many cases cores from the Deep-Sea Drilling Project (DSDP) to determine both regional patterns of current activity and the history of this activity (Jones et al., 1970; Ewing and Hollister, 1972; Kennett et al., 1974; Berggren and Hollister, 1974; and Berggren and Hollister, 1977).

Because the strongest currents associated with thermohaline flow are expected along the western boundaries of the ocean basins (Wüst, 1936, 1958; Stommel and Arons, 1960), research on all aspects of the influence of thermohaline currents has concentrated on these margins (Berggren and Hollister, 1977). Only a small amount of research has been devoted to studying current evidence in the center of ocean basins. Ewing et al. (1971) have argued on the basis of seismic profiles, the distribution of suspended matter, bottom photographs, and limited current meter measurements that an active current system involving Antaractic Bottom Water exists in the Argentine Basin.

On the Bermuda Rise Ewing et al. (1973) have pointed out anomalously thick distributions of sediments and speculated that deposition occurred from bottom currents. Fox et al. (1967) and Taylor et al. (1975) have argued that accumulations of sediments on the flanks of seamounts might also be due to current deposition. Silva et al. (1976) have pointed out an extensive accumulation of bottom current deposits on the northern Bermuda Rise, about 1000 km from the continental margin.

It was primarily through my work in the Silva et al. (1976) paper and the difficulty I encountered in accounting for thick bottom current deposits on the northern Bermuda Rise in terms of the classic abyssal circulation that led to a search for alternative models. The subsequent publication by Worthington (1976) of a model of the Gulf Stream System which included significant transport at abyssal depths over the areas of interest led to this study of the geologic influence of the Gulf Stream System.

In order to study both the present-day and the past effects of the Gulf Stream System on the sediments of the northern North American Basin, this paper will summarize evidence for present-day bottom current activity in the area. These patterns will then be related to the flow of the Gulf Stream System as interpreted by Worthington (1976) in order to demonstrate the degree of influence that the Gulf Stream System may have on deep-sea sedimentary processes within the basin.

The present-day activity of the Gulf Stream System will be described through a summary of published literature on the deep transport of the Gulf Stream System, current meter observations, the distribution of suspended matter, bottom photographs, and surficial sediment character. The historical aspects of Gulf Stream System activity will be interpreted through a description of the major post-Horizon A sedimentary bodies beneath and adjacent to the Gulf Stream System. This work will be based on an interpretation of all existing Woods Hole Oceanographic Institution and Lamont-Doherty Geological Observatory seismic profiles and an interpretation and summary of selected Giant Piston Cores and DSDP cores in the area.

CHAPTER II

CIRCULATION PATTERNS AND THE MODERN EFFECTS OF THE GULF STREAM SYSTEM

A. Introduction

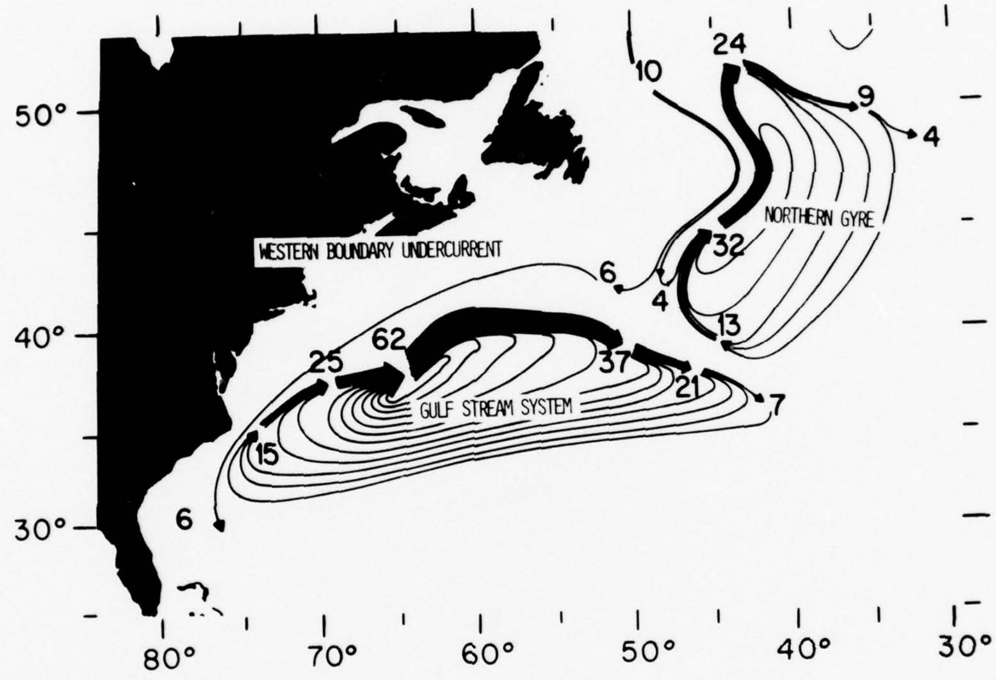
This section will discuss the modern circulation pattern of the Gulf Stream System based on calculations of transport and current velocity observations. Evidence of currents from bottom photographs will be introduced in support of this model. The distributions of both suspended and surficial sediments will then be used to briefly discuss modern sedimentary processes beneath the Gulf Stream System.

B. The Gulf Stream System

Using hydrographic data and Swallow float trajectories Worthington (1976) outlined a pattern of deep circulation beneath the main thermocline (4°) in the North Atlantic. The three most significant features are the flow of the Western Boundary Undercurrent along the western margin of North America and the two clockwise rotating gyres, the Gulf Stream System and the Northern Gyre (Fig. 1).

The Gulf Stream System is the circulation system of primary interest because it lies above the northern North American Basin. Several features of its circulation should be emphasized. Since it is a gyre it is a closed circulation

Fig. 1 The primary elements of North Atlantic circulation below $4^{\circ}\theta$ according to Worthington(1976). Each line represents 5 SV of transport.



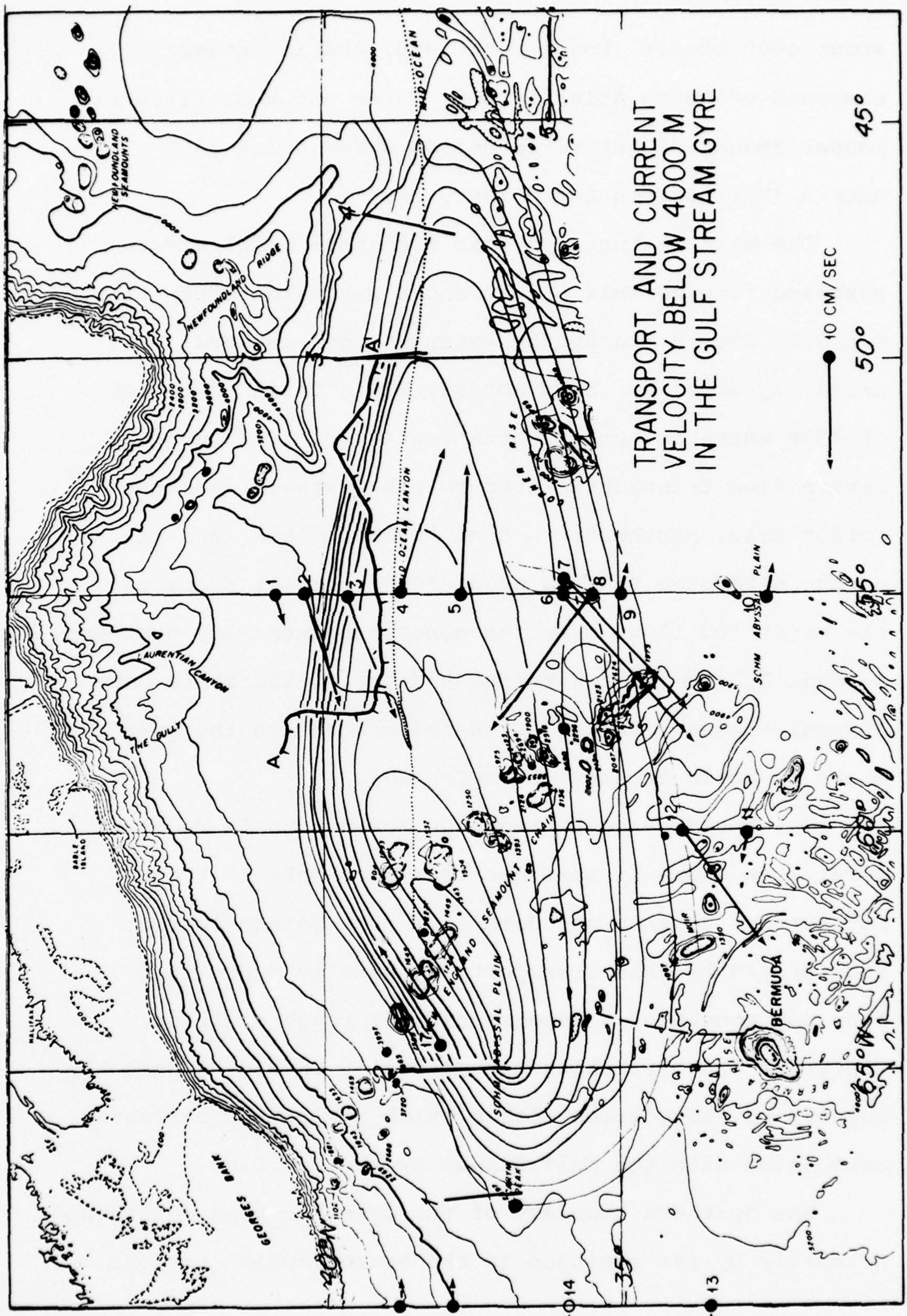
WESTERN BOUNDARY UNDERCURRENT
NORTHERN GYRE
GULF STREAM SYSTEM
24
9
4
10
32
6
4
13
62
25
37
21
7
15
6
50°
40°
30°
80°
70°
60°
50°
40°
30°

system with continuous recirculation of water masses. Recirculation of this general nature was also embodied in the earlier models of the Gulf Stream by Sverdrup et al. (1942) and Stommel (1966); however, the models differ markedly in the details of this recirculation. Sverdrup et al. (1942) outlined a model of flow above the thermocline for the entire North Atlantic. Recirculation involved northward advection of warm water in primarily the western North Atlantic with subsequent cooling and then southward return flow in the eastern North Atlantic. Stommel's (1966) model involved northward advection above the thermocline of warm water into the Labrador Sea with subsequent cooling and southward return flow beneath the thermocline as part of the abyssal circulation.

Worthington's model differs from Sverdrup et al. (1942) both in the smaller size of the gyre and the inclusion of horizontal flow beneath the thermocline. Significant differences from Stommel's (1966) model are the constraint of the Gulf Stream to the North American Basin and the inclusion of horizontal return flow both above and below the thermocline.

Transport below the 2° Theta isotherm in the North American Basin is shown in Fig. 2 (Worthington, 1976, Table 5). This potential temperature is found below

Fig. 2 Transport of the Gulf Stream System below $2^{\circ}\Theta$ (4000 meters) and current velocities near 4000 meters. Transport is from Worthington(1976) Table 5 and current velocities are from Schmitz(1977) (#s1-16) and Zimmerman(1971) (#17). Profiles 1-5 are the hydrographic profiles used by Worthinton and the hatchured line A-A' is the northern surficial boundary of the Gulf Stream according to Fuglister and Worthington (1951).



TRANSPORT AND CURRENT VELOCITY BELOW 4000 M IN THE GULF STREAM GYRE about 4000 meters (Fuglister, 1960) and is primarily composed of North Atlantic Deep Water which overlies a lesser amount of Antarctic Bottom Water below 4800 meters (Worthington and Wright, 1970).

The main features of this transport model are an eastward flowing Gulf Stream and a westward return flow. The Gulf Stream transports water to the eastward primarily above the Sohm Abyssal Plain until just east of 45°W where it turns to the west (Fig. 2). Here the return flow transports water to the westward over the Corner Rise, Southeastern Sohm Abyssal Plain, and the northern Bermuda Rise to about 70°W where it turns to the north and flows over the contact between the northern Bermuda Rise and the Hatteras and the Southwestern Sohm Abyssal Plains. Near 37°N the flow turns to the east where it again becomes the main flow.

It should be cautioned that Worthington's model of gyral flow shows first-order transport only. It does not purport to show the details of the bottom current flow driven by this transport, especially where this flow may encounter a topographically rough seafloor. Therefore the gyre shown schematically in Fig. 2 does not specify the boundaries within which the bottom currents associated with the Gulf Stream System can flow.

The northern boundary of the gyre has been determined primarily by its position in the hydrographic sections

(Fig. 2) used to estimate its transport. Between sections 2 and 3, the primary control are temperature profiles which show the boundary between Slope Water and Sargasso Sea Water above the thermocline (Fuglister and Worthington, 1951). The position of the boundary between section 2 and about 60°W is well determined because of the density of sea surface temperature profiles (Fuglister and Worthington, 1951). East of this point, however, only a single profile exists (A-A^1 in Fig. 2). This profile was ignored and the boundary was drawn as a straight line to section 3. Examination of the position of the 10° isotherm in the region from Gulf Stream 60 (Fuglister, 1963, Fig. 4) suggests that the boundary may be moved to the south to coincide with the profile A-A^1. This relocation is particularly important because it helps to reconcile seemingly contradictory current measurements that will be presented in the section that follows on current velocities.

Worthington located the southern boundary of the gyre by reference to the temperature, salinity, and silicate characteristics of the water masses involved rather than by calculation of transport from hydrographic sections. Above 2200 meters the position of the warm, salty tongue of Mediterranean overflow water constrains the gyre to lie north of about 30°N. Below the level of Mediterranean water the gyre is constrained north of about 32°N by a distinct boundary in dissolved silicate (Metcalf, 1969).

In order to gain a better idea of the boundaries of the Gulf Stream System and to begin assessing the probability of this system being geologically important, measurements of abyssal currents must be made. The next section summarizes deep current measurements within the adjacent to the Gulf Stream System.

C. Measurements of Current Velocity

Schmitz (1977) has found support for the existence of the Gulf Stream Gyre in long-term current meter observations. He reported the average for velocities for nine month records from fifteen separate current meters set at 4000 meters or deeper within the northern North American Basin (Fig. 2). If the northern boundary of the main flow can be moved several degrees further to the south east of about 60°W as was argued in the previous sections, then the average speeds ($\sim$10 cm/sec.) at sites 4-8 support a main flow (sites 4 and 5) and return flow (sites 6-8) at 4000 meters near 55°W. This shift moves the northern deep boundary of the Gulf Stream south of sites 2 and 3 and places it in the region of eastward flowing currents at sites 4 and 5. The significance of the strong currents flowing westward above the abyssal plain at sites 2 and 3 is not entirely clear, although it is possible that this is the part of an equatorward flowing abyssal circulation in which the Western Boundary Undercurrent is embedded (Hollister and Heezen, 1972).

Further evidence for a strong return flow is found in the average velocities for sites 10 and 11 (about 7 cm/sec.) and in the short-term measurements of 9 cm/sec. average velocity to the NE (7 days) by Zimmerman (1971) near 37°41'N and 65°16'W where the Gulf Stream is about to flow through the New England Seamounts.

The low (<2 cm/sec.) average velocities at sites 8 and 9, and 12-16 provide a general idea of the southern and western boundaries of the strong current flow within the return flow. The averages at sites 8 and 9 firmly constrain the return flow north of about 35°N over the central portion of the Sohm Abyssal Plain. The high average velocity at site 11 and the low average velocity at site 12 constrains the return flow on the northern Bermuda Rise to flow north of between 31° and 34°N. The low velocities at sites 4-7 all suggest that the main and return flows do not extend west of 70°W.

Schmitz (1976) has used current meter evidence to point out several other important and interesting features of the deep flow of the Gulf Stream. Large scale eddies are present within the deep flow and are not found in the regions immediately adjacent to the north. Kinetic energy is distributed in roughly equal proportions between the mean and eddy flows (Schmitz, 1976). Later sections will discuss both the possible modern and long-term geologic effects of both the mean flow and the energetically similar eddy flow; however, it is appropriate now to mention the relation of the eddy flow to the overall mean flow. Holland and Linn (1975 a and b) suggests in numerical experiments with a two layer wind driven ocean that the deep mean circulation is driven solely by the eddies and that if the eddies were not present the steady circulation itself would not occur. This may imply that if geologic evidence of mean flow activity can be found this mean flow must have been accompanied by an eddy flow.

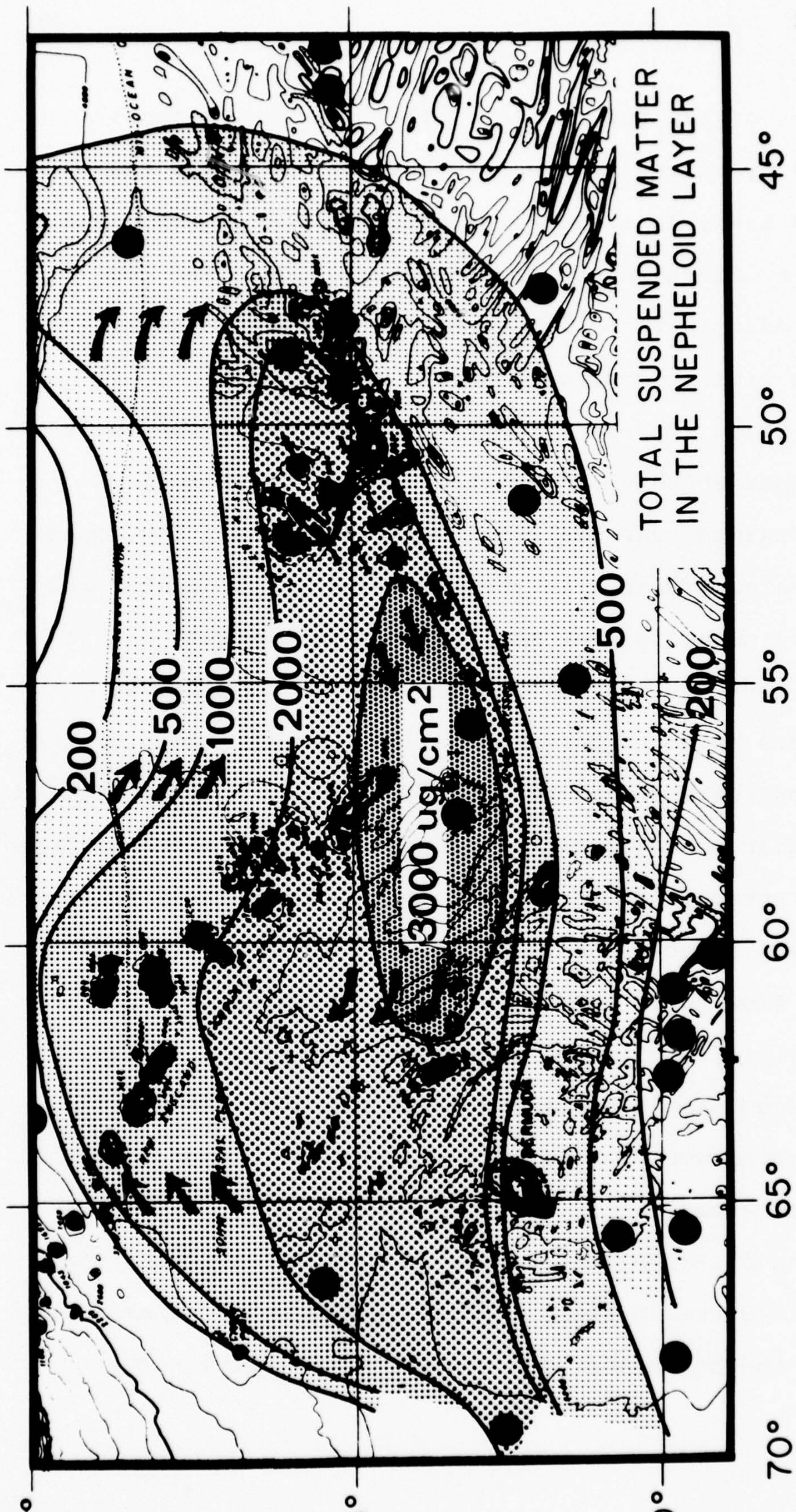
Worthington (1976) shows that no strong density gradients exist below 4000 meters. In the absence of these gradients it is expected that the current speeds measured at 4000 meters will extend to greater depths to the top of the layer of logarithmic velocity decrease, about 1 meter above the sea floor (Wimbush, 1976). This is particularly important because in later sections it will allow a rough estimate to be made of the capacity for currents of these speeds to erode, transport, and deposit the local sea floor sediments.

D. Distribution of suspended matter

The horizontal and vertical distribution of suspended matter can give information about the vigor of current systems near the sea floor. Vertical profiles of suspended matter typically show a region of relatively higher values which begin several hundred meters above the sea floor. The exact thickness of this layer, called the nepheloid layer, varies from place to place on the sea floor and with time at any one location (Biscaye and Eittreim, 1974). The suspended matter in this layer is typically fine silt to clay range and it is believed to be the result of resuspension of sea floor sediments by turbulence within the Benthic Boundary Layer.

Biscaye and Eittreim (1976) estimated the net amount of material suspended in the nepheloid layer ($\mu g/cm^2$) and published a distribution map for the Atlantic Ocean. Several features of this distribution in the North American Basin give insight into abyssal process within and adjacent to the Gulf Stream Gyre (Fig. 3). The shape of the distribution bears a strong geometric resemblance to that of the gyre itself. This resemblance suggests some form of interrelationship between the two phenomena. This resemblance may be due to active erosion and transport of sea floor sediments by the bottom currents of the Gulf Stream. It is difficult to say more about this process due to the sparseness of nephelometer profiles within the gyre. It is very important to note, however, that the maximum values of net suspended matter in the entire North American Basin exist below the southern

Fig. 3 Total suspended mass (excess mass above "clear" water values) in the nepheloid layer modified after Biscaye and Eittreim (1976). Note the maximum values are found on the northern Bermuda Rise beneath the return flow of the Gulf Stream System. A point has been added from Gagosian et al. (1976) and from unpublished results kindly supplied by Derek Spencer of the Woods Hole Oceanographic Institution.


TOTAL SUSPENDED MATTER
IN THE NEPHELOID LAYER
200
500
1000
2000
3000 ug/cm2
500
200
45°
50°
55°
60°
65°
70°
40°
35°
30°

portions of the return flow. This maximum, which is defined by values on the Sohm Abyssal Plain and the Bermuda Rise, is a clear indicator to the presence and geologic effectiveness of the return flow. The low sample distribution within the main flow precludes drawing similar conclusions.

A third important feature of this distribution is the manner in which the values rapidly decrease from their maximum near the return flow to normal, low, open ocean values further to the south and to the east. This boundary suggests that most of the geologically active bottom currents on the Bermuda Rise are confined to latitudes north of Bermuda (∿32°N). It is likely that these currents are associated with the Gulf Stream System. No similar boundary can be found in the nephelometer data on the northern boundaries of the gyre. This is to be expected, because the westward flow north of the Gulf Stream flowing in proximity to the Gulf Stream will be responsible for its own resuspension and transportation. The sparse sample distribution is not adequate to distinguish between the effects of the two current systems in these areas.

The distribution of suspended matter suggests that the Gulf Stream System is actively resuspending sediments within the North American Basin. Such active resuspension could be accompanied by the formation of flow-related sedimentary bedforms which could be recorded in bottom photographs.

E. Bottom Photographs

Hollister (1967) reports very murky conditions above the southeastern Sohm Abyssal Plain in the region of the flow. Fox et al. (unpublished manuscript) report on a series of oriented bottom photographs taken on the slopes of the Eastward Escarpment near 32°N. These photographs were taken on the southward facing slope of a re-entrant into the Bermuda Rise and on the northward facing slope of the same re-entrant immediately to the south. They saw evidence of eastward flowing currents on the northern slope and westward flowing currents on the southern slope. They interpreted these results as indicating the clockwise flow of Antarctic Bottom Water around the Bermuda Rise with Antarctic Bottom Water coming from the north, entering the re-entrant, and exiting at the south. While Antarctic Bottom Water is no doubt the water mass in motion at these depths it is probable that the portions of return flow impinging upon the Bermuda Rise drive contour following currents to the south. Photographs on top of the Rise showed evidence of westward flowing current, probably part of the return flow.

