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ECHO CHARACTERISTICS, REFLECTOR HORIZONS AND GEOLOGY
OF THE WESTERN CENTRAL NORTH ATLANTIC

by

THOMAS HOWARD SHIPLEY

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

Thesis Director's Signature:

Houston, Texas

March 1975
ABSTRACT

ECHO CHARACTERISTICS, REFLECTOR HORIZONS AND GEOLOGY
OF THE WESTERN CENTRAL NORTH ATLANTIC

THOMAS HOWARD SHIPLEY

An extensive geological and geophysical study of 250,000 km$^2$
of ocean floor with about 100 stations and 16,000 km of track was
undertaken in the western North Atlantic 600 km southeast of Bermuda.
A bathymetric chart of the area including parts of the Bermuda
Abyssal Hills, Bermuda Rise and Nares Abyssal Plain was prepared
at a 100 fathom (0.25 sec) contour interval. Two northwest trending
valleys are found in the area with one nearly continuous to the
Mid-Atlantic Ridge at 24°N. The abyssal hills province contains
irregular hills and basins 10-16 km wide with about 600 m of relief
probably generated by ridge flank volcanism and faulting. Conical(?)abyssal hills 5-10 km wide with about 400 m of relief are thought to
represent a later stage of mid-plate volcanism probably related to
the Oligocene uplift of the Bermuda Rise.

The 3.5 kHz echo characteristics of the surficial sediments
were combined with piston core data to produce a geologic map with
five main units. Pelagic brown clay sedimentation has been fairly
constant at 1 to 2 m per million years since mid-Cretaceous. In
some of the high areas and on the Bermuda Rise at depths less than
5600 m a 30 m opaque unit records carbonate sedimentation that
began sometime in the Pliocene with lowering of the calcium car-
bonate compensation depth. Three distinct echo characters are
observed from the various stratified sediment bodies. One is due
to near outcrop of a deep reflector unit. Another unit is composed
of discrete closely spaced (about 8 m) reflectors of the Nares Abyssal Plain and parts of the southern fracture valley. A third unit contains widely spaced (20 m) reflectors restricted to the more northerly fracture valley and certain cross valleys. The stratified sediments in both the Nares Abyssal Plain and the fracture valleys consists of brown clays at the surface and gray clays at depth. The gray clays are interpreted as turbidites with 12% more silt than the brown clays and always occurring in water depths greater than 5800 m. The turbidity currents crossed the Nares Abyssal Plain into the southern valley and over low sills into the northerly fracture valley. The cap of brown clay indicates that turbidity currents probably have not been active in this area for at least 300,000 years.

Seismic profiler records indicate that Horizon A and a prominent reflector above "A" are continuous into the northern Nares Abyssal Plain and probably into the two fracture valleys where the older reflector, "A", was only slightly deformed and raised with the Bermuda Rise uplift. Based on the reflector geometry the southeastern part of the Bermuda Rise was likely already a high by mid-Eocene.

The abyssal hills province exists because the area is elevated with respect to the Nares and Sohm Abyssal Plains. The elevation differences in basement of about the same age might be a result of changes in ridge crest elevation along strike in the Cretaceous or are related to the uplift of the Bermuda Rise or other crustal warping. Normal crustal thicknesses have been reported for this area and on the Bermuda Rise suggesting that the cause for the basement elevation (or depressions) is mantle related.
ACKNOWLEDGEMENTS

The late Maurice Ewing suggested this project and supervised the field work. His experience and wisdom were shared unselfishly with the fledging student. J. Lamar Worzel has given continuing support and arranged for my introduction to sea duty to be under the direction of Maurice Ewing, resulting in the most intense learning experience I will ever undertake.

The program of research began while I was a student at Columbia University (Lamont-Doherty Geological Observatory) and continued in a cooperative program between the Department of Geology at Rice University and the Geophysics Laboratory of the University of Texas Marine Science Institute. For the success of this program I am indebted to the late Maurice Ewing and to John J. W. Rogers.

M. Talwani and J. Ewing made valuable ship time available on CONRAD and VEMA. The assistance of M. Truchan, chief scientist of VEMA 31, in carrying out a profiling and coring program is greatly appreciated. Stimulating discussions with fellow students and staff at Lamont, Rice and Texas added greatly to the thesis. Discussions with R. W. Embley, S. Connary, T.-C. Shih, S. K. Addy and my advisors J. L. Worzel and R. E. Casey were especially helpful. Illustration work was aptly handled by L. Swickheimer, photography by J. Ellis and R. Emerson and drafts of the manuscript were typed by C. Castille.

Various parts of this investigation were supported by the National Science Foundation NSF GX-34659, Scope G to Lamont-Doherty
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INTRODUCTION

Knowledge of the deep ocean floor has been rapidly expanded in recent years. Major reconnaissance surveys of the world oceans have now been completed. However, new data recently collected by the D. V. GLOMAR CHALLENGER is certainly as important as that collected by its namesake the H.M.S. CHALLENGER in its major expedition from 1872 to 1876. Most present and past geological and geophysical work has been directed at the continental margins and associated abyssal plains, mid-ocean ridges and rises and low and high latitude studies of biogenic sediments. Little attention has been given to the study of areas far removed from the major sources of biogenic and terrigenous sediments.

Part of the reason for this apparent lack of study may be directed at the present interest in geological sciences with the theory of plate tectonics which supposes that the important geologic problems exist only at rigid plate margins (Wilson, 1965; McKenzie and Parker, 1967). Morgan (1968) has further stated that there is "no stretching, folding, or distortion of any kind within a block." This early rigid plate tectonics, senso stricto, was responsible for redirecting most work to the plate margins. It has since become clear that plates are not nearly as rigid as first suggested by Morgan (1968). Another reason for the lack of study, particularly of small scale features, has been the absence of necessary instruments and techniques for detailed surveys.
Statement of the Problem

The major physiographic provinces of the world oceans are known from the extensive reconnaissance surveys. Heezen, Tharp and Ewing (1959) prepared a physiographic diagram of the North Atlantic Ocean which shows the salient features of the North Atlantic. Part of their diagram is shown in Figure 1. Note that along the axis of maximum depth (dot-dash line) lay the abyssal hills, widespread features on both sides of the Mid-Atlantic Ridge. These areas of abyssal hills occupy well-defined areas in the important world oceans. A particularly large area of abyssal hills occur in the Northwest Pacific Ocean. Several very small areas in the Pacific abyssal hills have been studied in great detail by investigators at Scripps Institution of Oceanography using a DEEP TOW system (Moore and Heath, 1967; Luyendyk, 1970; Naugler and Rea, 1970; Mudie and others, 1972). Rona, Harbison and Bush (1974) have recently completed a survey of a small area (about 3 square degrees) in the abyssal hills east of the Mid-Atlantic Ridge at about 23° N. Little work has been done elsewhere in areas of abyssal hills. This is particularly true when one considers the extent of abyssal hills areas which often contain economically important deposits of manganese nodules.

The present study was undertaken to describe a portion of the abyssal hills province in the western North Atlantic, to explore the origin of the abyssal hills and their modification through time and to compare these abyssal hills with the few others that have been studied (as noted above). Because abyssal hills areas
Figure 1  Physiographic diagram of the western North Atlantic Basin (after Heezen and others, 1959). Bathymetry of the boxed area is shown in Figure 2.
occur as fairly well-defined provinces in the ocean basins some of the physiographic boundaries of the province were studied to help understand the distribution of abyssal hills areas. Finally, the study of the physiography and sedimentation patterns in this area far removed from biogenic and terrigenous sources was undertaken to examine the processes that modify the ocean floor morphology with time and to attempt to explain the occurrence, and particularly, the distribution of manganese nodules in this part of the western North Atlantic.

Area of Investigation

The area chosen for the relatively detailed study is 600 km southeast of Bermuda, and about 2000 km east of Miami, Florida (Figure 2). The area represents the northwestern part of the Bermuda Abyssal Hills Province bounded on the west by the Bermuda Rise, south by the Nares Abyssal Plain, north by the Sohm Abyssal Plain and to the east by the flank of the Mid-Atlantic Ridge (Figure 1). The area studied here includes the boundaries of the abyssal hills province with the Bermuda Rise and the Nares Abyssal Plain. Two northwest trending valleys form another important physiographic component of this area.

The area was originally chosen for a fairly detailed study of the occurrence and distribution of manganese nodules under the International Decade of Ocean Exploration, Seabed Assessment Program (Ewing, Shipley and Connary, 1973). The survey area was later extended to cover an expanded area with greater emphasis on the origin of the abyssal hills province and its sediments
Figure 2. Bathymetric chart of part of the western North Atlantic (after Uchupi, 1971). The boxed area outlines the main survey region. Contour interval is 400 meters.
(Shipley and Ewing, 1974) and their relation to the occurrence of manganese nodules (Shih and others, 1974; Addy and others, 1974).

Techniques Employed

The study of features on the ocean bottom a few tens of kilometers in width with less than a kilometer of relief from a surface ship six kilometers from the bottom requires precise navigation, good electronic equipment and winches with more than 6000 meters of cable for bottom sampling.

**Underway data**

Satellite navigation systems combined with standard dead reckoning techniques allows navigational accuracy of the order of 1/3 kilometer or better depending on the amount of maneuvering and time between satellite fixes. The fairly low current velocities in the Sargasso Sea helped increase the navigational accuracy to better than average for single channel satellite navigation systems.

While underway the total intensity of the earth's magnetic field was continuously recorded. The proton precession magnetometer has an accuracy of about 1 gamma. The difference between this recorded field and a reference field (IAGA, 1969) is the magnetic anomaly.

3.5 kHz and 12 kHz continuous (one pulse per second) precision depth recordings were made while underway from hull mounted transceivers. The time to bottom can be routinely determined to 1/200 of a second. However, in areas of rough terrain, for example the abyssal hills,
the actual bottom cannot always be found and multiple echos caused by the nearby bottom configuration can cause difficulties in judging the true bottom echo. The time delay for the bottom return is usually converted to nominal fathoms, where one second of two way reflection time is 400 fathoms (750 meters). This depth is usually less than the true depth. Since most data is collected in uncorrected (nominal) fathoms, all maps in this paper will use the nominal fathom which is readily convertible to seconds or nominal meters. 3.5 kHz PDR records are used extensively in this study to relate acoustic signature in the bottom and near subbottom with core samples. The 3.5 kHz records show reflectors up to 0.2 seconds subbottom in certain sediment bodies in the abyssal hills area.

One other underway geophysical method which essentially extends the subbottom penetration observed with the 3.5 kHz data is here called the seismic profiler system (profilers). A high pressure air gun is used as a sound source with a repetition rate of 10-20 seconds while an array of hydrophones towed behind the ship receives the return from the bottom and subbottoms. The air guns produce energy at about 10-100 Hz and thus have greater penetration, less resolution and a longer sampling rate than the 3.5 kHz records. Seismic profilers commonly obtain subbottom penetration of 1-2 seconds in sediments.

Station Data

Direct sampling of the ocean bottom and subbottom was accomplished using several different devices.
Free-fall grab samplers (grabbers) were used extensively in the investigation of the distribution of manganese nodules. Often several were released normal to a slope so that a profile of the surface manganese nodule distribution could be investigated as a function of depth. Various box corers which obtained a large volume of undisturbed sediment to a depth of about a meter were also used in this region. Both of these sampling devices were used primarily for manganese studies. The results are presented elsewhere (Ewing, Shipley and Connary, 1973; Amos and others, 1973; Shih and others, 1974; Addy and others, 1974; Addy and Ewing, 1974).

Sampling techniques used in studying the origin and evolution of the abyssal hills province included bottom cameras with nephelometers, dredges and piston cores.

Bottom camera stations usually recorded 8-15 photographs at 2 to 5 minute intervals as the ship drifted over bottom (usually at 0.5 kts or less). Bottom photographs are slightly oblique and cover an area of about 1.2 x 2 meters. Often attached to this instrument is a nephelometer, a device which measures the scattering of light which is related to the amount of material in suspension.

Attempts to sample volcanic rock outcrop were made with dredges placed on the bottom while the ship slowly moved in an up slope direction. Little success was achieved in the abyssal hills area with this device due to the veneer of sediment covering most of the bottom.
Most station data was collected by piston coring devices. Fifty-nine piston cores were obtained in the survey area. The average length of good core recovered was eight meters.

A problem with bottom sampling in the rough terrain of abyssal hills is the presence of side echoes on the 3.5 kHz records which "stretch out" when the ship drifts on station and the difficulty of relating the acoustic nature of the 3.5 kHz records with the returned bottom sample, particularly in areas where the sediments appear to change laterally. In later cruises a down looking 12 kHz transducer (pinger) was often attached to the bottom sampling device. This Pingerprobe (Ewing, Embley and Shipley, 1973) allows better control of bottom sample location with respect to the acoustic nature of bottom observed from the surface ship and often indicates, since the instrument drifts just over the bottom for a while, the lateral variation in the acoustic nature of sediments.

Ship time

Data used in this study came from four different ships between 1965 and 1974. The ship time data is summarized in Table 1. The bulk of the ship time is from Lamont-Doherty Geological Observatory, New York. Detailed surveys were made on two cruises of LDGO's CONRAD and one cruise of Duke University's EASTWARD. The author participated in all three of these cruises.

Data quality fluctuated depending on the ship and for the same ship at different times. The data collected on the ten cruises used in this paper and their quality is summarized in Table 2.
### Table 1

**Ship Time Data**

<table>
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<tr>
<th>Cruise</th>
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<td>*E14-73</td>
<td>M. Ewing</td>
<td>28 Sept.-6 Oct. 73</td>
<td>S&quot;C&quot;-S&quot;S&quot;</td>
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<tr>
<td>RC10-02</td>
<td>D. Hayes</td>
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<td>S4-6</td>
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<tr>
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<td>S3</td>
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<td>S203-S232</td>
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<td>V31-07</td>
<td>M. Truchan</td>
<td>28 July-1 Aug. 74</td>
<td>S191-S195</td>
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E - R/V EASTWARD - Duke University, N. C.

RC - R/V ROBERT D. CONRAD - Lamont-Doherty Geol. Obs., N. Y.

SHL - R/V SIR HORACE LAMB - Palisades Geophysical Institute, N. Y.

V - R/V VEMA - Lamont-Doherty Geol. Obs., N. Y.

* author on board
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<th>Piston Core</th>
<th>Box Core</th>
<th>Bottom Camera</th>
<th>Nephelometer W/camera</th>
<th>Free-Fall Sampler</th>
<th>Dredge</th>
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1. 12kHz PDR = 12 kHz precision depth recordings
2. 3.5kHz PDR = 3.5 kHz precision depth recordings
3. Profiler = low frequency (10-100 Hz) bottom profile recordings
BATHYMETRY

Depth sounding surveys of the ocean bottom were the very first type of bottom data to be collected about the ocean floors. Producing contour charts of the ocean bottom from soundings has been routine for many years. With the development of methods of continuous recording the data began to swamp mapping organizations. It became obvious that inaccuracy in open ocean navigation would allow only moderate scale mapping of the bottom because ship track intersections often show large apparent differences in water depth. With the advent of satellite navigation systems mapping has become much more precise with few inconsistencies at track intersections.

