51. THE EVOLUTION OF THE CENTRAL NORTHEASTERN ATLANTIC— SUMMARY OF RESULTS OF DSDP LEG 41

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INTRODUCTION

The main objective assigned to Leg 41 was to obtain as complete a record of the sedimentary history of the eastern North Atlantic and its margin, therefore only a few selected long holes were drilled and coring was as continuous as possible. Of the five sites drilled (Figure 1) two were deep basin sites (367 and 370), two were rise sites (366 and 368), and one was on the African continental slope (369). The deep basin sites are located on old oceanic crust, within the Jurassic magnetic quiet zone, and only the oldest part of the record, as expected, provides a good stratigraphic control because the younger sediments have been deposited mainly below the carbonate compensation depth (CCD). The younger part of the record has been sampled by drilling on rises of two different kinds. Sierra Leone Rise, a typical aseismic rise, is covered by a thick blanket of purely pelagic sediments where the entire Tertiary could be sampled. Cape Verde Rise, which was expected to be covered with pelagic to hemipelagic sediments, was unexpectedly found to be covered with deep basin sediments and these findings introduced Tertiary tectonics as an important factor in the evolution of the eastern North Atlantic. The site drilled on the African continental slope, just South of the Canary Islands, was found to be characterized mainly by pelagic sedimentation and provided elements for comparison with Sierra Leone Rise located at a much lower latitude.

Although limited in number, the Leg 41 drill sites provide a reliable enough set of data, so that when studied in conjunction with other sites previously drilled both in the western and eastern North Atlantic (Hollister, Ewing, et al., 1972; Hayes, Pimm, et al., 1972; see also map in pocket at back of this volume) and with the help of a relatively dense seismic reflection coverage, they allow for a tentative synthesis of the evolution of that part of the ocean. We will first briefly summarize the drilling results obtained at each site and then discuss the evolution of the eastern North Atlantic from the Late Jurassic.

SUMMARY OF DRILLING RESULTS

The location of each of the five drill sites is shown on Figure 1. Statistical data on each hole actually drilled at each site are given in Table 1. The principal results obtained at each site are briefly described below. Graphic representations of these results appear on Figure 2.

Site 366 (Holes 366 and 366A)—Sierra Leone Rise

The sedimentary section on Sierra Leone Rise was continuously cored to 850.5 meters and a complete pelagic record of the Cenozoic was recovered. The hole bottomed in upper Maestrichtian sediments and was abandoned due to plugging of the drill bit. The section consists of nannofossil oozes and marly oozes grading downward to chalks and marls and then to limestones and marlstones. Chert and porcellanite were found in middle to lower Eocene sediments. Two minor hiatuses only were observed, between the early and middle Miocene and between the middle and late Miocene, respectively. The co-occurrence of different microfossil groups in most of the section makes it an especially interesting reference section for the Cenozoic zonation in the tropical-subtropical zone of the North Atlantic. The Sierra Leone Rise has been in a deep water pelagic environment, although well above the CCD, since at least the latest Cretaceous. The rate of accumulation appears relatively constant throughout the Tertiary except for a noticeable decrease around the middle Miocene. The nature and age of the basement as well as that of the deepest sedimentary layers remain unknown.

Site 367—Cape Verde Basin

A 1153-meter section was sampled at this site, which is located southeast of the Cape Verde Islands and is within the Jurassic magnetic quiet zone. The hole bottomed in basaltic extrusives overlain by Upper Jurassic sediments. The Mesozoic part of the section is strikingly similar to the one sampled in the North American Basin during Leg 11 (especially Site 105). It consists of Oxfordian-Kimmeridgian red argillaceous limestones overlain by Tithonian-Neocomian white limestones interbedded with dark gray marls, both rich in Aptychi. Above red and green Barremian claystones, the Aptian-Cenomanian sediments consist of black carbonaceous shales. The upper part of the section, comprising Upper Cretaceous through Quaternary sediments is predominantly terrigenous although an increase in pelagic calcareous components is noticeable in the Neogene sediments. The main seismic reflectors have been correlated (from bottom to top) with oceanic