Although it is impossible to make quantitative estimates of flow velocity from bed forms observed in bottom photographs, it is possible to make qualitative distinctions as to the presence or absence of currents and vigorous versus tranquil flow conditions (Hollister and Heezen, 1972). Oriented photographs can give information as to flow direction. Tucholke et al. (1973) summarized all bottom photographs taken on the western half (to 60°W) of the North American Basin. One photograph was taken beneath the Gulf Stream System, about 60 km to the southeast (37°N, 65°W) of Zimmerman's current meter observation. It shows northeastward flow in keeping with the current vector reported by Zimmerman. Taylor et al. (1975) summarized a series of bottom photographs on the flanks and at the base of Gillis Seamount (35°15'N, 58°15'W) and suggested that northeast or southwest and southward flowing currents were observed below 2000 meters. Photographs above the abyssal plains were very murky suggesting significant suspended material.

Current velocity data plus evidence from bottom photographs suggest that the Gulf Stream System flows as a clockwise rotating system of abyssal currents in the northern North American Basin. Evidence from bottom photographs and the distribution of suspended matter suggests that this system is currently geologically active. It is important to examine the surficial sediments within this region to determine whether the sediment types and distribution are consistent with this interpretation.

F. Surficial Sediments

The texture, mineralogy, and lithology of surface sediments can provide information concerning modern sedimentary processes, such as whether it is plausible for a given current system to erode, transport, or deposit a given sediment type.

Horn et al. (1971) have investigated the grain size distribution in surficial sediments in the North American Basin and have found only fine-grained clays and silty clays on the Bermuda and Corner Rises. Much coarser (turbidite) sands and silts are found on the surrounding Hatteras and Sohm Abyssal Plains. Mineralogically the fine fraction of all these sediments is dominated by illite (Biscaye, 1965; Lisitzin, 1972). The percentage of calcium carbonate ranges between 10-50% within the central North American Basin with values below 4000 meters on the Northern Bermuda Rise ranging between 25-50% (Biscaye et al. 1976).

The dominance of illite in the fine-fraction suggests a terrigenous source in eastern North America and the high carbonate percentages suggests that erosion has not recently been a significant factor at this site, as significant erosion (1-2 meters) would have exposed the lower carbonate sediments (Silva et al. 1976) of the last glacial episode that accumulated at these depths.

These sediment parameters could indicate deposition on the Bermuda Rise and the Corner Rise from either bottom currents or by pelagic processes, but in and of themselves they cannot distinguish between the two. Silva (1976) presented C14 date based sedimentation rates from a single Giant Piston Core (GPC-5) taken in these fine grained lutites on the Bermuda Rise. Very high, carbonate-free sedimentation rates (170 cm/1000 years) were recorded for the last 210 years. These rates are much higher than those associated with the pelagic accumulation of fine-grained, terrigenious sediments (Lisitzin, 1972). This observation coupled with the observation by Biscaye (1965) that authigenic clay minerals are not present suggests that these sediments are not of pelagic origin.

G. Discussion

The association of the maximum of suspended matter with the return flow and its associated eddy field suggests that this anomaly may be due to either or both of these current fields. Since the eddies typically have velocities exceeding 40 cm/sec and the mean flow 10 cm/sec it is interesting to speculate that the eddies are of primary importance in resuspending sediments and the mean flow is responsible for redistribution.

Discussing this speculation in quantitative terms is made difficult by the numerous problems in relating necessarily simplified laboratory experiments on the erosion of sediments to the very different deep-sea environment. This is both because experiments have failed to duplicate such potentially important factors as *in situ* strength, cementation, grain orientation, microtopography, and the influence of biological activity; because they have used sediments with differing clay mineralogies, organic carbon contents, and grain size distributions than the surficial sediments of the Bermuda Rise.

Lonsdale and Southard (1974) show that North Pacific red clays with water contents similar to those on the Bermuda Rise are first eroded in currents between 35-45 cm/sec. Postma (1967) suggests velocities in excess of 70 cm/sec are necessary to erode estuarine sediments of similar water content. The Pacific red clays differ from Bermuda Rise sediments in percentage organic carbon, but are similar in clay mineral compositions. The Pacific red clay average from 0.01-0.05% carbon (Hessler and Jumars, 1974) whereas surficial sediments on the northern Bermuda Rise average about 0.5% carbon (Farrington, personal communication). Organic carbon in cohesive sediments has physico-chemical nature similar to that of clay minerals (Lamb & Whitman, 1969) and for this reason the higher organic carbon content in the Bermuda Rise sediments may indicate a higher critical erosion velocity than might be indicated by analogy to the red clays. The estuarine sediments tested by Postma should have an organic carbon content closer to that of the Bermuda Rise sediments, although Postma (1967) does not state the organic carbon content. However, the composition of both the clay and silt fraction of these sediments differs significantly from the Bermuda Rise sediments, having less illite and higher quartz and feldspar. For these reasons it is also difficult to apply Postma's results directly to the Bermuda Rise sediments.

Lonsdale and Southard (1974) have shown that the presence of manganese nodules and presumably other elements of microtopography lower the critical erosion velocity of a given sediment type. Bottom photographs show in some cases a fairly complex bottom with small scale scarps and ridges, and occasional clay blocks (Fox et al., unpublished ins). Presumably these features would lower the critical erosion velocity for any given sediment below that for a smooth, featureless bed as was indicated by Lonsdale and Southard.

Lonsdale and Southard (1974) have also suggested that injection of material into the currents flow by organisms might be an important factor in entraining sediments. In this circumstance the term "erosional velocity" has no meaning and the most important factor is of course the velocity necessary to keep the sediments in suspension. They have also suggested that very low levels of erosion take place at lower current velocities; however, the frequency and the energy of the eddies probably minimize the geologic effectiveness of this process.

Because of these problems it is not possible to determine unequivocably whether the eddy field alone or the combined eddy field and mean flow are responsible for the maximum in suspended mass in the Bermuda Rise. It is probable, however, that given the much higher velocities observed in the eddy field, that the eddies are the primary agent for resuspending sediments and the mean flow responsible for the westward redistribution.

CHAPTER III

POST-HORIZON A SEDIMENTS

A. Introduction

This section will divide the region beneath and adjacent to the Gulf Stream System into acoustic provinces based on airgun and 3.5 kHz seismic profiles and present the evidence for the geologic character and age of the sediments.

Tucholke (1977) has discussed the deep acoustic stratigraphy of this region up to and including Horizon A and shown that Horizon A is a relatively smooth reflecting surface that extends throughout most portions of the North American Basin and which can be divided into a complex of four separate, closely spaced reflecting horizons with differing areal distributions. Three of these reflecting horizons have been found to be composed of chert, volcanic sediments and siliceous turbidites deposited during the early and early middle Eocene. The fourth is a hiatus in Tertiary sediments that formed along the continental margins during the late Eocene. Levelling processes dominated the pre-Horizon A sedimentary regime of the North American Basin producing the relatively smooth seafloor on which the Horizon A complex developed (Tucholke, 1977). Post-Horizon A sedimentary processes appear to have been dominantly constructional in nature, building distinct sedimentary bodies upon the Horizon A complex. It is these sedimentary bodies that will be discussed in the following sections.

In order to interpret how the Gulf Stream System influenced post-Horizon A sedimentary activity in the North American Basin, five separate sedimentary features will be described: (1) acoustically laminated Pleistocene sediments on the eastern margin of the central to northern Bermuda Rise; (2) acoustically non-laminated Miocene/Pliocene deposits that comprise the major portion of an anomalously thick sediment accumulation on the northern Bermuda Rise; (3) a partially eroded ridge (the Gulf Stream Outer Ridge) of probable Miocene/Pliocene age that forms the transition between the southwest Sohm Abyssal Plain and the northern Bermuda Rise; (5) a second ridge (the Hudson Outer Ridge of Miocene/Pliocene age that lies partially buried beneath portions of the lower continental rise south of the Hudson Fan; and (6) turbidites beneath the Sohm and Hatteras Abyssal Plains and ponded behind the Hudson Outer Ridge.

This description will be primarily based on an examination of available air gun and 3.5 kHz seismic profiles. This work is supplemented by available core and drilling results.

B. Acoustically Laminated Deposits

Distribution

Acoustically laminated sediments are distributed primarily on the northern Bermuda Rise and portions of the Corner Rise (Fig. 4). The thickest deposits are found on the eastern margin of the central and northern Bermuda Rise. In this region they extend southward from the New England Seamount chain to slightly south of the latitude of Bermuda. They are found in the interior of the plateau to about the longitude of Bermuda. At this point several ridge-like deposits extend even further to the west (Fig. 11).

These sediments form caps on the small plateaus and hills in the Plateau province (Heezen and Tharp, 1959) and do not appear on the scarps that form the sides of these features except near 34°N and 58°W where crumpled sediments at the base of a scarp have been interpreted as slumps (Silva et al., 1976). These deposits generally cap pre-existing topography, but they do not lie conformably on it (Fig. 5).

Similar deposits appear to blanket the north face of the Corner Rise (McGregor et al., 1973); however the relative scarcity of profiles in this region (McGregor et al., 1973) precludes division of this region into acoustic provinces as on the Bermuda Rise.

Fig. 4 Distribution of acoustically laminated and non-laminated sediments on the Northern Bermuda Rise. Acoustically laminated sediments cap non-laminated ones on the eastern margin of the rise. Data base for this is Lamont-Doherty Geological Observatory (Ewing et al.,1974) and Woods Hole Oceanographic Institution collected seismic profiles.

ACOUSTIC PROVINCES ON THE NORTHERN BERMUDA RISE

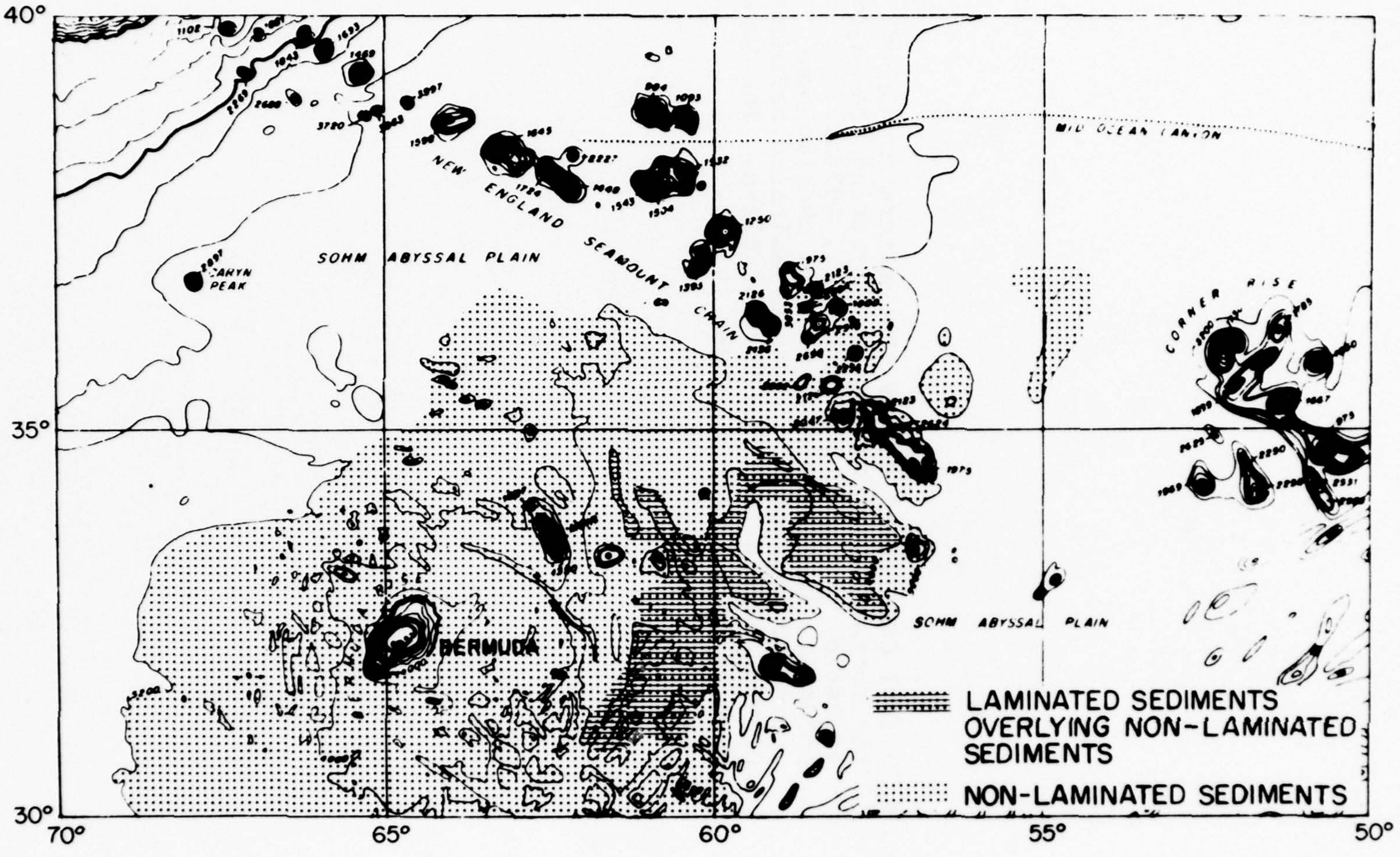


Fig. 5 V 2601 CSP record across the eastern margin of the northern Bermuda Rise illustrating the major acoustic provinces (Ewing et al., 1974a). Acoustically laminated sediments overlie non-laminated sediments. The non-laminated sediments plunge beneath the Sohm Abyssal Plain. The location of this figure is shown in Fig. 8.

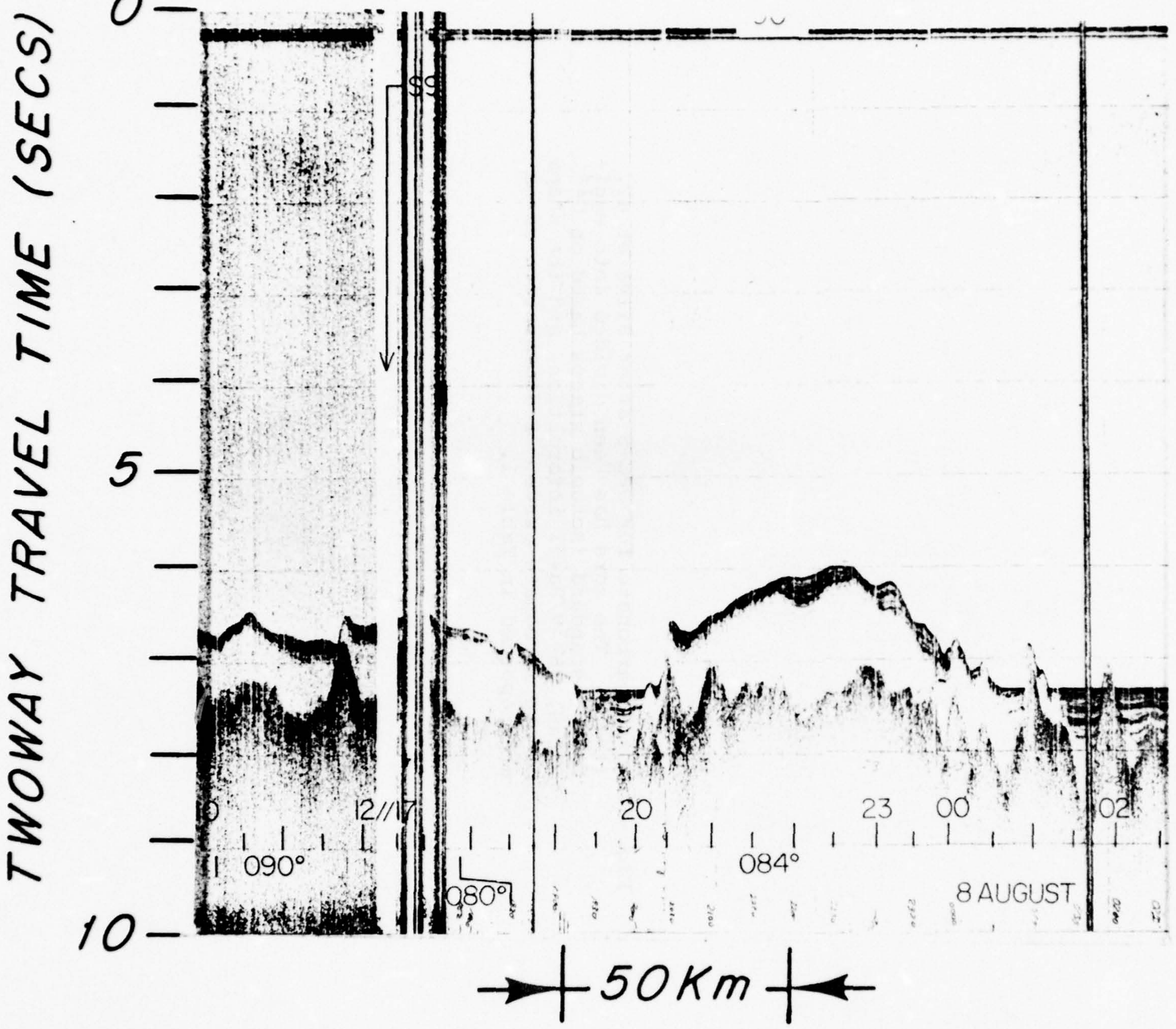
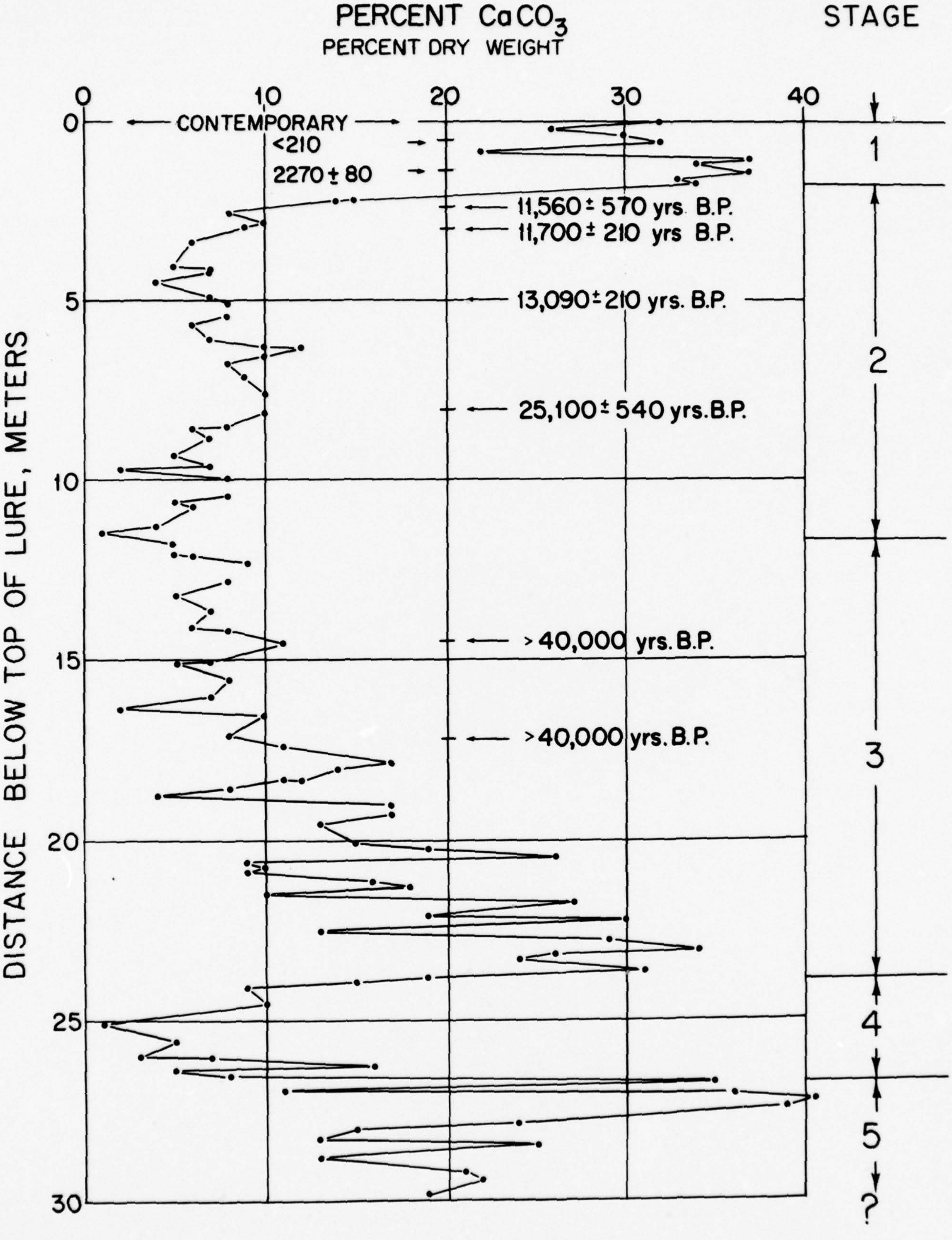

TWOWAY TRAVEL TIME (SECS)
0
5
10
S9
12//17
20
23
00
02
090°
080°
084°
8 AUGUST
50Km

Fig. 6 Total carbonate for GPC-5 after Silva et al. (1976). The core has been divided into equivalent standard isotopic stages based on C^{14} dates, Th^{230}/Pa^{231} information, and the shape of the carbonate curve. Sedimentation rates are reported in Table 1.


PERCENT CaCO$_3$
PERCENT DRY WEIGHT
STAGE
0
10
20
30
40
CONTEMPORARY
<210
2270 ± 80
11,560 ± 570 yrs. B.P.
11,700 ± 210 yrs B.P.
13,090 ± 210 yrs. B.P.
25,100 ± 540 yrs. B.P.
>40,000 yrs. B.P.
>40,000 yrs. B.P.
DISTANCE BELOW TOP OF LURE, METERS
0
5
10
15
20
25
30
1
2
3
4
5
?

Age at the Base of the Laminated Sediments

Silva et al. (1976) reported total carbonate values and sedimentation rates based on C14 dates from GPC-5 (Fig. 6). These sedimentation rates are given in Table 1.

In order to estimate the age at the base of the laminated sediments and also to discuss the effect of climatic changes on sedimentation, the age at various depths in GPC-5 was estimated. Variations in the total carbonate curves have previously been shown to mirror variations in oxygen isotope ratios in Northern Atlantic (McIntyre et al., 1972; Emiliani, 1970) and Equatorial Atlantic (Damuth, 1976) cores. These isotopic curves have been divided into stages and ages assigned to the beginning and end of each stage (Hays et al., 1976). By comparison of the carbonate curve for GPC-5 with the curves of isotopic variation, isotopic stages were identified and ages assigned to points in GPC-5. This procedure was supplemented by the C14 dates in the upper portions of the core and limits on the possible age at depth supplied by interpretation of Pa^{231}/Th^{230} results (Bacon, 1977, personal communication). All age assignments made by interpretation of the carbonate curve are in agreement with the C14 and Pa^{231}/Th^{230} constraints.

Table 1. Sedimentation rates for various intervals in GPC-5. The upper rates are based on C^{14} dates reported by Silva, et al. (1976) and the lower rates are based on an interpretation of the calcium carbonate curve (Fig. 6) based on the C^{14} dates and Pa^{231}/Th^{230} information. The figures in parentheses are carbonate-free accumulation rates.