All data used in construction of the bathymetric charts for this abyssal hills area were collected in conjunction with satellite navigation. An attempt was made to add random track which used only celestial and/or LORAN for navigation with little success. Because of the high variability in bottom topography it was not possible to adjust these tracks to fit the better data with any certainty since there are practically an infinite number of possible adjustments, each of which will satisfy the known precise data.

Approximately 16,000 km (10,000 n.m.) of satellite navigated ship track with continuous precision depth recordings were used in the construction of the bathymetric chart shown in Plate 1. Data sampling interval along track was normally every 3-5 minutes (about 1/2 n.m. or 3/4 km) and more often where needed to record extreme highs and lows. Plate 2 shows most of the track used in construction of the chart. Most data was compiled on worksheets
where one degree of longitude equalled 24 inches (1:160,000 at 27° Mercator projection) and reduced about 84% to the scale in Plate 1 of 1:953,642 (at 27°, Mercator projection) or one degree longitude equals 4.08 inches. Two small areas were extensively surveyed with 1-2 km track spacings. The locations of these areas are shown in Plate 2 and the bathymetric charts and track control are shown, respectively, for the north detailed survey area in Figures 3 and 4 and the south detailed survey area in Figures 5 and 6. All bathymetric maps were contoured at 100 fathom (0.25 sec) intervals. This contour interval was chosen to allow reproduction of the map at a reasonable scale and to conform with earlier charts of this and adjacent areas. It is believed that a 50 fathom interval would not substantially add to the information available from the bathymetry of this area. The 100 fathoms contours are probably the best that can be obtained with the present data density. Since the contours are interpolated between data points the precision of the interpolated contour position in areas of the best control is probably of the order of 1 to 2 km and falls off rapidly with a decrease in data density in the eastern, northeastern and southwestern part of Plate 1.

General Features

Parts of three important physiographic provinces are illustrated in Plate 1. The Bermuda Rise is northwest of a line connecting 29°N, 61°W and 27°N, 63°W while southeast of this line are the abyssal hills. The third important physiographic province is the Nares Abyssal Plain bounded by the Bermuda Rise (to the west)
Figure 3 The north detailed survey area bathymetric map of an abyssal hill. G=grab sample, C=RC15 core, K=camera, D=dredge (after Ewing, Shipley and Connary, 1973). Contours in hundreds of fathoms (or times 0.25 for two way travel time in seconds).
Figure 4  Track lines for bathymetric control in the north detailed survey area.
Figure 5 Bathymetric chart of the southern detailed area. Station symbols as in Figure 3 with BC=box core (after Ewing, Shipley and Connary, 1973). Depths in hundreds of fathoms.
Figure 6  Track lines for bathymetric control in the south detailed survey area.
and by the abyssal hills province (to the northeast).

A significant northwest trending bathymetric grain is observed in Plate 1. This is produced by two northwest trending valleys that occur in the abyssal hills province and a third on the Bermuda Rise. These valleys will be referred to as the Bermuda Fracture Valley, the $24^\circ$ North Fracture Valley and the Nares Fracture Valley (see Plate 1 for locations). A subdued northeast trend is also observed within the abyssal hills province though it is significantly weaker than has been reported by other workers (see Figure 2 and Johnson and Vogt, 1971).

The mean depth in Plate 1 is about 3100 fathoms. The shallowest area is a high isolated peak less than 2200 fathoms in the northwestern part of the map and a basin over 3400 fathoms deep in the east central part of the map, a relief of more than 1200 fathoms. Within the abyssal hills province and the Bermuda Rise the mean depth decreases slightly to the northwest. It is interesting to note that if the Nares and the $24^\circ$ North Fracture Valleys are neglected the axis of maximum depth for the western North Atlantic Basin would be shifted much farther east toward the flank of the Mid-Atlantic Ridge.

It is immediately evident from examining Plate 1 that greater slopes occur in the abyssal hills province than on the Bermuda Rise or Nares Abyssal Plain. The mean slope is about 2-3$^\circ$ while maximum slopes of about 15$^\circ$ occur on some isolated high abyssal hills and the sides of the $24^\circ$ North Fracture Valley. It is impossible to directly measure slopes greater than a few degrees, and 15$^\circ$ represents an average between two data points of smaller slope separated by an area of greater slope.
Bermuda Rise

On the Bermuda Rise the bathymetry is subdued when compared with the abyssal hills province. This is not due to lower data density because the profiler records show a thickening of the sediments above basement and the rise of the basement depth above the level found in the abyssal hills area. The water depth is generally less than 3000 fathoms on the Bermuda Rise and greater than 3000 fathoms in the abyssal hills province.

Nares Abyssal Plain

Regionally the Nares Abyssal Plain is essentially flat, dipping gently to the north and east. It is interrupted only by isolated volcanic peaks and basement highs. A northwest trending basement high at the southwestern boundary of the abyssal hills province forms a nearly continuous ridge separating these two physiographic units. Another broad high trending west-northwest (from 24°N, 59°W) almost separates the main abyssal plain into two units at 25°N. Northeast of this ridge the abyssal plain has a gradient of about 1:6000, considerably smaller than reported for the main part of the abyssal plain to the southwest of this WNW trending ridge.

Bermuda Abyssal Hills Province

There are five basic components to the bathymetry of the abyssal hills area. These are the 24° North and Nares Fracture Valleys, the broad and high abyssal hills and isolated basins.
Fracture Valley Abyssal Plains

The 24° North Fracture Valley contains an abyssal plain at a depth of about 3375 fathoms. The abyssal plain has a gradient of about 1:1000 dipping to the southeast with some minor slope reversals. Northwest of 61°W the slope increases to 1:5000 and the width of the flat floor diminishes rapidly toward the western terminus of the valley.

The Nares Fracture Valley also contains an abyssal plain but at a depth of about 3280 fathoms. Its gradient is about 1:4000 southeast of 61°W and dips to the southeast. Like the 24° North Valley it also contains minor slope reversals. This valley is connected with the Nares Abyssal Plain by a ramp dipping to the east with a gradient of about 1:550 entering the Nares Fracture Valley at 60°W. One unusual feature of the Nares Fracture Valley is that northwest of 61°W the mean gradient increases to 1:750 dipping to the southeast while the bottom is gently undulating with apparent wavelengths of about 2 to 6 km and apparent amplitudes of 20–30 fathoms.

Abyssal Hills and Basins

If the major fracture valley bathymetry is neglected the abyssal hills province consists of numerous medium scale hills and basins of irregular shape. Heezen, Tharp and Ewing (1959) have defined abyssal hills as ranging in height from 50 to 600 fathoms and generally 4 to 10 miles in width.

A closer look at the bathymetry of this area indicates two different types of hills. Within the classification scheme of Krause and Menard (1965) these are termed broad high swells and
high abyssal hills. For convenience these will be referred to as the broad and high abyssal hills, respectively. The broad abyssal hills occur at depths less than 3000 fathoms, have a relief of about 200 fathoms and a width of 6 to 10 miles (10-16 km). Small apparently conical high abyssal hills from 3 to 6 miles (5 to 10 km) in width and having about 150 fathoms of relief sometimes occur either on the broader abyssal hills or elsewhere.

Isolated basins about the same size as the broad abyssal hills occupy areas greater than 3200 fathoms with a maximum relief of about 200 fathoms. The floors of some are flat and nearly level while others are moderately smooth but sloping. Deeper isolated basins are more common in the eastern part of the map area north of the 24° North Fracture Valley.
NEAR BOTTOM SEDIMENTS

The bottom and shallow subbottom sediments discussed here are those that have been directly sampled by coring or may be mapped on the basis of their 3.5 kHz acoustic signature. The direct samples are limited to about 14 meters subbottom and acoustic mapping is limited to about 0.2 seconds subbottom due to the attenuation of the sound energy. Bottom samples have been examined in an effort to determine their origin, ages, provenance and depositional processes involved in their spatial distribution within the abyssal hills and surrounding areas and their relationship to the acoustic signature.

Lithologies

Bottom samples of sediments were collected by the normal piston coring method (Bouma, 1969). A total of 59 cores were obtained in the vicinity of the abyssal hills, Bermuda Rise and the Nares Abyssal Plain. A few cores from the Sohm Abyssal Plain were also examined. The maximum length of useful core was 1413 cm for RC15 C188 (ROBERT CONRAD Cruise 15, Core 188) in the 24° North Fracture Valley taken in a water depth of 3365 fathoms. Columnar sections illustrating the important lithologic units are shown in Figure 7(b-j) and the locations of the cores are indicated in Plate 2 with the exception of RC16 C178 located at 22°07'N, 60°40'W. Lithologic descriptions are based on my shipboard notes, ship and laboratory core descriptions and my own laboratory observations.
Figure 7a  Lithologic sections of sixty piston cores are presented in b-j. The key to the symbols is given above. Data for the sections was compiled from shipboard and laboratory description logs and personal examination of the cores. The cruise, core number and water depth in which the core was taken is given at the top of each core. Core locations are plotted in Plate 2 (except RC16 C178 at 22°07'N, 60°40'W).
Figure 7b
Figure 7g
Considering the widespread area that was examined the core lithologies varied little with most cores containing a very large fraction of clay sized material. Biogenic components were generally limited to cores obtained in the shallowest regions though some cores with older carbonate layers (several meters subbottom) occur at moderate depths. Volcanogenic and authigenic components occur in various special situations. Brown clay was found in cores at all depths sampled and probably represents a pelagic blanket while the gray clays are limited to cores obtained at the greatest depths.

**Biogenic sediments**

Grouped as biogenic sediments are foraminiferal ooze, foraminiferal marls, marls, diatomaceous oozes and diatomaceous clays. Fourteen piston cores contained some biogenic sediments.

**Carbonate Constituents.** Of the 59 cores obtained in the study area only 13 contained some carbonate (RC15 C191, C192, C198, C203, C204, C205; RC16 C194, C198; V25 C4; V31 C162, C164, C165, C166). This carbonate existed largely as foraminifera tests and fragments in the coarse fraction (greater than 62 microns) and unidentifiable carbonate in the fine fraction. The term foraminiferal ooze is used for the sediments containing more than 80% coarse fraction, consisting largely of the tests of foraminifera. The term foraminiferal marls is used for sediments containing between 5-30% coarse fraction consisting mainly of foraminiferal tests. Marls are sediments containing significant carbonate in the matrix.
Diatomaceous Constituents. Three cores RC16 C186, C191 and V31 C166 contain significant components of diatomaceous oozes and diatomaceous clays. Diatomaceous oozes contain more than 80% coarse fraction consisting largely of diatoms and some sponge spicules. The term diatomaceous clay is used for sediments containing between 5 and 30% coarse fraction of diatoms and lesser amounts of sponge spicules. No radiolara were observed in any samples that were examined for possible age determinations.

In general the biogenic sediments are limited to the highs that exist today and the few cores consisting largely of biogenic sediments are limited to the highest areas such as RC15 C204 at 2438 fathoms and RC16 C197 at 2231 fathoms and to areas nearer the Bermuda Rise. Marly layers within predominately clayey sediments, with the exception of RC15 C191, all occur at some depth in the core and constitute only a minor fraction of the total core volume. The combination of the low surface water productivity of the Sargasso Sea where most pelagic biogenic sediment constituents originate and the calcium carbonate compensation depth which is well above the median depth of about 3000 fathoms in this area accounts for the scarcity of carbonates in the sediments. The diatomaceous sediments generally occur at moderate depths. The siliceous tests dissolve as they settle to the bottom but not as fast as carbonate tests. The differences in the apparent dissolution rates between carbonate and silica tests could account for the occurrence of carbonates on the highs and silicious sediments at moderate depths as on the Bermuda Rise.
**Age Dating.** The biogenic sediments are the only sediments that contain components that can be dated paleontologically. R.E. Casey (Rice University) attempted to date the fauna from a few selected cores. The precision possible with the assemblages present was poor. The best that could be done with the microfossil fauna was epoch precision dating. Two Pliocene, one Pleistocene and two Quaternary ages were determined as indicated in Figure 7. The significance of these ages and sedimentation rates will be discussed in a later section.

**Authigenic Constituents**

Authigenic constituents of the sediments included in the core descriptions of Figure 7 are manganese nodules, manganese sand and crust, orange clay and manganese micronodes.

**Manganese Nodules.** Manganese nodules are very common on the sediment surface of most of the highs in the area east of the Bermuda Rise. Manganese nodules were found at the surface or at depth in 15 of the piston cores. The nodules were almost always associated with other forms of manganese or brown clay.

**Manganese Sand, Manganese Crust.** Several of the cores contain units of sand sized grains of manganese (manganese micronodes) or manganese crust in striking contrast to the common clays. The six cores containing manganese sand or crust were obtained in water depths of less than 3100 fathoms (except RC16 C197 at 3219 fathoms) and outcrops of rock are suggested from bottom photographs. Other nearby core samples and dredges near RC15 C200, RC16 C191 and RC16 C196. Also, the camera station near RC16 C188(K176)
shows possible rock outcrop, but this identification is not as
confident. V23 C137 and RC16 C197 which contain manganese have
no collaboratory data concerning rock exposure. It appears, however,
that manganese sands and crusts usually occur at moderate or shallow
water depths and are associated in some way with volcanic rock
outcrop.

**Orange Clay.** Often associated with the manganese crusts
and in the centers of nodules is a very distinctive orange clay.
Diffraction patterns of these clays are difficult to interpret.
Addy and others (1974) believe that these clays may represent
altered igneous rock. Nayuda (1964) has identified similar material
as largely palagonite. Their occurrence in the piston cores
is usually associated with manganese crust, volcanic sands, volcanic
gravels and altered igneous rock.

**Manganese Micronodules.** Observed in most of the sediment
samples of this region were manganese micronodules. Though most
of the clays contained much less than 5% coarse fraction, the
coarse fraction usually contained a significant portion of manganese
micronodules. One important group of sediments which often did
not contain abundant micronodules were the gray clays. The implications
of this important exception will be dealt with later.

Manganese micronodules have been reported in most sediments
of the deep sea (Mero, 1964). In areas where there is more rapid
deposition or a larger component of biogenic or terrigenous coarse
fraction, micronodules are probably still present but are not
easily observed.
Volcanogenic Constituents

Volcanogenic constituents are those containing sands and gravels composed of altered igneous rock and massive altered igneous rock. Only RC15 C199 contained volcanic sand underlain by a gravelly sand. The gravel sized, fairly angular rock fragments are composed of highly altered igneous rocks. A gravelly sand is also found in RC10 C5 overlain by yellow and orange clay. RC15 C190 and V25 C83 both contained fairly massive altered igneous rock in which both cores bottomed.

Terrigenous Sediments

The most abundant sediments occurring in the survey area are lutites normally containing about 1% coarse fraction. The lutites have been subdivided into two groups based on their color. After a description of the cores, particle size distribution and clay mineralogy data will be presented which shows that the color is in fact a good macroscopic tool for separating distinctly different lutite sediment units.

