# 27. GENERAL SYNTHESIS

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## INTRODUCTION

The general synthesis of the Leg 14 results is divided into several semi-independent categories. The discussion of most categories embraces the results of only two or three of the Leg 14 Sites. This is largely due to the fact that the sites were distributed over a large geographic area (Figure 1), and several of the site locations were chosen to investigate unique structural or sedimentation problems. The categories of discussion include: (1) the age of the oceanic crust at sites where basalt was sampled; (2) the generalized stratigraphy of the continental rise of northwest Africa; (3) a detailed comparison of the sedimentary histories of the proximal sites, 137 and 138; (4) a discussion of local tectonism, particularly as it relates to the question of salt diapirs in the deep ocean; (5) the distribution of palygorskite and its genesis; (6) a brief comparison of the sedimentary history of the eastern and western margins of the Central North Atlantic; and (7) a highly speculative discussion of the sedimentary history of the Guyana Basin and its possible relationship to regional tectonism and eustatic sea level changes.

Absolute age dates referred to in the following discussion are taken directly from the biostratigraphic time scale given in Table 1. Caution must be exercised in comparing the absolute ages assigned in this volume to those appearing in other publications. In particular, the detailed ages assigned to the stages of the Cretaceous have undergone recent revision largely based on the results of the Deep Sea Drilling Project (P. Roth, pers. comm.). We recommend that the actual biostratigraphic stages determined be used when comparing relative ages deduced by various investigators, especially when the absolute biostratigraphic time framework is not explicitly given.

The reader will note that a synthesis of our drilling results at Sites 142 and 144 is not included in this account. Because these two sites occur in widely differing locations they do not lend themselves to a regional synthesis study. For this reason more extensive discussions are given in the respective site reports (Chapters 9, 10).

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## THE AGE OF THE OCEANIC BASEMENT AS DEDUCED AT SITES WHERE BASALT WAS SAMPLED

Basalt was recovered from four sites (136, 137, 138, 141) of Leg 14 of the Deep Sea Drilling Project.

The depth to the basalt at Sites 136 and 137 is in good agreement with the expected depth to the acoustic basement (layer 2) based on an analysis of seismic reflection profiler data. The depth to the basalt at Site 138 is slightly less, by about 50 to 100 meters, than the depth to acoustic basement anticipated from seismic and auxiliary data. Site 141 was located on the crest of a small piercement structure and the section sampled there, including basalt, cannot be directly related to the seismic record.

In order to properly compare the inferred ages of the basement from the eastern North Atlantic with those of the western North Atlantic, several assumptions must be made in establishing points of reference. For example, the North Atlantic Ocean is several hundred kilometers narrower in the area just south of the Azores-Gibraltar lineament (35°-40°N) than it is near 20°N. Therefore, a direct comparison of basement ages, using the present ridge axis or the continental slope as a reference point, is not meaningful. Careful consideration must be given to establishing once contiguous points from opposite sides of the ocean, to evaluating normal "geographic effects" of plate tectonics, and to incorporating all the available geophysical information (especially the magnetic lineation pattern) to describe the temporal and spatial history of sea floor spreading. Pitman and Talwani (1972) have investigated these and many other factors in presenting a proposed history of sea floor spreading in the North Atlantic. Their comprehensive study provides the only acceptable basis against which we can test our results on the basement ages of the eastern North Atlantic.

The basalt samples were all too highly altered to allow radiometric age dating. If we assume the age of the basalt to be essentially that of the immediately overlying sediments, then the crust at Sites 136 and 138 is anomalously young when compared with the basement isochrons deduced by Pitman and Talwani (1972). A knowledge of the true age of the oceanic crust at all drill sites in the North Atlantic is critical in properly evaluating the history of the early opening and sea floor spreading between North America and Africa. The possible reconciliation of the apparent age discrepancies could lie with any of the following general explanations:

(1) The oldest sampled sediments are not indicative of the age of the underlying basalt either because: (a) an unrecognized major sedimentary hiatus exists between the

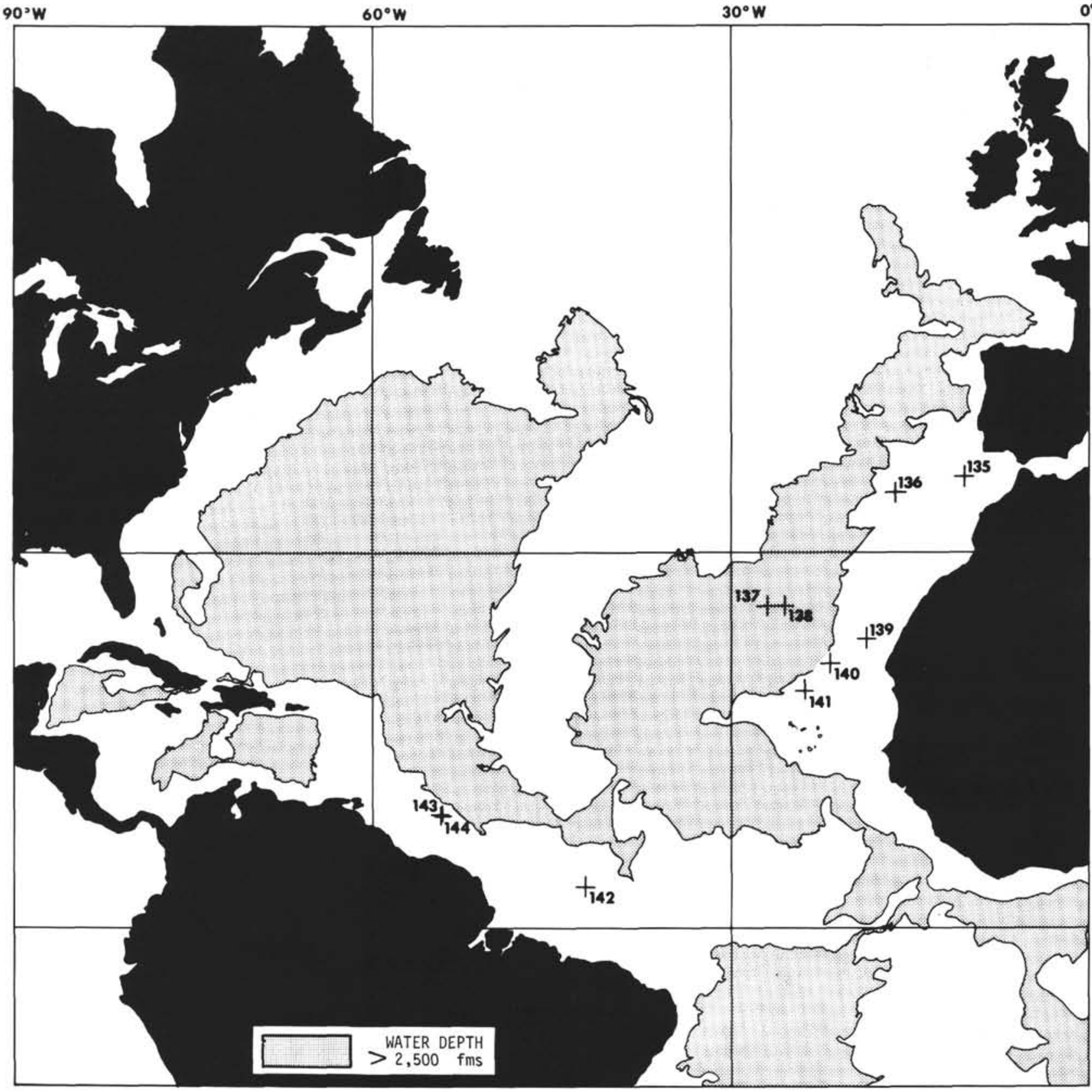


Figure 1. *Location of Leg 14 drill sties.*

oldest dated sediments and the basalt, or (b) the sampled basalt represents an intrusive flow with older sediments below.

(2) The Pitman and Talwani isochrons are incorrect either because: (a) their linear interpolation of basement ages between control points corresponding to ages of about 80 m.y. b.p. (magnetic lineation pattern and DSDP Site 10) and 155 m.y. b.p. (DSDP Site 105) is invalid (i.e., spreading rates are highly variable within this time interval), or (b) the crustal growth on opposite sides of the accreting ridge has been grossly asymmetric.

We will examine in detail the evidence at Sites 136, 137, and 138, in an attempt to establish the most plausible explanation for the basement age discrepancies between our results and those of Pitman and Talwani (1972)

### Site 136

The basement age at this site (106-109 m.y.) is the one in greatest disagreement (by about 30 m.y.) with the basement age predicted by Pitman and Talwani (1972). The sediment cover overlying the acoustic basement and the drilled basalt is anomalously thin considering the proximity of the site to the west African continental margin. We know that at least one explanation for the thin sediment cover lies in the fact that there is a significant gap (about 60 m.y.-Miocene to Santonian/Coniacian) in the stratigraphic record found at the site from our drilling results. The oldest dated sediments are situated 19 meters above the basaltic rock sampled. Since the inferred basement age of 108 m.y. (as discussed later) is anomalously young when compared with the age of the oceanic crust obtained from

TABLE 1
Absolute Ages Used in This Volume

| Millions of Years | Age | | |
|---|---|---|---|
| 0 | | | |
| 1.8 | Pleistocene | | |
| | Pliocene | | |
| 5 | | Upper | Tertiary |
| | Lt. Miocene | Upper | Tertiary |
| 10.5 | | Upper | Tertiary |
| | M. Miocene | Upper | Tertiary |
| 16 | | Upper | Tertiary |
| | E. Miocene | Upper | Tertiary |
| 22.5 | | | Tertiary |
| | Lt. Oligocene | Lower | Tertiary |
| 30 | | Lower | Tertiary |
| | E. Oligocene | Lower | Tertiary |
| 37.5 | | Lower | Tertiary |
| | Lt. Eocene | Lower | Tertiary |
| 43 | | Lower | Tertiary |
| | M. Eocene | Lower | Tertiary |
| 49 | | Lower | Tertiary |
| | E. Eocene | Lower | Tertiary |
| 53.5 | | Lower | Tertiary |
| | Lt. Paleocene | Lower | Tertiary |
| 60 | | Lower | Tertiary |
| | E. Paleocene (Danian) | Lower | Tertiary |
| 65 | | | |
| | Maestrichtian | Upper | Cretaceous |
| 72 | | Upper | Cretaceous |
| | Campanian | Upper | Cretaceous |
| 80 | | Upper | Cretaceous |
| | Santonian | Upper | Cretaceous |
| 84 | | Upper | Cretaceous |
| | Coniacian | Upper | Cretaceous |
| 87 | | Upper | Cretaceous |
| | Turonian | Upper | Cretaceous |
| 91 | | Upper | Cretaceous |
| | Cenomanian | Upper | Cretaceous |
| 100 | | | Cretaceous |
| | Albian | Lower | Cretaceous |
| 104 | | Lower | Cretaceous |
| | Aptian | Lower | Cretaceous |
| 109 | | Lower | Cretaceous |
| | Barremian | Lower | Cretaceous |

the western Atlantic by considering other DSDP holes, and as deduced from marine magnetic anomalies, the question of the validity of the age at Site 136 is of extreme importance.

The site is located about 160 km north of the island of Madeira, a site of known Middle Tertiary and younger volcanism. Consequently, the Albian-Aptian age inferred for the basalt has been questioned by some on the basis that the basalt sample at Site 136 represents a young volcanic event perhaps related to volcanism on Madeira. However, there are several pieces of evidence which have a direct bearing on the question of whether or not the basalt sampled is primeval oceanic basement (seismic layer 2). The seismic reflection profiler data available for this area strongly indicate that the basalt we sampled corresponds to the seismic basement-sediment interface. This interface can be traced over many tens of kilometers to the north as a continuous reflector (see Chapter 3, Figure 2) exhibiting all the typical acoustic properties defining the oceanic basement, and recognized elsewhere in the world. The considerable relief of the basement reflector near Site 136 and elsewhere is one of the characteristics that serve to define it as layer 2. Site 136 was located on the flank of a small basement high. As the *Challenger* approached the site, a side echo from a prominent peak extending above the ocean floor was encountered. On departing from the site the ship passed directly over the beacon and there was no evidence of any topographic peak. There is no correlation of magnetic anomaly highs or lows with the peaks or the troughs of the basement reflector. This is the normal situation over basement relief. In contrast, volcanic seamounts are frequently associated with prominent magnetic anomalies. The magnetics data, therefore, provides no evidence for rejecting our interpretation that the acoustic basement is normal oceanic basalt (layer 2).