TABLE 1

SEDIMENTATION RATES FOR GPC-5

C14 based rates

Depth Interval	Interval Rate
0. -0.5 m	240 cm/1000 yr. (170)
0.5-1.5 m	48 cm/1000 yr. (36)
1.5-2.5 m	11 cm/1000 yr. (8)
2.5-3.0 m	143 cm/1000 yr. (130)
3.0-5.0 m	164 cm/1000 yr. (150)
5.0-8.0 m	25 cm/1000 yr. (24)
0. -8.0 m	32 cm/1000 yr. (27)

RATES BASED ON INTERPRETATION OF THE CARBONATE CURVES

Stage	Depth	Rate
1 (0-10 K yrs.)	0-2.0 m	20 cm/1000 yrs. (14)
2 (10-29 K yrs.)	2.0-12.0 m	53 cm/1000 yrs. (49)
3 (29-61 k yrs.)	12.0-24.0 m	38 cm/1000 yrs. (32)
4 (61-73 k yrs.)	24.0-26.5 m	21 cm/1000 yrs. (20)
Rate to 26.5 m		36 cm/1000 yrs. (33)

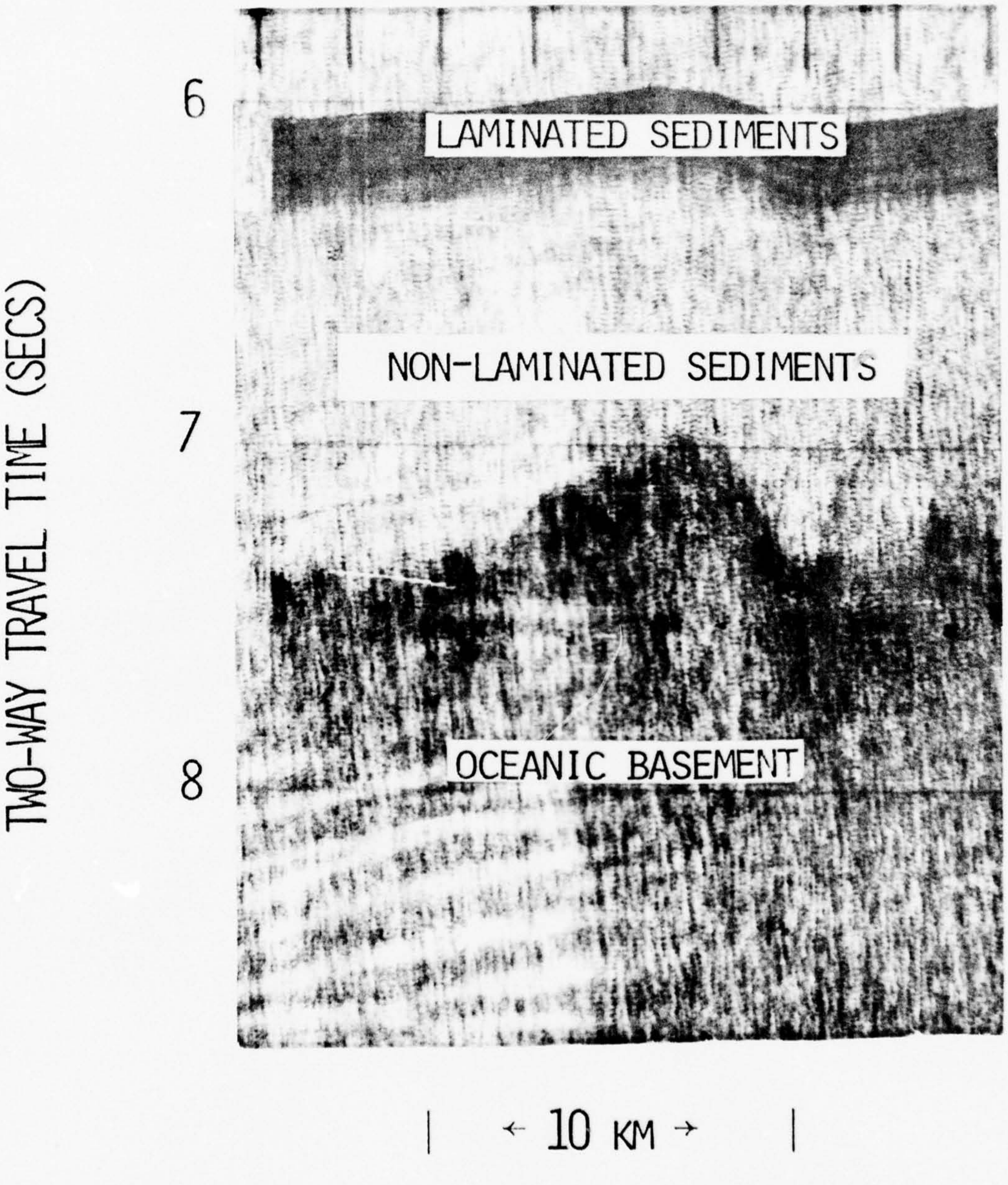
Following this procedure, sections of the core have been assigned dates as follows: the high carbonate section from 0-2.0 meters to Stage 1 (0-11,000 years BP); the low carbonate section from 2.0 to 11.5 meters to Stage 2 (11,000-29,000 years BP); the section of alternating low and high carbonate values between 11.50 and 24.0 meters to Stage 3 (29,000-61,000 years BP); and the low carbonate section from 24.0 to 26.5 meters to Stage 4 (61,000-73,000 years BP).

Stage 1 represents the warm climatic conditions of the present interglacial (Holocene) and the C14 dates in the uppermost portions of the core suggest that this zone has been properly assigned with the core. Stage 2 represents the climatic cold period of major glaciation at the end of the Pleistocene. The two C14 dates at 2.5 and 3.0 meters suggest that the Stage 1-2 boundary has been properly assigned in the core and the date at 8.0 meters supports the base of stage being deeper. Stage 3 represents a period of alternating warm and cold climates based solely on the shape of the carbonate curve and Stage 4 is the brief period of intense cold at the end of the last interglacial. The results of the Pa^{231}/Th^{230} analysis indicate that the age of the base of the core cannot be greater than 100,000 years (Bacon, 1977, personal communication).

Using the total carbonate values given in Fig. 6, average carbonate-free sedimentation rates have been calculated for all intervals and the results entered in Table 1.

The C14 dates in GPC-5 indicate that the uppermost portions of the Pleistocene and also the entire Holocene are present. This establishes a minimum age for the laminated sediments on this part of the Bermuda Rise. The age at the base of the laminated sediments can be estimated using sedimentation rates and the true thickness of the sediments. The laminated sediments beneath GPC-5 are about 0.3 sec. of two-way travel time thick (Fig. 7). This travel time can be converted to a thickness if some estimate is available for the interval velocity of the laminated sediments. Houtz (1974) has presented equations for the variation of sediment compressional wave velocity with depth (time) for various geographic localities and sedimentary environments. These equations are based on measurements of interval velocities obtained by oblique incidence reflection-sonobuoy techniques (LePichon et al., 1968). Although equations for many environments are presented the acoustically laminated sediments on the Bermuda Rise are not included. The most similar province in the nearby area is the Western North Atlantic Continental Rise and its

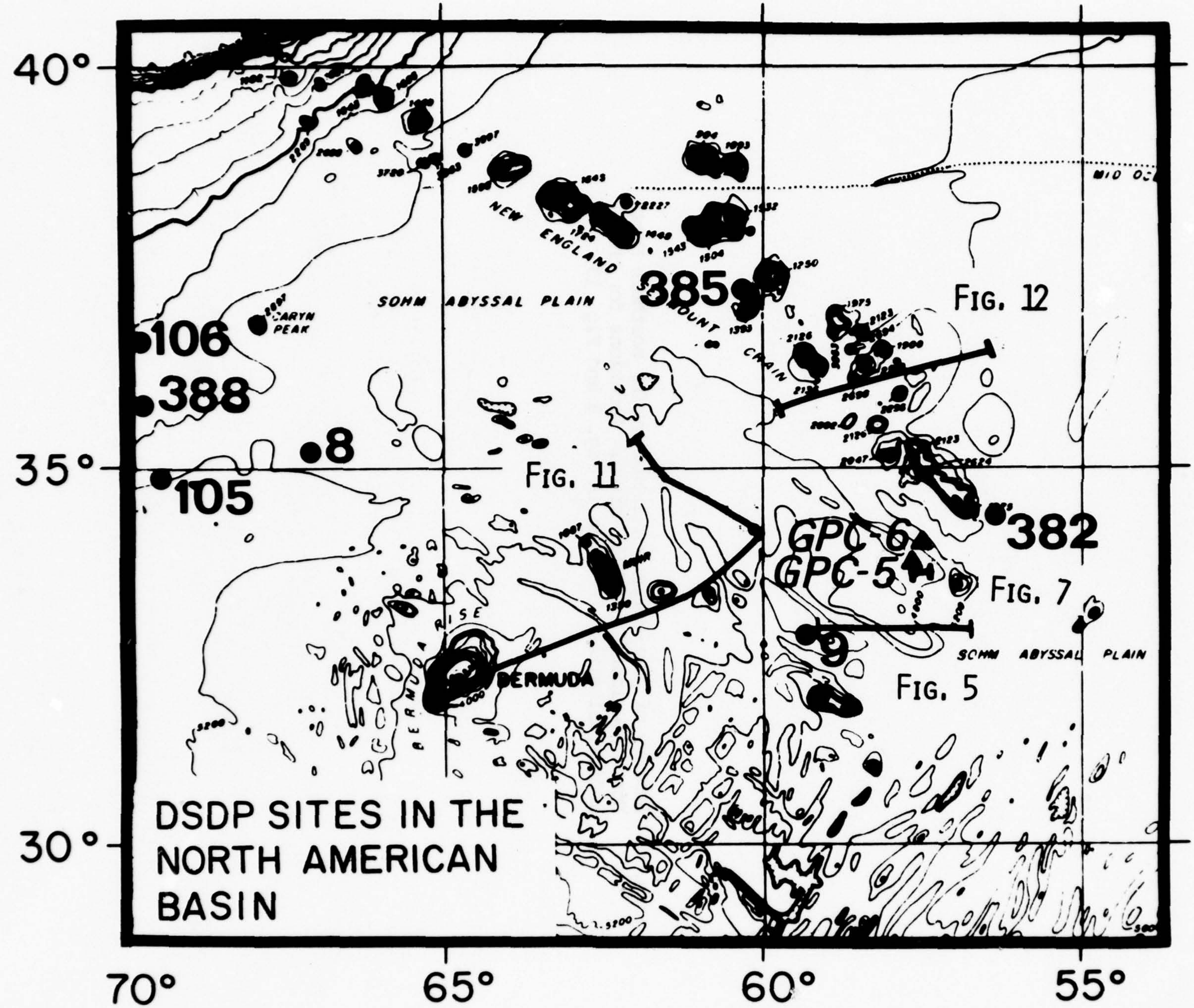
Fig. 7 KN 31-1 CSP record showing acoustic stratigraphy at GPC-5. About 0.3 seconds of acoustically laminated sediments cover older non-laminated sediments. This profile is located in Fig. 8.


TWO-WAY TRAVEL TIME (SECS)
6
7
8
LAMINATED SEDIMENTS
NON-LAMINATED SEDIMENTS
OCEANIC BASEMENT
← 10 KM →

equation was used to calculate the sound velocity at the base of the sediments. In fact any of the several equations for Atlantic Ocean environments would have produced substantially similar results.

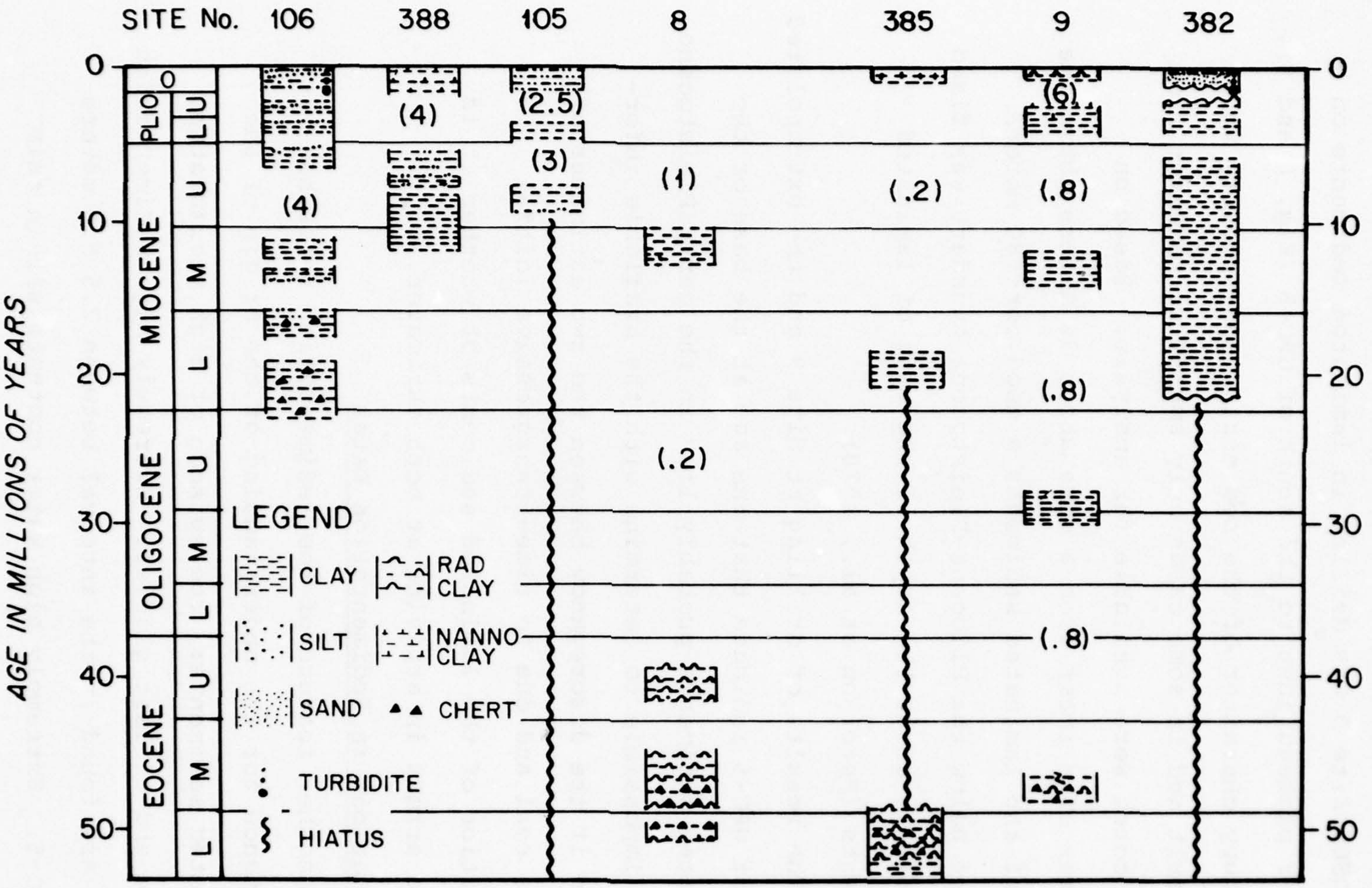
Using the measured two-way travel time thickness of 0.3 sec. and the calculated interval velocity of 1.7 km/sec. a depth of about 260 meters was calculated for the base of the laminated sediments. Using the average sedimentation rate of 36 cm/1000 years that was obtained at the base in GPC-5 the age at this depth is estimated to be about 0.7 My BP, the lower part of the Upper Pleistocene. It should be noted that this calculation does not take into account post-depositional changes in thickness due to compaction or changes in sedimentation rates. If compaction has occurred then the calculated age is too young. If changes in sedimentation rate have occurred then the calculated age is either too old or too young. There is evidence which suggests in an indirect way that sedimentation rates were lower in the earlier portions of the Pleistocene. Shackleton and Opdyke (1973) and van Donk (1976) have both given evidence for less severe and shorter glaciations prior to about 0.7 My BP. It is not unreasonable to assume that under these conditions that lower amounts of terrigenous material were injected into the ocean basin and ultimately deposited on the Bermuda Rise.

Fig. 8 DSDP sites, Giant Piston Cores, and seismic profile locations in the northern North American Basin.



DSDP SITES IN THE NORTH AMERICAN BASIN

Fig. 9 Summary of post-Horizon A lithology for northern North North American Basin DSDP sites. Locations for the individual sites are given in Fig. 8 and Fig. 13.


SITE No.
106
388
105
8
385
9
382
AGE IN MILLIONS OF YEARS
0
10
20
30
40
50
PLIO
MIOCENE
OLIGOCENE
EOCENE
Q
U
L
U
M
L
U
M
L
U
M
L
(4)
(4)
(2.5)
(3)
(1)
(.2)
(.2)
(6)
(.8)
(.8)
(.8)
LEGEND
CLAY
RAD CLAY
SILT
NANNO CLAY
SAND
CHERT
TURBIDITE
HIATUS

DSDP Site 9 was drilled in laminated sediments on a similar plateau just to the south of GPC-5 (Fig. 8 and 9). The soupy character of the sediments made recovery very difficult and in some cases only smears of sediment from empty cores were available for analysis. Based on analysis of a smear from a core about 30 meters above the base of the laminated sediments a good core 80 meters further below the Pliocene-Pleistocene boundary was fixed tentatively about the depth of the base of laminated sediments (Peterson et al., 1970).

The results of drilling at Site 9 and the extrapolated date of GPC-5 indicate that the age at the base of the laminated sediments probably lies in the early Pleistocene. It is impossible to determine with the available information if the discrepancy between the two estimates of age is real and due to time-transgressive initial deposition of the laminated sediments or whether it is due to errors in arriving at both estimates.

Fluctuations in Sedimentation Rates

Another feature of the sedimentation rates has importance for the understanding of the origin of the laminated sediments: the episode of high accumulation at the end of last glacial. Extremely high sedimentation rates are found in the interval between 2.5-5.0 meters in GPC-5. Extremely high water contents within this interval indicate that the sediments accumulated so rapidly that the sediments could not properly compact (Silva et al., 1976). This pattern of sedimentation can also be related to climatic events on the continent. Kennett and Shackleton (1975) have shown that between 17,000 and 13,500 years BP the majority of the melt-water from eastern and central North America drained southward through the glacial Mississippi River system. About 13,500 years BP the eastern fraction of this melt-water began to drain through the St. Lawrence system into the Atlantic. This switch-over was complete about 11,500 years BP. The high sedimentation rates in GPC-5 are probably a result of the sudden increase of input of terrigenous material that accompanied the change. By 11,000 years BP most of the glacial ice had disappeared and the input returned to more normal interglacial levels.

This result suggests that the laminated sediments may be derived from eastern Canada. This speculation needs to be examined in more detail in terms of the lithologic characteristics of the sediments.

Sedimentary Characteristics of the Laminated Deposits

Several features in the visual core description, textural analysis, and clay mineralogy of GPC-5 have bearing on the origin of the laminated sediments. Silva et al. (1976) have reported the clay mineralogy

Table 2. Grain size of the carbonate-free fraction of the upper portions of GPC-5 estimated using Coulter counter technique of Gardner (1977). These figures are biased slightly low due to use of HCl to remove the carbonate which has the effect of dissolving some chlorite. Due to the low chlorite contents (∿10%, Silva, et al. (1976)) the effect on the grain size estimates should be minimal.

TABLE 2

GRAIN SIZE OF GPC-5 SEDIMENTS
(Carbonate free)

Depth	Average Grain Size
5 cm	3.42
60 cm	3.65
110 cm	3.96
149 cm	3.95
200 cm	3.08
250 cm	4.00
260 cm	5.08
287 cm	6.99
317 cm	2.94
349 cm	2.69
360 cm	2.11
370 cm	2.70

Preceding Page Blank - Filmed

(<2μm fraction) of GPC-5 to be dominantly illite (70%) with lesser montmorillonite (14%), chlorite (10%), and Kaolinite (6%). Hathaway (1972) and Piper et al. (1977) has shown that shelf and estuarine sediments north of Chesapeake Bay and in eastern Canada are dominated by illite with secondary chlorite. This composition was thought to reflect mechanical weathering processes in the metamorphic terrane of New England and eastern Canada. South of the Chesapeake, sediments are characterized by montmorillonite and secondary kaolinite. This is thought to be the result of the intense chemical weathering of the southern drainage basins. Therefore, composition suggests that these fine-grained sediments have their source in New England or eastern Canada. This ambiguity as to source can be narrowed down by examining the colors of the sediments in GPC-5.

A cyclic series of subtle color variations in GPC-5 is reminiscent of the repetitive red and rose-grey lutite units described by Hollister (1967) and traced back to a source in New Brunswick and Nova Scotia. This series appears in the low carbonate sections of GPC-5 between 252-1460 and 2368-2621 (Johnson and Driscoll, 1976). Each of these 16 units is separated from those above and below by sharp though subtle contacts. The average thickness of each unit is 91 cm with extremes from 35 to 193 cm.

Each unit is divided into two sections: a lower short (average 15 cm) section of greyish-orange brown lutite grades upward over an interval of about 10 cm into a longer average (76 cm) section of brownish-olive grey (5Y 5/2) lutite.

The presence of cyclic units containing sections with sediments in the same hue family (red-orange) as the red lutites described by Hollister elsewhere in the basin suggests that these lutites may be very dilute equivalents of the reddish lutite and may bear a similar source.

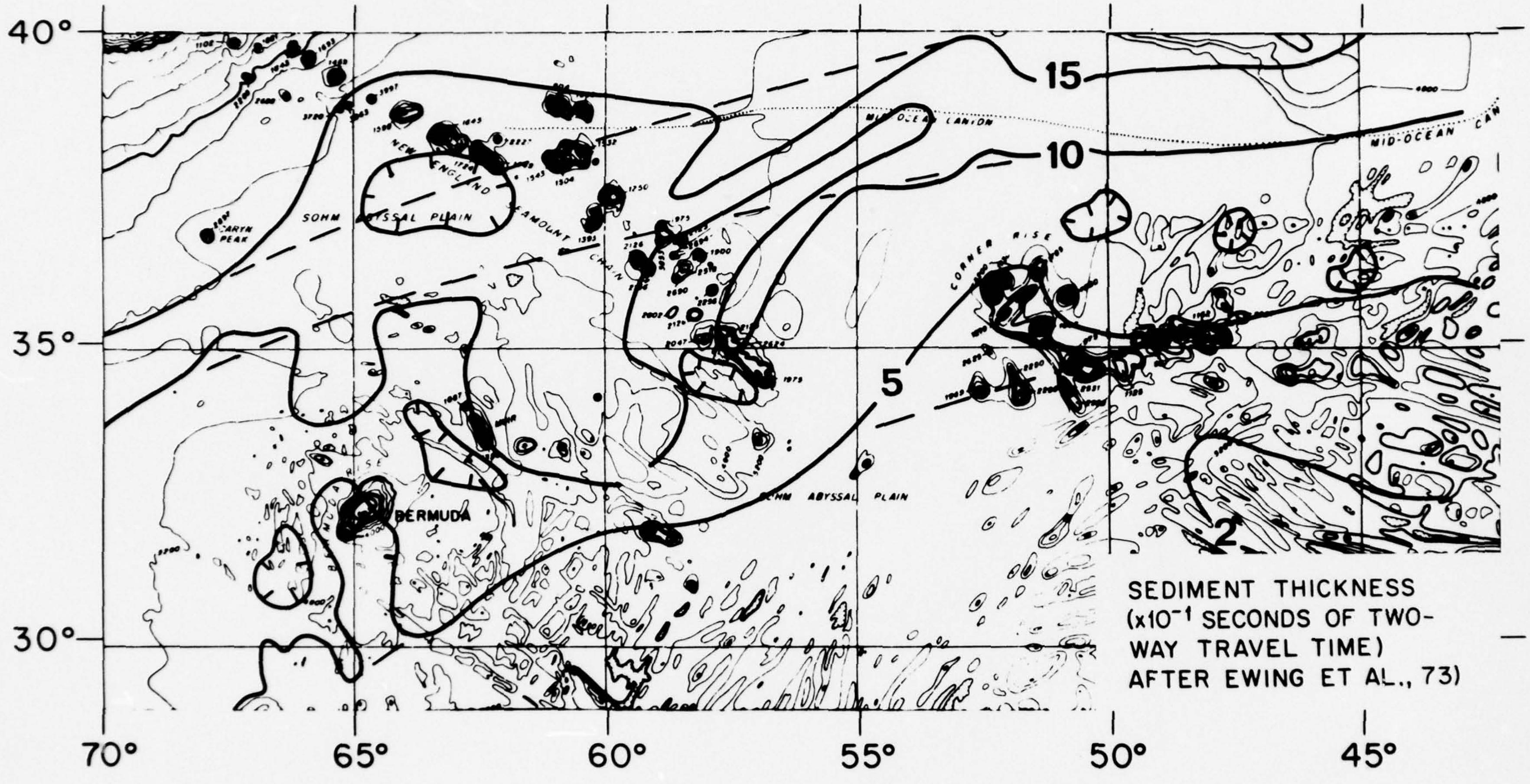
Silva et al. (1976) reported on the sand/silt/clay percentages of GPC-5 and found average values of 1% sand, 36% silt, and 63% clay (<2µ). Samples from the upper portions of GPC-5 were treated with 6% HCl and the resulting non-carbonate fraction analyzed for grain size using the Coulter counter technique of Gardner (1977) (Table 2). It is realized that treatment with HCl will dissolve portions of the chlorite in these sediments; however, since chlorite is such a small fraction in the total (Silva et al., 1976), the influence of this error in technique on the final results is probably negligible.