Brown Clays (Red Clays). Brown clays are sediments of tan to dark chocolate brown containing less than 5% coarse fraction greater than 62 microns. The coarse fraction consists of occasional foraminifera, sponge spicules, fish teeth, echinoid spines, quartz grains, rock fragments and abundant manganese micronodules. These are basically the so-called red clays described in the early literature of deep ocean sediments. Fifty-five of the 59 cores obtained in this survey area contained brown clay units. Of the 4 cores that did not contain brown clays V25 C83 cored only altered igneous
rock, RC16 C188 consisted of localized manganese crust and sands, 
RC16 C205 at a depth of 2438 fathoms contained a significant coarse 
fraction from biogenic sources in a matrix of brown clay and V31 
C166 on the Bermuda Rise contained a significant fraction of diatoms 
in a brown clay matrix. Thus, all four exceptions can be explained 
due to localized conditions.

The brown clays appear throughout the depth range of this 
area and for 23 the whole core is composed of the brown clay. 
Thus it appears that this is a pelagic clay settling throughout 
the area, but is "washed out" in some areas by the addition of 
significant biogenic, authigenic or turbidite components.

Gray Clay. The term gray clay is used here for sediments 
containing less than 5% coarse fraction greater than 62 microns 
but with color variations from green to dark gray. These sediments 
of various shades of green and gray are grouped together because 
it was found that their colors change, sometimes from gray to 
green between the time they are originally described on board 
the ship and described again in the laboratory. However, it may 
be possible that two different sedimentary units are being discussed 
as a single unit here. Later evidence, I believe, will show that 
this is not the case. The coarse fraction tends to be about 1% 
consisting of components similar to those in the brown clay except 
that manganese micronodules are usually absent as a significant 
component.

Gray clays, always interbedded with brown clays or overlain 
with brown clay occur in 13 of 59 cores in the survey area. The 
water depth range for these cores varies from 3115 to 3372 fathoms.
No gray clay occurs above 3100 fathoms. Physiographically, only four of the cores were not obtained in the abyssal plains of the Nares, the Nares Fracture Valley and the 24° North Fracture Valley. Three of these four cores are located in the area between the two main fracture valleys and two of these RC15 C194 and V31 C163 occur along north trending lows that connect the two fracture valleys. RC15 C189 also on the ridge at a depth of 3126 fathoms only contained an 8 cm layer at the core top composed of brown clay grading into gray clay within the 8 cm zone. RC15 C194 in 3222 fathoms just north of the 24° North Fracture Valley is located in a small closed basin separated from the main abyssal plain by a low sill.

With the exception of RC15 C189 (3126 fms) which contained a minor gray clay layer, all other cores containing the gray clays are found within abyssal plains or closely associated cross valleys connecting the abyssal plains. Thus the sediments are physiographically and depth dependent. Their distribution is controlled by either bottom water properties, provenance and/or the transportation and depositional regimes. Bottom water properties can probably be ruled out because Ewing, Shipley and Connary (1973) while reviewing the distribution of manganese nodules in this area reported no evidence of any unusual bottom water properties from salinity and temperature versus depth data. The depositional regime and provenance have been considered by looking at particle size distribution and clay mineralogy. The origin and distribution of the clays can be explained after this data has been reviewed.
Particle Size Analysis

Quantitative analyses of particle size often indicates differences between samples, environments of deposition and provenance. Particle size of the clay samples may indicate differences between the gray and brown clays and differences within the clay color groups not readily observable macroscopically.

Methods

Most samples of brown and gray clays have about 1% or less of a coarse fraction greater than 62 microns. A significant portion of this fraction consists of authigenic manganese micronodules and an occasional large grain of quartz. No volcanic glass shards were observed, and it is believed that if once present they have been altered to clays or are effectively used as macro or micro manganese nodule nuclei.

Particle size of the silt/clay fraction were determined using a hydrophotometer. The hydrophotometer, using the light extinction in the measurement of particle abundance has been aptly described by Jordan, Fryer and Hemmen (1971). This instrument allowed relatively rapid measurements of fine grained sediment size distribution. However, it was found that with the very large portions of very fine grained particles smaller than 8 μ {φ = -\log_{2}(diameter in mm)} and very small amounts of silt (4-8 μ) detailed particle size distribution by 1/2φ units was not possible. The results tabulated in Table 3 indicate the particle size only by silt (4-8 μ) and clay (greater than 8 μ). Histograms of the number of samples versus silt percent is shown in Figure 8.
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Figure 8  Histograms of the silt percent in the gray clays, brown clays and all the samples.
Results

A wide range of values for the silt percent in the samples is observed. For all samples (except V22 C231) the silt percent ranges from 7 to 75% with a mean of 21.3%. Gray samples had a silt content between 7 and 75% with a mean of 28.6%. The brown clays had a range of 7 to 33% with a mean of 16.3% silt. A test was made using the students' t-distribution (Alder and Roessler, 1968) developed for small sample populations to determine if the means were significantly different. There is about a 5% probability that the mean of all the samples could be the same as that of the gray clays. There is less than 0.1% probability that the mean of the total population is the same as the mean of the brown clays. It was also determined that the mean of the brown clays was different from the mean of the gray clays at about a 0.5% significance level. Thus the gray and brown clays have significantly different means, with the gray clays containing on the average 12% more silt.
Clay Mineralogy

The study of clay mineralogy of deep sea sediments has become routine. Biscey (1965), Jacobs (1970), Venkataraman and Ryan (1971) and Venkataraman and Biscey (1973) have studied the distribution of clay minerals within the sedimentary cores of deep sea sediments. Efforts have largely been directed at relating the mineralogy to the provenance of the sediments. It was with this aim that a study of the clay mineralogy was undertaken.

Method

X-ray diffraction analysis of the fine grained sediment is necessary to determine the structure and thus the mineral species. The method of Biscey (1965) has been adopted with minor changes introduced by later investigators of deep sea clays. Briefly, sample preparation consisted of washing originally air dried samples in distilled water to remove the soluble salts. The samples were dispersed and the grains greater than 32 microns in diameter were allowed to settle out before the remaining suspension was pipetted off onto a microscope slide and allowed to dry at room temperature. This procedure produces an oriented sample of clay minerals suitable for x-ray diffraction studies. Copper radiation with a nickel filter was used throughout as the x-ray source. The samples were scanned at 2° 2Θ (λ=2d sinΘ) per minute at a recorder speed of one inch per minute. Each air dried, oriented sample was run from 2° to 38° 2Θ and selected samples were run again after being saturated with ethylene glycol and again after heating at 600°C for one hour.
Identification

The four main mineral groups of clay present are illite, kaolinite, chlorite and montmorillonite. Also present were quartz, amphibole and mixed layered clays.

**Illite.** Common to all but one sample was the mineral group illite. The sequence of basal reflections at 10, 5 and 3.3Å were used in the identification of this group. The peaks are not affected by glycolation or heating.

**Kaolinite and Chlorite.** Kaolinite was found in most samples. The kaolinite group can be recognized and distinguished from chlorite easily by heating (Carroll, 1970) which destroys the kaolinite structure. The kaolinite reflections at 7.2 and 3.6Å overlap the chlorite reflections which occur at 14, 7.1, 4.7 and 3.6Å. The 14 and 7 and 3.6Å peaks before and after heating at one hour at 600°C were used in the identification of these two minerals.

**Montmorillonite and Mixed Layered.** The montmorillonite group was identified by the shift of the (001) reflection to 17Å on glycolation. Often there was not a single clear peak at 17Å but a range of peaks between 10-17Å not present before glycolation. This is interpreted as a mixture of several mineral species consisting of both expandable and nonexpandable structures.

**Sample Mineralogy**

The clay mineralogy was examined in 48 samples from 19 piston cores. The qualitative results are summarized in Table 4. The determination of the abundance of clay mineral species in heterogeneous samples by x-ray diffraction has been attempted by many
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<tr>
<th>Procedure</th>
<th>Illite</th>
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<th>Chlorite</th>
<th>Montmorillonite</th>
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Table 4 (cont.)
Clay Mineralogy

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1 - oriented, air dried
2 - oriented, glycol saturated
3 - oriented, heated at 600°C for one hour
X - abundant
0 - present
*

* - 33°29'N, 54°10'W, 2930 fms
workers. The history of the sample (Biscaye, 1965), mounting techniques (Gibbs, 1965) and variations among different instruments makes this at best semi-quantitative. An attempt was made to follow the method of Biscaye (1965) but the results were inconclusive and are not presented here. A qualitative estimate appears more reliable and is represented in the table as abundant, present or absent.

Quartz and feldspars were common in all samples. The less than 32 micron size fraction includes some silt that is present and explains the occurrence of quartz and feldspar observed in these and almost all other samples of deep sea sediments (Biscaye, 1965).

All the samples of brown and gray clay contained abundant illite and kaolinite (except RC15 C190 at 463 cm in which kaolinite was present but not abundant). Chlorite is abundant or present in most of the samples along with montmorillonite. The mixed layered clays (probably consisting of montmorillonite and chlorite) occur in six samples.

There appears to be little systematic variation in the clay mineralogy of the samples as a function of color or amount of silt in a sample. Nor does there appear to be any relationship between the physiographic setting and mineralogy.

Illite is probably the most common clay mineral of the world oceans. Biscaye (1965) attributes the abundance of illite to its common occurrence in many soils and resistance to chemical weathering. Kaolinite in recent sediments of the ocean is concentrated near
continental areas of intense tropical weathering (Biscaye, 1965) and like illite is most probably a mineral species more or less directly derived from the continents. Kaolinite has a distribution and origin similar to illite. Chlorite was also reasonably common in all the samples from the abyssal hills. The distribution of chlorite in recent deep sea clays indicates that chlorite is probably largely derived from high latitude continental soils. Biscaye (1965) also observed that a "vermiculite-type" mineral tends to alter to chlorite if the sample is dried but that this mineral has the same distribution pattern as chlorite. Thus, the three most common minerals in the abyssal hills sediments are probably largely derived from continental sources.

There is apparently some differences of opinion among deep sea clay mineralogists as to the significance of montmorillonite. Nayuda (1964) indicates that montmorillonite is formed by further diagenesis of palagonite. Peterson and Griffin (1964) reach similar conclusions for samples from the southeast Pacific. However, Biscaye (1965) suggests that these results are not necessarily valid in the recent sediments of the Atlantic. In the Atlantic, particularly in the North Atlantic, montmorillonite is not an abundant mineral compared to the quantity of illite and kaolinite and its occurrence appears unrelated to known volcanic sources. This situation is reversed for the South Pacific where montmorillonite is generally abundant in relationship to illite and kaolinite and, often associated with zeolites, palagonite and glass shards. Thus in the North Atlantic recent sediments, montmorillonite probably
consists of a large component from continental sources and a minor component from volcanic associations. Because no zeolites or significant amounts of glass shards or palagonite were observed in the piston cores of "older" sediments in the abyssal hills, it seems likely that observed montmorillonite is also a mix of both continental and local volcanic sources.

From the standpoint of provenance it appears that the brown and gray clays are ultimately derived from the same source with some local volcanogenic sources possible. In the core sampled from the Sohm Abyssal Plain (V22 C231) a significant 8.4Å peak believed to be amphibole was found in the gray clays. This same 8.4Å peak occurred in only one of 56 samples in the main survey area. This means that the turbidity currents that cross the Sohm Abyssal Plain do not extend into the abyssal hills area. Since the mineralogy of the gray clays from the Nares Abyssal Plain are about the same as the gray clays sampled in the main survey area, the gray clay must be related to the Nares Abyssal Plain and the north traveling turbidity currents crossing the abyssal plain.
Origin of the Brown and Gray Clay

The abyssal hills area is a long way from coarse grained terrigenous sources with the Bermuda Rise and the Puerto Rico Trench today acting as barriers to much bottom transported material. The post-Eocene turbidite sediments of the Nares Abyssal Plain have probably been transported along a path from the Hatteras Abyssal Plain, through the Vema Gap and then northerly across the Nares Abyssal Plain (Horn and others, 1972). Only the most distal parts of large turbidity currents can reach far north into the area surveyed. This would account for the fine grain sizes observed in the abyssal plain at about 24°N. The very deep water in the region of the survey, combined with the low surface water productivity in the Sargasso Sea, precludes any important component of biogenic sediment constituent.

The very fine material must be either derived from wind blown dusts over the oceans, or settling of fine material originally introduced to the ocean floor by turbidity currents or other processes at the continental margin. The settling velocity of wind blown dust may be speeded up by a process such as the clay particles being included in the test of an organism which then dissolves at it descends through the water column or it may be concentrated in fecal pellets which also dissolve in their descent to or soon after reaching the ocean floor. The finer material of a turbidity current could be suspended in the near bottom water mass and travel farther than the coarse grained material before settling to the bottom.
The clay mineralogy suggests that the two main color groups of clay are derived from similar sources. However, differences are suggested in sedimentation rate (presented in the next paragraph), particle size and color. The basic premise is that the gray clays represent deposits at the distal ends of turbidity currents, ultimately derived from the North American continental margin and the brown clays represent the even finer material originally introduced into the deep ocean waters off of river mouths or by passing turbidity currents with only a minor component contributed by wind blow dust to the top of the water column.

Age dating of these sediments are difficult due to the lack of biogenic components. However, a few intervals were tentatively dated by R. E. Casey (Rice University). Two cores RC15 C188 and RC16 C186 containing interbedded gray and brown clay have been dated and give minimum average sedimentation rates of 9.4 meters per million years and 2.4 meters per million years, respectively. If one believes that the gray clays are rapidly deposited by turbidity currents, the rates could be recalculated disregarding the gray clay section. This gives rates of 2.7 meters per million years and 0.2 meters per million years, respectively. Three cores RC15 C191, RC15 C192 and RC15 C198 consisting largely of brown clays, respectively, give minimum rates of 0.4, 1.2 and 3.0 meters per million years. The rates for the brown clay are in the range commonly found for "red" clays of 1 to 4 meters per million years. While the amount of data on rates of deposition presented here is limited, it appears that cores containing gray clays may have higher average sedimentation rates.
Data presented earlier on particle size distribution indicates that there is a significant difference in silt content between the color classes. The gray clays contain on the average 12% more silt sized material than the brown clays. An increase in silt content may be the only indication of a distal turbidite deposit, considering the great distance between the source region and depositional area and the very low regional gradient.

The basic reason for the color difference in the clays does not appear to be reflected in the mineralogy of the clays. An interesting phenomena was observed when the various clay samples that were prepared for x-ray analysis were heated at 600°C for one hour. The purpose of heating was to destroy the kaolinite structure so that chlorite could be detected if present. Diffraction patterns showed little difference after heating within experimental error except for the absence of kaolinite peaks, as expected. I later observed that both the gray and brown samples were shades of brown and that the gray color was no longer observable on any of the heated slides. This color change cannot be attributed to the destruction of kaolinite and seems most likely to reflect a change in the oxidation state of iron. Further, S. K. Addy (personal communication) found a 10 fold increase of free carbon in the gray clays as compared to the brown which supports the hypothesis that the gray clays contain unoxidized iron indicative of a reducing environment. A reducing environment is probably not favorable for manganese micronodule growth as indicated by the general lack of micronodules in the gray clays. The occurrence of green, gray or black sediments is usually attributed to rapid
deposition of relatively organic-rich sediments which have not had time to be oxidized by dissolved oxygen in the water. Turbidite sediments are typically rich in organic material and are one of the principle agents in transporting organic material basinward.