The petrology and elemental chemistry of the basalt show that it is typical of tholeiites associated with spreading ridges (see Chapter 23, this volume). In addition, the magnetic properties of the basalt at this site are representative of typical oceanic basalts, and the inferred inclination of the NRM vector is in reasonable agreement with that anticipated if the basalt acquired its stable magnetization in Cretaceous time (see Chapter 25, this volume).

Although 19 meters separate the last cored sediment sample dated as Late Aptian to Early Cenomanian (97-105 m.y.) from recovered basement, cuttings recovered from the drill bit contained nannoplankton of Early Aptian age (about 108 m.y.). Several sites in the western and eastern North Atlantic have indicated major sedimentary hiatuses and although these hiatuses are not entirely synchronous, they are in all cases (except at Site 99, DSDP Leg 11) confined to strata younger than Albian. There is no evidence from the Leg 11 results in the western Atlantic Basin of a regional hiatus in the pre-Albian sedimentary sections (Hollister and Ewing *et al.*, 1972). This, of course, does not exclude the possibility that such a hiatus exists in the eastern Atlantic, but there is no good reason to propose that one does.

If we assume a typical sedimentation rate for the unsampled 19-meter section of 3 m/my for brown clay to

10 m/my for marl ooze, the basal sediments at the basalt-sediment interface would be 2 to 6 m.y. older than the last cored sample, and we believe that 106 to 109 m.y. is the best estimate of the age of the basal sediments at Site 136.

We therefore conclude that the basalt sampled at Site 136 does represent the top of the oceanic basement, layer 2, and that it was formed about 108 m.y. ago.

### Site 137

The assumed age of the basalt at this site is 101 m.y. and is considered to be well-determined by an extensive nannoplankton flora from a sample 3 meters above the basalt-sediment interface. Pitman and Talwani predict an age of the crust at this site of 111 m.y. which is in fairly good agreement with our result.

The basalt is highly altered and the petrology of the original rock is unknown. The remanent magnetization of the basalt samples at this site was unstable (see Chapter 25, this volume) and probably reflects the extensive alteration of the sample. The average compressional wave velocity of the entire sedimentary section overlying the basalt is 2.0 km/sec assuming that the acoustic basement at 0.4 second corresponds to the basalt sampled.

We conclude that the 101 m.y. age inferred for the crust at this site is valid.

### Site 138

If the basalt is true oceanic basement then the age of the basal sediments resting on the lower sampled basalt is anomalous in two respects: (1) the inferred age of the crust is 20 to 25 m.y. younger than that predicted by the Pitman and Talwani analysis, and (2) the age of the sediments above basalt is equal to or slightly younger than that inferred from Site 137 located about 130 km to the west and closer to the axis of the mid-Atlantic ridge.

We believe there is a high probability that the basalt encountered at Site 138 is not part of layer 2, but a younger sill. The reflection time to acoustic basement was 0.5 second and the drilled depth to the basalt was 437 meters. If these units are correlated, an average compressional wave velocity of 1.75 km/sec is obtained, and this value is relatively low considering the thickness of the section, lithologies encountered, and the higher average velocity deduced at nearby Site 137. This interpretation is also supported by an analysis of correlatable stratigraphic units between Sites 137 and 138, as discussed in detail elsewhere in this synthesis. The elemental chemistry of the basalt shows that it is more similar to the alkalic basalts found on seamounts (Chapter 23) than to the tholeiitic basalts associated with layer 2 of the oceanic crust. A small (50 cm) basalt sill was sampled about 3 meters above the basal basalt. The chemical compositions of the two basalts are similar.

We conclude that the basalt at the bottom of hole 138 is not the upper surface of layer 2, but is also a younger flow or sill, and, therefore, the basement age at this site is not determined by our drilling results. We anticipate that an additional 50 to 100 meters of sediment are present above the true basement at this site, and that they would record roughly 5 to 10 m.y. of sedimentary history, thus suggesting a possible basement age of 110 m.y. This compares favorably with the 120 m.y. age predicted at this site by Pitman and Talwani. We remain puzzled by the fact that we see no reflectors on the seismic record across this site that sensibly correlate with the presumed basalt sill.

### Site 141

This site is located on an obvious piercement structure which has apparently been active at least as late as Paleogene time. The age of the basal sediments is estimated at about 70 m.y., but is not considered pertinent to the question of the age of the oceanic crust.

### Conclusions

We believe our drilling results have established valid ages for the formation of oceanic crust at two points within the eastern North Atlantic; Site 136 at 106-109 m.y. and Site 137 at 101 m.y. The age at Site 137 is reasonably compatible with the North Atlantic spreading history proposed by Pitman and Talwani. Site 136 is about 30 m.y. younger than the age predicted at that location by Pitman and Talwani. Since Pitman and Talwani have linearly interpolated ages between control points at 80 m.y. and 155 m.y., Site 136 could be reconciled with these data by assuming a non-uniform spreading rate during this interval. If this is done, however, the ages at Site 136 and 137 are then internally inconsistent unless there was a dramatic change in the rate of seafloor growth between the time that crust at Site 136 was formed and the time that crust at Site 137 was formed.

At the time this volume was going to press, a very significant new theory had been proposed by Larson and Pitman (1972, in press). In brief, they conclude, on the basis of correlating Mesozoic magnetic lineation patterns in the western North Pacific with the Keathley sequence in the western North Atlantic, that spreading in the Atlantic was very slow (about 1 cm/yr half-rate) during the formation of the Keathley anomalies between about 155 m.y. and 110 m.y. Spreading during the formation of the Cretaceous Atlantic magnetic quiet zone from about 110 to 80 m.y., increased markedly to about 3 cm/yr half-rate (Larson and Pitman, 1972).

If the Larson and Pitman (1972) hypothesis is correct, then the ages of the oceanic basalt inferred at Sites 136 and 137 are in reasonable agreement with the ages predicted by the magnetic anomaly pattern and are internally consistent as indicated below:

| Site | Estimated Age of Oceanic Crust from DSDP Leg 14 Results | Age of Oceanic Crust Predicted by Larson and Pitman (1972) | Age of Oceanic Crust Predicted by Pitman and Talwani (1972) |
|---|---|---|---|
| 136 | 106-109 | ~115 m.y. | ~140 m.y. |
| 137 | 101 | ~97 m.y. | ~111 m.y. |
| 138 | 105-110[a] | ~103 m.y. | ~120 m.y. |

[a]Oceanic Basalt (layer 2) probably not sampled - age estimated by extrapolation of sedimentation rates.

A comparison of our estimates of the age of oceanic crust with the predicted ages, leads us to concur with the timing of major seafloor spreading changes in the North Atlantic and elsewhere as proposed by Larson and Pitman (1972).

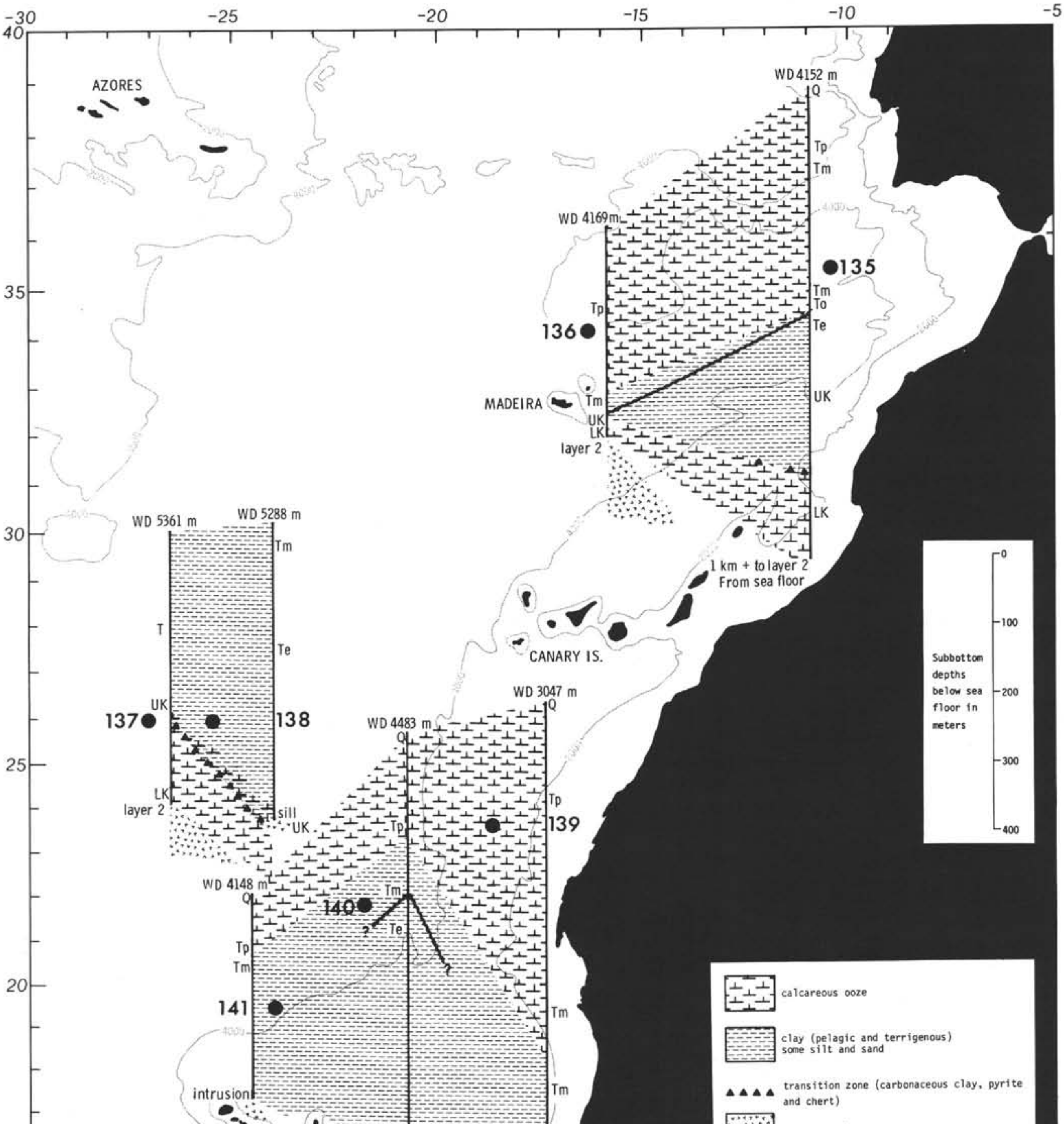


Figure 2. *Schematic stratigraphic correlation of Leg 14 drill sites off West Africa.*

## GENERALIZED LITHOSTRATIGRAPHY OF LEG 14 SITES OFF WEST AFRICA

The schematic fence diagram, Figure 2, is an attempt to correlate geologic information between the Leg 14 drill sites off northwest Africa. The most important features of this correlation are listed below, and more detailed discussions concerning each particular point located elsewhere, are referenced. This information from Leg 14 sites has been integrated into a regional correlation (end of this chapter) for most Deep Sea Drilling Project sites in the North Atlantic.

1. Sites 135, 136, 139, 140, and 141 show a mostly pelagic calcareous ooze sequence of Quaternary to Pliocene

age. Below this is a predominantly terrigenous clay-silt-sand facies of mostly Miocene and older age. Note that at Site 136 the terrigenous sequence is exceptionally thin because of the presence of a major hiatus during which time considerable erosion took place (see discussion of hiatuses this chapter). This abrupt transition between a clay facies to carbonate facies close to the Miocene/Pliocene boundary at many of our sites (and also at several other DSDP sites on Legs 2, 3 and 4) is interpreted as indicating a sudden lowering, perhaps by as much as 1000 meters (see Chapter 26), of the carbonate compensation depth at the end of the Miocene.

At Site 135, the boundary between these two facies coincides with a hiatus which probably indicates uplift of the area (Horseshoe Abyssal Hills) above the influence of terrigenous sedimentation (see Site Report, Hiatus and Tectonism sections this Chapter).