C. Acoustically Non-Laminated Sediments

Ewing et al. (1973) have presented a map of sediment thickness in the Atlantic Ocean in which an anomalously thick sequence of sediments lies beneath the Gulf Stream System on the northern Bermuda Rise (Fig. 10). This deposit is bound on the north by the New England Seamounts and on the south by a parallel, though less well developed seamount chain of which Muir Seamount is the largest. The accumulation has an eastern border at the Eastward Scarp. On the west the deposit is isolated from sediments further to the west by a depression in the isopachs near 37°N and 62-65°W (Fig. 10). Thicknesses exceed 1 sec. of two way travel time, or about 1000 meters if an interval velocity of 1.90 km/sec. is used (Houtz, 1974).

The sediments which comprise this pile are primarily non-laminated (Fig. 5 and 10) although near the eastern boundary of the Bermuda Rise they are overlain by 0.1-0.3 sec. of the acoustically laminated sediments previously discussed. It is difficult to trace the Horizon A complex of Tucholke (1977) beneath the pile from any of the locations where it is well-identified. Its distribution is very spotty, being mainly found in the valleys between local basement highs. A diffuse reflection event spread out over about 0.3 sec. of travel time does appear in some profiles (Fig. 11) in the region between the two parallel

Fig. 10 Sediment thickness in the northern North American Basin after Ewing et al. (1973). The solid lines are contours of measured sediment thickness and the dashed lines represent a smooth decrease in thickness away from the continent. Note the angmalously thick pod of sediments centered about 34°N and 61°W. This accumulation is composed primarily of acoustically non-laminated sediments capped by laminated sediments in the east. The return flow of the Gulf Stream System flows above this accumulation.



SEDIMENT THICKNESS
(x10^{-1} SECONDS OF TWO-WAY TRAVEL TIME)
AFTER EWING ET AL., 73)

seamount chains. The general effect of this acoustic interval is to smooth topography. Because of its presence the sediments are best characterized as non-laminated rather than acoustically transparent.

The non-laminated sediments thin noticeably away from the 1.0 sec. thick pile. To the north they extend through the New England Seamounts forming in many cases pockets of sediments resting on the flanks of the seamounts (Taylor et al., 1975). North of the seamounts they plunge beneath the Sohm Abyssal Plain and can be traced only with great difficulty to the north (Tucholke et al., 1977). The acoustic opacity of the turbidites makes it impossible in most cases to measure the thickness of the non-laminated zone. Just north of the seamounts, however, occasional thick "islands" of the non-laminated sediments rise from beneath the turbidite (Fig. 12). In these instances there is no capping of laminated sediments.

To the east of the Bermuda Rise the non-laminated sediments plunge beneath the Sohm Abyssal Plain where they can be traced further to the east as a thinner (0.3 sec.) sequence. They can be found on the flanks of the Mid-Atlantic Ridge in thin accumulations above Horizon A. To the northeast they are also found on the Corner Rise in accumulations that sometimes exceed 0.75 secs. of thickness.

To the south the non-laminated sediments thin to less than 0.5 secs. thickness between the Muir Seamount Chain

Fig. 11 V 23-07 CSP from Bermuda into the center of the anomalously thick non-laminated sediments on the northern Bermuda Rise (Ewing et al., 1974a). Note the thin sequence between Bermuda and Muir Seamount and the thickening to the north of the seamount. A diffuse reflector appears mid-way between the basement and the sediment surface.

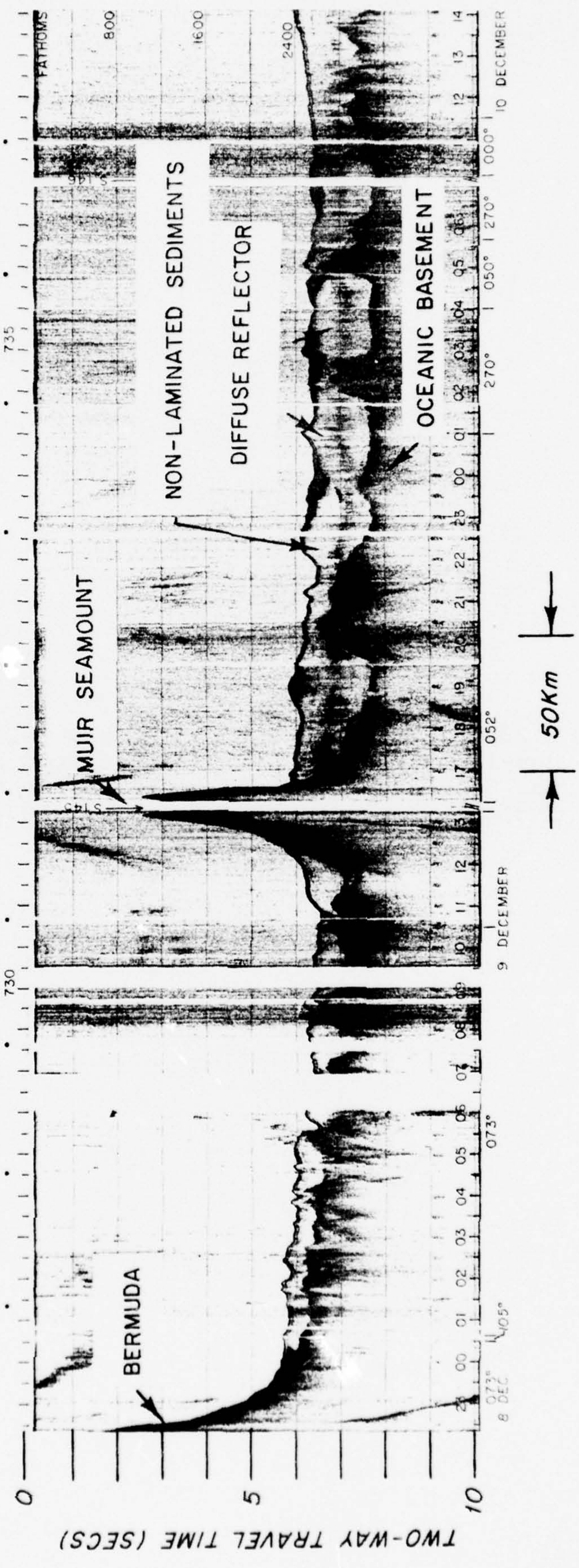
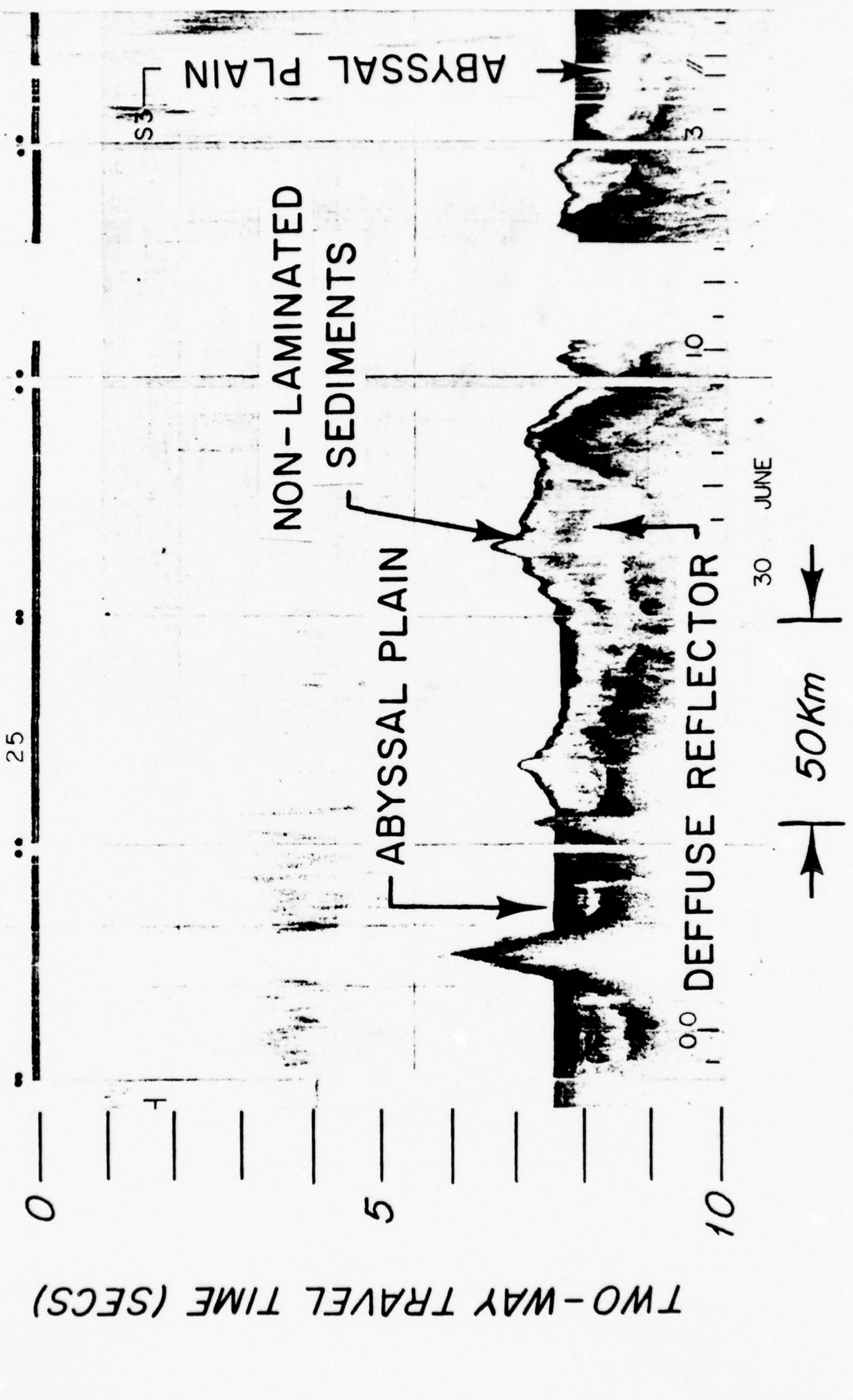

TWO-WAY TRAVEL TIME (SECS)
0
5
10
FATHOMS
800
1600
2400
730
735
BERMUDA
MUIR SEAMOUNT
NON-LAMINATED SEDIMENTS
DIFFUSE REFLECTOR
OCEANIC BASEMENT
50Km
8 DEC
073°
105°
073°
9 DECEMBER
052°
270°
050°
270°
000°
10 DECEMBER

Fig. 12 V 2801 CSP record across several islands of non-laminated sediments that extend above the Sohm Abyssal Plain north of the New England Seamounts (Ewing et al., 1974b).


TWO-WAY TRAVEL TIME (SECS)
0
5
10
25
0.0
30
JUNE
10
3
S3
ABYSSAL PLAIN
NON-LAMINATED SEDIMENTS
ABYSSAL PLAIN
DEFFUSE REFLECTOR
50Km

and Bermuda. To the south of Bermuda these sediments thin until they occupy an interval less than 0.2 sec. thick between the sea surface and Horizon A.

The non-laminated sediments thin to the west until they reach the center of the depression on the western Bermuda Rise at which time they merge with the deposits of the Gulf Stream Outer Ridge.

The acoustically non-laminated sediments have been sampled in four locations: three times by the DSDP at Sites 9, 382, and 385 (Tucholke et al., 1977) and once by GPC-6 (Silva et al., 1976) (Figs. 8, 9). In all cases the sediments were fine grained hemipelagic lutites with interspersed zones alternately rich and depleted in carbonate.

This accumulation is anomalous for several reasons: the first relates to the presence of a pile of sediments of significantly greater thickness than those surrounding it. The simplest accumulation model predicts steady decrease of sediment thickness with increasing distance from the nearby continental margin as illustrated in Fig. 10. The second anomalous feature of this accumulation is its presence beneath very unproductive surface waters of the Sargasso Sea (Emery and Uchupi, 1972). The presence of a thick sequence of sediments rising 800 meters above the bordering Sohm Abyssal Plain in the absence of basement structure (Fig. 5) suggests that some process has actively and perhaps selectively deposited sediments on this portion of the Bermuda Rise.

Sedimentation rates for the hemipelagic sediments range between 0.1-1.0 cm per thousand years (Tucholke, 1977; Silva et al., 1976). These rates are consistent with either a bottom current or pelagic origin. Based on the presence of plant debris, the presence of fine quartz, and the absence of authigenic minerals, and the absence of silt or sand layers, these deposits have been interpreted as bottom current deposits (Tucholke, 1977). The Tertiary hiatuses found at Sites 382 and 385 (Fig. 9) have been interpreted as due to bottom current erosion (Tucholke et al., 1977). Slumping has been ruled out on the basis of seismic profiles.

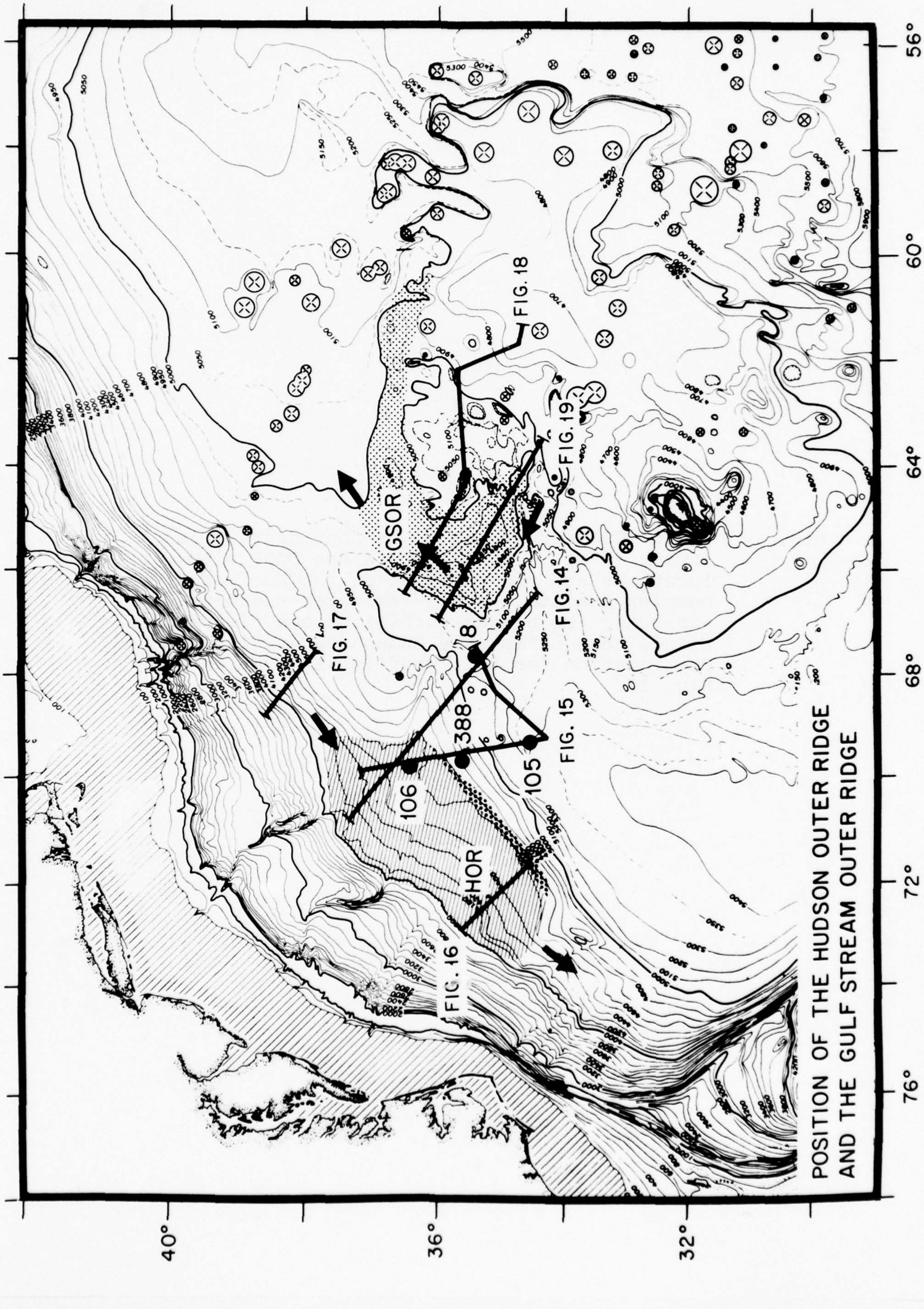
The non-laminated sediments are easternmost of the two major post-Horizon A formations that are found on the northern Bermuda Rise. To the west these sediments thin remarkably (Fig. 18) creating a depression in the iospachs (Fig. 10). To the west of this depression lies the second major accumulation, the Gulf Stream Outer Ridge.

D. Hudson Outer Ridge

The sedimentary structure and the resulting shape of the continental rise adjacent to the Gulf Stream System are distinctly different from the provinces both to the north and south. Heezen et al. (1959) first pointed out that the morphology of the continental rise between the Hudson Fan and the Hatteras Transverse Canyon is internally homogeneous and distinct from that in the provinces to the north and south. In this region, termed the northeastern United States region, the continental rise consists of two relatively smooth and flat terrace-like features separated from each other by a more steeply dipping slope. These features are termed the upper and lower continental rises. The flatest portions of the upper rise are about 67 km wide, have gradients of 1:275, and lie between 2650-3020 meters. The lower continental rise has slopes of about 1:1400 and lies at about 4300 meters. The transition zone between the lower continental rise and the abyssal plain is the region of lower continental rise hills.

North of the N.E. seamounts, the continental rise morphology is distinctly different. The terrace-like features are not present and the continental rise descends from the continental slope beginning with gradients of 1:60 (at steadily decreasing slopes) until it merges with the Sohm Abyssal Plain at a gradient of about 1:1000. A similar shape is observed in profiles across the small segment of continental rise between the Hatteras Transverse Canyon and the Blake Outer Ridge.

Fig. 13 Location of the Gulf Stream Outer Ridge and the Hudson Outer Ridge. Note the ponded turbidites behind the Hudson Outer Ridge. Note also the DSDP site locations and the positions of seismic profiles in later figures.



POSITION OF THE HUDSON OUTER RIDGE AND THE GULF STREAM OUTER RIDGE

Fig. 14 V 2307 CSP across the lower continental rise (Ewing et al., 1974a). Note the DSDP site locations and the presence of the Horizon A complex beneath the non-laminated sediments. Stripping the ponded turbidites away leaves a ridge, here called the Hudson Outer Ridge. The location for this profile is given in Fig. 13.

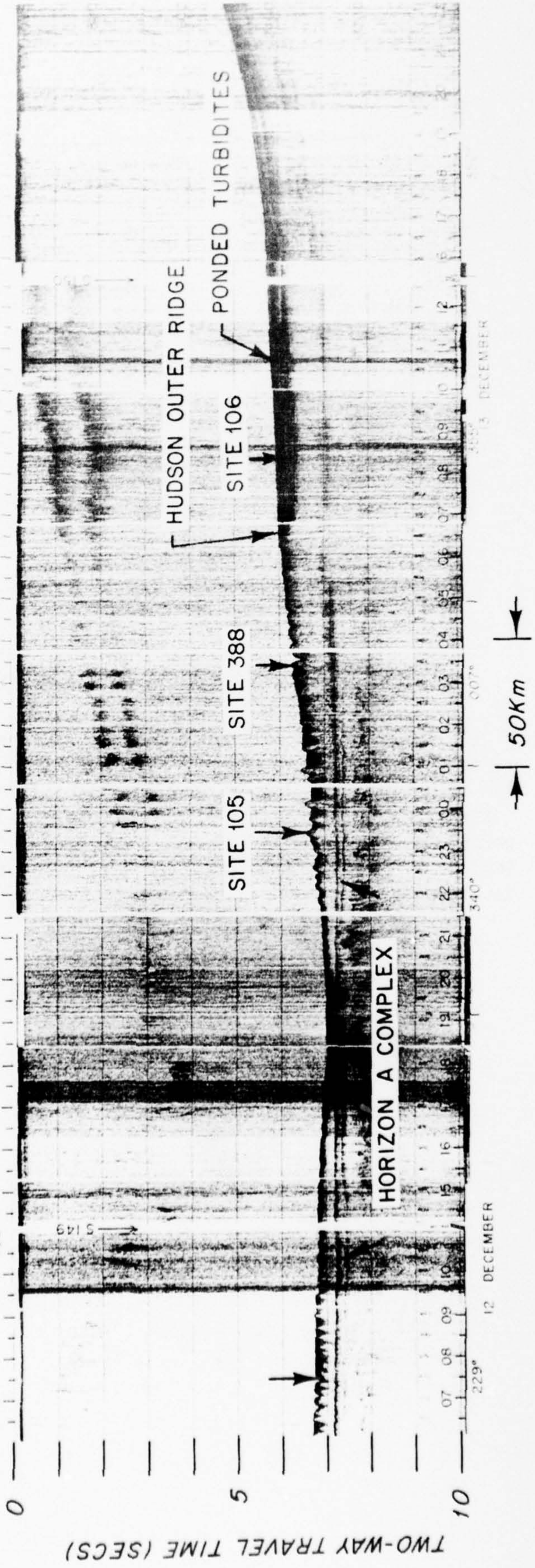

PONDED TURBIDITES
HUDSON OUTER RIDGE
SITE 106
SITE 388
SITE 105
HORIZON A COMPLEX
50Km
750
755
S 149
229°
340°
007°
12 DECEMBER
13 DECEMBER
07
08
09
10
15
16
18
19
20
21
22
23
00
01
02
03
04
05
06
07
08
09
10
11
12
0
5
10
TWO-WAY TRAVEL TIME (SECS)

Fig. 15 C 1101 CSP record across the lower continental rise (Ewing et al., 1974b). Note the presence of the Hudson Outer Ridge and the seaward thinning of the non-laminated sediments eastward to the position of the Gulf Stream Outer Ridge. The location for this profile is given in Fig. 13.