One last observation that supports the hypothesis that the brown clays are pelagic and the gray clays are turbidite deposits is the spatial distribution of these sediments. The piston cores, obtained at all depth ranges, recovered brown clay layers. Gray clays had a much more limited depth range, always occurring below 3100 fathoms (though not in all cores taken at depths greater than 3100 fathoms) and usually in abyssal plains and cross valleys connecting the abyssal plain. It should be noted that the Nares Abyssal Plain sloping down to the north is at a depth of about 3120 to 3180 fathoms.

Thus, sedimentation rates, particle size populations, manganese micronodule occurrence, carbon content-oxidation state-color and spatial distribution all support the theory that the gray clays represent turbidite deposits and the brown clays represent slow pelagic deposition.
Acoustic Signature

Earlier it was noted from the piston core data that the sediment types varied as a function of depth and physiography. Further data bearing on the distribution of various sediment types and thus origin can be gained from the acoustic nature of the sediments observed in the 3.5 kHz records. A much more detailed picture of the sediment distribution and lateral variation of the near bottom sediments can be obtained in this fashion than with the few cores. The piston cores can possibly be used to calibrate the various acoustic signatures that have been observed. Subsidiary data from box cores, bottom photographs, free-fall samples and core data have been integrated with the 3.5 kHz records to produce Plate 3.

Represented in Plate 3 is a map of the various acoustic signatures of the near bottom sediments and selected section locations. The data used in the preparation of Plate 3 included the 3.5 kHz records from Conrad Cruises 15 and 16 and Vema cruise 31. This track control is superimposed on the bathymetry in Plate 4. The main echo characters differentiated in Plate 3 are (1) 100 meters transparent, (2) 100 meters with stratification, (3) hyperbolated, (4) 30 meter opaque, (5) undulating bottom, widely spaced reflectors, (6) abyssal plain closely spaced reflectors, (7) abyssal plain widely spaced reflectors, (8) stratified ponds and (9) inferred rock outcrop. These units and their relationship to bottom samples and to one another suggest interesting insights into the processes that modify the deep ocean floor.
One hundred meter transparent unit.

The 100 meter thick transparent unit is the most widespread acoustic unit within the abyssal hills. Assuming an average velocity of 1.8 km/sec for these sediments, the unit varies in thickness from 60-120 meters. The bottom echo is strong, sometimes coherent, often fuzzy as in the left side of the 3.5 kHz section M1 (Figure 9) at 7.5 seconds. The accompanying profiler record (at a different scale) shows the top of acoustic basement at 7.8 on the left side of the record. Examples of this layer are also shown in sections M2-M5, E1 and E2 (Figures 9, 10, 11, 12 and 17). This unit is usually conformable with acoustic basement and appears to underlay the abyssal plain sediments (as indicated in section M1). The lower limit of this unit is usually an intermittent hyperbola, rarely a coherent interface. By comparison with profiler data, the depth to the hyperbolas agree well with the depth to the profiler acoustic basement. The hyperbola may be the result of roughness at the top of layer 2 (basaltic layer) which could produce corner reflectors. The transparent unit thickness varies locally, sometimes (Figure 11), but not always (Figure 12), being thinned on slopes as observed in profiler data. The bottom echo fuzziness is usually ascribed to surface roughness (Laughton, 1962) but in bottom photographs there is little evidence of bottom roughness on the order of centimeters. This 100 meter transparent conformable layer can be observed on isolated highs in the Nares Abyssal Plain at least as far south as 22°N.
Figure 9 Portions of 3.5 kHz records and simultaneously recorded seismic profiler records, right. The section locations are shown in Plate 3, with all sections oriented south to north except as noted. Section M1 shows the 100 meter transparent unit on the left and a finger of the level bedded, highly stratified sediments of the Nares Abyssal Plain on the right. Section M2 3.5 kHz record also portrays the 100 meter transparent unit with small scale bottom irregularities, a stronger bottom return and discrete subbottom hyperbolas attributed to subbottom roughness. The subbottom hyperbolas observed in both 3.5 kHz records are at the acoustic basement observed in the profiler records (right) and is interpreted as the top of layer 2. Vertical exaggeration of the 3.5 kHz records is about 20x, the profiler records 25x. The time between horizontal lines on the 3.5 kHz records is 0.05 seconds or 20 fathoms and one nautical mile is about 13 mm depending on the ship speed. For the profiler records the horizontal lines are one second apart and the horizontal scale is about 2 mm per nautical mile.
Figure 11  An example of the 100 meter transparent unit thickened on the west (left side, see profiler record) with a fairly discrete opaque layer in the upper 20 meters. This unit is on the edge of the Bermuda Rise and the surface opaque unit may be transitional to the 30 meter opaque unit. The scales are the same as in Figure 9.
Figure 12  Section M5 illustrating the 100 meter transparent unit conformable with the acoustic basement even in small depressions. The scale is the same as in Figure 9.
One hundred meter unit with stratification.

The unit described above is gradational into a similar unit which does contain some internal reflectors. This unit is observed in a few patches on the ridge between the Nares and 24° North Fracture Valleys (Figure 13) and on the Bermuda Rise where it thickens and becomes the dominant unit.

Cores obtained in the two 100 meter units consist almost wholly of brown clays. The lithologic contacts, usually color, burrowing or consistency changes observed in the cores are not observed as reflectors within this group. These 100 meter units represent the pelagic sediments that have accumulated since the ocean floor was formed. The occurrence of a few more internal reflectors in the Bermuda Rise unit might be a result of variations in compensation depths with time or current activity along the edge of the Rise. The observation that approximately 100 meters of transparent pelagic sediments overlay probable igneous ocean floor suggests that the source and depositional regime has been fairly uniform since the basement was formed about 90 million years ago (Pitman and Talwani, 1972). A gradual thickening of the unit is observed westward - consistent with postulated sea floor ages. This also gives an average sedimentation rate of about one meter per million years, somewhat low for brown clays. Hyperbolated.

In addition to the hyperbolated subbottom reflector observed at the base of the 100 meter transparent unit, hyperbolated bottom occurs in patches throughout the surveyed area, usually developed upon the upper surface of the transparent layer. Figure 14 (M8)
Figure 13 Section M6 and M7 3.5 kHz and profiler records showing the 100 meter conformable unit with some internal stratification. This unit is most common on the Bermuda Rise. The scale is the same as that given in Figure 9.
Figure 14  Sections M8 and M9 3.5 kHz and profiler records. The 3.5 kHz record of M8 illustrates the hyperbolated bottom observed in some areas in the survey region. These hyperbola are apparently developed by small scale surface roughness on the top of the 100 meter transparent layer. Other areas of hyperbolated bottom have a smaller hyperbolation wavelength. The 3.5 kHz record M9, north of the Bermuda Fracture Valley shows an example of the 30 meter opaque unit which often has a fuzzy bottom interface developed above the typical 100 meter transparent unit as indicated in the profiler record. Scales are as indicated in Figure 9.
is an example of this character. Others have more closely spaced hyperbola suggesting a smaller scale surface roughness.

The actual surface configuration in areas of hyperbolas have rarely been observed. Flood and others (1974) and Hollister and others (1974) using a DEEP TOW package recently documented an area of hyperbolas on the Blake–Bahama Outer Ridge that shows hyperbolas are created by steep-sided (0.5 to 20 meters deep) flat floored furrows (1 to 100 meters wide). Several attempts were made to determine a possible symmetry direction from hyperbola wavelength in the abyssal hills area by varying the ship course in several areas but with no success. It seems likely that these features represent some erosional process and any non-deposited or eroded material may be transported to ponded sediment bodies observed elsewhere on the ridges.

Thirty meter opaque.

Restricted to the northwest part of the map area, but common on other areas of the Bermuda Rise, is a unit that apparently overlays the transparent units. Section M9 (Figure 14) is an example of this showing on the left side of the 3.5 kHz record, the opaques unit extending from 6.77 to 6.81 seconds. The accompanying profiler record suggests that it is underlain by the transparent pelagic unit. The unit is fairly opaque with the bottom fuzzy, somewhat increased in thickness in small scale depressions. Based on RC15 C204 and RC15 C205, this unit probably consists of interbedded foram ooze, foram marl and marl.

Assuming an average sedimentation rate of 10 to 25 meters per million years and a thickness of about 30 meters, the carbonate-
rich sedimentation began 1 to 3 million years ago or earlier. Prior to this time it appears that the pelagic brown clay was dominant. This change in sedimentary regime could be due to (1) increased surface water productivity, (2) lowering of the calcium carbonate compensation depth, (3) rise of the ocean floor towards the compensation depth or (4) downslope transport from nearby highs. Evidence has been accumulating from the DSDP project that significant fluctuations have occurred in the calcium carbonate compensation depth and that it began dropping dramatically at about the Mio-Pliocene boundary, to its present low level. The thirty meter opaque unit occurs at depths less than 3000 fathoms, shallower than most of the rest of the abyssal hills area. From the spatial distribution of these sediments their occurrence is probably a result of the lowering of the calcium carbonate compensation depth in the Pliocene. The present critical lower depth for marly sediment deposition appears to be about 3000 fathoms (5600 m) in the abyssal hills area.

Nares Abyssal Plain and Fracture Valley.

The Nares Fracture Valley sediments can be divided into two provinces based on their echo characteristics. The northwestern part of the Nares Fracture Valley comprises one province and the southwestern part of the Nares Fracture Valley and the Nares Abyssal Plain constitute the other.

Undulating surface, widely spaced reflectors. In the northwestern part of the Nares Fracture Valley described earlier as the area with a gently undulating floor, an interesting acoustic signature is observed in the surficial sediments. The water depth is about
3200 fathoms (8 seconds) and the bottom return is at the top of the 3.5 kHz record hidden under the outgoing pulse. Section N4 (Figure 15) is difficult to interpret because of this but the bottom can be distinguished at 8.1 seconds on the right hand side of the section. The upper 20 meters is fairly opaque (possibly closely spaced hyperbola?) but below this two sets of discrete reflectors are observed at about 70 meters and faintly at 110 meters separated by transparent material particularly in the center of the section at about 8.2 and 8.25 seconds. The subbottom reflectors are generally warped concordantly with the water/sediment interface. The one piston core obtained in this reflector unit was V31 C165 which consisted of interbedded brown and gray clays common to all the abyssal plain sediments. However, this core also contained a marly layer at about 9 meters, not found in any other abyssal plain core. This unit is considerably different from all other units to be described below and is suspected to be an outcrop of an older reflector unit. This will be discussed in a later section.

Nares Abyssal Plain (and Fracture Valley) closely spaced reflectors. The second most common surficial acoustic signature in the abyssal hills area is found in the Nares Abyssal Plain and east of 61°W in the Nares Fracture Valley. This unit consists of closely spaced discrete reflectors averaging about 8 meters separation to the limit of the sound energy (about 0.1 sec). An example of this is shown in section N11 (Figure 16) where at about 8.3 seconds the reflectors appear to thin out and are gently undulating on some crossings. Section M1 (Figure 9), in the Nares
Figure 15 3.5 kHz section N4 and N9 in the Nares Fracture Valley. Section N4 illustrates the typical undulating surface with widely spaced undulating subbottom reflectors restricted to the western part of the Nares Fracture Valley. Section N9 illustrates the typical closely spaced, flat, nearly horizontal reflectors present in the eastern part of the Nares Fracture Valley. A significant transition between these two reflector types is mapped in Plate 3 in the vicinity of 61° W. The scale and section locations are as in Figure 9.
Figure 16 3.5 kHz sections N10 and N11 in the eastern part of the Nares Fracture Valley and NB in an associated tributary of the Nares Abyssal Plain. The southern (left side) of N10 is thought to be an isolated pond not directly connected with the main valley. Aside from this pocket the sections show the closely spaced level reflectors commonly found in the Nares Fracture Valley and Abyssal Plain. In N11 at 8.3 seconds, undulations of more widely spaced reflectors is observed. The scale is the same as in Figure 9. The location of the sections is shown in Plate 3.
Abyssal Plain, shows the relationship between these sediments and the 100 meter transparent unit. The stratified sediments are located in and infill the lows and appear to overlay the transparent layer which is conformable with basement. This is also supported by the profiler record in Figure 9. Thus, some of the transparent material is older than the oldest stratified sediment. Figures 15 and 16 (Sections N9-N11) show other examples within the Nares Fracture Valley of this sediment type. The south part of N10 (Figure 16) contains fairly widely spaced reflectors which is interpreted as a local sediment pocket slightly deeper than the main plain (the north part of N10) and possibly isolated from it.

The piston cores obtained in these highly stratified sediments contained a thin brown clay layer at the top, the rest of the core being gray clay. The presence of the pelagic layer 30 to 50 centimeters thick suggests that there has not been turbidite activity for 300,000 to one million years in this distal part of the Nares Abyssal Plain and the Fracture Valley.

24° North Fracture Valley and Widely Spaced Reflectors.

A large number of ship crossings were made of the 24° North Fracture Valley with excellent 3.5 kHz records. Figures 17-23, E1-E11, are selected crossings of the valley, starting with sections at the extreme northwest end and proceeding to the southeast. The valley at E1 and E2 does not contain appreciable sediment fill. Hyperbolas compose the bottom return in E1. These hyperbolas are interpreted to be the upper surface of the conformable trans-
Figure 17 Sections E1 and E2 3.5 kHz records. Hyperbolated bottom returns developed on the 100 meter transparent unit is observed in E1. Section E2 shows another example of the ubiquitous 100 meter transparent layer. No stratified sediments are observed in these two profiles of the western end of the 24° North Fracture Valley. The scale is the same as in Figure 9. Sections E1-E11 are south to north crossings of the 24° North Fracture Valley proceeding from the western terminus to the east (Plate 3).
Figure 18 3.5 kHz records of sections E3 and E4. Farther to the east, these sections show a widening of the valley floor and the presence of thin stratified units. The subbottom reflectors are only poorly developed, somewhat discontinuous and the intervening layers are only semi-transparent. The stratified sediments are transitional to the common stratification observed in other profiles. The scale is the same as that given in Figure 9.
Figure 19  Typical 24° North Fracture Valley 3.5 kHz sections E5 and E6 illustrating the widely spaced discrete reflectors. The scale is the same as in Figure 9.
Figure 20  Section E7 illustrating the widely spaced reflectors in the 24° North Fracture Valley. The scale is the same as in Figure 9. The location is given in Plate 3.
Figure 21 3.5 kHz records of sections E8 and E9 in the 24° North Fracture Valley. The scale and section locations are the same as given in Figure 9.
Figure 22  Section E10 3.5 kHz record of the 24° North Fracture Valley stratified sediments. A discrete reflector is observed at greater than 0.2 seconds subbottom on the south side where the recording instrument gain was high. Note that when the gain was reduced penetration was reduced to 0.1 seconds subbottom. The scale is as in Figure 9.
Figure 23 3.5 kHz record of section E11 at the extreme western end of the 24° North Fracture Valley mapped in Plate 1. Scale and location as in Figure 9.
parent layer described above. E3 shows the valley widening and containing a very thin pocket of stratified sediments. E4 is transitional into the fairly wide spaced reflectors observed in E5 through Ell. The few discrete reflectors separated by acoustically transparent layers allows for far greater penetration than is normally possible since the energy is not greatly attenuated because of the lack of numerous reflecting horizons. In Ell reflectors are observed at up to 0.2 seconds subbottom with the 3.5 kHz recordings.