At Site 141, the pelagic carbonate/clay transition occurs at a total depth of 4228 meters, which is approximately 400 meters shallower than the estimated depth of the carbonate compensation depth in Late Miocene-Early Pliocene times. Therefore, local uplift at Site 141 is inferred (see Tectonism section this Chapter).

2. Sites 135, 136, and 137 show an older Lower to Upper Cretaceous calcareous sequence passing up into a younger Upper Cretaceous to Lower Tertiary deep-sea clay sequence. This facies change is interpreted as recording the subsidence associated with the lateral migration of the sites away from the Mid-Atlantic Ridge axis, thereby passing from depths lying above the carbonate compensation depth to depths below it (see Chapter 26, this volume).

3. The Cretaceous calcareous sequence found at the bottom of Site 137 was not penetrated at Site 138. The basalt, in which drilling at Site 138 terminated, is interpreted as a sill below which a calcareous sequence, similar to that found at Site 137 nearby, is presumed to exist. The inferred calcareous sequence would lie between the sill and the basalt forming layer 2 of the oceanic crust (see Site Reports, Chapter 26, and Basement Ages and Comparison of Sites 137 and 138 sections this Chapter).

## COMPARISON OF SITES 137 AND 138

Site 137 is situated in an area of abyssal hills close to the foot of the continental rise in a water depth of 5,361 meters. Site 138 is situated just on the lower limit of the continental rise, about 130 km east of Site 137, in a water depth of 5288 meters.

Despite their proximity, the two sites were chosen as a pair for drilling because the acoustic character of the sediments at the sites is quite different. The drilling results confirm that certain aspects of the sediment disposition at these sites are different. Several problems exist, however, in correlating the two sites with each other and with their seismic profiles.

A continuous seismic reflection profile down the continental slope to Site 138 and into abyssal hills at Site 137 is given in Chapter 4, Figure 2. Enlargements of the profiles at each site are given in Figure 3. There is a pronounced topographic feature (fracture zone ?) of approximately 1000 fms. relief between the two sites. Lattimore, *et al.* (1971) believe this feature trends ENE (Chapter 4, Figure 1 - inset). Other fracture zones and lineaments off this part of West Africa trend WNW and some features, such as the Atlantis Fracture Zone, may extend from the ridge axis all the way to the continental margins of the eastern United States and northwest Africa. Pitman and Talwani (1972) suggest that the New England Seamounts and the Canary Islands are the morphologic expressions of these extensions. Whatever the trend of the feature between Sites 137 and 138, it appears, on lithological evidence, to have acted as a partial barrier to material coming down the continental rise in the Tertiary.

The stratigraphic correlation adopted here, and also by Berger and von Rad (Chapter 26), is shown in Figure 3. This correlation is based on the assumption that both sites have had a history of subsidence down the flank of the Mid-Atlantic Ridge associated with seafloor spreading. In so doing, both sites should have developed a similar sequence of facies beginning with pelagic carbonates passing through a unique transitional pyrite-rich carbonaceous clay and chert facies into an oxidized deep water clay deposited below the calcite compensation depth. Although our results are not definitive, there is some paleontological evidence to suggest that Site 138 passed through the transition facies, dated as Cenomanian by Radiolaria, earlier than Site 137 where the same facies is dated as Late Cenomanian to Turonian on calcareous microfossils. The relative age difference of the transition facies is consistent with what we would predict on the basis of our assumptions.

One contrast between the transition facies in each site is the cyclical occurence of dolomite-rich beds in Site 138. Although the genesis of the dolomite is not firmly established at this time, it is suggested here that it may be a metamorphic effect due to intrusion of basalt sills. Nanno marl beds occur in the transition facies at Site 137 so, possibly, the dolomite at Site 138 has developed from similar material. One distinctive feature of the dolomite cycles requires explanation. The greatest concentration of dolomite occurs in the middle of each bed and gradually decreases to the top and bottom (see Chapter 18, this volume). This suggests some primary sedimentary feature concentrated the calcium carbonate, and thus the dolomite, following metamorphism.

From Figure 3 it can be seen that 245 meters of clay in Site 137 is correlated with 400 meters of clay plus detrital material. It is proposed that the presence of the large topographic high located between these two sites prevents most of the detrital material coming down the continental rise from reaching Site 137, which is situated on the downslope side of the barrier. The water depths at both Sites 137 and 138 are greater than the calcite compensation depth. However, a piston core (*Vema* core 27-167 at 25° 56.2'N, 26° 35.1'W) taken on the lower flank of the topographic high, in a water depth of 5099 meters recovered interbedded marl, chalk, brown clay, and foraminiferal ooze. The presence of *Globigerinoides ruber* indicates a Recent or Subrecent age of the core (J. Beckmann, pers. comm.). Preservation of foraminifera in the calcareous sediments in this piston core shows varying solution effects from strong to very weak. The well-preserved, delicate planktonic foram tests in the foram ooze at a water depth below 5000 meters, suggests the fauna is re-deposited, which is further indicated by a slight size-grading of the tests. The marl with strongly dissolved foram

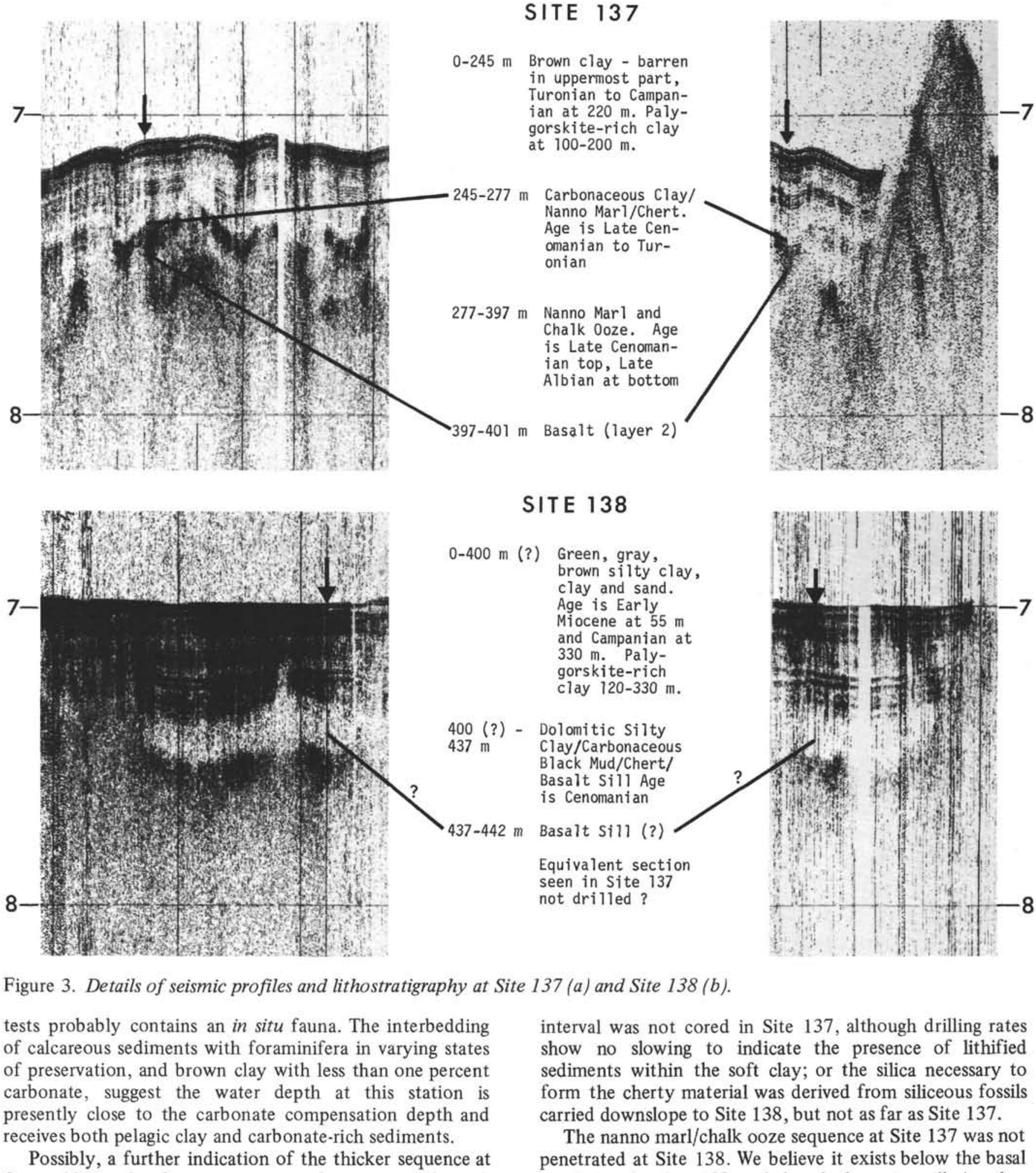


Figure 3. *Details of seismic profiles and lithostratigraphy at Site 137 (a) and Site 138 (b).*

tests probably contains an *in situ* fauna. The interbedding of calcareous sediments with foraminifera in varying states of preservation, and brown clay with less than one percent carbonate, suggest the water depth at this station is presently close to the carbonate compensation depth and receives both pelagic clay and carbonate-rich sediments.

Possibly, a further indication of the thicker sequence at Site 138 is the first occurrence of an extremely rich palygorskite clay at about 184 meters compared with a similar clay first appearing at only 100 meters depth in Site 137. The thickness of the palygorskite-rich clay zone is thicker at Site 138 than at Site 137 (see X-ray data in Chapter 19, and palygorskite section this Chapter). A silicified mudstone-chert interval is present within the upper clay sequence at Site 138, but is not seen in Site 137. Two explanations may account for this: either the same interval was not cored in Site 137, although drilling rates show no slowing to indicate the presence of lithified sediments within the soft clay; or the silica necessary to form the cherty material was derived from siliceous fossils carried downslope to Site 138, but not as far as Site 137.

The nanno marl/chalk ooze sequence at Site 137 was not penetrated at Site 138. We believe it exists below the basal basalt cored in Site 138, and that the latter is a sill. Another basalt layer of similar petrology (Chapter 23) to the lower basalt in Site 138 was cored 10 meters above it.

Unfortunately, a petrologic study of the basalts at Sites 137 and 138 (Chapter 23) provides no direct evidence of their origin, and all samples were too altered for potassium-argon or fission track dating. The two basalts at Site 138 have alkalic affinities. The strongly altered nature of the basalt at Site 137 and 138 may be indicative of hydrothermal alteration caused by the interaction of an extrusive flow with sea water. Wright, *et al.* (Chapter 23) state that the moderate crystal size, small amount of glass, nature of the groundmass, and the 50 cm thickness of the upper basalt at Site 138 suggest that it is a sill. Neither the petrography nor chemistry indicates whether the lower basalt is a sill or flow.

Several additional problems also exist when the drilling results, discussed previously, are related to the seismic profiles at each site. Regardless of whether the lower basalt at Site 138 is a sill or oceanic basement, it is hard to reconcile this with its being the lowest observed reflector at 0.50 second on the seismic record (see discussion of basement ages elsewhere in this Chapter). As the intermediate reflectors at Site 138 are too shallow to be correlated with the basalt recovered, the only conclusion that agrees with the lithologic correlation is that the basalt (and the hard sedimentary rocks immediately above it) does not produce a recognizable reflector. This conclusion is unsatisfactory in the light of evidence from other deep sea drilling legs where basalt sills or flows do correlate with sharp reflectors, for example, Deep Sea Drilling Project Leg 4, Site 23, and Leg 17 (E. L. Winterer pers. comm.).

## HIATUSES

### Introduction

Several large hiatuses were detected or inferred from the drilling results during Leg 14. Many of the earlier Deep Sea Drilling Project Legs (1, 2, 3, 4, 11, 12 & 13) of this project have also indicated the presence of major hiatuses. For the purposes of this paper a hiatus is defined as follows: (1) where a significant stratigraphic gap is indicated by an abrupt discontinuity in the paleontologic ages within a cored interval, or (2) where the calculated average sedimentation rate between cored intervals is less than 1/10th the sedimentation rate typical for the sediment type presumed present in the uncored interval. Hiatuses are inferred where the calculated average sedimentation rate for uncored intervals are within the range of 1/3rd to 1/10th less than the typical rate.