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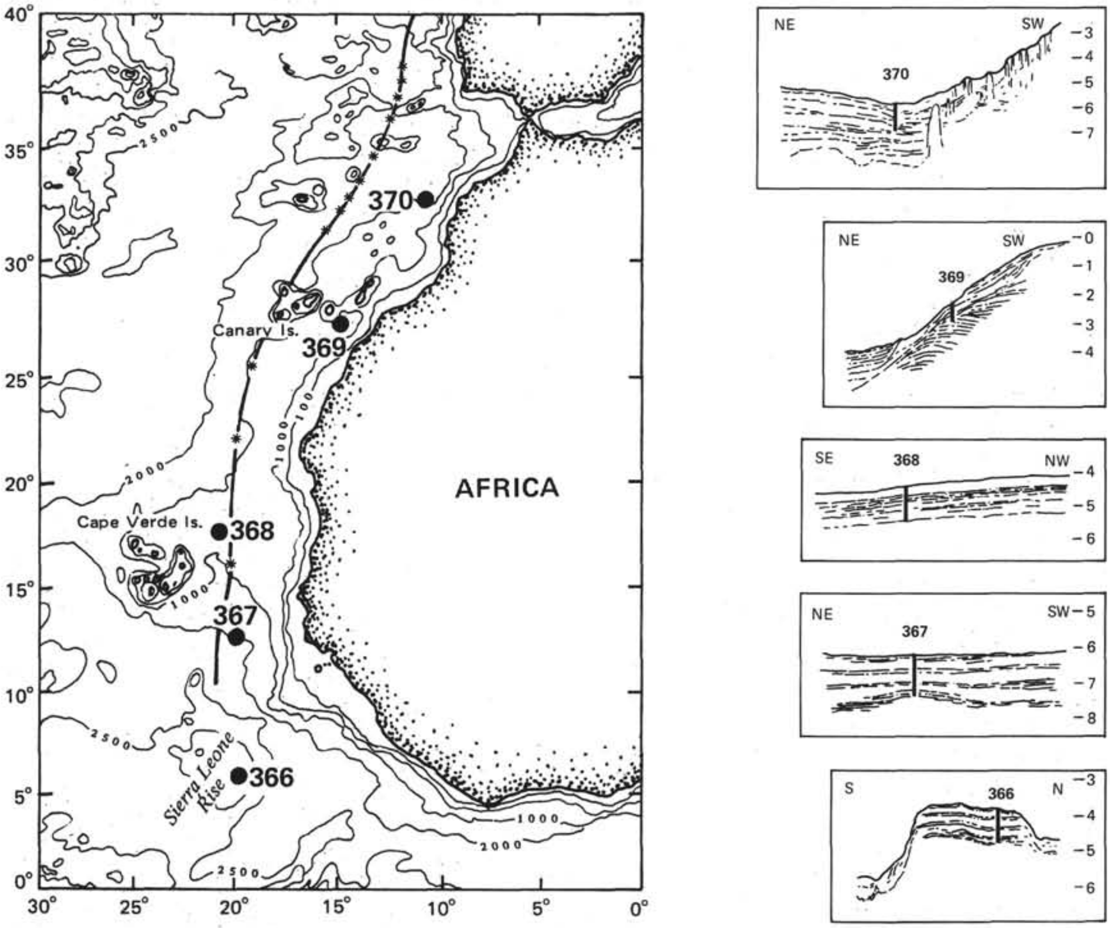

Figure 1. *Location of Leg 41 drill sites. The line interrupted with stars is the magnetic quiet zone boundary from Hayes and Rabinowitz (1975).*

basement, hard limestones, the top of the black shales, and Eocene cherts. These results compare relatively well with those of Leg 11 (Lancelot et al., 1972) except that Horizon B is not well defined in the Cape Verde Basin.

Site 368—Cape Verde Rise

Sediments at this site were sampled down to a subbottom depth of 984.5 meters. Unexpectedly, the sediments consist mainly of terrigenous turbidites and are almost devoid of carbonates except in the post Miocene part of the section. Near the base of the hole, sediments consist of Albian-(?)Turonian black carbonaceous shales with interstratified diabase sills of Miocene age. These sills are responsible for the presence of a very sharp discontinuous reflector on the seismic profiles. Three observations strongly suggest that the Cape Verde Rise resulted from a broad uplift of probably about 1000 meters that must have taken place during the Neogene: (1) occurrence of Miocene intrusions probably related to a peak of volcanic activity on the nearby Cape Verde Islands; (2) presence of abundant terrigenous sediments deposited below the CCD by turbidity currents during the Late Cretaceous-Paleogene; (3) occurrence of pelagic carbonates only in the uppermost part of the section.

TABLE 1
Leg 41 Drill Sites Statistics

Hole	Dates (1975)	Latitude (N)	Longitude (W)	Water Depth (m)	Penetration (m)	No. of Cores	Cored (m)	Recovered (m)	Recovery (%)
366	22-27 Feb.	05°40.68′	19°51.08′	2860	850.5	55	518.0	304.0	59
366A	27 Feb./1 March	05°40.70′	19°51.10′	2860	367.0	39	367.0	278.0	76
367	3-10 March	12°29.21′	20°02.83′	4748	1153.0	40	347.0	174.3	50
368	13-20 March	17°30.43′	21°21.23′	3367	984.5	63	582.5	327.7	56
369	24 March	26°35.55′	14°59.92′	1760	42.0	5	42.0	36.1	86
369A	24-26 March	26°35.55′	14°59.96′	1760	488.5	47	446.5	350.3	79
370	29 March/8 April	32°50.25′	10°46.56′	4216	1176.5	51	483.0	202.7	42
Total					5062.0	300	2786.0	1673.1	60