The widely spaced reflectors of the surficial sediments filling this valley are quite different from the closely spaced reflectors of the sediments filling the Nares Abyssal Plain to the south or the Sohm Abyssal Plain to the north. In all crossings the bottom echo is distinct at its upper surface but occasionally fuzzy at its bottom as in E10 (Figure 22) where the bottom is at 8.43 seconds but the fuzzy bottom echo extends to 8.46 seconds. The crossings further to the southeast, E8-Ell, contain this prolonged fuzzy bottom reflection. The deeper reflectors are generally discrete and often appear as doublets in the upper four subbottom reflectors as in the center of section E6 (Figure 19) at 8.42, 8.43, 8.46 and 8.48 seconds. These doublets are not always resolvable due to changes in pulse length of the transceiver. At greater depth, subbottom, the reflectors occur as single fine, nearly continuous horizons across the valleys though these might have shown as doublets if the energy was not so greatly attenuated. The longest piston core (RC15 C188) in the survey was obtained near the E6 section and contained 14 meters of clay. The slightly prolonged bottom return in E6 is attributed to several discrete brown clay units
each about one meter in thickness. The acoustically transparent layer may represent the 9.5 meters of gray clay and the top of the reflector at the base of the upper transparent layer may represent the contact between the gray and brown clay at 13 meters subbottom. The discrete doublets might be due to grain size contrasts at the top and bottom of an individual turbidite. Reflections are caused when there is a sufficiently high impedance (density times velocity) contrast on an interface (Hersey, 1965; Ryan and others, 1965). The grain size analyses presented earlier indicate that the gray clays contain on the average 12% more silt than the browns which should affect the density though also the velocity. However Ryan and others (1965) have shown that grain size changes do correlate in a general way with observed reflectors.

Section M10 (Figure 24) contains the characteristic widely spaced reflectors common in the 24° North Fracture Valley. However this section is located in a cross valley at about 3300 fathoms between the Nares Fracture Valley at a depth of about 3260 fathoms and the 24° North Fracture Valley at a depth of about 3370 fathoms. Section M11 (Figure 25) is also along a possible path where sediments can enter the 24° North Valley from the south. V31 C163 was located in this sediment pocket and recovered interbedded brown and gray clays. The occurrence of these sediments in lows connecting the two valleys is strong evidence supporting the hypothesis that the sediments are transported to the 24° North Valley through the Nares Valley.

Within the main 24° North Valley the relief on the floor of sections normal to the valley axis is only 2 or 3 fathoms,
Figure 24  3.5 kHz record and seismic profiler section M10. The 3.5 kHz record illustrates the widely spaced reflectors common in the 24° North Fracture Valley. Here, on the ridge between the Nares and 24° North Fracture Valleys, ponds of these sediments occur at 3302 and 3318 fathoms well above the level in the 24° North Fracture Valley of 3370 fathoms. The scales are the same as in Figure 9. The location is given in Plate 3.
Figure 25  Profiler and 3.5 kHz record of section M11 on the ridge between the Nares and 24° North Fracture Valleys illustrating a set of reflectors with characteristics intermediate between the widely spaced reflectors in the 24° North Fracture Valley and the closely spaced reflectors in the Nares Fracture Valley. This section may be along a path connecting the two major valleys. The scales and location information are the same as in Figure 9.
while in the Nares Fracture Valley the sea floor is essentially flat normal to the valley axis. In the 24° North Fracture Valley the subbottom reflectors are concordant with the sea floor relief, but greatly accentuated, and the thickness of the transparent layers is greatest in the deepest part of the valley, the increased thickness greater for deeper reflectors. From the geometry of the subbottom reflectors, it appears that the sediments are infilling the 24° North Fracture Valley which had its deepest axis near the north wall of the valley and that sedimentation has been greatest in the deeper part of the valley, tending to reduce the relief of the valley floor with time. It appears, as in section E8 (Figure 21) that in some areas along the valley axis the floor had a relief of at least 0.05 seconds (greater than 20 fathoms), now reduced to 2 or 3 fathoms. Profiler records, to be discussed later, also show this feature.

**Stratified ponds.**

In several areas isolated ponds of stratified sediments are observed. An example is shown in section M12 (Figure 26). Other similar occurrences are observed and shown on the map in Plate 3. The 3.5 kHz and profiler records indicate that the ponds are fairly thin units of stratified sediments overlying the conformable transparent unit. The origin of these sediments is somewhat in doubt since none have been sampled. Their most likely source is from slumping off the surrounding slopes possibly caused by submarine earthquakes. This seems possible, because thinning of the slope materials is seen in some profiler records and basement
Figure 26. Seismic profiler and 3.5 kHz records of an isolated stratified sediment pocket north of the Z460 North Fracture Valley. The scale is the same as in Figure 9.
rock exposures are observed by various bottom sampling methods. It is possible, however, that currents too slow to actively erode the bottom may cause locally slower sedimentation or non-deposition. If sediments from the abyssal hill slopes move they would most likely be redeposited in local depressions. The periodicity of this influx of sediments should cause appreciable differences in physical properties with respect to first order brown pelagic clays possibly producing the observed acoustic reflectors.
Origin of the Surficial Sediments

The origin of the sedimentary units found near the surface today and/or during the Pleistocene have been suggested in the above sections. A further discussion of these sediments, the relationships between the various units, their most likely immediate origin, and significance of differences in the characteristics of the stratified sediments is presented here.

The 100 meter transparent unit conformable with basement appears to contain only pelagic brown clay. The general absence of internal reflectors suggests that pelagic sedimentation has been fairly constant for about 90 million years. Ultimately the clays must be derived from the continents. The surface circulation of the central North Atlantic Ocean has been a slow clockwise motion throughout its history and a site of convergence (Berggren and Hollister, 1974) with low surface water productivity. While dust storms and haze have been observed by surface ships in the Atlantic, they are most common offshore from continental deserts. The only likely source of significant pelagic brown clays for this area is from the near bottom nepheloid layer observed in the major oceans (Ewing and Thorndike, 1965). Studies of the circulation and nepheloid layers of the North Atlantic Basin have been made by Eittreim and Ewing (1972). They conclude from the three profiles that were available in the abyssal hills area that a significant part of the "load" was contributed by the Antarctic Bottom Water flow as in other areas of the North Atlantic Basin. The mean diameter of the particles in the nepheloid layer were found to be about
1.8 microns (about 9\(\mu\)) with a range from at least 0.8 to 3.2 microns (about 8 to 10\(\mu\)). This agrees well with the grain size of the brown clay which generally contained 80 to 90\% of the particles smaller than 8\(\mu\)(3.9 microns) in diameter. Presented in Figure 27 are nephelometer profiles from 21 stations in the abyssal hills area. The clearest water occurs at about 2000 fathoms with the sharp increase in gradient, corresponding to an increase in particulate matter in the water, occurring at about 2500 fathoms. Thus the strong bottom nepheloid layer extends well above the regional topography. Bottom water circulation changes more slowly and is less affected by short term changes in the atmosphere and surface water. Thus stratification as indications of change should be less common for sedimentation derived from the nepheloid layer. The nepheloid layer is probably the primary source of the brown clays found covering the abyssal hills and smoothing the ocean floor topography. Possibly significant load is introduced into the nepheloid layer by turbidites or more or less directly from river runoff.

The 30 meter opaque unit observed in and north of the Bermuda Fracture Valley overlies the transparent unit. This opaque bottom may be the result of fairly recent Pliocene carbonate deposition due to a lowering of the calcium carbonate compensation depth. The regional depth is slightly less here and carbonate would be more likely. Alternatively the highs on both sides of the Bermuda Fracture Valley may be the primary site of carbonate deposition and the observed distribution is related to downslope movement.
Figure 27 Light scattering profiles in the abyssal hills area. Deflection to the right of vertical is increased light scattering. $E$ is $\log_e$ of the measured value and $E_0$ is the $\log_e$ of a reference value. NAP=Nares Abyssal Plain, NFV=Nares Fracture Valley, EFV=24° North Fracture Valley, R=ridge between the Nares and 24° North Fracture Valleys, NS=north detailed survey area, SS=south detailed survey area and BFV=Bermuda Fracture Valley.
The other main sedimentary units are the various stratified sediment bodies. Of most interest here are the thinly stratified sediments of the Nares Abyssal Plain and Nares Fracture Valley east of 61°W and the widely spaced reflectors observed in the North Fracture Valley. It has been demonstrated by various authors and the Deep Sea Drilling Project that stratified sediments of the main abyssal plains are deposited by turbidity currents. The grain size grading in successive deposits may be sufficient to produce the acoustic impedance necessary for reflections to occur (Hersey, 1965).

Horn and others (1969) have demonstrated that there is a decrease in maximum grain size as one approaches the more distal parts of an abyssal plain. The lack of significant coarse grained material from the inferred gray clay turbidity current deposits sampled in the Bermuda area fracture valleys is explained in this same fashion.

The thinly spaced reflectors of the Nares Abyssal Plain can be observed throughout the extent of the abyssal plain. The bathymetry indicates only one or two possible avenues through which bottom controlled currents can enter the Nares Fracture Valley after travelling across the Nares Abyssal Plain. The 100 fathom depth difference of the plains can be explained in several ways. The thin passage between the main plain and valley may effectively restrict the inflow of sediments, the Nares Valley may have deeper basement than the nearby Abyssal Plain while receiving about the same amount of sediment or a sill may have existed at an earlier time which could not be breached until a significant amount of
back filling occurred.

The widely spaced reflectors of the 24° North Valley are more difficult to comprehend. The only likely source of these sediments is from the turbidity currents which cross the Nares Abyssal Plain and Fracture Valley. As with the Nares Fracture Valley, there is no significant source area for these sediments on the Bermuda Rise. This is indicated by the bathymetry and further, sediments on the Bermuda Rise contain a significant portion of biogenic components which should be preserved if they were redeposited on the floors of the valleys. The cores recovered in the valleys contain no significant carbonate fraction. Bottom currents carrying sediments would presently be able to enter this valley through three of four low divides in the ridge separating the two valleys (Plate 1). Today, only the most easterly of these paths allows free access to the 24° North Valley. The other paths are low sills requiring the turbidity current to bridge a low rise. One could imagine then that the coarser material, nearer the bottom of the flow might be trapped within the Nares Valley with only the finer suspension reaching the 24° North Valley. The gray clays found at about 3300 fathoms indicate that an occasional turbidity current can cross the ridge and that turbidity currents have significant thicknesses. Only an occasional exceptional large flow or one containing exceptionally large particles would reach the 24° North Valley to deposit sediment with sufficiently different physical properties to cause an acoustic impedance contrast needed to create a reflection. Normally, large particles from small flows might be trapped in the Nares Valley with only the
fine grained overflow reaching the 24° North Valley. The floor of the 24° North Valley is about 100 fathoms deeper than the Nares Valley. This appears to be a result of different basement depths and not significant differences in sediment thickness. The earlier sedimentation history derived from the seismic profiler data will be presented later.
Surficial Manganese Nodule Distribution

One of the interesting discoveries of the H.M.S. CHALLENGER was the occurrence of manganese and iron rich nodules on the surface of the ocean floor. Considerable interest in the occurrence of manganese concentrations in deep sea sediments was generated by their discovery. Today, full scale mining operations for the recovery of manganese nodules, crust and pavement is underway. The copper, nickel and cobalt are economically the most important metals, though manganese and iron are most abundant and traces of many other metals are present. The collection of data on the distribution of manganese nodules on the ocean floors has been increased in recent years. The most common occurrence of nodules has been found to be in red clay provinces of the world oceans probably largely a function of the low sedimentation rates (Mero, 1964).

Abundant manganese nodules on the ocean floor have been observed throughout the Bermuda Rise and Abyssal Hills Province. In general, manganese nodules are not common in the Atlantic because of the relatively small size of the ocean and large volume of terrigenous material introduced to the basins from the bordering continental land masses. The area of abyssal hills (above 3100 fathoms) is one of the few places isolated from significant turbidite influx and below the effective calcium carbonate compensation depth, a site of red clay deposition. The distribution of nodules within the abyssal hills has been studied primarily with free-fall grab samplers, bottom photographs and dredges at several hundred sites. The distribution of nodules is not random. This is aptly demonstrated
by a ships station on the northwest flank of a high hill at 29°05'N
and 61°05'W. An underway 3.5 kHz profile of the station is presented
in Figure 28 with the station data superimposed on this profile
at the appropriate positions. RC15 C202 and C203 both obtained
brown clay while grab samplers G105–G108 were recovered empty
but G109 contained 4.5 lbs of small nodules. A bottom camera
obtained a series of 24 bottom photographs in two areas. Frames
F2–F16 in Figure 29 (Frame 1 was tripped at the surface) were
located in the depression at the base of the hill and showed a
flat mud bottom. A striking contrast is observed in the photographs
of frames F17–F25 which were taken (after some delay) near the
crest of the hill. These photographs indicate massive rock outcrop
in two frames and an almost 100% manganese nodule cover in the
others. Basically this one station summarizes what was found
for all stations, the manganese nodules occur only on the upper
slopes and hill tops (above 3100 fathoms, most commonly above
3000 fathoms) and are often associated with rock outcrop. Manganese
nodules were not found on the abyssal plains or lower slopes of
the hills though they were not always found on all hill tops or
on the same hill top less than a kilometer away. The distribution
of manganese nodules can be summarized by stating that they do
not occur in water depths greater than 3100 fathoms and are spotty
at shallower depths.

A discussion of the origin of manganese nodules is beyond
the scope of this study. It is enough to say that a great amount
of ongoing research in geochemistry is directed at this problem.
Figure 28  A 3.5 kHz record in the vicinity of 29° 05'N, 61° 05'W on the northwestern slope of a high hill with locations of bottom data. G=grab sample, C=RC 15 core and F=frame number of bottom photographs.
Figure 29a  Bottom camera photographs of the frames shown in Figure 28.
It is difficult to account for the spotty distribution of the manganese nodules at similar depths. Of the 59 bottom photograph stations, in only one was there good evidence of bottom current activity from ripple marks, a northwesterly current in the eastern end of the Nares Fracture Valley. Currents, then, are not likely as a possible cause of the spotty distribution.