The locations of all sites with major hiatuses are given in Figure 4 and their time spans are indicated in Figures 5 and 6. Hiatuses spanning similar times are also seen on the continent, continental shelf and slope of West Africa. Recent Deep Sea Drilling Project cruises have indicated the presence of important hiatuses representing approximately the same time gaps both in the Caribbean and the Pacific Ocean. (e.g. Legs 15 and 17 reported in Geotimes).

### West African Continental Margin

#### Spanish Sahara

Beneath the continental slope, structures are truncated by an unconformity whose magnitude suggests it developed during the Oligocene, a time of major local folding (cf., Martinis and Visintin, 1966; Querol, 1966). A major unconformity is also identified by Rona (1970) off Villa Cisneros and Cap Blanc; he regards it as the buried margin of the continental terrace. Although Rona does not make any conjecture as to the actual age of this buried slope, he states that it appears to be of erosional origin and is now mantled by a constructional wedge of slope sediments.

**TABLE 2**
**Review of Evidence for Hiatuses in the Atlantic. Data Re-interpreted or Taken from Initial Reports of the Deep Sea Drilling Project, Volumes 1, 2, 3, 4, 11, 12, and 13 (in Press)**

| Site | Lithology: Above Hiatus | Lithology: Below Hiatus | Computed Average Sedimentation Rate of Uncored Interval Where Hiatus Thought to be Present, and Other Comments |
|---|---|---|---|
| | **WESTERN NORTH ATLANTIC** | | |
| 99 | Clay | Limestone and chert | 0.2 m/my; Middle Pliocene cored 21 m above Hauterivian-Miocene recovered in *Vema* piston core (see Leg 11) so hiatus spans time from 120 to 10 m.y. |
| 101 | Hemipelagic mud | Hemipelagic mud | 0.5 m/my |
| 105 | Silty clay | Carbonaceous clay | 0.3 m/my |
| 4 | Calcarenite, silty clay | Calcarenite, nanno marl | 1 m/my |
| 5 | Calcareous mud, marl | Calcisiltite, marl | 0.5 m/my |
| 10 | Chalk ooze | Chalk ooze | 1.5m/my–hiatus or hiatuses/ only inferred within partially drilled 60-meter interval which ranges from Pliocene to mid-Eocene |
| 111 | Nanno ooze | Zeolitic clay | Hiatus cored |
| 111 | Chalk | Shallow water carbonates | Hiatus cored |
| 111 | Shallow water carbonates | Sandstone and and shale | Hiatus cored–seismic evidence suggests this horizon marks an angular unconformity |
| | **EASTERN NORTH ATLANTIC** | | |
| 13 | Clay | Radiolarian ooze | 2.5m/my–hiatus inferred. Center bit sample contained early Miocene material so actual hiatus may only encompass Oligocene and Late Eocene. |
| 135 | Foram-nanno ooze | Terrigenous silty clay, sand | 0.3 m/my |
| 136 | Clay | Clay and ash | Hiatus cored |
| 140 | Diatom ooze | Siliceous clay and sand | 1 m/my |
| 118 | Terrigenous clay | Nanno clay | Hiatus cored–at an unconformity |
| 119 | Nanno clay | Clay | Hiatus cored–at an unconformity |
| 120 | Nanno ooze | Nanno clay | 0.7 m/my |
| 116 | Foram-nanno ooze | Foram-nanno ooze | 3.2 m/my |
| 117 | Cherty limestone | Calcareous clay and chert | 1.8 m/my–hiatus inferred |
| | **SOUTH ATLANTIC** | | |
| 17 | Nanno ooze | Nanno ooze | Hiatus cored |
| 19 | Clay | Nanno ooze | 1.5 m/my |
| 20 | Clay | Marl ooze | Hiatus cored |
| 21 | Nanno ooze | Nanno ooze | 0.2 m/my |
| 22 | Nanno ooze | Nanno ooze | Hiatus cored |
| 22 | Nanno ooze | Nanno ooze | 4.5 m/my–hiatus inferred |
| | **CARIBBEAN** | | |
| 29 | Nanno ooze | Radiolarian ooze | 1 m/my |

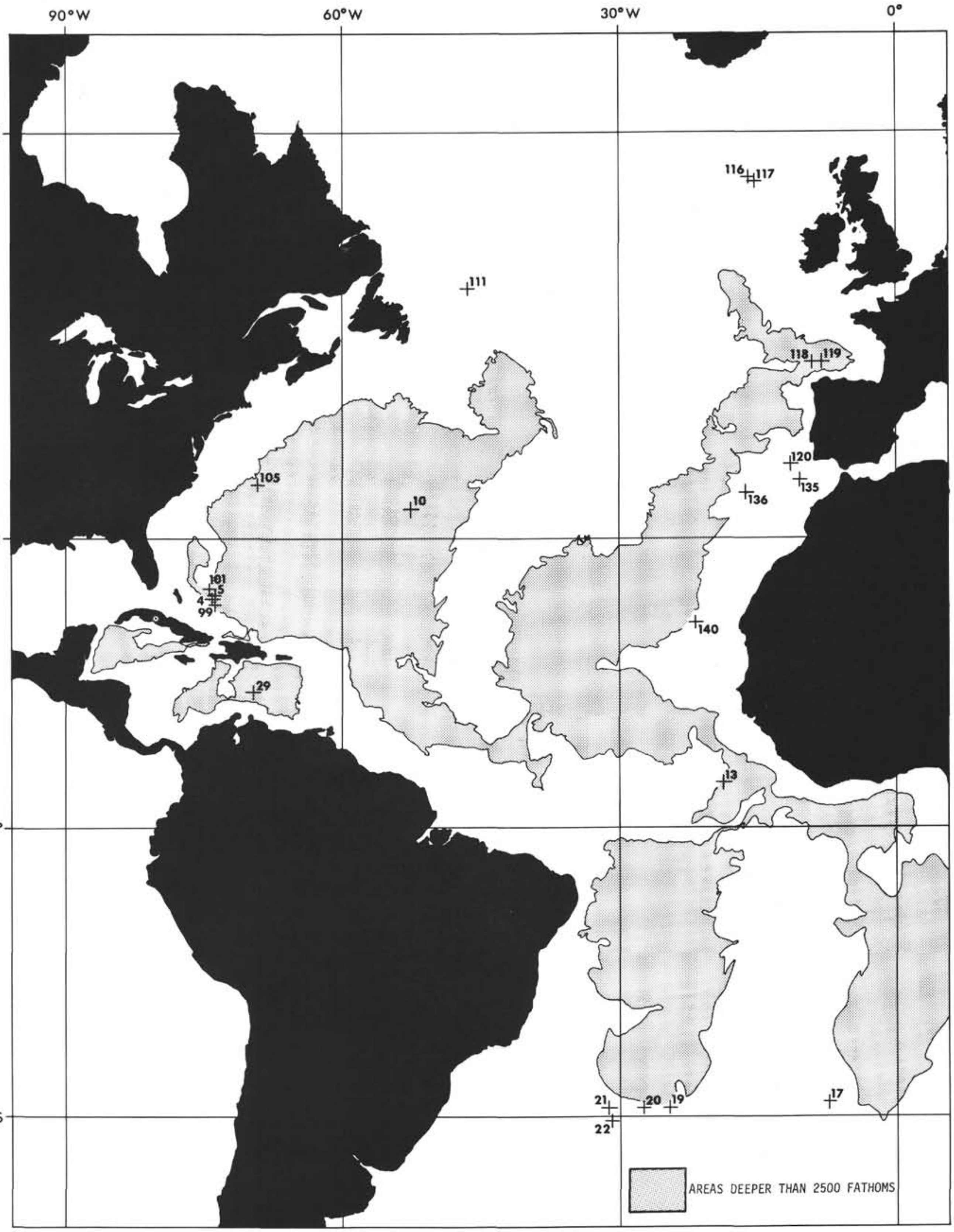


Figure 4. *Locations of DSDP sites in the Atlantic in which major hiatuses were detected from drilling results.*

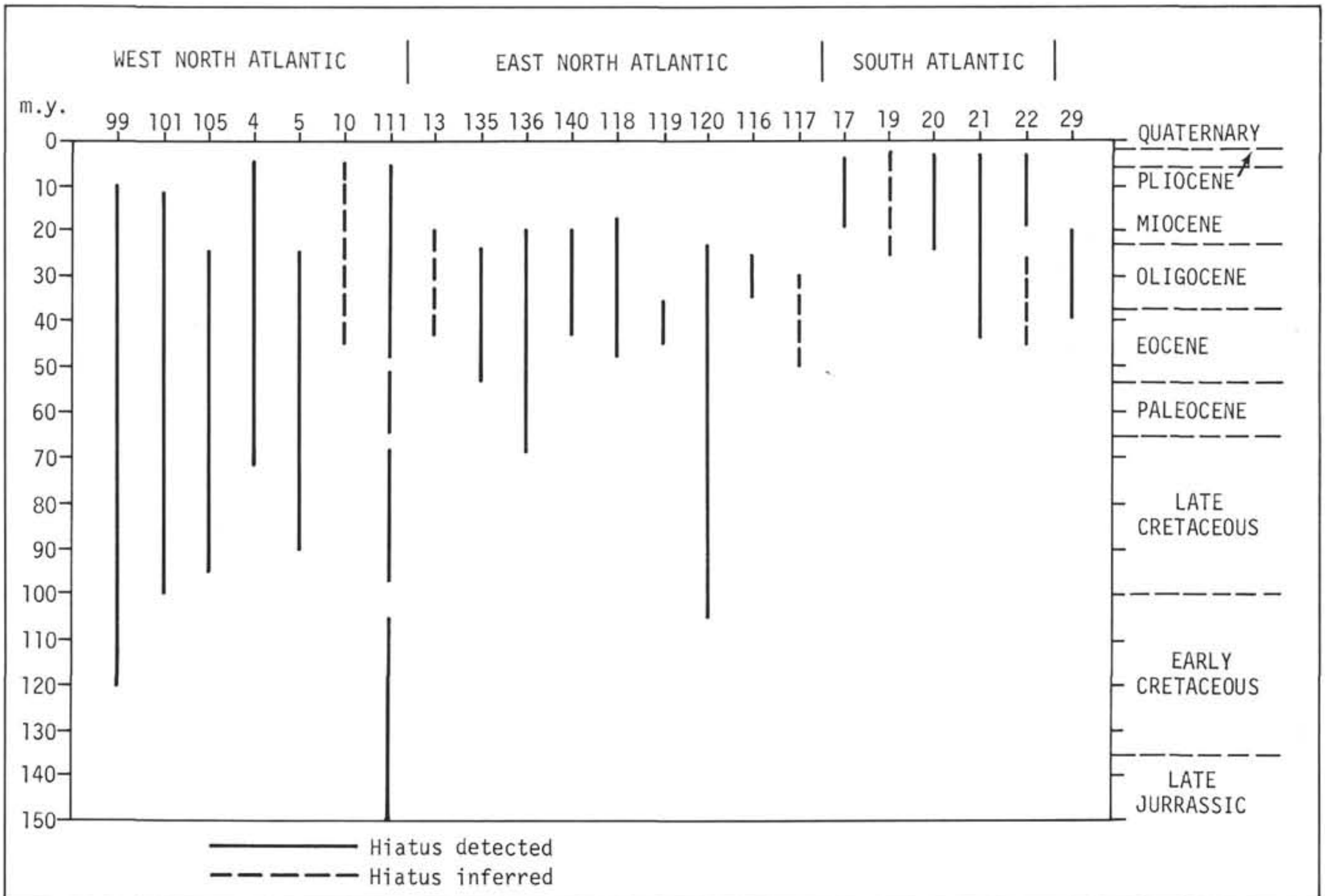


Figure 5. *Time span of hiatuses in the Atlantic. Note Site 29 is located in the Caribbean (see Figure 4).*

Pliocene and Miocene rocks outcrop on the shelf above an unconformity and, not far north of Cap Juby, it is underlain by Eocene rocks on the outer shelf (Dillon, 1969); its Oligocene age seems reasonably confirmed.