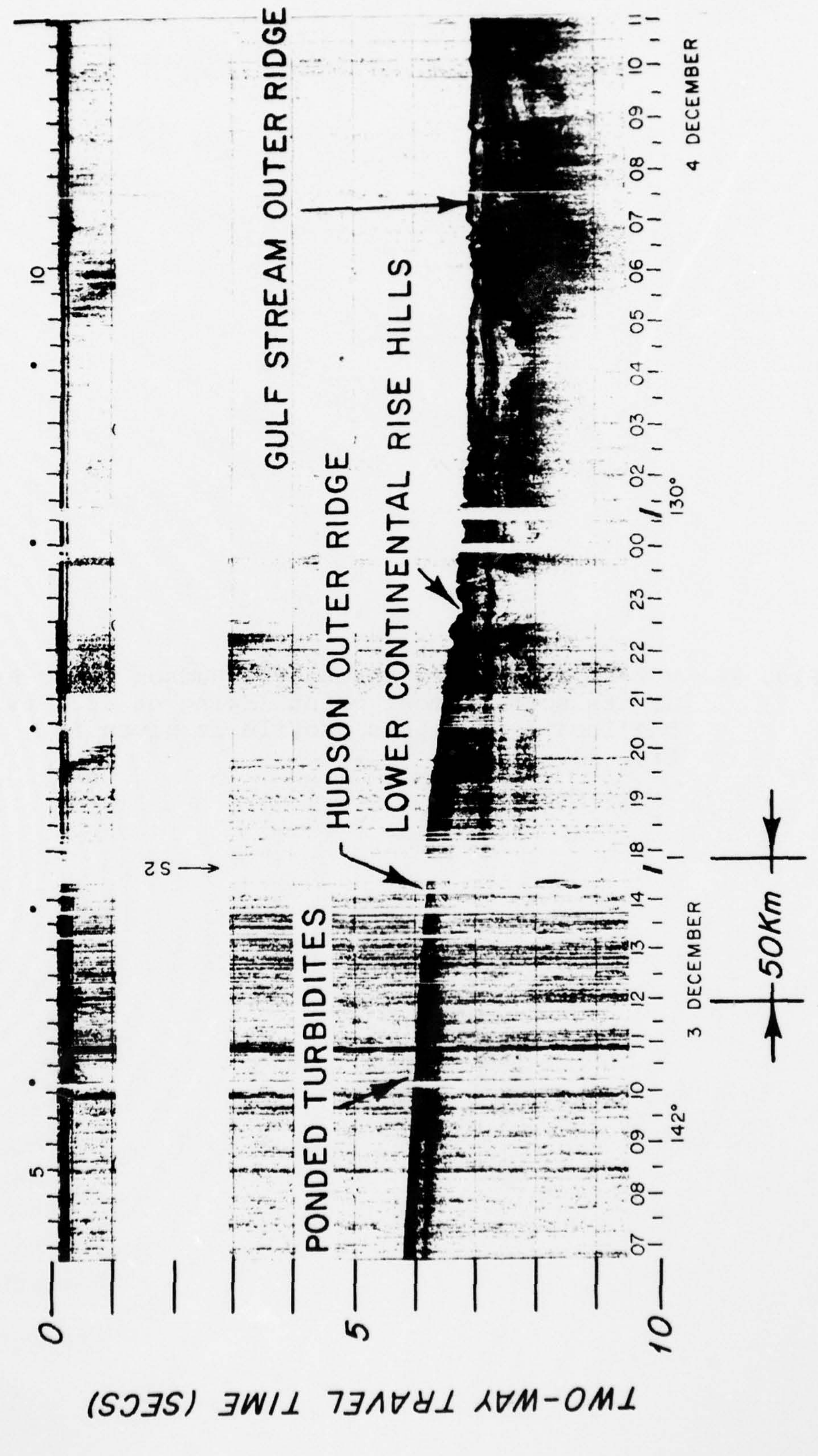

GULF STREAM OUTER RIDGE
HUDSON OUTER RIDGE
LOWER CONTINENTAL RISE HILLS
PONDED TURBIDITES
S2
TWO-WAY TRAVEL TIME (SECS)
0
5
10
07
08
09
10
11
12
13
14
18
19
20
21
22
23
00
02
03
04
05
06
07
08
09
10
11
142°
130°
3 DECEMBER
4 DECEMBER
50Km

Fig. 16 V 2401 CSP record across the Hudson Outer Ridge at its southernmost point (Ewing et al., 1974a). The location of this profile is given in Fig. 13.

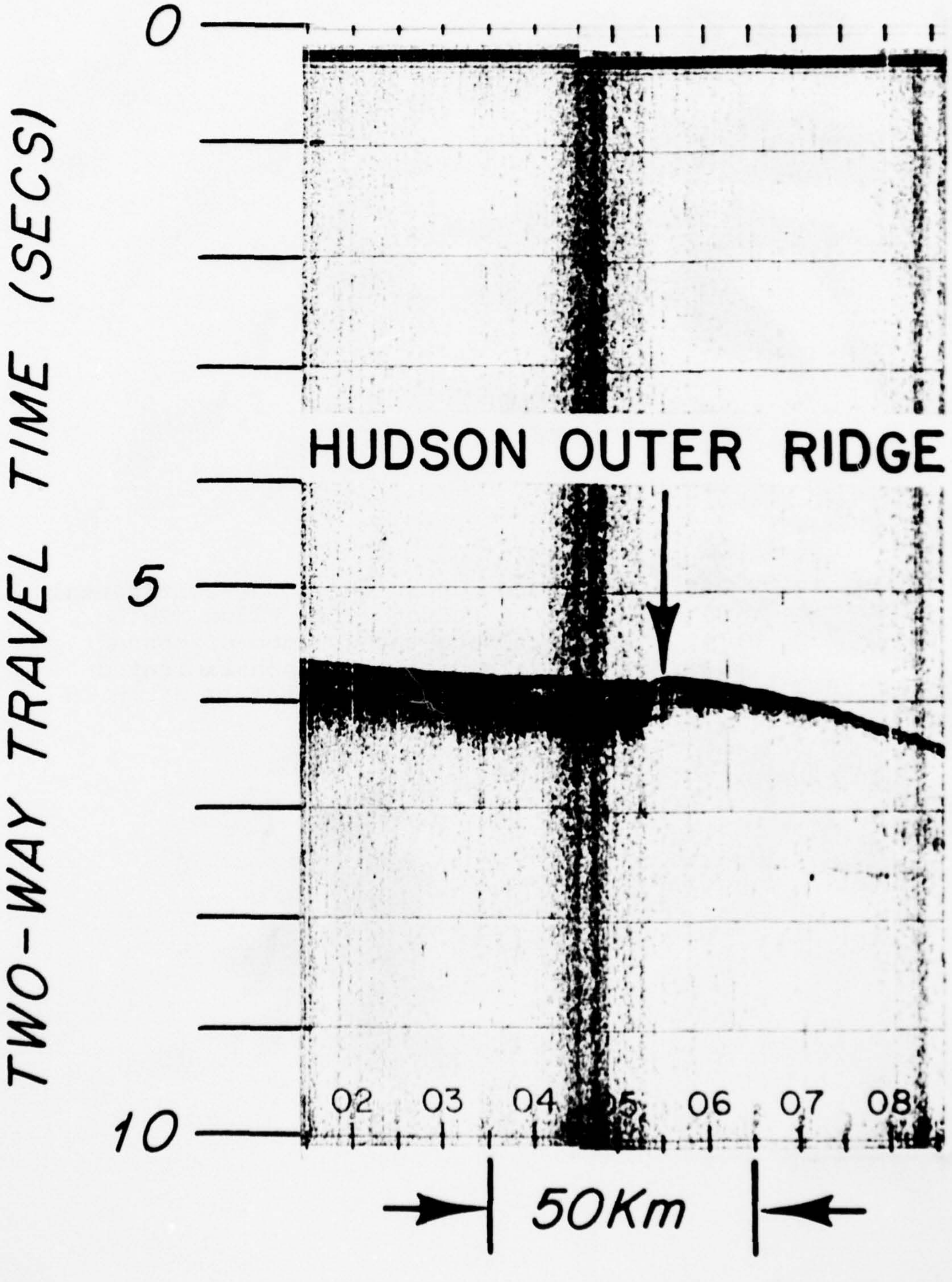
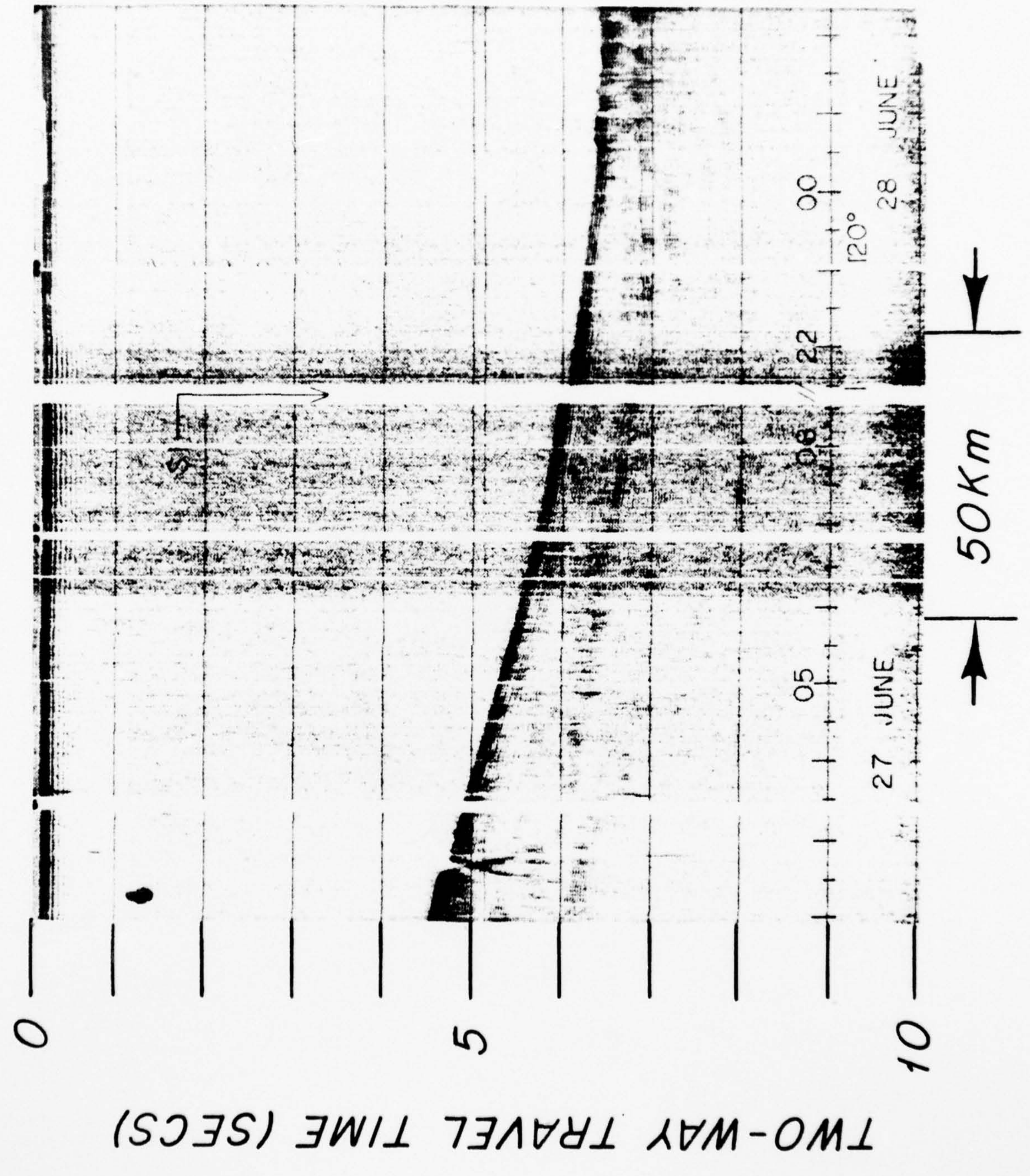

TWO-WAY TRAVEL TIME (SECS)
0
5
10
HUDSON OUTER RIDGE
02
03
04
05
06
07
08
50Km

Fig. 17 V 2801 CSP record across the lower continental rise north of the Hudson Outer Ridge (Ewing et al., 1974b). Note the absence of ponded turbidites and a *ridge* in the non-laminated sediments. This profile location is given in Fig. 13.


0
5
10
TWO-WAY TRAVEL TIME (SECS)
05
27 JUNE
06
22
00
120°
28 JUNE
S1
50Km

Ewing and Hollister (1972) examined seismic profiles and the cores from DSDP Sites 8, 105, and 106 and outlined the basic sedimentary structure of the lower continental rise just south of the Hudson Fan. Although it is difficult to trace Horizon A beneath portions of the lower continental rise this complex acoustic horizon dips smoothly to the seaward with constantly decreasing slope beneath the entire lower continental rise (Ewing and Hollister, 1972). Because of this simple shape neither the morphology or the more complex sedimentary structure of the overlying continental rise deposits can be due to the direct control of pre-existing topography. Two acoustic units lie above Horizon A in this province (Figs. 13-16). The underlying unit is one of acoustically non-laminated sediments. These sediments are built-up into the form of a ridge on the seaward side of the lower continental rise and a trough behind the ridge on the landward side (Figs. 14-16). This ridge will be called the Hudson Outer Ridge. The seaward flank of the ridge is the steep transition zone between the lower continental rise and the abyssal plain and the area in which the lower continental rise hills are found. The crest and the landward flank of the ridge are covered by flat-lying acoustically laminated sediments (Figs. 15 and 16). It is the top surface of these acoustically laminated sediments which forms the extremely gentle slope of the terrace of the lower continental rise. These sediments appear to be ponded behind the ridge.

Drilling at DSDP Sites 8, 105, 106, and 388 (Ewing and Hollister et al., 1972; Benson et al., 1976) has shown that the non-laminated sediments are Miocene and Pliocene hemipelagic fine silts and clays of continental origin (Figs. 8 and 9). Drilling at Site 106 shows that the acoustically laminated sediments at this site are Pleistocene turbidites lying conformably upon the deeper non-laminated sediments.

The buried ridge and trough morphology extends southward from the Hudson Fan region along the entire length of the northeastern segment of the lower continental rise. In Figure 13 the crest of the ridge and the limits of the flat-lying acoustically laminated sediments (turbidites) are shown. It is clear from this distribution that the entire terrace of the lower continental rise is underlain by acoustically laminated turbidites ponded up against the landward facing flank of the Hudson Outer Ridge.

In seismic profiles both to the north and south of the northeastern United States segment of the continental rise no evidence is found for either a buried ridge like the Hudson Outer Ridge or for ponded turbidites. The continental rise north of the Hudson Fan region appears to be primarily a wedge of sediments lying in contact with the deeper surface of Horizon A (Fig. 17). A similar structure is found in the small segments of continental rise between the Hatteras Transverse Canyon and the Blake Outer Ridge (Emery et al., 1970; Fig. 14).

E. Gulf Stream Outer Ridge

The feature termed in this paper the Gulf Stream Outer Ridge lies on the western Bermuda Rise between the acoustically non-laminated sediments and the Sohm Abyssal Plain (Fig. 18). The ridge is defined by the 5000 meter contour and has a maximum relief of about 150 meters above the abyssal plain. It is an arcuate feature which trends northward and then east-northeastward around the western part of the northern Bermuda Rise. Within the concave area formed by the arc of the ridge lies a depression with depths in excess of 5200 meters. The flanks of the ridge slope very gently into this depression. The flanks of the ridge facing the Sohm Abyssal Plain are steeper except in the northern portions of the region that Pratt (1965) has called the Divide.

Seismic profiles which cross the Gulf Stream Outer Ridge contain several important features relevant to the development of the ridge. Horizon A is a flat surface beneath the entire ridge with the exception of portions in the extreme northeast (Figs. 13 18 & 19). The ridge itself is built up from sediments which have accumulated

Fig. 18 V 2307 CSP record across westward thinning non-laminated sediments and the Gulf Stream Outer Ridge (Ewing et al., 1974a). Reflectors in this ridge thin to the eastward and the Horizon A complex lies beneath it. Note the westward facing outcrop and the flat-lying turbidites covering the non-laminated sediments of the Gulf Stream Outer Ridge. The location of this profile is given in Fig. 13.

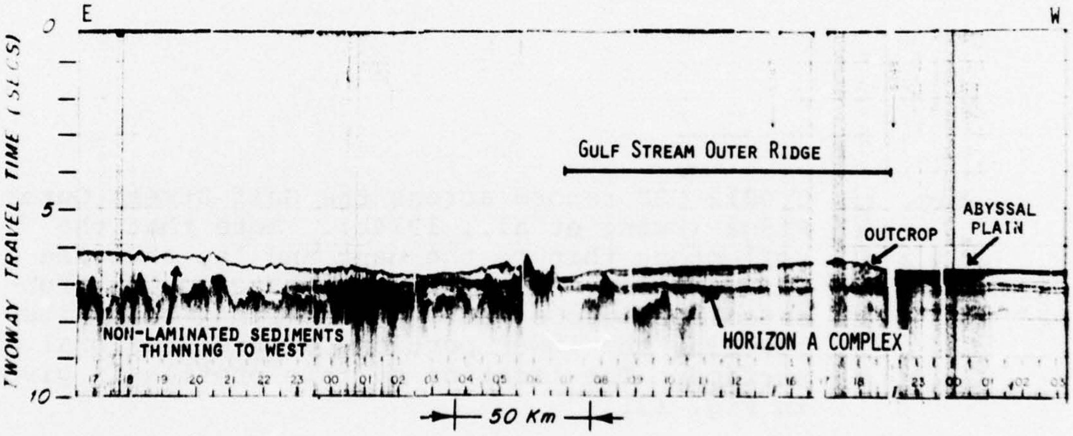

E
W
0
5
10
TWOWAY TRAVEL TIME (SECS)
GULF STREAM OUTER RIDGE
OUTCROP
ABYSSAL PLAIN
NON-LAMINATED SEDIMENTS THINNING TO WEST
HORIZON A COMPLEX
17
18
19
20
21
22
23
00
01
02
03
04
05
50 Km

Fig. 19 C 0812 CSP record across the Gulf Stream Outer Ridge (Ewing et al., 1974b). Note that the reflectors thin to the east and lap onto the Bermuda Rise. Also note the outcrop and truncated reflectors and the flat-lying turbidites covering the lower portions of the erosional surface. The location of this profile is given in Fig. 13.

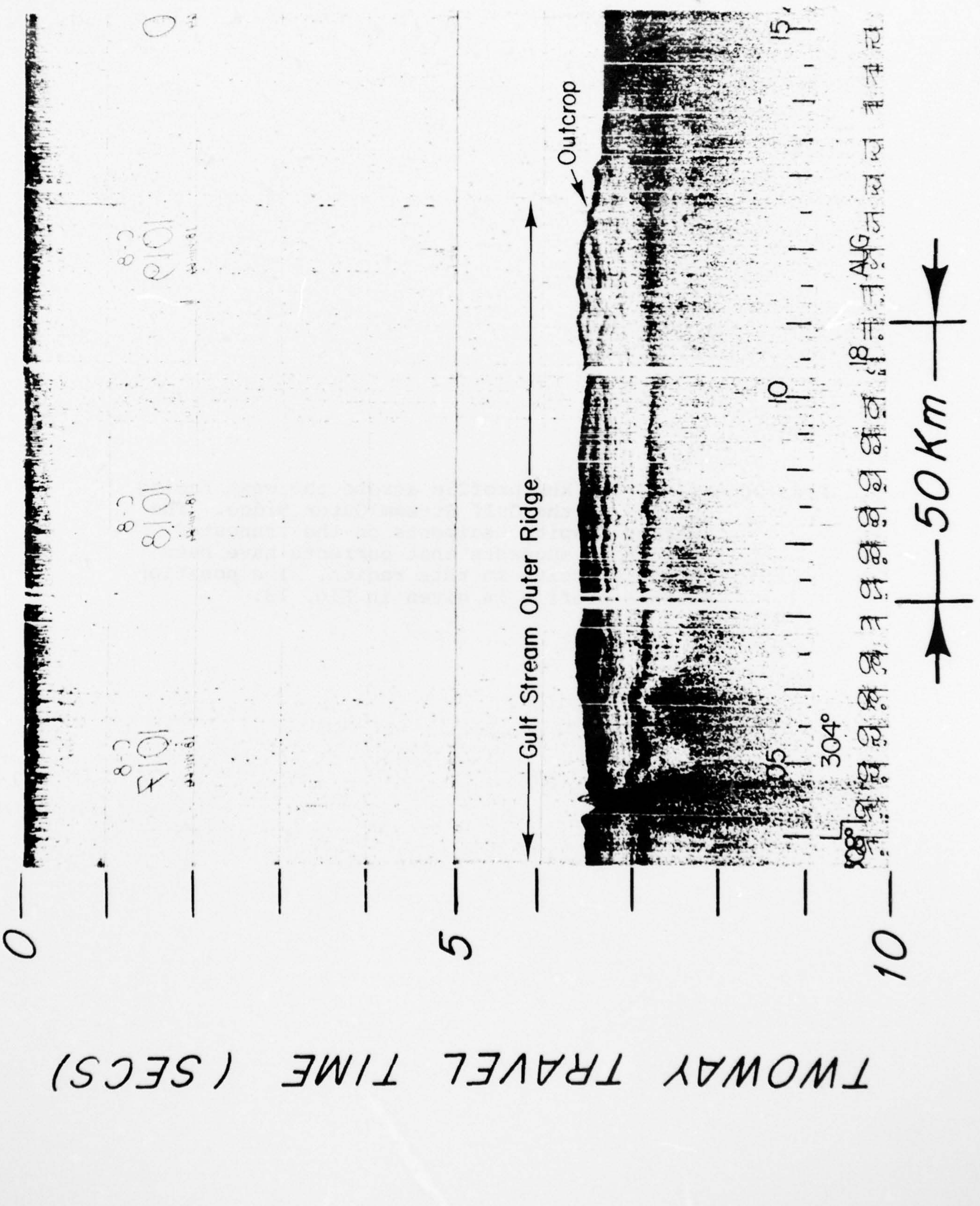

TWOWAY TRAVEL TIME (SECS)
0
5
10
Gulf Stream Outer Ridge
Outcrop
50 Km
18 AUG
304°
308°
05
10
15

Fig. 20 AII-67 3.5 kHz profile across the west facing outcrop of the Gulf Stream Outer Ridge. The lack of draping sediments on the truncated reflectors suggests that currents have been recently active in this region. The position of this profile is given in Fig. 13.

AD-A049 557 WOODS HOLE OCEANOGRAPHIC INSTITUTION MASS F/G 8/3
GEOLOGICAL EFFECTS OF THE GULF STREAM SYSTEM IN THE NORTH AMERI--ETC(U)
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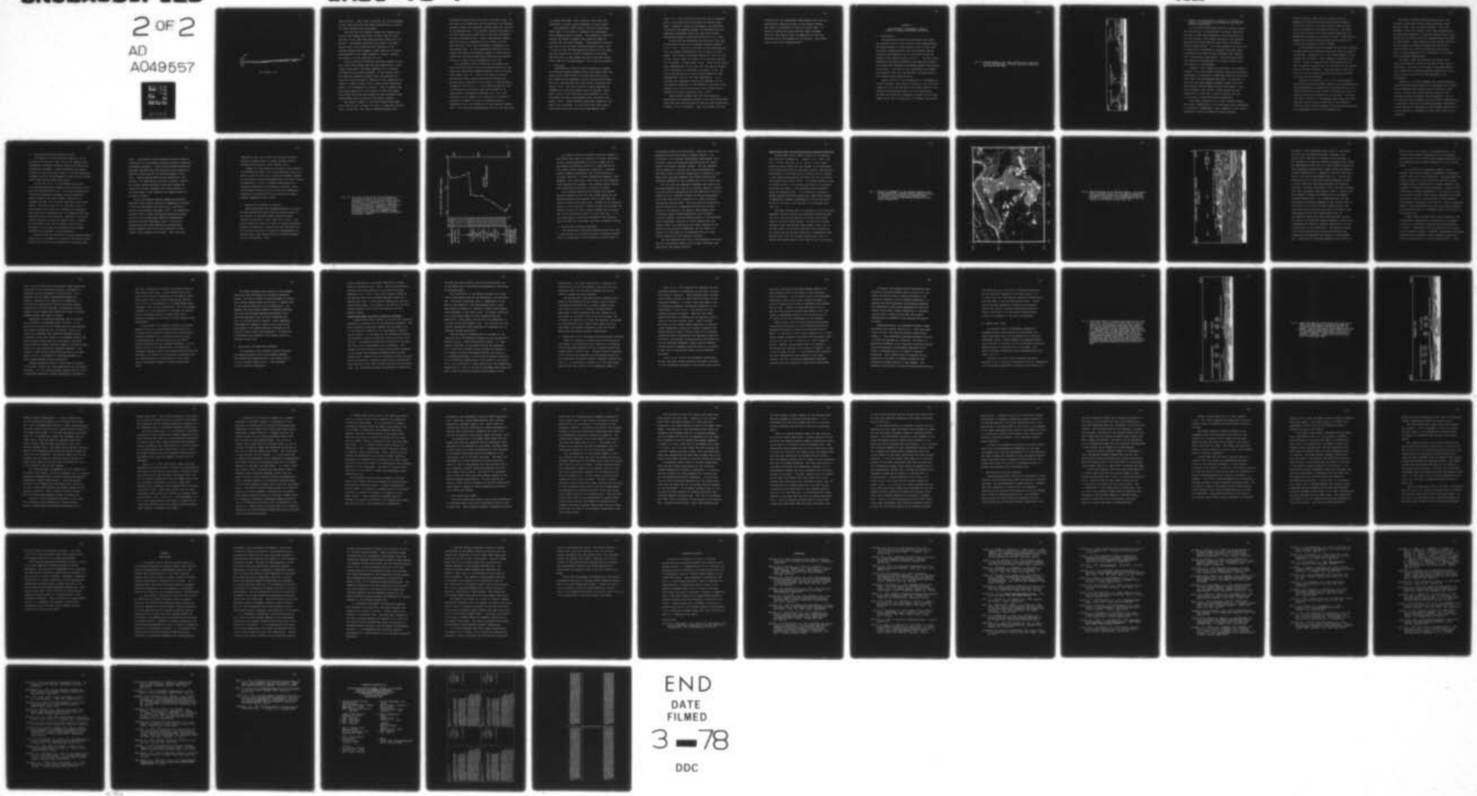
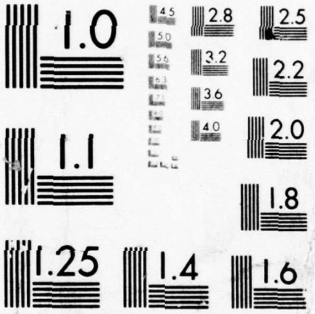
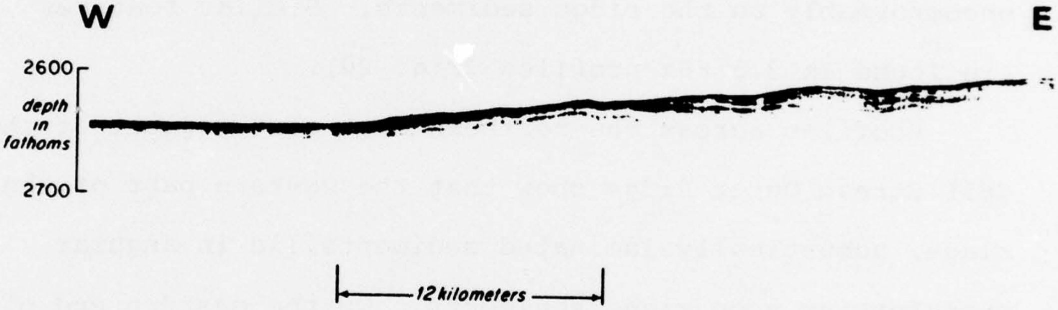


END
DATE
FILMED
3-78
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A


W
E
2600
depth in fathoms
2700
12 kilometers

upon Horizon A. This result indicates that the development of the ridge must have taken place post-Horizon A; during the last Paleogene and the Neogene.