A possible explanation for the distribution may be related to the occurrence of nuclei for manganese precipitation and/or local sources of manganese enriched water. Volcanism is an obvious source for both nuclei and metal-rich hydrothermal solutions. The areas of known or inferred rock exposure have been indicated in Plate 3. Rock outcrop can only be inferred from bottom photographs and piston cores that bottom in hard rock. The known exposures are limited to steep slopes and the high abyssal hills. The exposure of rock is not common on the broad abyssal hills. A period of post ridge crest volcanism that may have formed the high abyssal hills may be related in space and time to either the fracture zones or the elevation of the Bermuda Rise and abyssal hills area. Maybe such volcanism could contribute significant nuclei and metal-rich waters on a local basis. Ubiquitous volcanism does not seem to be likely. The general distribution of nodules appear to be in the elevated area associated with moderate to steep slopes. For instance the nodules do not appear as commonly in the area of shallower slopes in the middle of the ridge between the two main valleys and the area of only moderate slopes about 100 km northeast and parallel to the 24° North Valley.
Possibly the post ridge crest volcanism, also suggested from the geochemistry of the nodules (Addy, personal communication), was related to renewed (?) activity along the fracture zones or reactivation of the Bermuda Rise area and generation of the high abyssal hills.
SEDIMENT DISTRIBUTION AND THE DEEPER REFLECTORS

In the preceding section the distribution and origin of the near surface sediments was outlined. For several units the 3.5 kHz source penetrated to acoustic basement particularly for the pelagic units where the sediments were of the order of 100 meters in thickness. Only in the areas containing significant stratified sediments, the Nares Abyssal Plain, the two valleys and the Bermuda Rise, was basement not detected.

By using a lower frequency, greater energy sound source the stratified sediment can be explored to a greater depth. The lower frequencies in turn cause a reduction in resolution. An individual unit or groups of units would probably have to be at least 30 meters thick to be observed with a profiler while with the 3.5 kHz source a unit as thin as 0.3 meters might be detectable (though it could not be resolved if there were numerous reflectors at this spacing). If a comparison is made as in section E6 (Figures 19 and 30), the profiler record shows a fairly transparent unit near the surface while the 3.5 kHz record shows finely stratified sediments. This type of instrumental effect should be kept in mind while comparing the records in the following section with the equivalent 3.5 kHz records.

Fracture Valleys

\[24^\circ\text{ North Fracture Valley}\]

Seismic profiler records of the 24\(^\circ\) North Fracture Valley are shown in Figures 30 and 31. The sections E1-E11 correspond
Figure 30  Seismic profiler records and simplified line drawing interpretations of sections E1-E6 across the 24° North Fracture Valley. The valley bottom widens and contains stratified sediments east of E2. E6 illustrates the four main units of valley fill not all present west of this section. A top unit of transparent material with a few horizontal reflectors appears to be unconformably underlain by a unit of closely spaced reflectors (U1) downwarped near the center of the valley. This is underlain by a second transparent unit, much thickened near the center of the valley. This is underlain by a second set of closely spaced reflectors (U2) which is in turn underlain by a third transparent unit of unknown thickness. The sections are oriented generally north to south with the locations shown on Plate 3. The vertical exaggeration is about 25 x and the horizontal scale is about 2 mm per nautical mile.
Figure 31  Seismic profiler records and simplified line drawing interpretations of sections E7-E11. Note the prominent unconformity in section E10. The top transparent unit contains some horizontal reflectors overlain by dipping and possibly folded reflectors of U1(?). In section E8 and particularly E9 the sets of reflectors appear to be discontinuous or replaced by highly transparent areas. This is thought to be a result of gas in the sediments and not necessarily due to any real deformation of the sedimentary layers. The scale is the same as in Figure 30.
to the 3.5 kHz sections presented earlier in Figures 17 to 23. 
E1 and E2 at the northern terminus of the valley show no sediment 
filling the valley. This should be expected since the valley bottom 
here is well above the level of the abyssal plain floor. The 
prominent transparent layer located on the flanks of the valley 
at E2 thin dramatically near the valley floor. The valley floor 
is level in E3. There may be a small pocket of stratified sediments 
here but the gain is too high to clearly verify this. The valley 
at section E4 contains an obvious sediment fill of stratified 
sediments overlying acoustically transparent fill. The depth 
to basement for these first four sections is less than about 8.5 
seconds.

East of section E4 the depth to basement increases to greater 
than 9 seconds, possibly greater than 9.3 seconds. The actual 
base of the sediment fill is not usually observable because the 
sound energy has been greatly attenuated in the sediments. In 
some sections east of E5 (where the valley does not contain signifi-
cant basement roughness to make detection of acoustical interfaces 
difficult), the valley fill can be divided into three units, the 
top being a fairly transparent unit containing only a few internal, 
but horizontal, reflectors. The average maximum thickness of 
this unit is about 0.2 seconds but locally may reach 0.3 seconds 
as in E10. An unconformity separates this top unit from the intermediate 
and deep units. The intermediate unit is a zone containing a 
number of closely spaced reflectors (UI) gently depressed near 
the center of the valley. The thickness and lower boundary are 
difficult to define but the maximum thickness is about 0.2 seconds,
though variable. The best examples of this unit are in sections E6, 7, 10 and 11. This unit appears conformable with the next lower layer of fairly transparent material similar to the uppermost transparent unit except that the few internal reflectors are depressed near the center of the valley. The maximum thickness may be somewhat greater than the top transparent layer. Below this second transparent layer in sections E6 and E10 there is a suggestion of a possible deeper set of closely spaced reflectors (U2) and possibly another reasonably transparent unit.

There is no direct method by which the time framework of these reflectors can be determined. We do know that there are Pleistocene sediments occurring at 14 meters in the upper transparent unit but it is unlikely that the whole fill is of Pleistocene age because of the great distance of this area from terrigenous sources of material. The apparent warping of the lower units is likely a result of compaction or related to the original deposition processes and most probably is a combination of both. From the 3.5 kHz records it appears as if the curvature of the shallow subbottom reflectors is probably due largely to a depositional process since the transparent layers have a much greater thickness near the center of the valley and decrease greatly toward the sides. The observation that the top transparent unit as observed in the profiler records contains sub-horizontal reflecting horizons may indicate a hiatus at the base of this unit during which time some dewatering of the older sediments occurred. The fact that the reflectors are warped less in the more recent fill may be
because the original relief has been reduced by the earlier filling. Further speculations on the ages of these reflector units will be made later.

**Nares Fracture Valley**

Some very high quality seismic profiler records were obtained in the Nares Fracture Valley. Sections N1-N11 are reproduced in Figures 32-34. It was noted earlier that there is an important change in the near surface sediments filling this valley in the vicinity of 61°W. East of about 61°W (see N6) basement within the valley, where an estimate can be made, is at about 8.8 seconds or greater. Westward of 61°W the basement begins to shallow so that by the time water depth is at 8 seconds basement is at about 8.5 seconds or less. East of 61°W the sediment thickness is very nearly the same as in the 24° North Fracture Valley though its basement is at about 9.2 seconds. The volume in the Nares Fracture Valley is greater though because of its greater width. Again, as in the 24° North Fracture Valley, the top acoustic layer observed in the profiler data is basically transparent with a few nearly horizontal internal reflectors. The unit has a maximum thickness of about 0.2 seconds in N11 and decreases to the northwest until in the vicinity of 61°W it is thin or absent. Stratigraphically below this is a group of closely spaced reflectors (U1) which also decrease in thickness toward the west where they outcrop or nearly outcrop. This accounts for the change observed earlier in the 3.5 kHz acoustic signature from the closely spaced reflectors to the undulating bottom, widely spaced reflectors northwest of
Figure 32  Seismic profiler sections N1-N3 and simplified line drawing interpretations in the Nares Fracture Valley. Note the two sets of closely spaced reflectors (U1 and U2) separated by transparent zones. The lower reflector, U2, is thought to be Horizon A. The undulating sea floor is characteristic of the Nares Fracture Valley west of 61°W. Some of the apparent offsets of the reflectors in these sections are due to the rise of diapir-like structures from a deeper level while others may be a result of gas in the sediments. The scale and location are as given in Figure 30.
Figure 32
Figure 33 Nares Fracture Valley seismic profiler sections N4-N8 and simplified line drawings. Distorted reflectors, undulating bottom and thinned top transparent unit are observed in N4-N6. In sections farther east, N7-N8, the top transparent unit thickens and the sea floor is level. Scale and section locations are the same as in Figure 30.
Figure 33
Figure 34  Seismic profiler records and simplified line drawing interpretations of sections N9-N11, NA and NB. Observe the thickening of the top "transparent" layer in sections N9 to N11. NA and NB are sections of the tributary leading into the Nares Fracture Valley from the Nares Abyssal Plain. A high basement level of about 8.4 seconds is observed in NA, a little deeper than in the Nares Abyssal Plain. Sections are oriented south to north and scale and section locations are as in Figure 30.
Figure 34
61°W. In N9 the U1 reflectors are subparallel to top transparent layer while in N7, N8 and N11 the unit is discordant with respect to the overlying unit. West of 61°W the top transparent layer is thinned or missing and the ocean bottom roughness is basically a manifestation of the reflector surface. U1 is underlain by and conformable with a fairly transparent unit also of variable thickness, but observable in all sections. This is underlain by a second set (conformable with U1) of closely spaced reflector which will be referred to as U2. The maximum thickness is about 0.2 seconds, possibly increasing in thickness to the northwest. This is underlain by a third transparent unit of unknown thickness.

The Nares Fracture Valley abyssal plain floor southeast of 61°W appears to be a result of turbidite filling. Significant recent filling has not occurred in the area to the west because the floor is 10 to 80 fathoms higher than to the east. The distortion of the reflectors is not as regular as in the 24° North Fracture Valley. Examination of all sections suggests that most of the apparent deformation is a result of the process by which the turbidites differentially deposit more sediments near the deepest part of the valley and less on the higher valley floor flanks. Further disruption of the reflectors is found in many of the profiler records which appears to be due to diapir-like structures rising from depth causing discontinuities in the reflecting horizons. These features are most notable in sections N1–N6. It is not known if these represent actual diapirs of sediments possibly incompletely dewatered or to gas or cathrate formation which may not actually disrupt the
sedimentary structures but only the acoustic stratification. I will return to these questions and consider some possible explanations for the distribution and ages of the reflector units observed in the valleys after describing other nearby reflector units, particularly the few that have been sampled and dated.

Bermuda Rise

The Bermuda Rise and surrounding areas showing selected ship track, western limits of reflectors "β" and "A" and three DSDP drill sites is presented in Figure 35 and profiler sections in Figures 36-39. The eastern limits of Horizons A and β have been modified after Ewing and others (1968). J. Ewing and others (1966) have found Horizon A and a deeper reflector termed "β" in many parts of the Atlantic. During Leg 1 of the GLOMAR CHALLENGER Horizon A was drilled on the Bermuda Rise at sites 6 and 7 and found to represent a mid-Eocene turbidite sequence forming thin beds of chert, both underlain and overlayered by pelagic brown clays. Later drilling of Horizon A in other areas of the Atlantic and Horizon A" in the Caribbean suggests that the age varies from Late Cretaceous to Eocene (Bader and others, 1970) though it is probably mid-Eocene in this vicinity. A profiler record near sites 6 and 7 indicating the reflectors "A" and "β" is shown in Figure 36. The conclusion reached by the DSDP Leg 1 scientists is that Horizon A does represent a turbidite sequence and that the occurrence of "A" at the present elevated position of about 7.1 seconds implies that the Bermuda Rise has been uplifted post mid-Eocene after which time pelagic sedimentation has been dominant. While it can not be completely
Figure 35 Sketch map of the Bermuda Rise and surrounding area. Western limits of "A" and "P" are after Ewing and others (1968). Sites 6, 7 and 28 are Deep Sea Drilling Project drill hole locations. Sections A1-A5 and R1-R3 are locations of seismic profiles showing the relationship between reflecting horizons and basement elevations.
Figure 36 Seismic profiler record in the vicinity of the Deep Sea Drilling Project sites 6 and 7. Note the prominent folded reflecting horizons "A" and "β". Figure modified from Ewing and others (1968).
Figure 37  Profiler sections A1–A3 from the Puerto Rico Outer Ridge northward into the Nares Abyssal Plain. Section locations are shown in Figure 35. The identification of "A" in section A1 is from Ewing and others (1966). Section A3 in the northern Nares Abyssal Plain contains the two prominent reflecting horizons "A" (mid-Eocene) and U1 (possibly Upper Miocene). Note that basement in A3, the northern Nares Abyssal Plain, is deeper than in A2, the southern Nares Abyssal Plain.
Figure 38 Seismic profiler sections across the Bermuda Rise into the abyssal hills area. See the locations in Figure 35. The thickness of the material above basement generally decreases towards the southeast. The southeastern limit of Horizon A appears to be where the reflector merges with acoustic basement. The sudden drop in basement elevation and increased sediment thickness in the southeastern part of A5 is a result of crossing the northwestern terminus of the Nares Fracture Valley.
Figure 39  Seismic profiler sections R1-R3 in the Nares Abyssal Plain. These sections illustrate the rise in basement level towards the north in the Nares Abyssal Plain. The basement rise restricts the abyssal plain to a narrow passage at 25°N (see Plate 1). The basement level then increases again in the northern part of the Nares Abyssal Plain. Section locations are shown in Figure 35.
ruled out that Eocene turbidites could not have extended up on
the flank of the Bermuda Rise it does not seem likely that they
could have reached 7.1 seconds after crossing a probably much
deeper Eocene Hatteras Abyssal Plain. Probably better evidence
to support the hypothesis that the Bermuda Rise has risen since
post-Eocene is that Horizon A is folded and otherwise disrupted
on the Rise while it is basically a level subbottom horizon elsewhere.
The Bermuda Rise probably did not exist at anywhere near its present
size before mid-Eocene (about 49 million years ago). Aumento and
others (1974) have found from studies of a drill hole on Bermuda
Island that a significant increase in the volume of intrusive
rocks occurred about 30 to 34 million years ago. If these intrusives
are in some way related to the uplift of the Bermuda Rise, then
the sea floor was elevated to its present elevation 30 to 45 million
years ago (Middle Oligocene to post Middle Eocene). If the Bermuda
Rise did not act as a barrier for turbidites flowing eastward
off the continental margin before this time, any paleo-basins
east of Bermuda might also contain sediments derived more or less
directly from across the Hatteras Abyssal Plain.

With these possibilities in mind Sections A4 and A5 (Figure
38) across the eastern flank of the Bermuda Rise become fairly
important. The eastern limit of Horizon A is where the reflector
unit merges with basement. A local depression in the basement
occurs east of the main limit of Horizon A. This depression contains
a reflector which may very well be Horizon A. If the fracture
valleys existed prior to mid-Eocene (a point to be discussed later)
then their valley bottoms may also have been local depressions
in an otherwise elevated area. The depressions might receive
turbidite deposits while the surrounding highs were only sites
of pelagic sedimentation. A5 is a profiler record from within
the Nares Fracture Valley extending northwestward. The distance
between the last probable occurrence of "A" on the rise and the
most westward occurrence in the Nares Valley is about 65 kilometers.
The sharp rise in basement in this part of the record is due to
the abrupt end of the fracture valley and it is not seen on other
track across the eastern boundary of the Bermuda Rise.