### Morocco

In the Souss Trough, off Agadir, a deep unconformity rises towards the coast, cuts into Cretaceous strata, and Summerhayes, *et al.* (1971) assume that it represents the onset of Atlas folding during the Oligocene. Dillon (1969) recognizes the same unconformity in other parts of the Souss Trough, but designates its age as Upper Eocene, the period of regression prior to Oligocene folding.

Beneath the continental slope off the High Atlas Region, near Essaouira, the same Oligocene unconformity was recognized (Summerhayes, *et al.*, 1971). A Miocene conglomerate incorporating Eocene and Upper Cretaceous pebbles lies on the Oligocene erosion surface. The widespread occurrence of the conglomerate on the outer shelf implies that the shelf surface is a marine erosion plane cut in Early Tertiary time and modified little by Pleistocene sea level fluctuations.

## Discussion

The occurrence of major hiatuses over much of the Atlantic Ocean, in the Caribbean, the Pacific Ocean, and on the continental margin of West Africa indicates an event of worldwide significance. The time span of the hiatuses is mainly in the Lower Tertiary; regional differences in their duration, or their absence in some localities, may provide clues as to their origin.

In the eastern Atlantic some of the hiatuses can be related to local tectonic events. For example, in the Bay of Biscay, Site 118, the hiatus is due to uplift and erosion correlated with mountain building in the Pyrenees, and in Site 119 it is due to uplift and tilting of Cantabria Seamount (Leg 12 1972). At Site 135, a hiatus marks the uplift of the Horseshoe Abyssal Hills thus changing this area from one receiving terrigenous abyssal plain sediments to one receiving pelagic calcareous ooze.

Both offshore and onshore in the Spanish Sahara and Morocco the Oligocene unconformities, described above, are correlated with folding in this area. At other nearby sites (136, 140) in the eastern Atlantic, the hiatuses do not separate different lithologies and may not relate directly to Alpine tectonism.

In the western Atlantic no major tectonism occurred during Late Cretaceous or Tertiary times either on the continental U.S., or offshore. The results of Deep Sea Drilling Project Leg 11 (1972) demonstrate that the major hiatuses recorded in the drill sites can be correlated with an erosion plane seen as a pronounced reflector (Horizon A, Ewing *et al.*, 1970) on seismic profiles.

Non-deposition alone may account for the hiatus in a few sites, however, the general mechanism suggested here to account for most hiatuses in the North Atlantic is one of

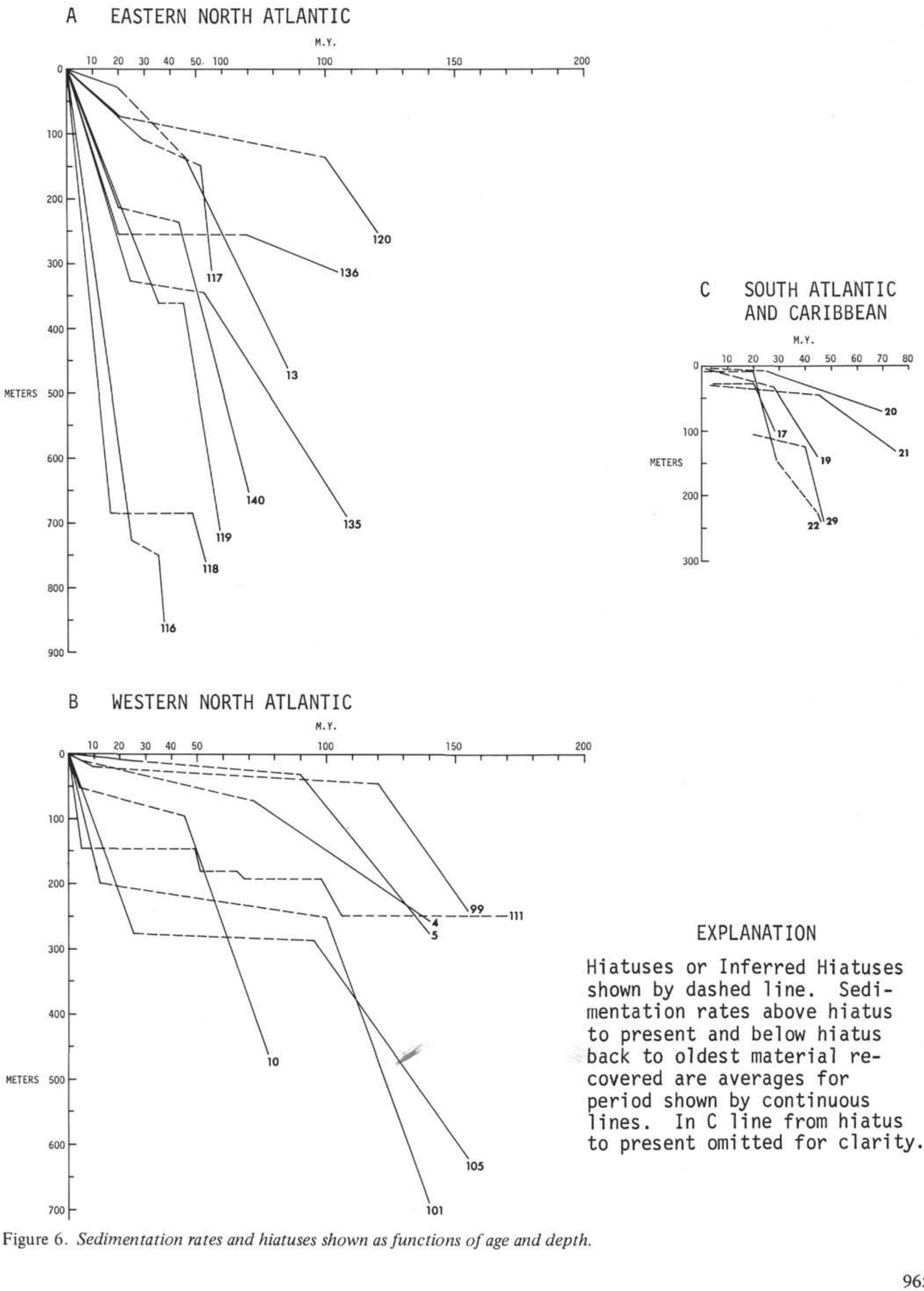


Figure 6. *Sedimentation rates and hiatuses shown as functions of age and depth.*

erosion caused by the development of a strong ocean current circulation system. This circulation pattern would probably have been initiated in the Late Eocene as practically all hiatuses observed in the North Atlantic span this time interval.

The fact that hiatuses observed in some sites can be related to local tectonic events, may be coincidental with the inferred causal mechanism of the most important factor, erosion, or non-deposition.

It can be seen from Figures 5 and 6 that, though the total time range of the hiatuses in different parts of the Atlantic span varying periods of time, they are fairly consistent within different geographic provinces. In the western North Atlantic the hiatuses span the longest time range–mostly Late Cretaceous to Miocene. Hiatuses in the eastern North Atlantic mostly span the Early Tertiary. The extension of the western Atlantic hiatuses further back into the Cretaceous may be an indication of the existence of stronger bottom currents which were able to erode sediments to a greater depth. Also, some of the hiatuses drilled in the western Atlantic have a younger upper limit than those both in the western and eastern Atlantic–Pliocene as against Late Oligocene/Early Miocene. In the Horizon A outcrop area, east of Cat Gap, bottom currents are sufficiently strong to have prevented sedimentation, or eroded all sediments deposited since Cretaceous times. Further evidence for stronger current action in the western Atlantic is seen in various places in the sediment record. The building of the continental rise off the eastern U.S. has been controlled throughout the Tertiary by powerful bottom currents (Heezen *et al.*, 1966). The sediments deposited were hemipelagic muds, terrigenous silty clays, and redeposited detrital carbonates. In strong contrast, the continental rise off northwest Africa is comprised of Lower Tertiary terrigenous and hemipelagic sediments, overlain by a mostly Upper Tertiary sequence of pelagic sediments–brown clay, calcareous ooze, and siliceous ooze (see stratigraphic correlation section in this Chapter). This pelagic history coincides with the period following the major hiatuses in the eastern Atlantic and suggest to us a waning of bottom currents here to the extent that they were no longer able to erode older sediments, transport terrigenous sediments, or even prevent the deposition of pelagic sediments sooner than a similar waning in the west.

If erosion is the primary cause of the major hiatuses, then the presence, duration, and absence of any hiatuses should be related to the position of a site with respect to the Early Tertiary deep-water current system. At the present time, the strongest bottom currents in the North Atlantic are along the continental rise and adjacent abyssal plain off the east coast of North America (Western Boundary Undercurrent). The extremely long duration (70-110 m.y.) of hiatuses of Sites (99, 101, 105) located in this area suggest that this present current system has been in existence throughout much of the Tertiary. Sites 4 and 5, located close to Sites 99 and 101, also have major hiatuses, but their duration is uncertain. In Site 100, situated between Sites 99 and 101, no core was taken above 200 meters, but at this depth the sampled sediment spans the Jurassic/Cretaceous boundary, implying that much of the Cretaceous/Tertiary section could have been eroded.

Throughout much of the Tertiary, brown clay was being deposited on the Bermuda Rise, and despite poor age determinations and the lack of closely cored intervals, the average sedimentation rates of 5 m/my in Site 7 and 12 m/my in Site 9 indicate that there is probably a complete sedimentary record for the interval spanned by major hiatuses in the sites located closer to the continental margin. The Bermuda Rise therefore seems to have been free from the influence of significant bottom currents throughout the Tertiary and Quaternary periods.

In Site 111 the exceptionally long duration of the hiatuses is due to its elevated position (water depth 1811 m) in the direct path of the strong Labrador Current so that erosion has always been dominant, particularly when the site was even shallower (Laughton and Berggren *et al.*, 1971). Site 112, situated in the mid-Labrador Sea in 3667 meters of water, probably has a complete record of Tertiary sediments not significantly affected by bottom currents.

In the eastern Atlantic three Sites (12, 137, 138), all situated very close to the narrow zone of abyssal hills between the continental rise and the flank of the mid-Atlantic Ridge, may also have a complete sequence of Tertiary sediments. The sediments located here are poorly fossiliferous or barren brown clays with average Tertiary sedimentation rates of 3.5 m/my (Site 12), 2.5 m/my (Site 137), and 4 m/my (Site 138). This latter site also contains a minor terrigenous component. The sediment type; sedimentation rate; and particularly the absence of a large abyssal plain, in contrast to the western Atlantic; all point to the absence of significant bottom currents in the eastern Atlantic.

In Site 141, situated about 220 km east of Site 12, a small hiatus in the Upper Miocene separates brown clay from overlying calcareous ooze and is due to a combination of dissolution and current action on this elevated feature. The winnowing effect of the currents continues up into the calcareous oozes as evidenced by an anomalously high content of foraminifera.

Hiatuses discovered in South Atlantic sites on the Mid-Atlantic Ridge (17, 19, 20) mostly span only the Upper Tertiary period, but those on the Rio Grande Rise (21, 22) also extend back into the Lower Tertiary. Significantly, only those sites on the lower portions of the Mid-Atlantic Ridge flank, close to the carbonate compensation depth, showed hiatuses. Their origin is probably due to non-deposition and partial dissolution (Site 17; also Site 10 in North Atlantic) or complete dissolution of carbonate with non-deposition of the insoluble residue due to bottom current action (Sites 19, 20). The Rio Grande Rise Sites (21, 22), with longer hiatuses occurring within a completely calcareous ooze sequence, cannot be explained by dissolution. This area has probably experienced currents strong enough to prevent the sedimentation of calcareous oozes through much of the Tertiary. Perhaps the elevated position of the Rio Grande Rise across the path of the currents flowing northward from Antarctica enhances their effects sufficiently to prevent sedimentation. Further evidence for current action at these sites is seen in the anomalously high proportion of foraminifera in oozes immediately above the hiatus (Pimm, 1970) indicating current winnowing of the finer fraction.

**Conclusions**

Hiatuses in the North Atlantic are primarily due to erosion caused by bottom currents. The current circulation system responsible for this erosion was probably initiated in the Eocene. The currents were more vigorous in the western Atlantic than in the eastern Atlantic. In some places in the western Atlantic, bottom currents are still actively eroding or preventing sediments from being deposited. Local tectonic events in some parts of the eastern Atlantic and adjacent land areas are correlated with the hiatuses, but the extent to which tectonism has modified a particular site's response to the postulated world ocean-wide event is uncertain.