Profiles over the boundary between the abyssal plain and the Gulf Stream Outer Ridge indicate that the outer portions of the ridge have been partially eroded (Fig. 18 and 19). Outcropping reflectors are found on the west-facing flank of the ridge and the turbidites of the adjacent abyssal plain appear in some cases to be resting uncomformably on the ridge sediments. Similar features are found in 3.5 kHz profiles (Fig. 20)

Profiles across the northern east-west segment of the Gulf Stream Outer Ridge show that the western part of the ridge, acoustically laminated sediments lie in angular unconformity upon ridge sediments. On the eastern end of the ridge the sediments abruptly thin and approach the prominent seismic reflector (Horizon A) that underlies the ridge at a depth of about 1 sec. Weak seismic reflectors appear to be truncated at this spot. Thus it appears that the outer boundaries of this portion of the Gulf Stream Outer Ridge have also been eroded and that turbidites rest unconformably upon portions of the erosion surface.

The southern segment of the Gulf Stream Outer Ridge thins from 0.8 sec. to about 0.2 secs. in east-west profiles (Figs. 18 and 19). The ridge is thinnest beneath the topographic depression to the east of the main ridge. To the east of this depression the acoustically non-laminated sediments appear and gradually thicken toward the interior of the Bermuda Rise. The intervals between reflectors of the Gulf Stream Outer Ridge thin to the west and appear to onlap the Bermuda Rise. These relationships suggest that the source of sediments for the ridge is to the west and that as the ridge developed it prograded onto the Bermuda Rise. In the southernmost portions of this segment the Hudson Fan sediments appear to merge continuously with the Gulf Stream Outer Ridge and the sequence thins as it laps onto the Bermuda Rise (Fig. 15).

The northward flowing connecting flow between the return and main flows of the Gulf Stream System lies just above the north-south trending segment of the Gulf Stream Outer Ridge (Fig. 13). Just to the north of the Gulf Stream Outer Ridge current meters have recorded near-bottom current velocities of 9.0 cm/sec. to the northeast (Zimmerman, 1971)(Fig. 2). It has been pointed out that 3.5 kHz profiles across the west facing flank of the ridge contain outcropping reflectors (Fig. 21). The reflectors do not appear to be overlain by a coating of sediments, although 1.0 meter of sediment could be undetected due to the resolution of the technique (Embley, 1975). If a Holocene sedimentation rate of 5 cm/1000 years is assumed (Milliman, 1976; Lisitzin, 1972) then this undetected 1.0 meter could accumulate in 20,000 years.

The absence of DSDP sites on the Gulf Stream Outer Ridge makes it difficult to determine its development and subsequent partial erosion. The presence of Horizon A beneath the feature suggests that formation began no earlier than the late Paleogene. The turbidites covering portions of the erosional surface provide an upper limit in time for both the development and erosion of the ridge. The next section will discuss turbidites in the North American Basin as they effect the age of the Gulf Stream Outer Ridge and the development of the laminated sediments.

F. Turbidites

Turbidites are found in thick accumulations beneath the Sohm and Hatteras Abyssal Plains and ponded behind the Hudson Outer Ridge beneath the Lower Continental Rise. The turbidites are composed of poorly sorted graded sands and silts interlayered with finer lutites (Hollister and Heezen, 1972). The fine fraction of these sediments is composed of illite with lesser chlorite (Biscaye, 1965). Cyclic units of red lutite have been detected in cores throughout the entire Sohm Abyssal Plain (Hollister and Heezen, 1972). These turbidites have been sampled by the DSDP in two locations: at Site 106 on the Lower Continental Rise and at Site 382 on the Sohm Abyssal Plain

(Fig. 8, 9). Site 106 was drilled very near the deepest point in the basin which lies behind the Hudson Outer Ridge. Sampling, though not continuous, was sufficient to position the boundary between the turbidites and the underlying hemipelagic muds very near the Pliocene-Pleistocene boundary (Hollister and Ewing et al., 1972).

At Site 382 the turbidites were drilled at the edge of the basin and the entire sequence sampled (Tucholke et al., 1977). The age of the base of the turbidites was 6 my, an average sedimentation rate of about 40 cm/10^3 years. The thickest turbidites adjacent to this site are 0.6 sec. thick, about 525 meters if an interval velocity of 1.75 km/sec. is used (Houtz, 1974). Using the 40 cm/10^3 years sedimentation rate at Site 382, the age at the base of the turbidites is estimated to be about 1.3 MY. The age at the base may be slightly older because of lower sedimentation rates in the lower Pleistocene. It is unlikely that compaction effects the sediments at this site because comparison of the density at the base of the turbidites at Site 382 with that at the surface show no increase with depth (Tucholke et al., 1977).

These results suggest that the final stages of development and subsequent erosion of the Gulf Stream Outer Ridge must have occurred earlier than the late Pleistocene, perhaps in the late Neogene. They also suggest that the turbidites of the southeastern Sohm Abyssal Plain and the acoustically laminated lutites on the eastern Bermuda Rise began to accumulate at nearly the same times. It should be pointed out that these two latter sediment units are very similar both in composition of the clay fraction and in the presence of red lutites. They differ only in grain size characteristics.

CHAPTER IV

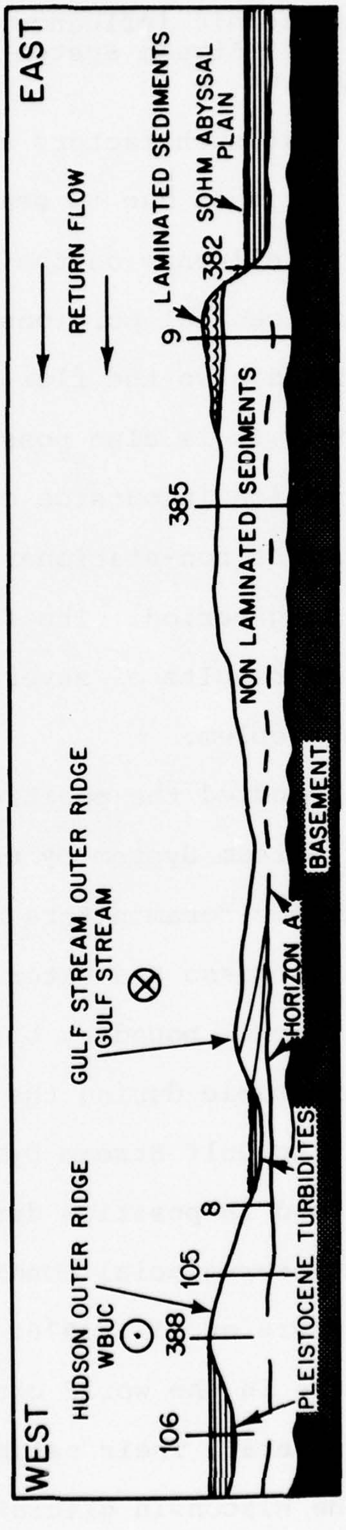
POST-HORIZON A SEDIMENTARY HISTORY: A MODEL OF DYNAMIC SEDIMENTARY PROCESSES

A. Introduction

The preceding sections have discussed five important acoustic units in the northern North American Basin. The relationships of these acoustic units to each other plus their sedimentological and stratigraphic characteristics are summarized in an E-W profile across the northern North American Basin (Fig. 21). The Gulf Stream System has also been discussed as has been the evidence for present-day sedimentary processes beneath and adjacent to the gyre. This section will synthesize the evidence and propose a model for post-Horizon A sedimentation in the northern North American Basin.

Before turning to this discussion it is necessary to briefly consider three separate topics: (1) the long term stability of the Gulf Stream in the central parts of the northern North American Basin; and (2) contrasting Tertiary and Quaternary sediments injected into the deep ocean basin; and (3) variability of abyssal circulation.

Fig. 21 Schematic summary of the primary acoustic units in the northern North American Basin. The major circulation elements and DSDP sites are also shown


WEST
EAST
HUDSON OUTER RIDGE
WBUC
GULF STREAM OUTER RIDGE
GULF STREAM
RETURN FLOW
LAMINATED SEDIMENTS
SOHM ABYSSAL PLAIN
106
388
105
8
385
9
382
NON LAMINATED SEDIMENTS
PLEISTOCENE TURBIDITES
HORIZON A
BASEMENT

B. Climatic and geotectonic influence on the shape and position of the Gulf Stream System and the Western Boundary Undercurrent

It is possible that such factors as climatic change and alternations in latitude due to seafloor spreading may have an important influence on the configuration of the Gulf Stream in the central portions of the northern North American Basin and also the flow of the Western Boundary Undercurrent. It is also possible that even with no significant alternation in outside conditions these circulations may still be non-stationary when examined over a sufficiently long period. The following section will examine published results of several workers that have bearing on this problem.

Ruddiman (1968) studied the position of the northern boundary of the Gulf Stream System by using the contrasting assemblages of planktonic foraminifera associated with cold Slope Water and warm Sargasso Sea Water. He was able to show that the sharp thermal boundary between these two water masses had been stable during the Holocene. This result suggests that the Gulf Stream System has been stable both in shape and in position during the last 11,000 years of warm inter-glacial conditions.

The CLIMAP (McIntyre et al., 1976) program studied sea surface temperature in the world ocean using assemblages of planktonic foraminifera. Their estimate of sea surface temperature during the Wisconsin glacial maximum

(18,000 years BP) shows that the strong horizontal temperature gradient that marks the northern boundary of the Gulf Stream in the North American Basin shifted about two degrees of latitude to the south. The shape of the Gulf Stream in the North American Basin was not appreciably changed by the altered climate. These results suggest that the Gulf Stream System may be stable even during the extremes of climatic changes.

In the geologic past the process of sea floor spreading altered ocean basin geometries and their position relative to latitude. Luyendyk et al. (1972) experimentally investigated the influence of these changes on surface circulation. Taking an absolute plate configuration for the late Cretaceous they were able to show gyrelike Gulf Stream flow in the North Atlantic. They were able to show that this was true for several postulated Cretaceous surface wind and climatic patterns.

Berggren and Hollister (1974, 1977) have presented surface paleocirculation models based on micropaleontological and sedimentological evidence and concluded that the Gulf Stream existed as a major element of circulation since the opening of the North Atlantic in the Jurassic. They also felt that a cooling in the Labrador Basin during the late Pliocene (3MY BP) may have been due to the southward shifting of the northern boundary of the Gulf Stream System, with subsequent cooling of the Labrador Sea.

The Western Boundary Undercurrent has been a geologically significant current along the western North Atlantic margin since the early Cenozoic. Ewing and Hollister (1972) and Tucholke (1977) have documented and discussed the presence of a possible regional hiatus lying beneath the continental rise and created during the middle or upper Eocene. They suggest that this hiatus was due to the initiation of vigorous thermohaline flow in the Atlantic after the rifting of Greenland from Eurasia. This flow was suggested to be a prototype of the present Western Boundary Undercurrent.

Hollister (1967) and Hollister and Heezen (1972) argue on the basis of brick red lutites in the Y-zone of continental rise cores as far south as the Blake-Bahama Outer Ridge that the Western Boundary Undercurrent was an active current during the glacial episodes of the Pleistocene.

These sets of results suggest that the oceanographic conditions have been suitable for the presence of an active Western Boundary Undercurrent since the middle or upper Eocene, and that the current may flow under the very different climatic regimes of the Pleistocene. This is not surprising since Stommel and Arons (1960) suggested from a theoretical basis that the Western Boundary Undercurrent existed because of thermohaline, wind stress, and vorticity factors and was not dependent on any of the three for its existence.

C. Tertiary/Quaternary Sedimentary Inputs

The absence of coarse-grained turbidites in the Miocene and Pliocene at DSDP 106 and 382 suggests some fundamental differences between Tertiary and Quaternary sedimentary processes. These differences have implications for the sedimentary history of the non-laminated sediments and for the development of both the Gulf Stream Outer Ridge and the Hudson Outer Ridge.

At Site 106 (Fig. 9) the Miocene and Pliocene fine-grained hemipelagic sediments were cored and no evidence of turbidites was found. The contact between the overlying Pleistocene turbidites and the underlying Neogene material was never actually cored so it is possible for some late Pliocene turbidites to have been missed. The other sites (8, 105, and 388) (Fig. 9) which penetrated the HOR also recovered no turbidites older than Late Pleistocene and it is possible that this hiatus could also be occupied by turbidites in the more central positions of the Sohm Abyssal Plain. However, the calculation made earlier suggests that all the turbidites in the basin are interpreted from seismic records can be assigned to the Pleistocene.

Since the DSDP has recovered no coarse-grained Neogene turbidites it is reasonable to question what factors might inhibit the injection of turbidites into the deep ocean basin. Climatically related weathering factors might be responsible for the textural contrasts between Pleistocene and Neogene sediments. During the Pleistocene mechanical processes dominated both the weathering and transport of sediments within and out of glaciated regions (Flint, 1971). Coarse-grained detritus was generated by this process. The combination of glacial transport, lowered sea levels, strong pro-glacial river and streams all combined to rapidly transport this coarse material to the ocean where it was injected into abyssal depths as turbidity currents.

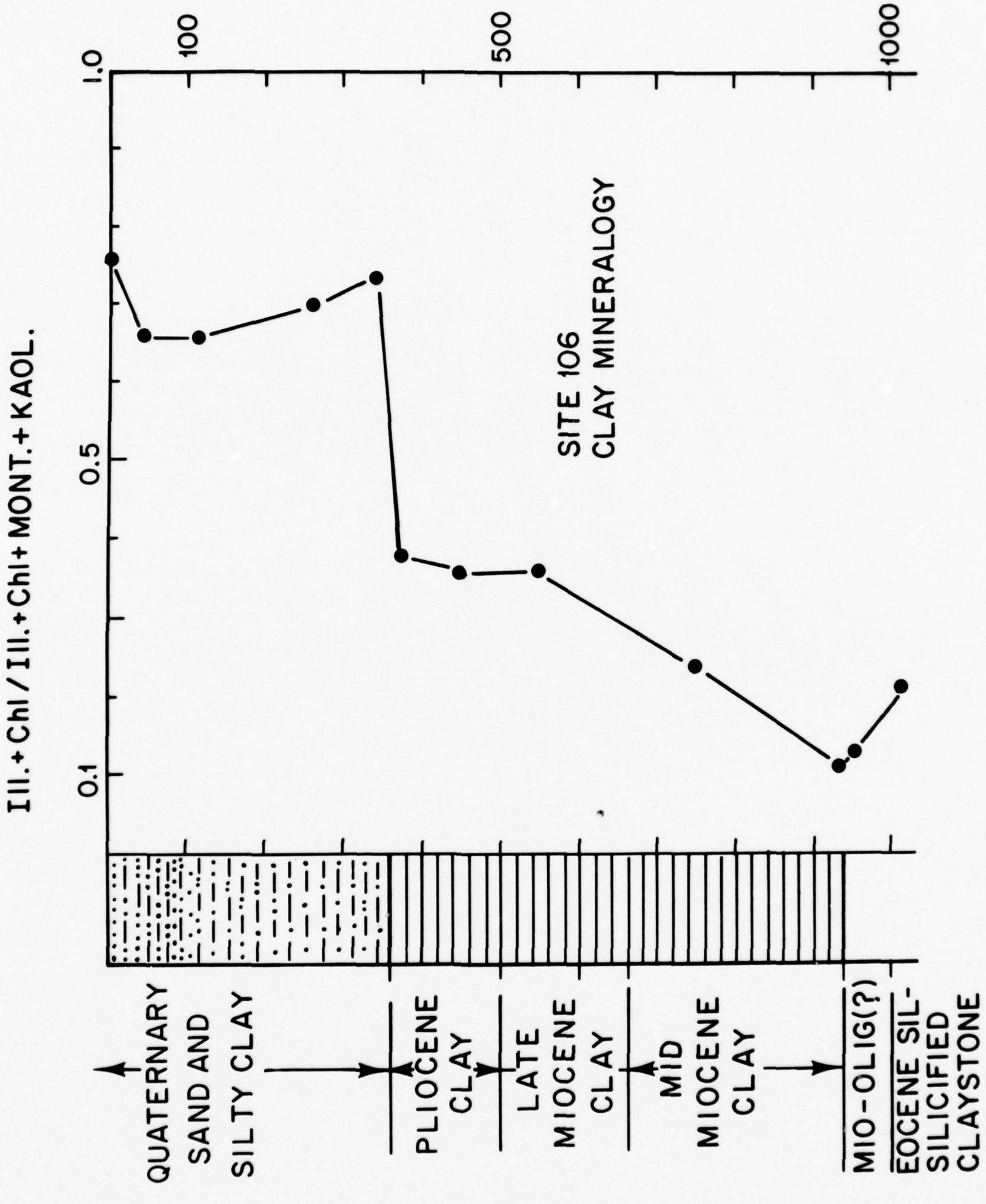
During the Neogene chemical weathering processes dominated those regions which were subsequently glaciated in much the same manner as they do now in the southeastern United States (Feininger, 1965). The weathering products of this slower and gentler weathering process are much finer grained than those from mechanically weathered terranes (Thornbury, 1966). The initial products must have been subjected to substantially greater hydraulic sorting as they travelled in more tranquil river systems to the ocean. Thus, the final sedimentary input was a much finer-grained turbidity current, perhaps similar to those recently reported (Tucholke and Hollister, 1976; McCave, 1977).

Support for this model can be found in the analysis of the dominant trends of the clay mineralogy (Rex et al., 1972) at Site 106 (Fig. 22). Above the boundary between the Pleistocene silts and Neogene clays, the clay fraction is dominated by illite, a mineral characteristic of mechanical weathering of metamorphic terranes. Below this boundary montmorillonite is much more predominant suggesting the production of this mineral by intense chemical weathering (Grim, 1953).

D. Variability of Abyssal Circulation

Marine geologists have proposed models for control of many geologic processes along the western margin of the Atlantic by presumed steady unvarying current. (Heezen and Hollister, 1963, 1964a and b, 1971). The entire broad flow along the margin is called the Western Boundary Undercurrent, although this use conflicts with the stricter definition of physical oceanographers of a distinct water mass flowing within the larger boundary current (Worthington, 1976).

Fig. 22 The ratio of the sum of the percentages of illite and chlorite to the sum of the percentages of illite, chlorite, montmorillonite, and kaolinite at DSDP site 106. Note the shift from primarily illite-rich sediments to montmorillonite-rich sediments at the Plio-Pleistocene boundary. This boundary also coincides with a textural boundary between Pleistocene turbidites and underlying Neogene, hemipelagic lutites.


Ill.+Chl / Ill.+Chl+MONT.+KAOL.
0.1
0.5
1.0
100
500
1000
SITE 106
CLAY MINERALOGY
QUATERNARY SAND AND SILTY CLAY
PLIOCENE CLAY
LATE MIOCENE CLAY
MID MIOCENE CLAY
MIO-OLIG(?)
EOCENE SIL-SILICIFIED CLAYSTONE

As currents along the boundary have been studied it has become clear that the picture of a single, monotonic current flowing equatorward is far too simple and it has become increasingly difficult to characterize the flow regime either temporally or spatially. Multiple current systems (Richardson, 1977) and variations in velocity structure at various frequencies (Webster, 1969; Thompson, 1971; and Luyton, 1977) have all been observed. These observations suggest a very complex current system with broad band variations in velocity structure.

The following sections will discuss the possible geologic effects of both the Gulf Stream System and the Western Boundary Undercurrent, both of which have components of mean and varying flow. Because of the energetic nature of the variations it should be kept in mind that the geologic effects of these current systems may be as much due to the time-varying flow as to the mean flow. It is the persistence of both these components over geologic time that modified and shapes sea floor sedimentary bodies

E. Acoustically Laminated Sediments

The acoustically laminated sediments which form caps on the plateaus on the eastern margin of Northern Bermuda Rise are hemipelagic lutites deposited at high rates of accumulation during the Pleistocene. They are illite-rich sediments derived from eastern Canadian sources. The turbidites in the adjacent Southeastern Sohm Abyssal Plain are also illite-rich sediments derived during the Pleistocene from eastern Canadian sources. The two sediments differ primarily in texture and locus of accumulation. The return flow of the Gulf Stream Gyre is inferred to flow above these laminated deposits and similar acoustically laminated sediments on the northern face of the Corner Rise.

The fact that the laminated sediments form caps on the plateaus suggests that they may be pelagic deposits; however, the high rates of accumulation and the observation that the deposits do not uniformly blanket pre-existing topography argue that they did not accumulate in a purely particle-by-particle vertical mode. The high rates of accumulation and the similarity in accumulation period and ultimate source to the adjacent, but deeper, Sohm Abyssal Plain turbidites suggest perhaps deposition from turbidity currents; however, the fine-grained nature of the sediments, their topographic isolation up to 800 meters above the abyssal plain, the observation that these deposits do not smooth out pre-existing topography, and the absence of deposits on the slopes of the Eastward Scarp all argue against deposition from turbidity currents.