Nares Abyssal Plain

Stratified sediments of up to about one second occur in the
Nares Abyssal Plain. The maximum thickness is found just north
of the Puerto Rico Outer Ridge and decreases northward. Horizon
A has been both cored and drilled on the flank of the Puerto Rico
Outer Ridge (Figure 35, Site 28). In section A1 (Figure 37) Horizon
A has been identified as the boundary between the transparent
and opaque material on the southern part of the profile. Tucholke
and Ewing (1974) believe that Horizon A extends northward under
the abyssal plain to at least 24° N, 64° W, the limit of their
map. Section A1, A2 and A3 are presented in Figure 37 to show
the continuation of the reflectors observed in A1 towards the
northeast. Note the section locations in Figure 35. The "A" reflector
is interrupted by basement and is difficult to distinguish in
section A2 east of 62° W but possibly reappears at the end of the
section. However a reflector above "A" is prominent in sections
A1-A3 (U1) and is interrupted only by isolated basement peaks.
While the age of this upper reflector is not known, it may be correlated with a Upper Miocene turbidite sequence observed in the Blake-Bahama Basin (Sheridan and others, 1974). In A3 the acoustic basement is deeper and a reflecting horizon can be detected below the intermediate reflector Ul. This deeper reflector is believed to be Horizon A. The thickness of the "A" reflector unit decreases northward compatible with an origin from the southern Nares Plain. Unfortunately no track exists from the north end of section A1 to the middle of A3 which might show the continuity of the subbottom reflectors more convincingly. Data to be presented in the next section will indicate that this proposed track is the only one that may not be seriously interrupted by a rise in basement as A2 (and R1) is.

Thus a reflecting horizon thought to be correlative with "A" occurs just south of the Nares Fracture Valley as does a possible Upper Miocene reflector unit but not on the Bermuda Rise just to the west. In the northern Nares Abyssal Plain Horizon A is at about 8.1 seconds and the Upper Miocene (?) reflector at about 7.9 seconds. Could a possible relationship exist between these reflectors and those occurring in the 24° North and Nares Fracture Valleys? At the western end of the Nares Fracture Valley the top of Ul occurs at a minimum depth of 8.1 seconds, increasing eastward in depth and thickness. U2 is at about 8.2 seconds also increasing in depth eastward but the thickness remains fairly constant. I would like to be able to say that the two sets of reflectors observed in the Nares (and possibly the 24° North) Fracture Valley are correlative with the section observed in
the adjacent abyssal plain where a fairly probable correlation has been made with other sections.

The depth to the reflectors in the Nares Abyssal Plain and in the Fracture Valley are not quite the same. This is probably due to the deeper basement observed in the fracture valley. The profiler sections indicate that the top transparent unit is thinned or almost absent west of 61°W, that erosional features observed in the 3.5 kHz and seismic profiler records indicate this area is not a site of sedimentation and that the water depth is 20 to 40 fathoms shallower than east of 61°W. The rise to the west of Horizon A though apparently of nearly constant thickness can be explained by the post mid-Eocene uplift of the Bermuda Rise. The thinning of the Upper Miocene (?) turbidite unit to the west can be compared with the present distribution of the top sediment fill in the valley. After the uplift of the Bermuda Rise the valley floor sloped down to the east and Upper Miocene (?) turbidites entered the valley and deposited greater thicknesses of sediments in the lower parts of the valley basin. Based on the discordance between the reflecting horizons of the Upper Miocene (?) and the more recent valley fill a possible hiatus in turbidite deposition occurred after Upper Miocene (?) time after which some compaction of the valley sediments occurred. The most recent influx of turbidites have back filled the valley, but only as far east as 61°W before this last phase of turbidites was shut off about 300,000 to one million years ago based on the pelagic sediment thickness overlying the gray clays. This same sort of history seems to be equally valid for the 24° North Fracture Valley. The very small scale
undulation along the axes of the present valley abyssal plains, of about 5 fathoms or less, can be ascribed to compaction in the last million years or so.

While it seems possible that the U1 and U2 reflector units may be correlative with the Upper Miocene event and Horizon A, respectively, the only way the hypothesis can be substantiated is by direct sampling. It has been shown that the Pleistocene influx of turbidites in this area, studied from the 3.5 kHz records and piston cores, did cross the Nares Abyssal Plain and enter the Nares and 24° North Fracture Valleys leaving level-bedded contemporaneous deposits of about the same thickness in the valleys (but not the same total volume), even though the floors are at discordant depths and entry to the 24° North Fracture Valley is highly restricted. In light of these observations it certainly seems possible that the second subbottom reflecting horizon observed in the Nares Fracture Valley and discontinuously in the 24° North Fracture Valley may be Horizon A. In both these valleys profiler data is sparse east of 59°W but except for apparent local ponding, the valleys contain no significant sediment fill east of about 55°W. This is compatible with the postulated correlations but adds no confidence to the hypothesis.

**Buried Ridge**

As noted above, the Nares Abyssal Plain dips towards the north. A study of profiler sections A1 and R2 (Figure 37 and 39) show that the rough acoustic basement, probably layer 2 volcanics, shallows towards the north. Sections R1, R2 and R3 are presented
to show that acoustic basement decreases in depth and presently outcrops (except for the pelagic cover) at the northern ends of the sections. These three sections terminate in the abyssal hills/fracture zone area. From the available data it appears that the present day Nares Abyssal Plain is restricted from northward extension except through a low sill in the ridge occurring at about 25°N between the Bermuda Rise and the low ridge. From the distribution of the deeper reflectors it appears that this low rise extending west-northwest has been in existence for a long time, at least as long as the southeastern part of the Bermuda Rise has been elevated (either from the original ridge axis elevation or other causes).

Basement Depths

The first impression one has in describing the abyssal hills province southeast of Bermuda is that it occupies the deepest part of the North Atlantic Basin. However, if the effect of deep basement associated with the fracture valleys is neglected the average depth to acoustic basement is 7.8 seconds. This compares with a depth to acoustic basement of about 8.5 seconds or more in the Nares Abyssal Plain in the vicinity of 26°N, 61°W or a depth to the abyssal plain of just under 8 seconds. Thus, in fact, a basement high extends northwestward from about 25°N, 55°W through the abyssal hills area to the Bermuda Rise. This high separates abyssal plains and depressed basement of about the same age to the northeast and southwest. One immediately needs to consider the relationship of this "high" to the Bermuda Rise and
the occurrence of the abyssal hills and abyssal hills province.
This will be returned to in the discussion on the origin of the
Bermuda Abyssal Hills Province.

Discussion

The continuation of Horizon A under the Nares Abyssal Plain
is probable. The occurrence within the fracture valleys of "A"
is possible (particularly the Nares Fracture Valley). It is known
that "A" does not seem to exist on the eastern side (Figure 40)
of the Bermuda Rise (except in the vicinity of the northern Nares
Abyssal Plain) or on the basement high that greatly narrows the
present abyssal plain at 25°N. It is possible with this data
to describe the paleobathymetry and implications on paths of turbidity
currents. The sediment thickness overlying the "A" horizon is
about 0.5 seconds in the A1 section decreasing to about 0.2 seconds
in A3 nearer the northern extreme of the abyssal plain. If the
conservative estimate of the age of "A" is used (50 my) and a
fairly low sound velocity of sediment (1.8 km/sec) then the average
sedimentation rate since "A" time has been 7-18 meters per million
years which may be one or more orders of magnitude lower than
should be expected for a sedimentary section which is basically
composed of turbidites.

This can be explained by significant changes in the bathymetry
which in turn affected the distribution of the bottom controlled
turbidity currents and the formation of the Puerto Rico Trench
as an effective barrier to sediments derived from that direction.
Figure 40 Mid-Eocene paleobathymetry. The shaded area is the extent of Horizon A. The eastern limit of "A" on the Bermuda Rise was probably about 2900 fathoms (5500 meters).
A pre-Bermuda Rise extent of abyssal plains can be approximated by the known limits of Horizon A (Figure 40). Prior to Oligocene time turbidity currents were depositing sediments in a much larger area than at present. The Vema Gap did not exist and the Puerto Rico Trench was not cutting off significant sediment possibly being derived from the southeast Bahama Banks (Tucholke and Ewing, 1974). Considerably more sediment was available from the continental margin and islands than presently. The Vema Gap was significantly narrowed sometime after Horizon A was deposited and the Horizon A and earlier sediments are disturbed here (Tucholke and Ewing, 1974) and on the Bermuda Rise. This narrowing was most likely related to the elevation of the Bermuda Rise in the Oligocene based on the borehole data of Aumento and others (1974). This combined with the deepening of the Puerto Rico Trench (Tucholke and Ewing, 1974) limited the terrigenous sediment supply to the Nares Basin. The Vema Gap became the only path through which sediment laden turbidity currents could enter the basin. This, in turn, might explain the apparent decrease in average sedimentation rates for the post Horizon A turbidite deposits.
REGIONAL ASPECTS AND CONCLUSIONS

Regional Magnetic Anomalies

Magnetic anomaly patterns on the ocean floor have been fairly well established and correlated with the absolute and stratigraphic time scales (Pitman and Talwani, 1972; Larson and Pitman, 1972; Vogt and Johnson, 1971). The exact cause of the anomalies is still not well documented but they have been found to be a world-wide phenomena.

Within the Bermuda Abyssal Hills Province the age of the igneous basement of the seafloor is believed to be between 70 and 110 million years (Pitman and Talwani, 1972). This time interval includes what has been termed the mid-Cretaceous smooth zone, thought to be a single period of normal polarity. The amplitude of the anomalies in this zone are of the order of 200 to 400 gammas. Vogt and Johnson (1971) recently attempted correlations within this region in the southern part of the Bermuda Abyssal Hills. Lattimore, Rona and DeWald (1974) recently published three track lines just to the north of the present study area and have attempted to correlate the observed anomalies with those of Vogt and Johnson. All of this track and anomaly locations are shown in Figure 41. The correlations are not, in my estimation, very good. Six additional tracks suitably oriented for magnetic studies are also presented. The anomalies for the 14 track lines (Figure 42) do not indicate obvious peak to peak correlations except for the four closely spaced lines of Vogt and Johnson. From the already published data, regionally, there is no significant offset of the anomalies, the isochrons trending northeast.
Figure 41 Magnetic anomaly locations, track and fracture valley trends. Tracks and anomaly locations 1-3 are from Lattimore and others (1974), 10-14 from Vogt and Johnson (1971). The 24° North Fracture Valley was described from the ridge to 52° W by Fox and others (1969).
Figure 42 Magnetic anomalies in the abyssal hills area. Lines 1-3 (top) are from Lattimore and others (1974) and the bottom four lines (10-14) are from Vogt and Johnson (1971). Note the low amplitude anomalies and poor correlation of sections.
The age varies from about anomaly '31' to anomaly K12. The present best estimate of anomaly '31' is 72 million years. There is no control on the age of the K anomalies. I would estimate that the age of K12 is about 100 million years.

A significant offset in the anomalies of Lattimore, Rona and DeWald occurs between the second and third tracks. The K-anomalies are offset left-laterally though this point was not emphasized by these workers. Three possible explanations for this offset are (1) misidentification of anomalies, (2) translation of the spreading centers parallel to the ridge strike in the Cretaceous or (3) offset of the ridge crest in the Cretaceous along fracture zones. No fracture zone has been observed in this vicinity though they are found along this strike further up on the Bermuda Rise. The explanation for the apparent offset is probably related to (1) or (2). The apparent lack of mid-Cretaceous high amplitude magnetic anomalies could be due to later modification of the magnetic signature by volcanism or tectonics or more probably there were not important changes in the magnetic field in this time interval.

Fracture Zones

Up to this point the long fairly linear valleys have been referred to as fracture valleys, a fairly descriptive term. While no earthquake epicenters are located on the trends, they are most likely inactive segments of fracture zones, the extensions of the active transform faults that occur between offset ridge crests. These valleys easily fit the description of fracture zone topography defined by Menard and Atwater (1969). In the early days of the
revival of plate tectonics the trend of the valleys were recognized as important with such workers as LePichon and others (1971) and many others using these trends to reconstruct the ocean floor for various ages.

It is interesting to note that the 24° North and Nares Fracture Valley west ends begin at about K10 while the Bermuda Valleys east end terminates at about the same anomaly. The small change in trend between the Bermuda (N54°W) and the western part of the Nares and 24° North Fracture Valleys (N58°W) apparently indicates a fairly important change in spreading rate (Voigt and others, 1971) and not a major reorientation of the ridge axis.

In the vicinity of 60°W the trends of the 24° North and Nares Fracture Valleys become N72°W and at this time a bifurcating valley is developed through the south wall of the Nares Fracture Valley. Here the valleys are continuous with no apparent terminations which implies an important change in the ridge axis orientation but not an important change in spreading rate at K2 time.

Data is presently available that indicates that the 24° North Fracture Valley extends all the way to the present ridge crest at 24°N. It is remarkable that this valley may be fairly continuous for over 1600 kilometers (Figure 41). Track coverage is not sufficient in the vicinity of 55°W and 53°W to be sure that this valley extends as an uninterrupted feature. Fox, Pitman and Shephard (1969) surveyed the valley from 24°N at the ridge crest to 52°W. They reported two different axis trends in this segment. East of about 47°W it trends N82°W, west of 47°W it trends N73°W. A segment
between about 53° to 54°W surveyed by Kane 9D (Anonymous, 1969) has a trend of N76°W. Thus, for the 1600 kilometers length of the valley the trends can be represented by five straight line segments approximating small circles about a pole of rotation.

The best estimates of the sea floor age from magnetic anomalies can be used to date the times of change of the poles of rotation from the main trends. These are 0-10 m.y., N82°W; 10-50 m.y., N73°W; 55-65 m.y., N76°W; 70-82 m.y., N72°W; 82-95 m.y., N58°W; and a sixth from the Bermuda Fracture Zone greater than 95 m.y., N54°W. These generally agree with the main trends observed by Vogt and others (1971) except that they found no significant pole changes occurring between 75 and 100 m.y. The 70-82 m.y. N72°W trend was apparently not observable in data available to them. The actual age during which the segments may have been active is not easily determined. Vogt and others (1971) have found in the North Atlantic that fracture zone segments are not active more than 10 m.y. after the formation of the adjacent ocean floor by evaluating offsets and Cenozoic magnetic data.

Rates of Seafloor Spreading

None of the data presented in this thesis can be used to find inferred rates of seafloor spreading. The magnetics of Lattimore, Rona and DeWald (1974) do give some indications of the rates of spreading. Using the magnetic stratigraphy time scale of Pitman, Talwani and Heirtzler (1971), Lattimore and others obtained average rates of 1.2 cm/year for the past 70 million years similar to those of Pitman and Talwani (1972). If the magnetic stratigraphy
of Larson and Pitman (1972) is used for the Mesozoic, anomaly '31' is 72 million years and J6(M4) is 117 million years. The average spreading rate for this interval is 2.4 cm/year which is within 20% of the earlier estimates of Larson and Pitman (1972) of 2.9 cm/year for a mid-Cretaceous interval in the central Atlantic. It should be noted that at present there is considerable controversy surrounding the dating of Mesozoic magnetic anomalies (for example see Berggren and others, 1975). With a time framework for both the age of crust and the distribution and age control for the pelagic and turbidite sequences the origin and development of this area of the Atlantic can be considered.