In the South Atlantic, hiatuses are due to dissolution and nondeposition on the Mid-Atlantic Ridge and current action on the Rio Grande Rise.

## TECTONISM AND THE SALT PROBLEM

The term "tectonism" is usually understood to imply crustal instability. In light of the currently accepted theory of seafloor spreading, all areas of the major, actively spreading ocean basins are experiencing a slow systematic tectonism in both a lateral and vertical sense. Evidence from Leg 14 drilling indicates that an additional type of tectonism has been experienced at least at two sites in the eastern central Atlantic.

At Site 135, located about 70-100 km south of the seismically active Azores-Gibraltar Fracture Zone, major uplift (several hundred meters) of the Horseshoe Hills occurred sometime between the Early Eocene and the Late Oligocene. The major change from pre-Early Eocene terrigenous sediments to post Late Oligocene pelagic sediments provides the evidence for the uplift. The site of deposition was changed from a deep abyssal basin environment to one of a topographic high that was inaccessible to the normal downslope transport of terrigenous sediments. Because a major unconformity exists between the terrigenous and pelagic sections at Site 135, it is impossible to pinpoint the time of the uplift. The unconformity surface is correlated with a prominent reflecting horizon that can be traced to the southeast of the Horseshoe Hills (see seismic records, Chapter 2, Figure 2). The reflecting horizon is offset by piercement type structures that are interpreted by Pautot *et al.* (1970) as being salt diapirs. If the presumed salt tectonism postdates the deformation of the reflector representing the unconformity, then the age of the salt piercements are more likely to be Middle Tertiary in age than Mesozoic as suggested by Glangeaud *et al.*, 1966. A pre-early Eocene age for salt tectonism in this area is incompatible with out interpretation of the chronology of tectonic events at Site 135. Although the age of the salt may be pre-Tertiary, as suggested by many (e.g. Pautot *et al.*, 1970), and may be related to the formation of enclosed basins during the earliest rifting history of North America from Europe or Africa, implacement of the salt as piercements probably relates to a post Eocene phase of tectonism. Although there is no evidence of evaporite sediments from the drilled section at Site 135, the seismic data indicate the source layer of the presumed salt diapirs is much more deeply seated than the depth of the recovered cores. Pitman and Talwani (1972) have proposed that a significant change in the rate of seafloor spreading between North America and Europe occurred about 53 m.y. ago. Krause and Watkins (1970) suggest that major tectonism began in the Azores at least 45 m.y. ago. It seems likely that the tectonism in the Azores (a part of the plate boundary between Europe and Africa), and the tectonic activity giving rise to the Horseshoe Hills, are both related to a change in the interaction of the European and African plates along the Azores-Gibraltar Fracture Zone that resulted when spreading slowed significantly between Europe and North America 53 m.y. ago. Major Alpine tectonism also occurred on the adjacent continents (e.g. early Tertiary tectonism in the Sub-Betic chain).

At Site 141, located about 200 km north of the Cape Verde Islands, local uplift of the sediment column of about 400 meters is inferred on the basis that non-carbonate clays are found well above the presumed level of the carbonate compensation depth at the time of their deposition. The depth of the transition from carbonate to non-carbonate facies at several DSDP drill sites off northwest Africa (see Figure 7), establishes that vertical uplift at Site 141 was not part of a more regional epeirogenic uplift. Small scale piercement type structures are common in the vicinity of Site 141 and are undoubtedly responsible for the local uplift of the sediments at Site 141. The small topographic expression of the structures ($<1/10$ of the inferred uplift) is difficult to explain but may relate to effects of bottom currents and winnowing (see Chapter 8). The similarity of the piercement structures near Site 141 and elsewhere (as they appear on seismic reflection profiles) to known salt diapirs, as well as the presence of major salt basins along the northwest African margin, have been the primary basis for interpreting the deep sea structures as salt diapirs (Schneider and Johnson, 1970; Rona 1969; Rona 1970; Pautot *et al.*, 1970). It should be noted that diapirism is the "process by which earth materials from deeper levels have pierced or appear to have pierced shallower materials," O'Brien (1968), and the "earth materials" may be sedimentary, igneous, or metamorphic in nature.

The recovery of highly altered basalt from the core of the structure drilled at Site 141 and normal distribution of Na and Cl in the interstitial waters of the sediments at that Site (see Chapter 21), provide strong evidence that the field of piercement structures mapped about 200 km north of the Cape Verde Islands are not salt diapirs.

This observation does not exclude the possiblity that major concentrations of salt and other evaporites occur in sediment in deep water areas along the West African margin as proposed by Rona (1969). In fact, the systematic increase of Na and Cl with depth in the interstitial waters of sediments collected at Sites 139 and 140, located 750 km and 350 km respectively to the northeast from Site 141, provide very strong evidence for the presence of deeply buried evaporite deposits in these areas of the middle and lower continental rise. It should be emphasized however, that there is no evidence of piercement structures in the immediate vicinity of Sites 139 and 140 as was erroneously reported in *Ocean Industry* (1971). The closest diapiric structure mapped by Rona (1969) lies about 350 km west of Site 140 and about 600 km west of Site 139. Similarly, the piercement field mapped by Schneider and Johnson

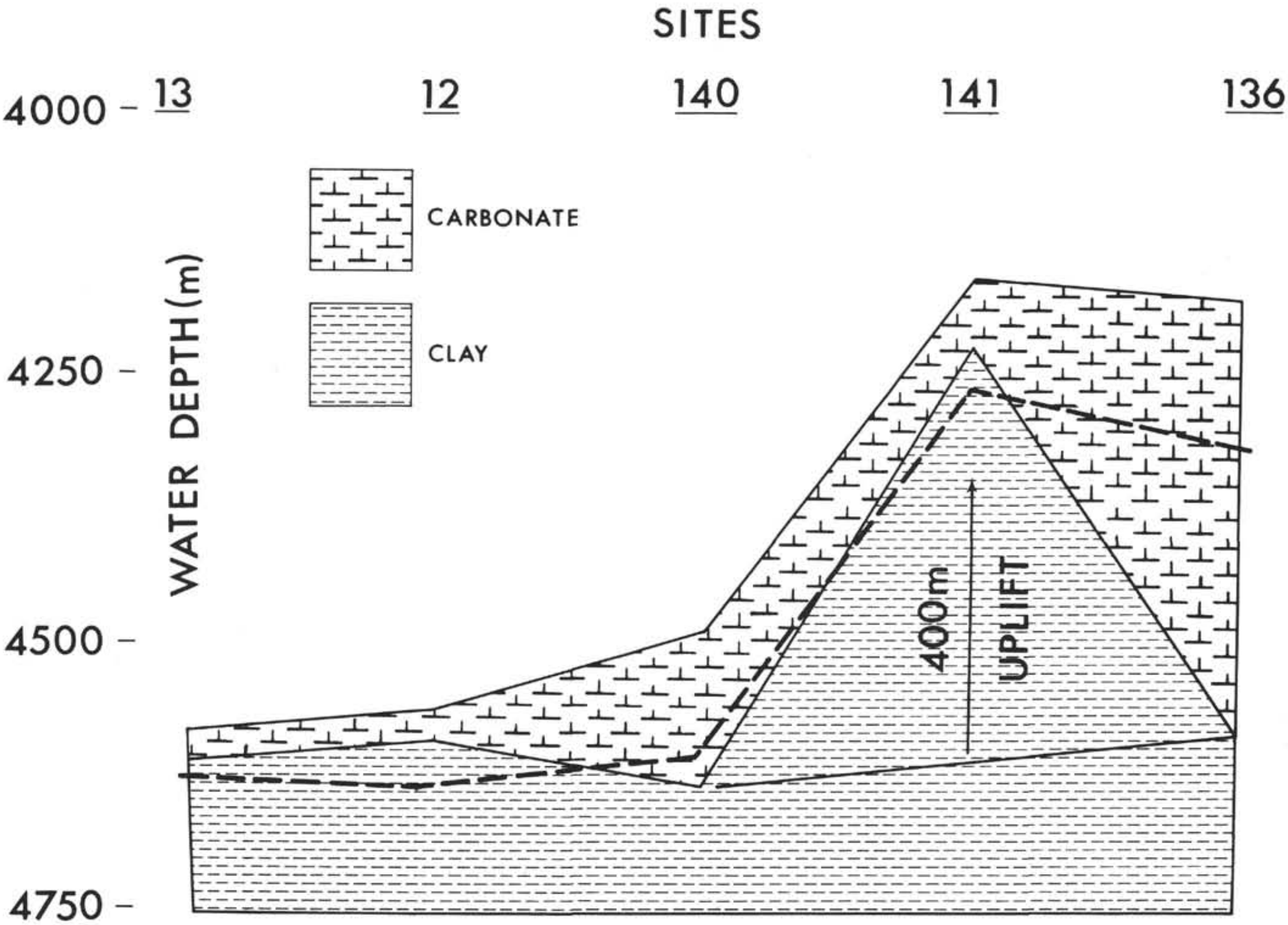


Figure 7. *Depth of carbonate-clay facies boundary in sites off Northwest Africa. The dashed lines mark the boundary between Pliocene and Miocene sediments.*

(1970) lies about 370 km to the southwest of Site 140 and about 750 km to the southwest of Site 139.

The important point to be stressed is that the appearance of piercement type structures on seismic reflection profiles is not, in itself, a good criterion for interpreting such structures as salt diapirs.

The occurrence of evaporite and igneous diapirism in close association with one another has been recognized "almost universally" (O'Brien, 1968). However, as O'Brien points out "it is not clear . . . whether the igenous intrusions localized the evaporite diapirs or vice versa, or whether the intrusion of evaporites has carried igneous rocks to the surface accidentally." The association between mafic igneous rocks and evaporite domes is therefore not a simple straightforward one, and there is no evidence for a local one-to-one correspondence between individual evaporite domes and the presence of igneous rocks.

The facts that major uplift of the sediments are indicated, that deformation (upwarping) of the sedimentary layers are shown on seismic records, that basalt was recovered from within the "core" of the structure, and that there is no evidence of anomalous salt concentration in the sediments at Site 141, led us to conclude that the structure drilled there represents an igneous intrusion and that other apparently similar structures in the immediate vicinity had a similar origin. An alternate hypothesis is that the structure at Site 141 is a mud diapir in local association with mafic rocks.

## PALYGORSKITE

At least 85 meters of palygorskite-rich clays of probable Early Tertiary age were recovered between 75 and 160 meters at Site 12 (DSDP Leg 2). Peterson, *et al.* (1970) favor an origin for the palygorskite that calls for the alteration of volcanic ash by high magnesium-rich brines. The proposed source of the brines is from a near shore or lagoonal concentration of sea water, and the ash is presumably from the Cape Verde Islands. As evidence for the presence of evaporite deposits, they (op. cit) point to the presence of the salt dome province off Senegal and Gambia, extending at least 60 km offshore, well down the continental slope.

One of the objectives of the Leg 14 drilling was to obtain more information on the extent of the palygorskite-rich clays.

From a careful examination of the Leg 14 X-ray data (Chapter 19), and that of many legs subsequent to Leg 2 both in the Pacific and Atlantic, it is apparent that palygorskite frequently occurs in deep sea sediments, particularly in clays. However, high values (40% or more of the crystalline fraction) and thicknesses as great as those recorded at Site 12, are uncommon. Occurrences of palygorskite found on Leg 14 Sites are listed in Table 3.

TABLE 3
Major Occurrences of Palygorskite in Leg 14 Sites

| Site | Depth (m) | Thickness (m) | Range of Palygorskite in Crystalline Fraction (Per Cent) |
|---|---|---|---|
| 137 | 100-220 | 120 | 38-86 |
| 138 | 118 | ~150 | 90 |
| | also | | |
| | 184 | | 24 |
| | and | | |
| | 333 | | 31 |
| 140 | 312-432 | 120 + | 46-92 |
| | also at | | |
| | 512-513 | | 21 and 86 (2 values only) |
| 141 | 118-120 | ~70 ? | 78-86 |
| | also at | | |
| | 192 | | 9 and 80 (2 values only) |

The area encompassing Site 12 (Leg 2) and Sites 137, 138, 140, and 141 (Leg 14), all containing a thick sequence of palygorskite, is about 500,000 sq. km. Although dating of these palygorskite clays is very poor, they all appear mostly in the Eocene, Paleocene and possibly down to the uppermost Cretaceous sediments. On depth evidence alone, it is possible that this palygorskite sequence can be correlated between all sites except Site 140 as it occurs in the interval from 80 to 200 meters below the sea floor. If one allows for the terrigenous influence at Site 140, then the palygorskite found there may still be correlatable with the same unit as in the other sites. Additional evidence to support this is that the Site 140 palygorskite is also Eocene to Paleocene (?) in age.