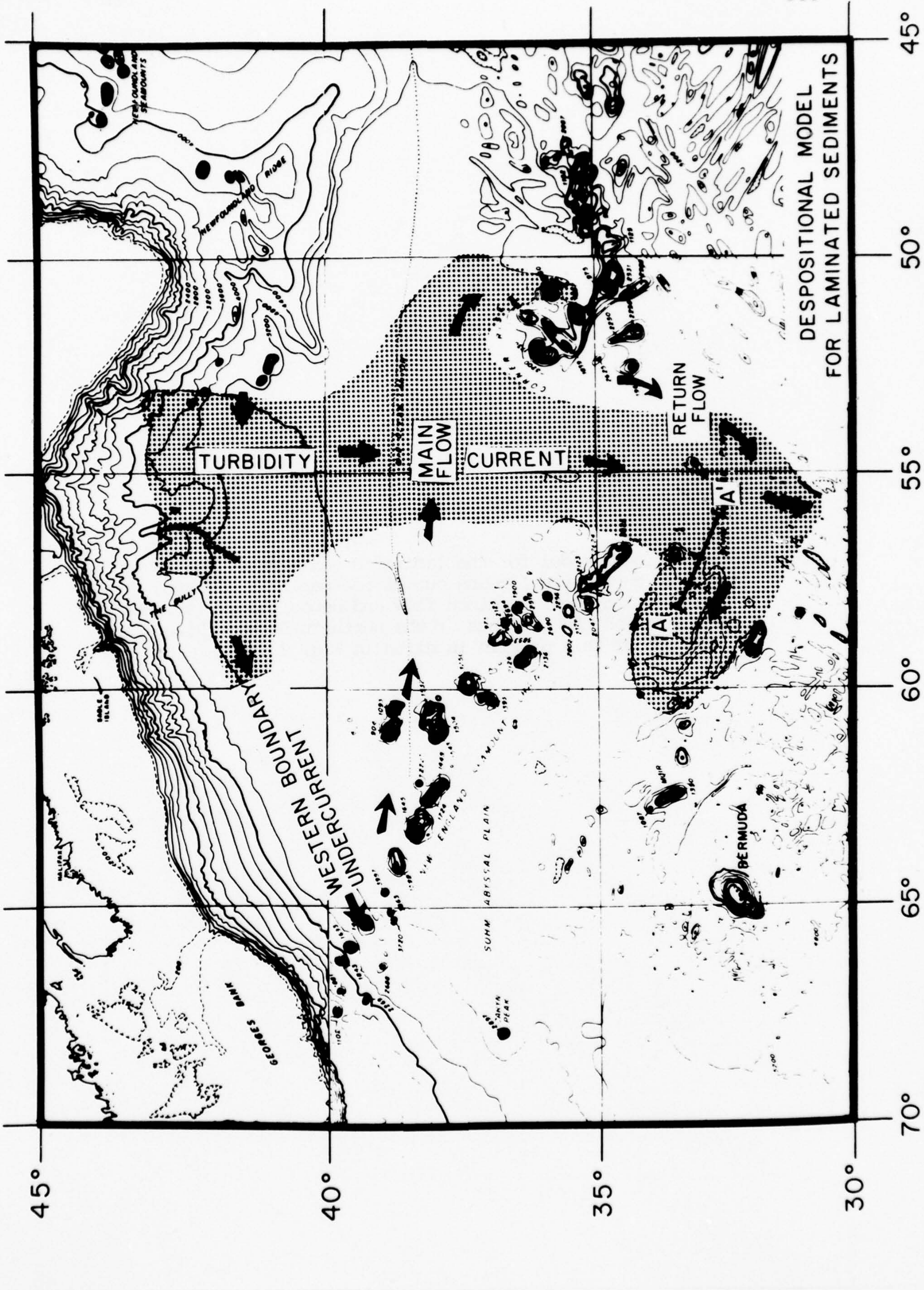
The high sedimentation rates, the topographic isolation and the fine-grained texture are all most consistent with deposition from bottom currents.

Depositional model for the Acoustically Laminated Sediments

Geologically active bottom currents on the Bermuda Rise have been suggested by Heezen et al. (1966), Fox et al. (1967), and Silva et al. (1976). In all cases Antarctic Bottom Water flow was thought to be responsible even though North Atlantic Deep Water rather than Antarctic Bottom Water is the water mass in contact with the bottom in the regions described by the latter two sets of authors (Worthington and Wright, 1970). If a Western Boundary type of current exists in the central portions of the northern North American Basin it most probably flows southward along the Eastward Scarp. It is difficult to imagine a current system localized against this slope being capable of depositing sediments immediately on top of and almost 500 km to the west in the interior of the Bermuda Rise (Fig. 4).

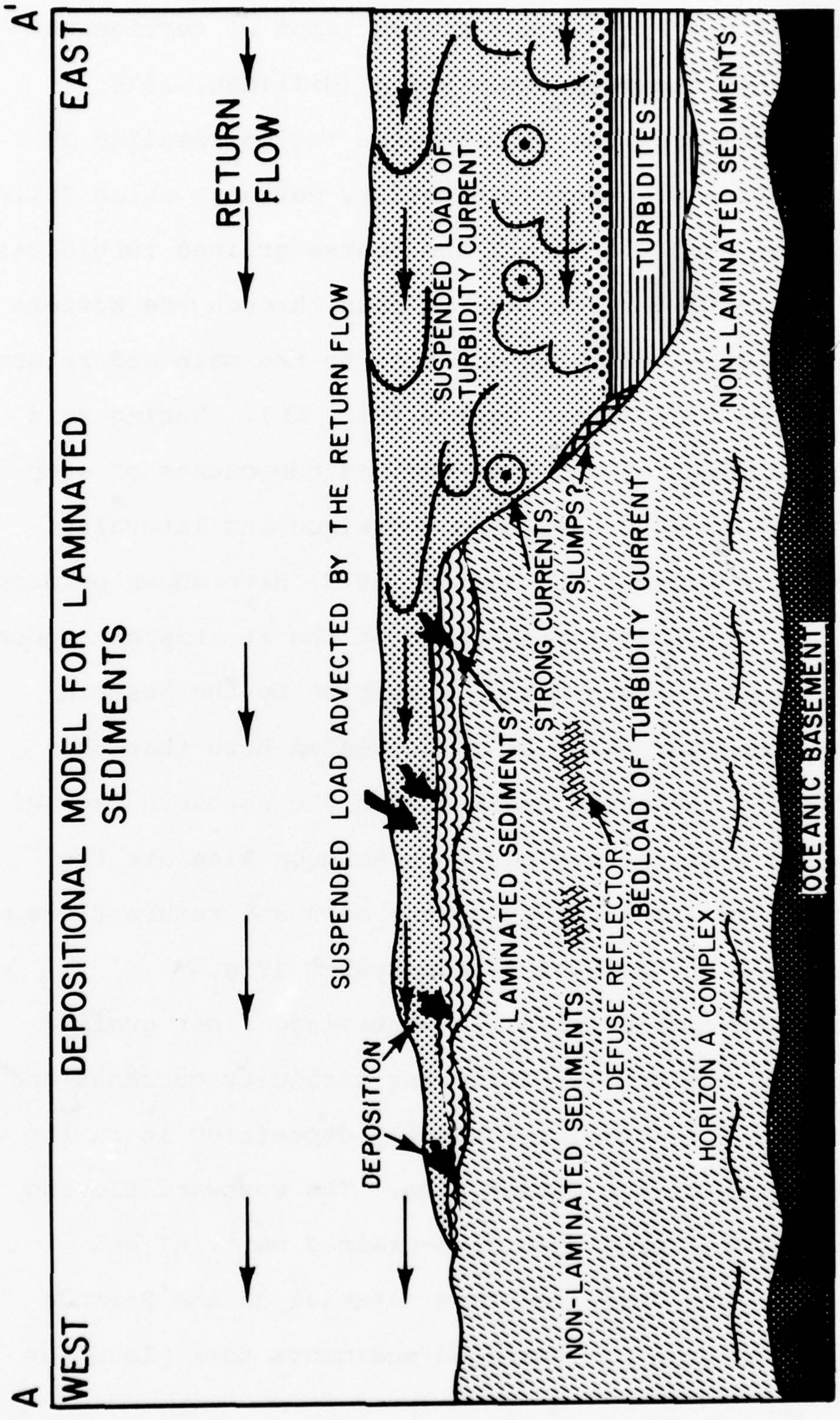
The model proposed here for deposition of the laminated sediments involves capture and subsequent downstream deposition of fine-grained material by the main and return flows of the Gulf Stream System. The main flow travels eastward across the northern Sohm Abyssal Plain, turn to the west north of the Corner Rise and flows westward as the return flow across the Corner Rise, southeastern Sohm Abyssal Plain, and the northern Bermuda Rise (Fig. 2). During the lowered stands of sea level of the cold glacial

Fig. 23 Model for the deposition of the laminated sediments on the northern Bermuda Rise. Southward flowing turbidites from the St. Lawrence fan are entrained by the westward flowing return flow of the Gulf Stream System and deposited on the northern Bermuda Rise.



DESPOSITIONAL MODEL FOR LAMINATED SEDIMENTS

Fig. 24 Depositional model for the laminated sediments. The suspended load of turbidites flowing out of the paper is captured by the westward flowing return flow and deposited as laminated sediments on the plateaus of the northern Bermuda Rise. The location of this profile is given in Fig. 23.



DEPOSITIONAL MODEL FOR LAMINATED SEDIMENTS

episodes of the Pleistocene direct input of terrigenous detritus into the deep ocean basin (Milliman, 1976; Damuth, 1977) from the St. Lawrence region resulted in the generation of numerous turbidity currents which filled the Sohm Abyssal Plain with the coarse grained turbidites. These turbidity currents had to pass through the Western Boundary Undercurrent, in addition to the main and return flows of the Gulf Stream System (Fig. 23). During this passage portions of the fine-grained components of each of these flows must have been entrained and laterally advected. Hollister and Heezen (1972) have shown evidence along the continental rise south of the St. Lawrence cone for southward transport and deposition by the Western Boundary Undercurrent. It is suggested here that the acoustically laminated sediments on the northern face of the Corner Rise and the northern Bermuda Rise are the result of similar activity by the main and return flows respectively of the Gulf Stream System (Fig. 23)
The eastward flowing main flow entrained finer grained portions of the southward flowing turbidity currents and transported the material laterally depositing it on the northern face of the Corner Rise. The westward flowing return flow captured more fine-grained material and transported and deposited this material on the Bermuda Rise. Deposition of laminated sediments took place for

about 500 km to the west of the Eastward Scarp. The thinning and eventual disappearance of the laminated sediments then must reflect either complete deposition of the suspended load or maybe acceleration of the current field.

It is difficult to determine whether a given sediment type will be eroded, transported, or deposited under a given set of flow conditions. In situ speeds are usually compared with the velocity fields for erosion, transportation, and deposition of similar sediment types measured in laboratory flume experiments. Because of the limitations of these experiments it is difficult to take into account numerous other factors including the effects of biologic activity, various scales of bed roughness, flocculation of sediments over time etc., and so comparisons based on these experiments are only first order estimates of the actual behavior of sediments under a given set of flow conditions.

Postma (1967) estimates that current speeds for the simultaneous transportation and deposition of sediments similar to the laminated sediments cannot exceed about 15 cm/sec. Present-day average speeds within the return flow are about 10 cm/sec., although instantaneous magnitudes associated with mesoscale eddies sometimes exceed this value by factors of two to three (Schmitz, 1970). From this it may be cautiously inferred that under present-day conditions little significant erosion or transport of sediments can be attributed to the mean flow. It is possible that the higher instantaneous speeds are, however, responsible for significant resuspension. It also might be inferred that during the cooler glacial periods when the major episodes of deposition occurred average current speeds were higher than those at present, perhaps greater than about 15 cm/sec.

Deposition of laminated sediments has not occurred on the flanks of the Eastward Scarp (Fig.24). It is difficult to be sure of the reasons why this has occurred, but several explanations can be offered. Silva et al. (1976) have suggested that laminated sediments cannot accumulate on the scarp slopes in thicknesses greater than several meters before they fail and slump to the base. They pointed out several possible slumps in the far northern portions of the acoustically laminated sediments. The problem is that similar slump-like features are not seen south of 33°N. The absence of laminated sediments on these slopes demands further explanation.

Another explanation might be high velocity currents (>15 cm/sec) flowing over these slopes which do not deposit sediments. It is in these southern regions that Fox et al. (unpublished manuscript) showed photographic evidence for what they interpreted as contour following currents on the slopes of the scarp. Such evidence might be the result of the direct interaction of the deepest (below 4800 meters) flow of the Gulf Stream System (Rhines, 1977) or due to the generation of trapped Rossby Waves (Thompson, 1971) by this interaction. With the evidence available it is only possible to speculate on possible current mechanisms acting on these slopes and a definitive explanation will have to await further field measurements.

In this model the turbidity currents on the Sohm Abyssal Plain are an intermediate source which link an eastern North American source with the acoustically laminated sediments of the Bermuda and Corner Rises. Stratigraphically, the turbidites are the coarse-grained equivalent of the laminated sediments. On the eastern margin of the Bermuda Rise the acoustically laminated sediments overlie the acoustically non-laminated sediments, the subject of the following discussion, and the characteristics and distribution of this latter group of sediments suggests a similar depositional model.

The model presented here explains in the broadest sense only the distribution of laminated sediments; however, the lack of detail in the knowledge of present-clay current systems makes it difficult to explain many of the puzzling details of their distribution. For example, the long linear ridges of laminated sediments that mark the furthest westward penetration of the laminated sediments into the central Bermuda Rise (Fig. 4) are difficult to explain. Their appearance and morphology suggests a smaller scale outer-ridge type deposit, but without detailed knowledge of the currents flowing about these deposits it is difficult to determine their meaning in the larger picture of westward return flow.

F. Acoustically Non-Laminated Sediments

An anomalously thick sequence of late Paleogene and Neogene deposits lies on the Northern Bermuda Rise beneath the inferred path of the return flow of the Gulf Stream System (Fig. 4). The sediments are fine-grained, hemipelagic lutites interpreted to have been deposited by bottom currents (Tucholke et al., 1977). Similar non-laminated sediments have been observed in the Corner Rise area (McGregor et al., 1973). This thick sequence begins at the Eastward Scarp and continues westward across the Bermuda Rise until it thins before merging with the Gulf Stream Outer Ridge. It is bound in the north by the New England Seamount Chain and on the south by the Muir Seamount Chain.

Depositional Model for the Non-laminated sediments

A depositional model similar to that for the laminated sediments is proposed for the non-laminated sediments. The most significant difference between the two models lies in the textural character of the intermediate turbidity current source. In the model for the laminated sediments the turbidity currents transported coarse as well as fine detritus. The coarse material was laid down as the sands and silts of the Sohm Abyssal Plain turbidites. The absence of large volumes of such coarse-grained turbidites in the Neogene and Paleogene sediments below the Sohm Abyssal Plain suggests that the turbidity currents carrying detritus fromthe St. Lawrence region during these periods were texturally much finer grained than during the Pleistocene. The interaction between the turbidity currents and the main and return flows of the Gulf Stream System led to the deposition of non-laminated sediments on the Corner and Bermuda Rises.

The localization of the deposits beneath the return flow on the Bermuda Rise can be explained in the following way. The abrupt thickening (Fig. 5) immediately to the west of the position of the Sohm Abyssal Plain is best explained by proximity to turbidity currents which supply these sediments to the return flow. If current velocities are in the proper range for both transportation and deposition a thick deposit can be built up immediately to the west of the Sohm Abyssal Plain. The thinning into the interior represents either depletion of suspended load or increased current velocities.

Less satisfactory explanations can be made for the localization of the sediments between the two sub-parallel seamount chains. These explanations include: (1) topographic constraint of the return flow by the seamounts; (2) a "snow fence" effect of flow through the seamounts; (3) trapping of meso-scale eddies between the chains; or (4) southward depletion in the volume of material available in the turbidity currents which is available to the return flow. It is difficult to judge these first three speculative explanations in view of the lack of knowledge about small and medium scale circulation patterns and processes on the

Bermuda Rise. The fourth explanation is based on the observation that the Sohm Abyssal Plain does thin and terminates near the latitude of Bermuda and on this basis is perhaps the best grounded.

The acoustically laminated and non-laminated sediments on the Bermuda Rise are Cenozoic bottom current accumulations derived from an eastern Canada source, most likely from the St. Lawrence drainage system. Deposition of these sediments has been inferred to be the result of the return flow of the Gulf Stream. The following two sections will deal with deposits interpreted as being derived from a Hudson River source and laid down under the combined influence of the Gulf Stream System and the Western Boundary Undercurrent.

G. Comparisons of the Laminated and Non-laminated Sediments

There are important similarities and differences in the acoustic and sedimentological character of laminated and non-laminated sediments and the proposed depositional models needs to explain them. The most obvious difference is the contrasting laminated and non-laminated nature of the Pleistocene and pre-Pleistocene sediments respectively (Fig. 5). A second major contrast is in the clay mineralogy of the fine fraction of the sediments (Table 3).

Silva et al. (1976) studied the laminated and non-laminated sediments to determine why each had a distinctive acoustic character. They observed highly variable water content profiles in GPC-5 which was taken in the laminated sediments. In GPC-6, which was taken in the non-laminated sediments (transparent sediments in the terminology of Silva et al.), the profile was very smoothly varying with depth. They felt that these observations were in keeping with the general acoustic nature of the two acoustic units: highly variable profiles of water content being indicative of similar, though unmeasured, profiles of acoustic impedance and thereby being at least a partial cause of the numerous reflections which characterize the laminated sediments. Similarly, the smoothly varying profiles associated with the non-laminated sediments indicate similar smoothly varying acoustic impedance profiles which is in keeping by the lack of reflections within the non-laminated sediments.

Silva, et al. (1976) also attempted correlations between the water content profiles and normal incidence 3.5 kHz reflections obtained at the surface while coring.

Tentative correlations were made between peaks in the water content profile and several of the individual strong reflectors. In the case of two of the shallowest reflectors a zone of high water content was shwon to be by C^{14} dating to be a zone of extremely high sedimentation rates. Whether the same explanation can be made for the tentative correlations deeper in the core cannot be determined because of the unreliability of C^{14} dates at the ages represented by their depths.

Embley (1975) has drawn good correlations between reflectors and variations in the carbonate profiles of sediments deposited in pelagic and turbidite environments. In the case of GPC-5, there appears to be a correlation between carbonate variations and the deeper reflectors at 15.1 and 26.8 m (Silva et al., 1976; Figures 6 and 8). However, Embley showed that the carbonate variations were mirrored by variations in density. This is not the case in GPC-5. It is possible that carbonate controls compressional wave velocity in this core; however, the lack of velocity measurements precludes anything more than speculation about this relationship.

It appears that rapidly varying Pleistocene sedimentation rates and possibly cyclic variation in carbonate content both have a strong influence on the reflective character of the laminated sediments. In contrast the pre-Pleistocene non-laminated sediments were deposited at much lower sedimentation rates and without significant climatic modulation of carbonate content and as a result do not have the physical characteristics necessary to be efficient reflectors of sound.

Sedimentologically the laminated sediments appear texturally very similar (Silva et al., 1976) yet composition of their clay fraction differs significantly (Table 3). The Pleistocene laminated sediments are rich in illite and secondarily, chlorite: the result of mechanical weathering of an unaltered, glaciated terrane. The pre-Pleistocene non-laminated sediments are far richer in montmorillonite, a product of chemical weathering. These compositional differences can be explained by the model of sediment production and transport discussed earlier in this chapter. The sediments issuing forth from pre-Pleistocene/post-Horizon

North American were the result of chemical weathering and non-vigorous transport to the ocean basins. As a result only very fine-grained turbidites flowed southward down what is now the Sohm Abyssal Plain. During the Pleistocene mechanical weathering and vigorous glacial and fluvial transport dominated causing the input to the basin to be relatively coarse-grained, illite-rich sediments in the form of turbidites.

H. Hudson Outer Ridge

An elongate ridge of hemipelagic sediments of primarily Miocene and Pliocene age lies beneath the Lower Continental Rise from the Hudson Fan to Hatteras Transverse Canyon. These sediments are montmorillonite rich relatives to the more illitic Plesitocene turbidites dammed behind the landward side of the ridge. The Western Boundary Undercurrent flows southward above this ridge (Fig. 13).

Hollister and Ewing (1972) described the basic acoustic units in the lower continental rise and interpreted the non-laminated sediments as deposits laid down by the

Fig. 25 Depositional model for the Hudson Outer Ridge and Gulf Stream Outer Ridge. Events are shown as they would be in the late Neogene with the Pleistocene, ponded turbidites stripped away from the landward flank of the Hudson Outer Ridge and the eroded sections of the Gulf Stream Outer Ridge restored. It is sugggested that the Hudson Outer Ridge formed from fine-sediments that issued from the Hudson Canyon during the Neogene and which entrained and deposited by the southward flowing Western Boundary Undercurrent. The portions of the Hudson Fan input that were not captured by the Western Boundary Undercurrent were entrained by the northward flowing Gulf Stream System and deposited as the Gulf Stream Outer Ridge

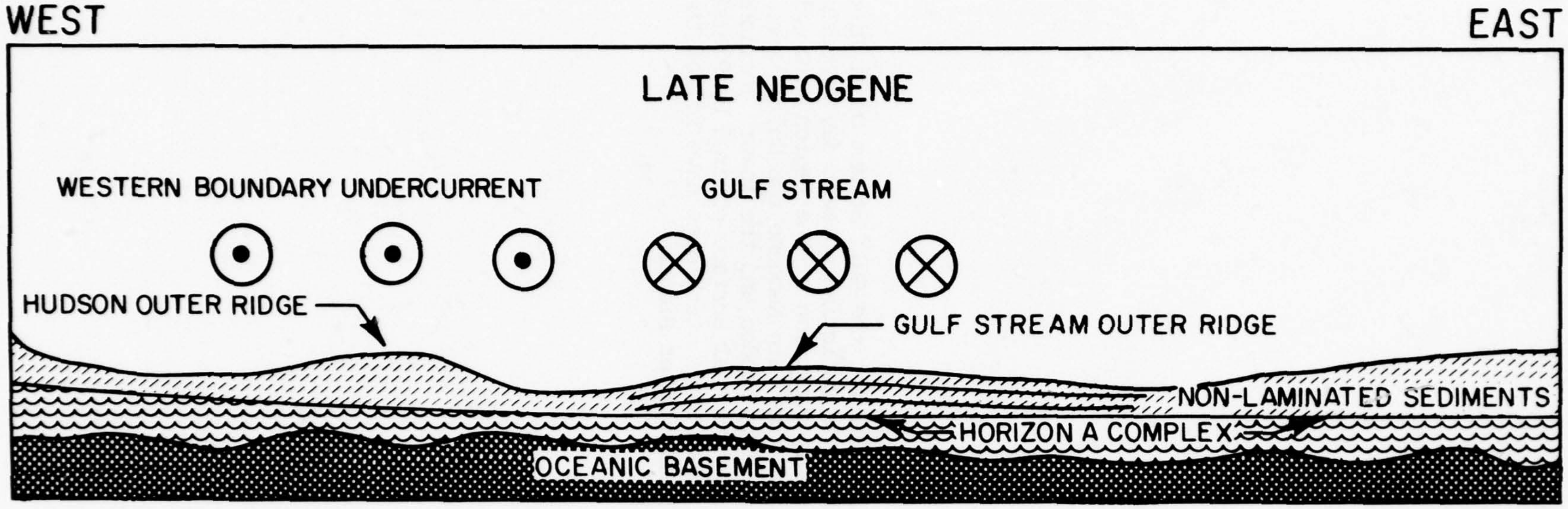
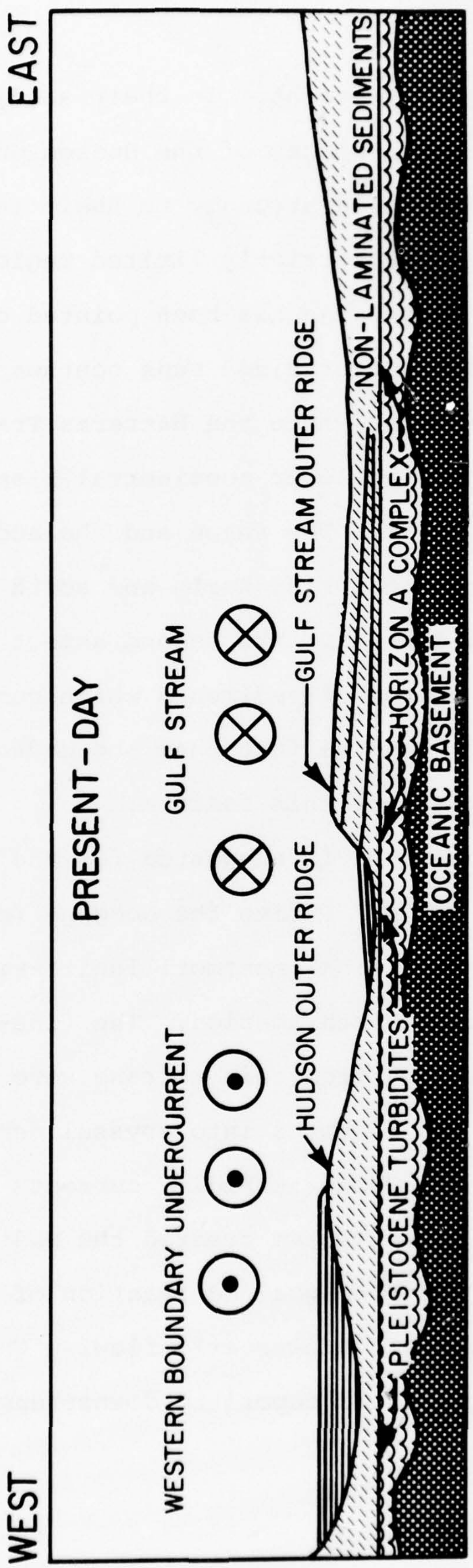

WEST
EAST
LATE NEOGENE
WESTERN BOUNDARY UNDERCURRENT
GULF STREAM
HUDSON OUTER RIDGE
GULF STREAM OUTER RIDGE
NON-LAMINATED SEDIMENTS
HORIZON A COMPLEX
OCEANIC BASEMENT

Fig. 26 Depositional model for the Gulf Stream Outer Ridge and the Hudson Cuter Ridge depicting present-day processes and illustrating the evolution of the region since the late Neogene. Since the late Neogene the Gulf Stream Outer Ridge has been partially eroded and the lower sections of the the resulting erosional surface covered by Pleistocene turbidtes. Pleistocne turbidtes have filled the trough behind the Hudson Outer Ridge.