Speculation on the Origin of the Abyssal Hills Province and the Bermuda Rise

The origin of the abyssal hills province is related to some important tectonic phenomena. A comparison of present slow and fast spreading ridges indicate some important physiographic differences even though the mechanism of spreading remains obscure. An example of a slow spreading ridge is the Mid-Atlantic Ridge spreading at about 1 cm/year. A fast spreading ridge of 5 cm/year can be represented by the East Pacific Rise. The fast spreading ridges are very broad features of low relief and no central rift valley. The slow spreading ridges are narrower, rise higher from the sea floor and contain a central rift valley along the axis of the ridge while the flanks are generally rougher than those of fast spreading ridges (Menard, 1967). The fact that the broad abyssal hills extend, in this vicinity, from the eastern edge of the Bermuda
Rise to the Mid-Atlantic Ridge suggests that the Cretaceous to recent spreading rates are all conducive to the formation of abyssal hills. Abyssal hill type topography is also observed on the flank of the fast-spreading East Pacific Rise on 10 million year old crust (Luyendyk, 1970) though these hills have a somewhat different morphology. It appears that the formation of first order abyssal hills is fairly independent of spreading rates. And if the isochrons are roughly northwest trending, then spreading can not be an important factor in the origin of the northern and southern boundaries of the Bermuda Abyssal Hills Province.

Regardless of spreading rates Sclater and others (1971) have shown by plotting age of basement versus depth to basement that after 15 to 20 million years the depth to basement is basically dependent only on age and is no longer a function of spreading rates. Sclater and others relate the increasing basement depth with age to thermal contraction of a cooling oceanic plate as it moves away from a spreading center (ridge axis). The paleobathymetry of this area for mid-Eocene (Figure 40) indicates that the eastern flank of the Bermuda Rise and the abyssal hills area was already a high in Upper Eocene. Using Sclater's empirical relationship the depth to basement at mid-Eocene time of Cretaceous crust should be about 5000 meters (2700 fathoms) probably above the level of any turbidite flows. The approximate western limit of Horizon A on the Bermuda Rise is at the K14 anomaly, probably about 105 million years. Using Sclater's relationships at mid-Eocene time the depth to basement should be about 5500 meters which is very similar to the depth of the Hatteras Abyssal Plain today. It
seems probable that the high observed in the paleobathymetry east of the eastern limit of Horizon A on Bermuda Rise is due to original ridge flank elevation though possibly it represents an insipient Bermuda Rise. The possible Horizon A observed in the 24° North and Nares Fracture Valleys may have filled local basement depressions in an otherwise high basement areas as is observed today for fracture zones near ocean ridge flanks. The brown clay sampled at the base of Horizon A at the DSDP site 7 may be the pelagic clay that accumulated earlier while the area was above the depth for turbidite deposition and below the calcium carbonate compensation depth.

Thus, the paleobathymetry is consistent with the sediment types (pelagic and turbidites), their ages and distribution, the age of the seafloor and spreading rates and expected elevations of basement except for one important area, the present northern Nares Abyssal Plain. If spreading is roughly parallel to magnetic anomaly patterns as is commonly observed then the virtual ridge crest must have been trending northeastward as does the Bermuda Rise Horizon A boundary. The fact that a pre-mid Eocene basement low was located in the northern Nares Abyssal Plain is difficult to explain. This problem will be discussed after considering the later history of this area.

If the widespread upper reflector observed in the profiler data is Upper Miocene (about 10 m.y.) and does represent a turbidite sequence it occurs throughout the Nares Abyssal Plain as does Horizon A but is not found on the Bermuda Rise. Thus the Bermuda Rise had risen above a level where turbidites were being deposited
and in fact, became a serious barrier to bottom sediments transported from the continental margin. The elevation of the Bermuda Rise occurred between about 45 and 10 million years ago. If the intrusive event into the volcanics of Bermuda Island (Aumento and others, 1974) is related to the rise then the uplift was probably between 45 and 30 to 34 million years ago (or Oligocene).

Thus the area of the Nares Abyssal Plain has been a depression since before Horizon A time and has continued as such to the present. It was shown earlier that layer 2 basement shallows toward the abyssal hills within the Nares Abyssal Plain but in section A3 (Figure 37) basement is still at about 8.5 seconds or deeper while nearby the abyssal hills basement is at about 7.8 seconds, a minimum difference of one kilometer. Thus an explanation is needed for the apparent depressed crust in the vicinity of the Nares Abyssal Plain and the elevation of the Bermuda Rise, probably in the lower Oligocene.

The Bermuda Rise is a fairly large northeasterly elongated aseismic rise about 800 km long x 500 km wide. Engelen (1964) suggests that a drift of the North American continent in the Mesozoic produced a decrease in pressure on the trailing margin. This is postulated to have produced a phase transition of sub-Moho rocks from eclogite to lower density gabbroic rocks increasing the volume and producing the Bermuda Rise. An early seismic refraction profile extending from Bermuda Island southeastward (Officer and others, 1952) found fairly normal depths to Moho and typical Moho velocities on the rise and in the adjacent abyssal hills province. Also present plate tectonic theory suggests that the North American
continent is firmly coupled to the oceanic lithosphere. Thus Engelen's hypothesis is not acceptable. However whatever caused the elevation of Bermuda Rise in the Oligocene probably does have its source in the upper mantle as does the apparent Nares Basin low. Heat flow is fairly normal in this area similar to the surrounding ocean floor (Langseth and Von Herzen, 1970). Menard (1969) has suggested that midplate rises may be the result of small time varying convection cells in the lithosphere. The Bermuda Rise could also be due to a "hot spot" in the sense of Morgan (for instance Morgan, 1972). Whatever the origin of the Bermuda Rise it must not be a singular solution for mid deep ocean rises are common.

An equally important question remains as to the origin of the anomalously deep part of the northern Nares Abyssal Plain and also probably the Sohm Abyssal Plain. According to the hypothesis of Sclater and others these areas should be at about the same elevation as the abyssal hills province, since the crust was formed at about the same time. Even if Sclater and other's empirical curve is found to be in error the difference in basement elevation parallel to supposed isochrons will need to be explained. It does not fit very well with the present concepts of sea floor spreading of fairly rigid plates. One possible explanation for this phenomena is that the ridge crest elevation varied along strike in the Cretaceous and for some reason, possibly related to the occurrence of the Bermuda Rise and the large fracture zones, thermal equilibrium has not yet been reached. Alternatively if one believes that it is the abyssal hills area which is anomalously
shallow the shallowing might be related to the occurrence of the
closely spaced fracture zones and the Bermuda Rise.

**Origin and History of the Abyssal Hills**

The abyssal hills are common to all the world ocean floors. From the regional bathymetric chart presented for the western North Atlantic (Figure 2) it can be seen that abyssal hills occupy more than 50% of the area. These small scale features are at least as common in the Pacific Ocean if not more so (Menard, 1964). As early as 1959 Heezen, Tharp and Ewing indicated that in general the abyssal hills could not be readily distinguished from the Mid-Atlantic Ridge flank topography.

Two morphologies have been observed for abyssal hills. Probably, less common is the more or less circular hills. These have been described at the western boundary of the Madeira-Cape Verde Abyssal Plain (Jones and others, 1966). By far the most common morphology of abyssal hills is elongate, often with paralleling troughs. They are also usually elongated parallel to the magnetic anomaly trends and have been described by Menard and Mammerickx (1967), Moore and Heath (1967) and others in the Pacific and by Rona and others (1974) in the Atlantic. These workers have generally concluded that the abyssal hills are related to the near ridge crest volcanism and faulting and have undergone only minor later constructional activity.

An important exception to these studies is one by Luyendyk (1970) in an area of elongated abyssal hills, parallel to the magnetic anomaly lineations (of about 30 m.y.) in the North Pacific.
In his detailed DEEP TOW study of two abyssal hills he found that one formed at the ridge crest vicinity by accumulation of volcanic rocks and that the other formed as a horst structure in faulting that began about 20 m.y. later also parallel to the structural grain imposed on the original crust.

The morphology of the hills in the present study appears to contain two components. (1) Broad highs from about 2800 to 3000 fathoms and 8 to 15 km across. Of the few areas intensively surveyed (for example Figures 3 and 5) no obvious trend is observed parallel to the northeast trending magnetic anomalies. While a strong northeast bathymetric trend is observed by other workers, it is present only as a weak trend in the bathymetry of this part of the Atlantic (Plate 1). The broad highs are generally covered with a 100 meter acoustically transparent pelagic blanket and are thus probably the remanents of the ridge crest volcanism and particularly faulting concomittant with the formation of the volcanic basement near the ridge crest.

The absence of an obvious northeast trend may be related to the occurrence of the second morphologic hill type. (2) Small, apparently conical hills are observed in this study area, sometimes upon the broad abyssal hills and other times apparently little related to the larger hills. They are about 3 to 5 kms across with several hundred fathoms of relief. The distribution of rock outcrop or near outcrop has been portrayed (Plate 3) and in many cases is coincident with the small hills. Based on the earlier discussion of the distribution and factors controlling sedimentation
here this is a result of either the slopes being too steep to accumulate significant thicknesses of the pelagic sediments or the hills are younger than most of the rest of the basement or a combination of the two. If these hills represent more recent volcanic activity its age would be extremely interesting. The best that can be deduced is that if it occurred fairly recently, there should have been evidence of volcanic components in the sediments throughout the area or their alteration products. No such component was found in the cores. The average sedimentation rates of the brown clays (the average long core length being about 10 meters) suggests that any volcanism was before about 10 million years ago. Based on the regional tectonic history the most likely period of volcanism would have been related to the elevation of the Bermuda Rise about 34 million years ago though this age would suggest that there should be some pelagic cover on these hills. However, it is still believed that fairly widespread volcanism, apparently unrelated to earlier structural grains may have occurred in this area at the time of uplift of the Bermuda Rise and at that time possibly obscuring much of a supposed northeast grain.

One other line of reasoning gives some suggestion of this more recent volcanic activity. The widespread occurrence of manganese nodules in this area has been observed earlier. They appear only in fairly high areas most commonly from about 2800 to 2600 fathoms. Certainly then they are related spatially to the high abyssal hills. Further, S. K. Addy (personal communication) has observed a distinct bulk chemistry difference between the inner and outer
rinds of manganese coatings of the nodules in the study area. This could possibly be related to changing sources of the manganese, iron and other important ions with time, possibly related to this postulated late stage volcanism.

Conclusions

Numerous observations about the sedimentation history and development of this part of the western North Atlantic have been discussed. Some of the more basic conclusions of this study are summarized.

1. Two sets of reflectors observed in the Nares Fracture Valley, 24° North Fracture Valley and the northern Nares Abyssal Plain are probably correlative with the Horizon A event and the Upper Miocene (?) turbidite event observed in the main Nares Abyssal Plain. Paths for entry of bottom following turbidity currents into the Nares Fracture Valley are obvious but for the 24° North Fracture Valley they now pass over low sills to reach the valley.

2. The eastern and northern limits of Horizon A indicate the paleobathymetry of the area. The east limit of Horizon A may have been the flank of the mid-Eocene Mid-Atlantic Ridge. The northern extent of Horizon A in the northern Nares Abyssal Plain, the occurrence of a probably Upper Miocene turbidite sequence and the present depth to basement of about 8.5 seconds suggests that this area has been a deep zone at least since pre-mid Eocene time.
3. The Bermuda Rise was below the calcium carbonate compensation depth for sometime before Horizon A was present (JOIDES Site 7) and was uplifted pre–Upper Miocene, most likely in the Lower Oligocene (30 to 40 m.y.).

4. The Bermuda Abyssal Hills Province exists today because basement is elevated with respect to basement of similar age in the adjacent Nares and probably the Sohm Abyssal Plains. The changes in basement depth parallel to the isochrons is unusual, but accounts for the occurrence of the abyssal hills province. It probably has its origin in the upper mantle since no abnormal thickening of layer 2 has been found.

5. Two fracture zones end and another begins at about anomaly K10 time suggesting changes in spreading rates and a minor change in pole of rotation. A major trend change occurs at about anomaly K2 time indicating a major shift in pole of rotation but not necessarily in spreading rates since the valleys are continuous through the trend changes.

6. The primary, broad abyssal hills originated at or near the ridge crest probably by volcanism and horst and graben structures. Later, possibly Oligocene mid-plate volcanism created smaller conical high abyssal hills in this vicinity and possibly obscured early bathymetric trends parallel to the ridge crest that are observed in other areas.

7. A map of the various 3.5 kHz acoustic signature provinces combined with the piston core data has shown that acoustic mapping can be directly related to different near bottom sediment lithologies.
The main units that can be differentiated include carbonate rich sediments, pelagic brown clays, local resedimentation of brown clay and two types of turbidite deposits.

8. Gray clays containing about 28% silt are distal turbidites observed in the Nares Abyssal Plain, 24° North and Nares Fracture Valleys and in the lows connecting the two valleys. A half meter of pelagic brown clays capping the gray clay indicates that turbidity currents have not occurred here for a minimum of 300,000 years.

9. Pelagic brown clay deposition has been dominant since the ocean crust was formed. The average accumulation rate is one meter per million years. Any lowering in the calcium carbonate compensation depth as observed in other areas (Hayes and others, 1972) must have been limited to depths less than about 5000 meters since mid-Cretaceous.

10. Clay mineralogy indicates that the gray and brown clays have the same ultimate origin. Possibly the turbidity currents and river runoff add much of the fine material to the bottom nepheloid layers probably responsible for a large part of the pelagic deposition here.

11. Only very local resedimentation has occurred in the abyssal hill area. A few depressions in the basement topography have been partially filled with stratified sediments from local slumping but most of the original basement morphology still exists.

12. Manganese nodules occur at relatively higher elevations and the distinct bulk chemistry of the nodules may coincide with the volcanism implied in the formation of the high abyssal hills.
BIBLIOGRAPHY


Contour Interval One Hundred Fathoms (0)
Based on data from:
  R/V CONRAD 10-02, 11-01, 15-10, 16-13
  R/V EASTWARD 14-73
  R/V VEMA 23-06, 25-01, 25-03, 31-0
F.V. = Fracture Valley
↑ = Sill
Plate 1 (T. Shipley, 1975)
Ship Track

○ Piston Core Location (C)

△ Bottom Photograph Showing Volcanic Rock Outcrop (K)

TRACK

R/V CONRAD CRUISE 10-02 (RC10)
R/V CONRAD CRUISE 11-01 (RC11)
R/V CONRAD CRUISE 15-10 (RC15)
R/V CONRAD CRUISE 16-13 (RC16)
R/V EASTWARD CRUISE 14-73 (E14)
R/V VEMA CRUISE 23-06 (V23)
R/V VEMA CRUISE 25-01 (V25)
R/V VEMA CRUISE 25-03 (V25)
R/V VEMA CRUISE 31-07 (V31)
Plate 2 (T. Shipley, 1975)