A detailed discussion of the salt diapir controversy was given earlier in this chapter, but some mention of it must be reiterated regarding evidence for or against the role of high magnesium brine in the hypothetical formation of the palygorskite mentioned earlier.

Of the Leg 14 Sites with palygorskite, only Site 140 showed anomalously high salinities with the interstitial waters. The presence of a pronounced salinity gradient, increasing with depth at Site 140 and also at Site 139, located higher up the continental rise, certainly indicate a deep evaporite source. However, none of the other sites which are situated in the abyssal hills or at the foot of the continental rise showed any sign of anomalous salinities. Unfortunately, no chemical data is available on the sediments from Site 12. None of the sites show any significant variations in Mg content with depth (see Chapter 21). A detailed examination of the complete X-ray results given in Chapter 19 yields no apparent relationship between palygorskite distribution and other minerals. In fact, if the development of palygorskite was related to Mg brines the occurrence of Mg rich minerals other than palygorskite might also be expected.

As there is not a progressive increase of palygorskite with depth, it appears that the palygorskite has not developed authigenically from a clay of uniform composition, but that it may have grown authigenically from clay of a unique composition which occurred almost exclusively in restricted horizons.

From an examination of the X-ray data, it does not appear that palygorskite is abundant in clays that contain a high content of minerals such as feldspar, montmorillonite, or zeolites that are recognized as being of volcanic origin.

Some geochemists hold the view that palygorskite might form as a direct precipitate under conditions of abundant free silica and a restricted pH range (R. Garrels pers. comm.). The source of the silica would most likely be dissolution of siliceous fossils. In Sites 138 and 140, the level of disappearance of diatoms and Radiolaria does coincide with the appearance of abundant palygorskite. In Sites 137 and 141, however, no siliceous fossils were detected throughout the clay sequences. In Sites 137 and 141, the palygorskite occurs in sediment with a pH range of about 6.7 to 7.1, but in Site 140, which has a pronounced salinity gradient, the pH values are higher–7.4 to 7.5; no data is available for Site 138.

## STRATIGRAPHIC CORRELATION ACROSS THE NORTH ATLANTIC

An attempt is made in Figures 8 and 9 to correlate stratigraphically selected sites drilled in the North Atlantic which are valuable in providing information on the history and development of this ocean between about 5 and 45 degrees N. In Figures 8 and 9 the cored intervals are shown in solid bars; the sites are positioned on the basis of their water depths and age, and facies correlations are indicated. All lithologies have been assigned to four facies categories:

Calcareous – pelagic carbonate, mostly nanno chalk or marl ooze

Clay – deep sea brown, occasionally green or black, clay

Siliceous – mostly Radiolaria ooze, chert, or silicified mudstone

Terrigenous – mostly silty clay and hemipelagic mud, some sand and resedimented shallow water carbonates.

Although certain features of the stratigraphy are common to several sites, no clear stratigraphic history is common to the entire region, and we recognize three distinct provinces each with a characteristic stratigraphy. These are:

(1) The Western North Atlantic Province which includes sites drilled on the lower continental rise off the Eastern United States and the Abyssal Plain immediately adjacent to it.

(2) The Bermuda Rise Province.

(3) Middle and Eastern North Atlantic Province which includes all sites now on the Mid-Atlantic Ridge and abyssal hills or continental rise off northwest Africa.

**Western North Atlantic Province**
**Sites: 4, 5, 99, 100, 105 (DSDP Legs 1, 11)**

**Composite Succession Based on Correlation in Figure 8**

| Age | Max. Thickness | Facies | Description | Comment |
|---|---|---|---|---|
| Recent to Latest Oligocene | 245m | Terrigenous | Hemipelagic mud, silty clay, and | Age range varies according to hiatus at base |

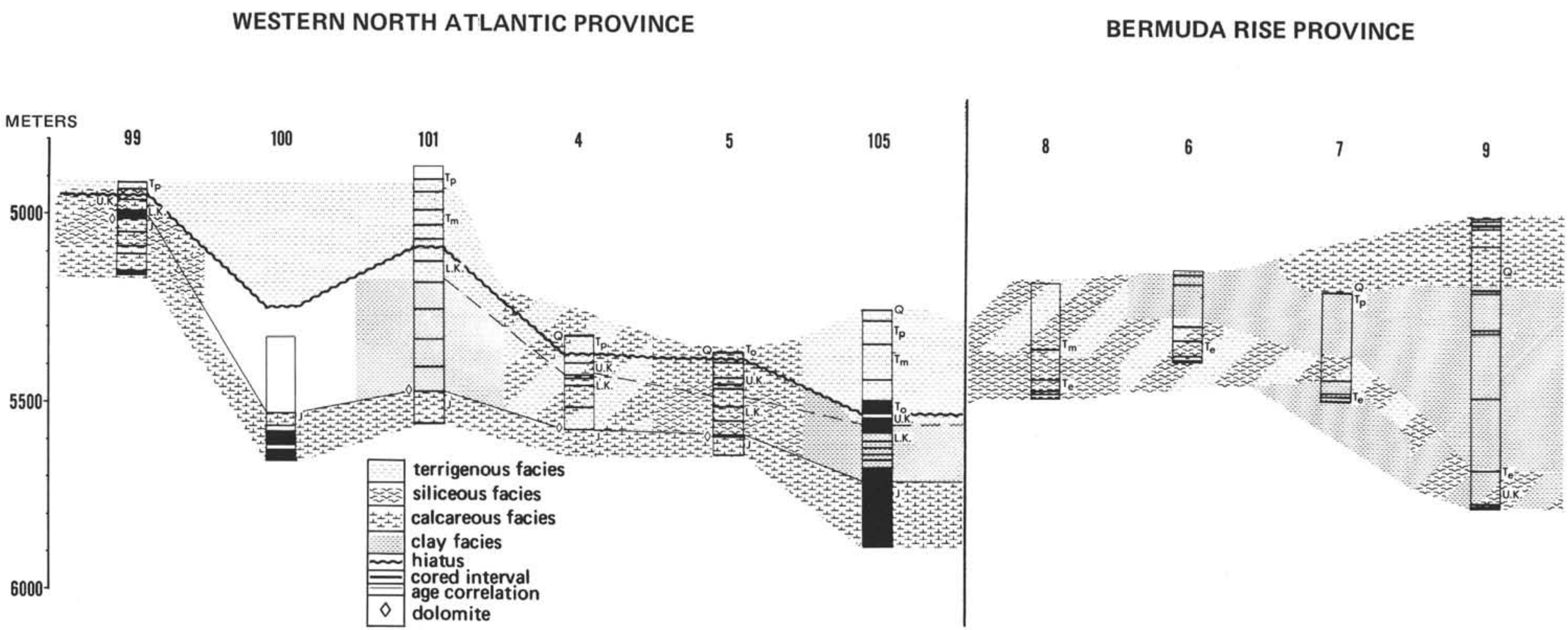


Figure 8. *Schematic stratigraphic correlation of DSDP sites in Western North Atlantic Province; Bermuda Rise Province.*

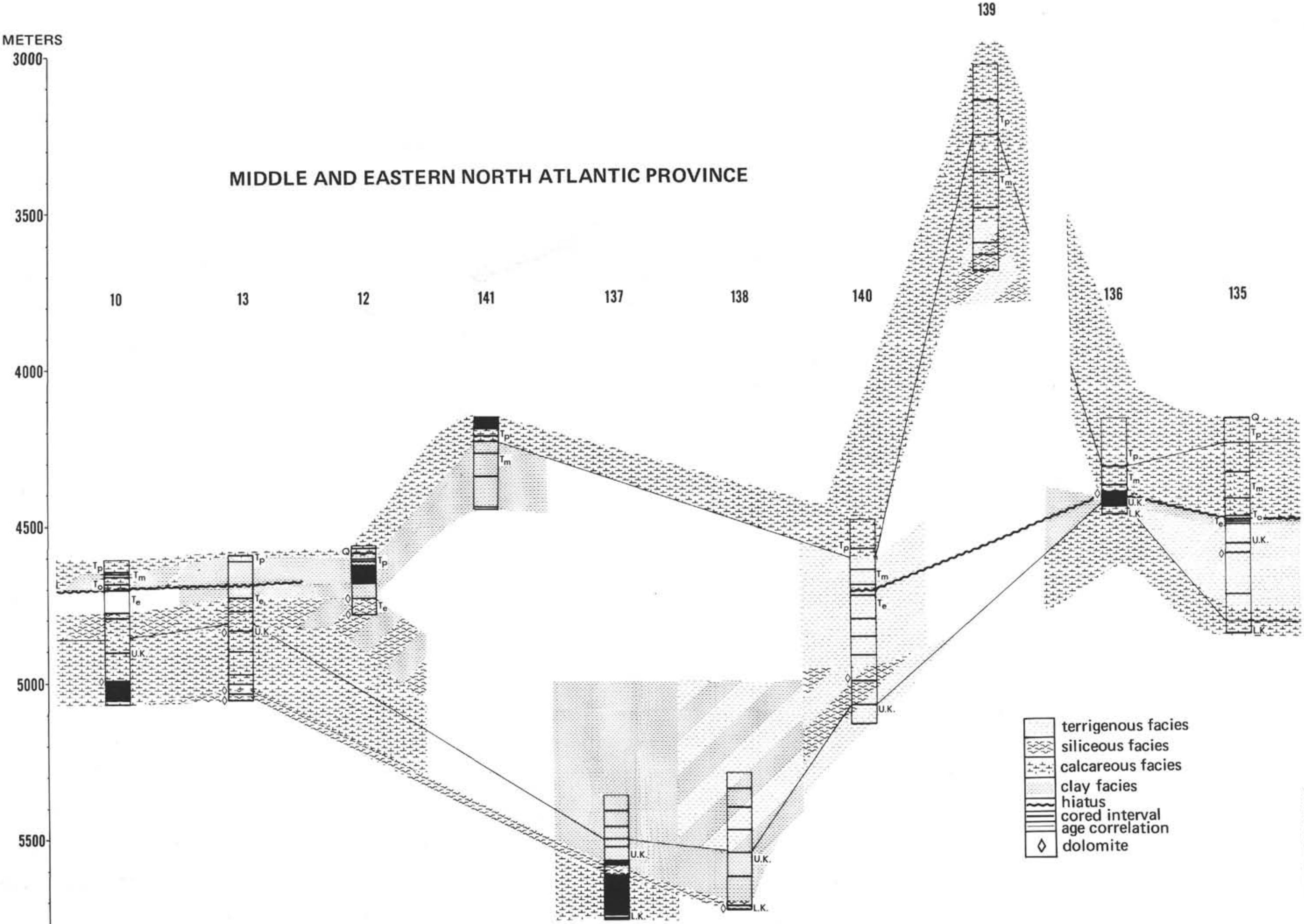


Figure 9. *Schematic stratigraphic correlation of DSDP sites in Middle and Eastern North Atlantic Province.*

| Age | Max. Thickness | Facies | Description | Comment |
|---|---|---|---|---|
| | | | sand. Minor pelagic and reworked carbonate | |
| | | HIATUS | | Probably erosion plane correlating with Horizon A |
| Late Cretaceous | 80m | Siliceous | Chert & radiolarian mudstone | |
| | | Calcareous | Reworked $CaCO_3$ debris, some nanno marl | Missing in most sites due to hiatus |
| | | Clay | Volcanic Clays | |
| Early Cretaceous | 290m | Terrigenous and clay | Black to greenish gray upwards—mostly clay mins. & qtz with nannos & forams (hemipelagic) | Albian-Aptian |
| | | | Black organic-rich shale-clay mins., qtz., mica & siderite important | Neocomian |
| | | Rarely Calcareous & Siliceous | Lst, nanno-marl chert, some dolomite | Two sites show this more pelagic sequence |
| Jurassic | 161m | Calcareous some clay | Mostly nanno-rich chalks or recryst. nanno Lst. with some brown and hemipelagic clay, some carbonaceous | The top forms horizon $\beta$ |