WEST
EAST
PRESENT-DAY
WESTERN BOUNDARY UNDERCURRENT
GULF STREAM
HUDSON OUTER RIDGE
GULF STREAM OUTER RIDGE
NON-LAMINATED SEDIMENTS
HORIZON A COMPLEX
PLEISTOCENE TURBIDITES
OCEANIC BASEMENT

Western Boundary Undercurrent. In their analysis they did not emphasize two aspects of the Hudson Outer Ridge which when considered add strongly to their interpretations. The first aspect is the strictly limited regional extent of the Hudson Outer Ridge. As has been pointed out previously (Fig. 13) the Hudson Outer Ridge runs southward from the Hudson Fan to the point where the Hatteras Transverse Canyon crosses from the lower continental rise to the Hatteras Abyssal Plain. The shape and the acoustic stratigraphy of the continental rise north and south of these two points are very different. The second aspect they did not consider was the source of sediments which comprise the Hudson Outer Ridge and the fact that the Hudson Fan lies at the northern limit of this feature.

The following model is suggested for the formation of the Hudson Outer Ridge. During the Neogene (Fig. 25) chemical weathering generated thick, montmorillonite-rich saprolite sequences in eastern North America. The fine-grained sediments which issued from this terrane were carried by rivers to oceans and injected into abyssal depths as fine-grained turbidites. Those turbidity currents flowing down the Hudson Canyon System created the Hudson Fan.

Portions of the fine-grained fraction of this input were entrained by the southwesterly flowing Western Boundary Undercurrent and deposited downstream as the

Hudson Outer Ridge. The northern boundary of the Hudson Outer Ridge was determined by the position of the Hudson Fan outpouring and the southern boundary by depletion of the suspended load of the Western Boundary Undercurrent.

With the present data, it is difficult to determine the details of the current flow; whether deposition took place from the main axis of a unidirectional undercurrent or from the shear zone between northward and southward flowing branches of the undercurrent in a similar fashion to the Blake-Bahama Outer Ridge (Markl, et al., 1970). This model explains both the geographic localization of the Hudson Outer Ridge and suggests a source for the sediments.

Emery et al. (1970) and Ballard (1966) have both suggested alternative models to explain the morphology of the ridge and the spatial distribution of acoustic units. Both authors feel that the Lower Continental Rise is an area of massive slumping and that the Hudson Outer Ridge is a possible crumpled toe to a major slump block. Sediments were presumed to have slumped from an unstable continental slope. DSDP holes drilled into the Lower Continental Rise contain no evidence for slumping (Ewing and Hollister, 1972; Ewing et al., 1968 and Benson et al., 1976) no disrupted strata were found; no repetition of strata was observed; and no obviously displaced shallow water fossils or sediments were noted.

In addition to the lack of evidence for slumping contained in the DSDP results, an examination of the mechanics of slumping and the acoustic stratigraphy and morphology of the Hudson Outer Ridge areas argue against significant slumping activity. Slumping from the continental slope onto the Lower Continental Ridge could have occurred in two possible modes: (1) as one or several large slump blocks of regional extent; or (2) as a series of smaller slumps that coalesced at the base of the rise to form the Hudson Outer Ridge. The first model is very unlikely for two reasons. It is very difficult to imagine that sediments could accumulate so homogeneously along about 1000 km of continental slope so as to become unstable at precisely the same moment. It is more likely that varying rates of accumulation and varying types of sediments along the slope combined to make first one region and then another become unstable and subsequently slump. Another objection to the massive slumping model lies with the submarine canyons that incise the continental slope. The effect of these canyons would be to break the slope up into small segments isolated from one another. Under these conditions failure of one small segment would not necessarily institute widespread slumping because it is not in mechanical continuity with the segments in each side of it. Without this continuity there is no effective mechanism for simultaneously transmitting strains laterally along the continental margin.

It appears more likely that if the lower continental rise is a slump feature it was formed by the coalescing of smaller slump blocks. It is instructive to examine the seismic records across the Hudson Outer Ridge to see if its shape is consistent with formation from such a process. The most obvious feature of the Hudson Outer Ridge is the profile to profile similarity of the ridge and the overall regional linearity of the ridge and ridge crest (Fig. 13). Several factors make unlikely the formation of such a homogeneous feature from the limiting of numerous, small slump blocks. These include collision between and deformation of individual blocks; differing distances of translation due to textural and slope irregularities in the glide planes; and concentration and dispersal effects of local topography. The effect of these factors should be a very irregular rather than homogeneous lower continental rise.

One unanswered question about slumping is why the Hudson Outer Ridge occurs only between the Hudson Fan and the Hatteras Transverse Canyon. Possible explanations involve either a difference in slumping style to the north and south or perhaps the absence of slumping at all in these regions. Either explanation assumes that the northern and southern boundaries of the Hudson Outer Ridge also mark distinct, sharp boundaries in sedimentary processes in the continental slope and upper continental rise. These may include sedimentation rate, sediment composition, sediment texture, etc. While there are considerable lateral differences in these processes on a regional scale significant changes do not occur at or near the key points or the margin (Emery and Uchupi, 1972).

The association of the Hudson Outer Ridge with the Hudson Fan source of sediments and the subsequent redistribution of the sediments by the Western Boundary Undercurrent serves as a better explanation for the structure of the Hudson Outer Ridge and the differences in the continental rise to the north and south. The model is a refinement of the one offered by Hollister and Ewing (1972) in that it does account for these features and it also presents a clearer association between the Hudson Outer Ridge and its source. Portions of the sediments derived from the source may have escaped capture by the Western Boundary Undercurrent. The next section will develop a model for the formation of the Gulf Stream Outer Ridge based on capture of these sediments by the northward flowing Gulf Stream.

I. Gulf Stream Outer Ridge

The Gulf Stream Outer Ridge is an arcuate accumulation of sediments which lies on the northwestern border of the Bermuda Rise. These deposits probably accumulated sometime within the late Paleogene and the Neogene although the lack of DSDP sites in this feature precludes a precise determination of the details of its formation or the sediments' sources. Portions of the western and northern boundary of the Gulf Stream Outer Ridge have been eroded and subsequently partially covered by turbidites. The southernmost segments of the ridge appear to be continuous with the Hudson Fan (Fig. 16). The present Gulf Stream flows northward and then northeastward over the north-south segment of the Gulf Stream Outer Ridge.

The juxtaposition of the southern boundary of the Gulf Stream Outer Ridge with both the Hudson Fan and the northern termination of the Hudson Outer Ridge may provide some clues as to how it formed. Seismic profiles across the southernmost segment of this feature (Fig. 16) show that the non-laminated sediments of the Hudson Fan lap onto the Bermuda Rise. In this region the Gulf Stream System has just turned northward. Portions of those sediments which entered this region may have been captured by this northward flowing arm of the Gulf Stream System and deposited the remaining portions of the Gulf Stream Outer Ridge (Figs.25-26) on the Bermuda Rise. Thus the Gulf Stream Outer Ridge can be considered as a primary outer ridge deposit derived from Hudson Fan sediments which escaped the Western Boundary Undercurrent and were transported and laid down by the northward flowing arm of the Gulf Stream System.

The age limits of the Gulf Stream Outer Ridge sediments agree with this model: because the Gulf Stream Outer Ridge lies above Horizon A it must have been deposited in the same interval of time as the Hudson Outer Ridge. The position of the Gulf Stream Outer Ridge and especially the juxtaposition of its southern boundary with the Hudson Fan are also in agreement with the model. The thickness of the Gulf Stream Outer Ridge sediments is less (.2-.3 sec.) than that of the Hudson Outer Ridge ($\sim$1.0 sec.), but it is also clear from the outcrops that a thicker sequence has been eroded. This indicates that deposition approaching the same order of magnitude as the Hudson Outer Ridge occurred on the Gulf Stream Outer Ridge.

The westward facing flank of the Gulf Stream Outer Ridge has been eroded and portions of this erosional surface subsequently covered by turbidites. In previous sections evidence has been presented for a Pleistocene age for North American Basin turbidites. If this holds true for those turbidites covering the Gulf Stream Outer Ridge then the upper age for the erosion must be sometime in the Pleistocene. The principle climatic event at this time was the deterioration of climates during the late Pliocene (Berggren and Hollister, 1972) and it is possibly this event that is reflected in the erosion on the Bermuda Rise. Berggren and Hollister (1972) have suggested that the Gulf Stream no longer flowed into the Labrador Basin and was confined to the North American Basin. It is speculated here that this change resulted in increased current velocities and erosion of the Gulf Stream Outer Ridge.

There is a second possible model for the evolution of the Gulf Stream Outer Ridge. Seismic profiles (Fig.16) show that the extreme southern segment progressively thins to the east as it progrades onto the Bermuda Rise. This observation could suggest that the Gulf Stream Outer Ridge is really an outlier of the present Lower Continental Rise that has been isolated on the Bermuda Rise by erosion. There are several reasons why this model is less acceptable than the one already presented. The shape and the age of the Lower Continental Rise immediately adjacent to the southernmost outcrops are not in agreement with the implications of the model. The model predicts that the surface of the Lower Continental Rise that slopes down to the abyssal plain floor must be an erosional outcrop (Fig. 21) Although the late Neogene sampling of the DSDP was not continuous at the three sites in this supposed outcrop (Sites 9, 105, and 388; Fig. 9) no hiatuses were either detected or inferred from the drilling results (Tucholke, 1977). Lack of hiatuses indicates that no significant erosion has taken place upon the Lower Continental Rise in this region and that the Gulf Stream Outer Ridge could not have been smoothly connected to the Lower Continental Rise to the west.

It has been pointed out in earlier sections that the morphology of the Lower Continental Rise between the Hudson Fan and the Hudson Transverse Canyon is remarkably homogeneous. The northernmost sections of this segment of the Lower Continental Rise are those which according to the model mow under discussion must be erosional. It is unlikely that erosional shaping of this northernmost section could have produced the morphological homogeniety along the entire segment of the Lower Continental Rise that has been observed. If the Gulf Stream Outer Ridge is an erosional outlier of the Lower Continental Rise then the fact that the northernmost segment wraps around the Bermuda Rise to the northeastward implies that the Lower Continental Rise extended at least 300 km further to the east than it presently does. Similar features do not exist on the margin both to the north and to the south (Emery and Uchupi, 1972). It is not at all readily apparent why the Lower Continental Rise should have prograded for from its present position during the Miocene and Pliocene, since there are no special features on the margin to require this. Erosion of the now missing portions of this postulated Lower Continental Rise requires increased activity by both the Gulf Stream System and the Western Boundary

Undercurrent. Increased activity by the Western Boundary Undercurrent is necessary because the greater portion of the missing material is near the continental rise. This erosion has to be constrained to occur only on the segments of the Lower Continental Rise north of the Hudson Fan since it is clear that south of this region little significant activity could have occurred. This constraint appears highly unlikely.

In view of the absence of erosion of the Lower Continental Rise, the morphological homogeniety of the Lower Continental Rise, and the improbability of first depositing and later eroding the sediments of the postulated extended Lower Continental Rise it appears unlikely that the Gulf Stream Outer Ridge is, in fact, an erosional outlier of a Miocene and Pliocene Lower Continental Rise.

J. Speculations on Current Structure

Discussing alternative models for development of these features involves speculation about the position, direction, structure, and the magnitudes of paleo-currents. Arguments have been presented in section B for the long-term stability of the position and direction of the Gulf Stream and the Western Boundary Undercurrent. The preceding section noted the close association between the Gulf Stream System and the Western Boundary Undercurrent, and the Gulf Stream and Hudson Outer Ridges and suggested on the basis of this association that these features may have been deposited under the influence of the two current systems. The following section will discuss in a speculative manner the details of the current systems that may have formed the Gulf Stream and Hudson Outer Ridges into their present morphology. The basis of this speculation will be assumptions about both the structure and magnitudes of the currents which flowed over these features.

There are several possible models for the manner in which the Western Boundary Undercurrent and the Gulf Stream System formed the Hudson Gulf Stream Outer Ridges. While the present data is not sufficient to conclusively chose between them it is instructive to examine each model.

Davies and Laughton (1972) have postulated deposition of linear ridges from the low velocity edges of rapid current systems (see Figs. 4 and 7 of Davies and Laughton, 1972). Below the axis of the current velocities are presumed to be so rapid that only scour occurs. They suggested that if the current were to flow along a flat sea floor twin, parallel ridges would be deposited from the edges of the current; whereas, a current flowing against a slope such as the continental rise would deposit a single ridge from its downslope edge.

Several authors (Markl et al., 1970; Tucholke et al., 1973) have suggested that deposition may occur from the shear zone between two anti-parallel flowing currents.

The common feature of these two models is the assumption that the velocities at the center of the current are too rapid to allow deposition and that deposition may only occur at the edges of the current where velocities are lower. This means that there are distinct regions within the current which either deposit, erode or transport sediments.

A third model has the entire velocity field of a current within the range of transportation and deposition of the available sediments. If the velocity structure of the current is such that the highest velocities are near the center of the current then the formation of a linear ridge downstream from a source of sediments is possible. This might involve downslope flow of turbidity currents crossing a contour-following current system. The low velocity edges of the contour current would entrain little sediment which would be deposited near its point of entrainment. The higher velocities in the axis of the current would entrain greater quantities of sediments

(Heezen et al., 1966) and deposit them at greater distances from their source. This would result in a ridge lying downstream from the locus of the turbidity currents beneath the axis of the current.

If the Hudson Outer Ridge is detached from the upper lower continental rise, i.e. if no bridge of sediment exists between the rise and the ridge in the Hudson Fan area, then it is possible that the model of Davies and Laughton (1970) applies here, and that deposition took place from the seaward edge of a rapid boundary current. If, however, the Neogene Western Boundary Undercurrent was less rapid, it is possible that deposition occurred from the axis of the current and the ridge is the result of the greater carrying capacity of the current. If a bridge does connect the Neogene ridge with the upper rise, then the simple model of deposition from the edges does not apply since the currents would most likely be deflected by the barrier. In this case, it is possible for a shear zone to develop between the currents flowing southward along the seaward facing slope and northward along the landward facing slope of the ridge, and deposition may have occurred from this shear zone. The problem with this model is that it requires pre-existing topography to guide the currents. This may have been provided by deflection of the turbidites to the right by the Western Boundary Undercurrent and/or the Coriolis force.

The Gulf Stream Outer Ridge lies on flat seafloor, but, because it is not composed of a pair of arcuate, parallel ridges, it was probably not laid down from the edges of a relatively high velocity Gulf Stream System.

The present contours of the western Bermuda Rise and the Gulf Stream Outer Ridge (Fig. 13) are such that the return flow of the Gulf Stream System may have first flowed south along the present eastern flank of the ridge and then northward along the western flank forming a shear zone between the opposing currents. This model suffers from the problem that there is no evidence in the seismic profiles (Figs. 18 and 19) for pre-existing topography which would guide the early development of the ridge. In this case, only the later development of the ridge may have been influenced by deposition from a shear zone.

There are fewer objections to the model of deposition from the axis of low velocity currents within the northward turning return flow of the Gulf Stream System. In this case, the turbidites which escaped the Hudson Fan and Outer Ridge crossed the Gulf Stream and presumably were entrained and distributed northward. The width (>150 km) of the Gulf Stream Outer Ridge suggests that the currents were part of a rather broad system.

The foregoing speculations should be viewed in light of two very important constraints placed on marine geologists. The section on resuspension (II-F) discussed the difficulties involved in estimating the capacity of a given current to erode, transport, and deposit sediments. The section on current variability (IV-C) discussed the present-day variability both in space and time of the Gulf Stream and the Western Boundary Undercurrent. Both these factors make it very difficult to quantify such phrases as "weak current" or "strong current" in the preceding discussion. Since the section is itself speculative, it is probably not necessary to extend the speculation into areas such as the possible current velocities of each current model.

CHAPTER V

CONCLUSIONS

1. The return flow of the Gulf Stream System with its associated mesoscale horizontal eddies flows over the region of maximum mass of resuspended material in the northern North American Basin. The return flow has average velocities of about 10 cm/sec. whereas the eddies contain instantaneous velocities over 40 cm/sec. It is suggested here that these relatively energetic mesoscale eddies are responsible for this maximum in resuspended mass and the return flow for redistribution of the sediments.

2. The results of drilling at Sites 106 and 382 plus an examination of seismic profiles across the abyssal plains of the northern North American Basin suggest that the thick sequences of coarse-grained turbidites observed in the Pleistocene are not abundant during the Neogene. Minerological contrasts also exist between Neogene and Pleistocene clay minerals with the Neogene being dominated by montmorillonite, a product of chemical weathering; and the Pleistocene dominated by illite, a result of mechanical weathering of metamorphic terranes. It is suggested that these textural and mineralogical differences can be explained by contrasting weathering and transportational

processes in the Pleistocene and Neogene. During the Pleistocene mechanical weathering and transportational processes dominated with active erosion and transport of coarse-grained particles by both glacial ice and energetic proglacial streams. Delivery of these sediments to the deep ocean basin was sufficiently rapid for chemical weathering to have been a relatively unimportant process, thus the final clay mineral suite deposited in the basins was relatively fresh, unweathered, and rich in illite. During the Neogene mechanical weathering was relegated to a relatively minor note due to the absence of an active ice margin and accompanying proglacial drainage on eastern North America and the average particle size of particles delivered to the ocean basins was significantly different than during the Pleistocene. Chemical weathering processes dominated during the Neogene creating a thick seprolite over the later glaciated terrane and resulting in much more montmorillonite sediments being delivered to the basins.

3. Homogeneous, hemipelagic lutites accumulated at high rates as bottom current deposits on the easternmost plateaus of the northern Bermuda Rise and the Corner Rise during the Pleistocene. It is suggested here that these lutites were deposited on the Corner and Bermuda Rises by the Gulf Stream and its return flow respectively. During primarily the glacial portions of the Pleistocene coarse-

grained turbidites were injected into the basin from the St. Lawrence drainage system. These turbidites flowed southward down the southeastern Sohm Abyssal Plain and crossed the westward flowing Western Boundary Undercurrent, the eastward flowing Gulf Stream, and the westward flowing return flow. At each encounter portions of the fine-grained fraction of the turbidity current were captured and carried downstream by the intersecting current system. This phenomena has been documented by Hollister and Heezen (1972) for the Western Boundary Undercurrent. The sediments captured by the Gulf Stream were carried eastward and deposited on the Corner Rise as acoustically laminated deposits and the sediments captured by the return flow were carried eastward and deposited as similar deposits on the northern Bermuda Rise.

4. Oligocene and Neogene non-laminated sediments both underlie the acoustically laminated sediments and extend this further to the west. Similar deposits are observed on the Corner Rise. They have been interpreted as bottom currents deposits by Tucholke et al. (1977) on the basis of their accumulation rates, the presence of displaced organic detritus, and the absence of authigenic minerals. It is suggested here that these deposits accumulated in a similar manner to the overlying laminated sediments.

5. The two primary sedimentary acoustic features investigated on the western margin of the basin are the Hudson Outer Ridge and the Gulf Stream Outer Ridge, both named for the first time in this paper. The Gulf Stream Outer Ridge is an arcuate ridge that lies along the western boundary of the northern Bermuda Rise. The Horizon A complex passes beneath the ridge and this places a lower limit in its formation of late Eocene or early Oligocene. The lapping of Pleistocene turbidites on portions of an outcrop on the west-facing flank of the ridge places a Pleistocene upper limit on the development of the ridge and suggests that erosion occurred in the early Pleistocene or late Neogene. The present-day Gulf Stream System flows above the Gulf Stream Outer Ridge.

The Hudson Outer Ridge is a ridge of primarily Neogene hemipelagic sediments that lies beneath the lower continental rise of the U.S. between the Hudson Fan and the point where the Hatteras Transverse Canyon crosses the lower continental rise to the Hatteras Abyssal Plain. Flat-lying Pleistocene turbidites are dammed behind the landward facing flank of the Hudson Outer Ridge. The ridge lies beneath the present southwestward flowing Western Boundary Undercurrent.

It is here suggested that both ridges formed during the Neogene as the result of the interaction between both elements of deep circulations and fine-grained sedimentary input to the Hudson Fan region. The Western Boundary Undercurrent entrained portions of the fine-grained Neogene turbidites and distributed them to the southward forming the Hudson Outer Ridge. Portions of the input escaped to the east and were entrained by the northward and northeastward flowing Gulf Stream System which distributed and deposited them as the Gulf Stream Outer Ridge.

During the late Neogene or perhaps early Pleistocene increased velocities of the Gulf Stream eroded the western face of the Gulf Stream Outer Ridge. During the Pleistocene turbidites filled the trough behind the landward flank of the Hudson Outer Ridge and also the lowest portions of the eroded face of the Gulf Stream Outer Ridge.

BIOGRAPHICAL SKETCH

I was born on February 13, 1947 in Voluntown, Connecticut and received my primary and secondary school education there. I graduated with a B.A. in Geology from Wesleyan University submitting an Honors thesis entitled, "A Geophysical Survey of a Buried Former Channel of the Connecticut River." Upon graduation I entered the MIT/ W.H.O.I. Joint Program and spent a year in residence in Cambridge until I received an offer to serve in the Federal Government that I felt I couldn't turn down. After about two years in the Army I returned to Woods Hole where I have been studying the interrelated problems of sediment acoustics and the sedimentary evolution of the oceans. Several months ago I accepted a position as a Research Associate at the Graduate School of Oceanography at the University of Rhode Island and I have been working there as I completed this thesis.

Publications:

Silva, A.J., Hollister, C.D., Laine, E.P. and Beverly, B.E., 1976, Geotechnical properties of deep sea sediments: Bermuda Rise. Mar. Geotechnology, 1:195-232.

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GEOLOGIC EFFECTS OF THE GULF STREAM SYSTEM IN THE NORTH AMERICAN BASIN by Edward P. Laine. 165 pages. January 1978. Prepared for the Office of Naval Research under Contract N00014-74-C-0262; NR 083-004.

The Gulf Stream System contains a clockwise rotating set of bottom currents which influence the sea bed in the northern North American Basin. It is possible to interpret the present-day and historical record of current activity in this basin in terms of the deep flow of the Gulf Stream. This interpretation provides a much more satisfactory and consistent explanation of the geologic record than previous interpretations based strictly on the influence of the classic abyssal circulation.

The present-day circulation of the Gulf Stream actively resuspends large quantities of sediment on and near the northern Bermuda Rise and it is suggested that this resuspension may be due to the eddy field which is embedded in the westward flowing return flow. During the late Cenozoic the Gulf Stream System was responsible for depositing and shaping the major acoustic/sedimentological units on the relatively smooth surface of the Horizon A complex. Fine grained, montmorillionite-rich sediments derived from the chemically weathered saprolites of the Hudson and St. Lawrence drainage basins were injected into the deep ocean basins by turbidity currents during the late Paleogene and the Neogene. Fine-grained turbidites from the St. Lawrence spread southward down the Southeastern Sohm Abyssal Plain across the eastward-flowing Gulf Stream and its westward flowing return

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1. Gulf Stream
2. Sediment Dynamics
3. North Atlantic Ocean

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