**Bermuda Rise Province**
**Sites: 6, 7, 8, 9 (DSDP Legs 1 and 2)**

**Composite Succession Based on Correlation in Figure 8**

| Age | Max. Thickness | Facies | Description | Comment |
|---|---|---|---|---|
| Quaternary | 100m+ | Calcareous | Foram-Nanno Ooze or Marl | Close to carbonate compensation depth in one site |
| Late Tertiary? | | Clay | Brown and greenish gray clay | Transitional up to calcareous facies in one site |
| | 500m | | | |
| Early Tertiary? | | Clay Siliceous | Mostly brown clay - zeolitic in part; chert and rad ooze | Much of siliceous material of turbidite origin |
| Cretaceous | 140 | Clay | Zeolitic clay enriched with Mn & Fe | Hydrothermally mineralized |

**Middle and Eastern North Atlantic Province**
**Sites: 10, 11, 12, 13, 135, 136, 137, 138, 139, 140, 141 (DSDP, Legs 2, 3, and 14)**

**Composite Succession Based on Correlation in Figure 9**

| Age | Max. Thickness | Facies | Description | Comment |
|---|---|---|---|---|
| Quaternary & Late Tertiary | 550m | Clay or Carbonate | Brown clay, part zeolitic Nanno ooze | Facies varies due to water depth Terrigenous component in some rise sites |
| | HIATUS DETECTED IN SEVERAL SITES | | | |
| Early Tertiary | 260m | Clay and Siliceous in Eocene | Zeolitic brown clay Rad ooze and chert | Only partial section in most sites due to hiatus |
| Late Cretaceous | 270m | Clay down into Carbonate with | Brown clay part zeolitic Nanno ooze | If clay in Lower Tertiary then in these sites continues down into part of Upper Cretaceous If siliceous in Eocene then carbonate here |
| | | Transition facies between or all carbonate | Clay nanno ooze, black clay chert | |
| Early Cretaceous | | Carbonate | Nanno ooze | |

## CLIMATE, SEA LEVEL, AND TECTONICS OF THE GUYANA BASIN

The prominent reflecting horizon at about 0.5 second at Site 142 (Figure 10) is essentially flat-lying and can be traced over an area of about $2 \times 10^5$ sq. km. The horizon is bounded on the south by the North Brazilian Ridge, on the north by the Ceara Rise and St. Paul's Fracture Zone, and on the west it is obscured by the highly reflective sediments of the Amazon Cone (Hayes and Ewing, 1970). Our drilling results establish that this reflecting horizon corresponds to a lithologic change from an upper nannoplankton chalk/marl ooze with clay sequence, essentially free from coarse detritus, to calcareous mark/chalk ooze with significant quantities of silty foram sand and terrigenous sand below. This change in sedimentation occurred about 7 m.y. ago near the boundary between Miocene and Pliocene time. The prominent reflector onlaps the flank of the Ceara Rise, a

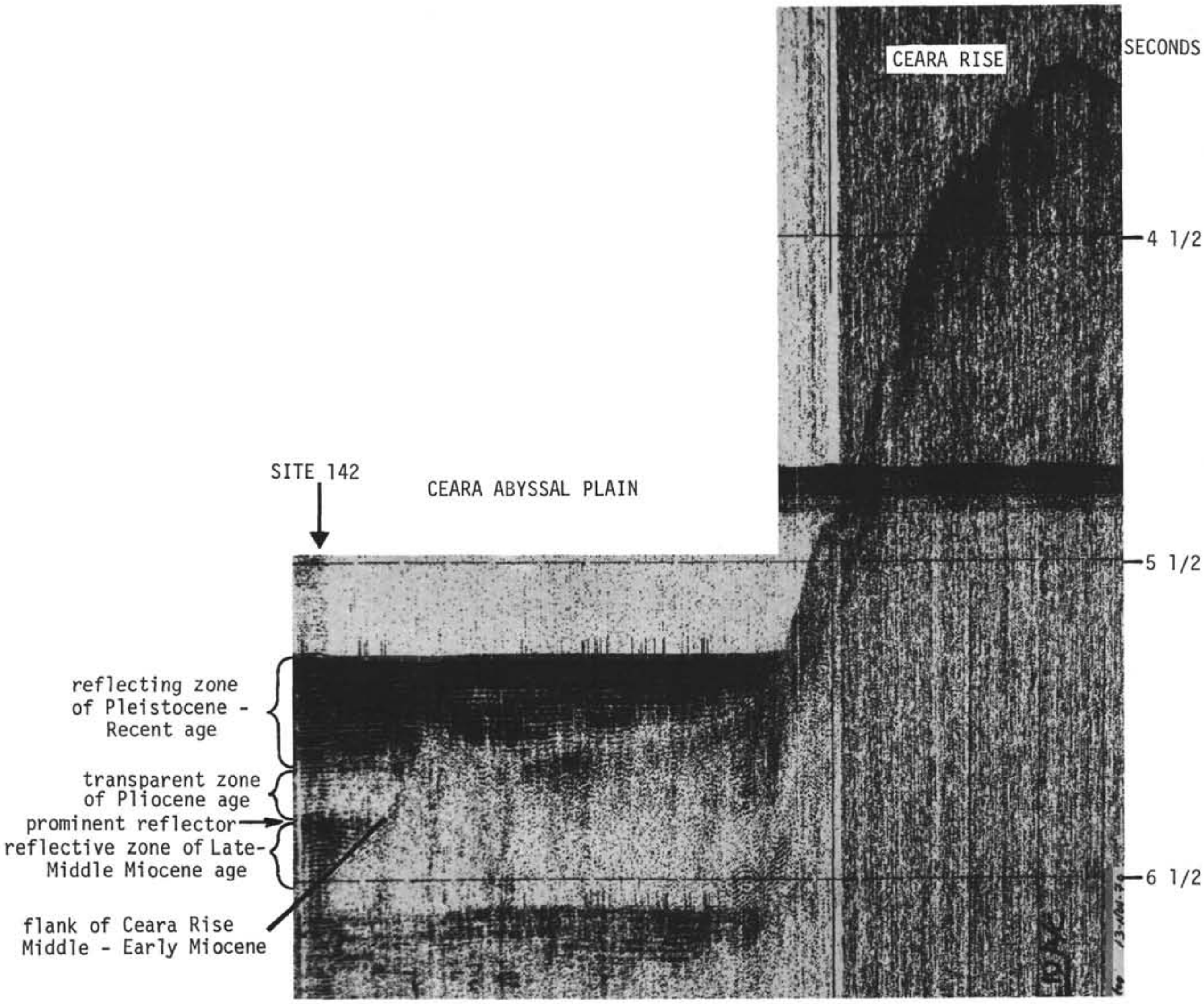


Figure 10. *Annotated* Challenger *seismic reflection profile at Site 142.*

feature composed at Site 142 of Middle Miocene and older sediments. Although the reflector is gently upturned at some places along the flank of the Ceara Rise, this deformation is so slight that any major uplift which may have involved the rise must have been completed prior to the latest Miocene. An independent check on the age of this reflector is possible by re-examining the results of Site 25, Leg 4 Deep Sea Drilling Project. Near this site, the same reflector abuts the north flank of the North Brazilian Ridge and is undeformed there (Hayes and Ewing, 1970). Shallow water limestones of Middle Miocene to Eocene age, and evidence of wave base erosion, was obtained at Site 25 from 60 meters below the top of the North Brazilian Ridge. The ridge now lies about 1600 meters below sea level. At this site, moderately deep water foram ooze was deposited from late Miocene to Recent. The pronounced subsidence at Site 25 must have occurred after Middle Miocene. This fact, taken with the pre-Late Miocene age of the sediments comprising the buried flank of the Ceara Rise, establishes a short time duration of about 7-12 m.y. during which the prominent reflecting horizon was laid down. At this time, the extraordinary supply of continental detritus, which gave rise to the lower, multi-layered reflective zone, must have been abruptly terminated, and a major influx of detritus did not occur again until Pleistocene time.

We infer that a significant change in the relative water depth occurred along the North Brazilian margin at the end of the Miocene. Although the total thickness of sediments above the reflecting horizon varies from a maximum of greater than 1 km in the west (near the Amazon Cone) to less than 0.5 km in the east, the "thickness" of the acoustically transparent zone is relatively uniform at about 0.15 second. This uniformity in thickness further supports the proposal that the transparent zone is comprised of pelagic sediments and is essentially free from rapidly implaced terrigenous layers that would give rise to numerous reflecting horizons. The main source of terrigenous material in this area is the Amazon River and its tributaries. Damuth and Fairbridge (1970) have shown that little terrigenous material was deposited in the Guyana Basin during the Holocene when sea level was relatively high. During this time, detritus carried to the ocean by the Amazon River could not be transported across the wide continental shelf at the mouth of the Amazon. However, during the glacial stages of the Pleistocene, sea level was lowered significantly. This effectively narrowed the continental shelf so that detritus was easily delivered to the Guyana Basin and sedimentation was extremely rapid (>150 m/my; see Chapter 9).

If our interpretation that the transparent seismic zone, typically present everywhere in the Ceara abyssal plain sediments, represents a period of about 5 m.y. when virtually no coarse terrigenous material was deposited, this implies that a major change in sea level occurred relative to the North Brazilian continental shelf and Amazon Basin. This relative change might have been caused by either: (1) Subsidence of the North Brazilian margin, or (2) a eustatic rise in sea level. There is conflicting evidence regarding both of these hypotheses. Although rapid major subsidence has occurred at least at one point on the North Brazilian Ridge since mid-Miocene and prior to Latest Miocene, this feature lies about 350 km from the continental slope of northern Brazil. Drilling results from Sites 143 and 144, located on the Demerara Rise along the Guyana Margin, suggests that subsidence there was significant, but that it occurred more or less uniformly since the Late Cretaceous. There is some lithologic-paleontologic evidence that subsidence occurred at the Ceara Rise in Early Miocene, but the possibility that the Ceara Rise sediments were once flat-lying and deposited in a deep basinal environment and subsequently uplifted cannot be discounted. Slight upwarp of the Pliocene-Miocene reflecting horizon, as it abuts the Ceara Rise at some places, suggests minor post-Miocene uplift of the rise.

The onset of major continental glaciation of the Antarctic has been inferred by many to have begun in the Early to Middle Miocene. If the accumulation of the ice there was rapid, we would expect to see an abrupt and significant eustatic lowering of sea level. Such a lowering should, in general, give rise to a major increase in the amount of terrigenous sediments supplied to basins adjacent to major river systems and might explain the apparent dominance of terrigenous deposition in the Guyana Basin during the Miocene. A relaxation (interglacial stage) would then have to be invoked to account for a eustatic rise in sea level and the reduction of terrigenous sedimentation.

It should be emphasized that the above discussion is highly speculative and our inability to distinguish between the two alternative explanations of the acoustically transparent sediments of the Ceara abyssal plain sediments, requires a careful examination of the regional or global extent of similar sedimentary units. If the Pliocene acoustic sediment section is typically present on a global scale, then its explanation probably lies in invoking a major eustatic sea level rise in the Late Miocene. Such a rise of sea level could be related to the relaxation of a major stage of glaciation in Antarctica. Alternatively, Larson and Pitman (1972) have recently suggested that a rapid pulse of seafloor spreading would alter the mean steady state profile of the ocean floor, giving rise to a greater proportion of young (relatively shallow) ridge and thus causing an effective eustatic change in sea level and global marine transgressions. Although a global change in the pattern of sea floor spreading occurred about 10 m.y. ago (Late Miocene), there is insufficient evidence to conclude that it caused a significant change in sea level.

If the acoustic sediment zone of the Ceara Abyssal Plain is exclusive to the western equatorial Atlantic, it was probably caused by epeirogenic subsidence of the North Brazilian margin, thus cutting off the supply of terrigenous material to the deep basin.

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