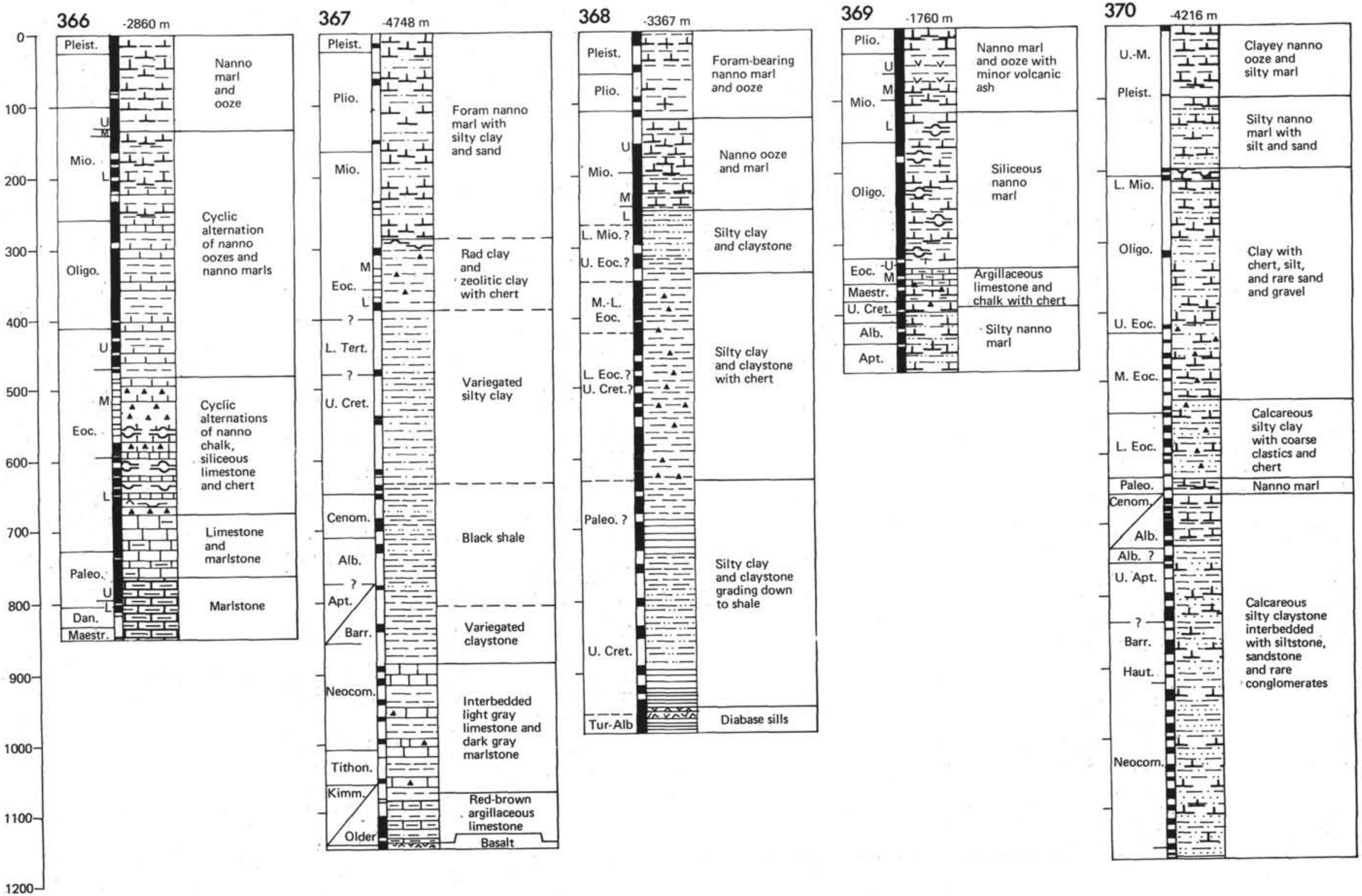

Figure 2. *Graphic hole summaries.*

Site 369—Continental Slope Off Spanish Sahara

The upper part of the thick sedimentary section of the continental slope has been continuously cored down to 488.5 meters below the sea floor. The sediments are predominantly pelagic with only a minor terrigenous contribution. They consist mainly of nannofossil marls with some limestones and chalk. Redeposition by slumping is evident but of relatively minor importance, and the stratigraphic section (Aptian to Recent) is more complete than had been anticipated. Major hiatuses remove the late Albian to Campanian, the Paleocene and the early Eocene, whereas minor ones were observed in lower upper Eocene and upper Pliocene sediments. The microfossil record suggests a relative permanence of the water depth since the Early Cretaceous. No shallow water sediments were found. The sediments reflect permanent continental slope environments, above the CCD, since the late Aptian. Barite rosettes, partially replaced by calcite, were found in dark brown to blackish Aptian-Albian silty marls. The origin of these clearly authigenic mineral is problematic. It might be related to the migration of solutions originating in the Jurassic evaporites that underlie the continental shelf and slope.

Site 370—Moroccan Basin

Nearly 1200 meters of the sediment section within the oceanic basin adjacent to the Moroccan continental margin have been sampled at Site 370. The uppermost section, down to 420 meters, was very sparsely cored, but below that level coring was closely spaced until lack of time forced us to abandon the site. The sediments are predominantly terrigenous and hemipelagic with abundant silty and sandy thin layers, and occasional conglomerates. Most of these layers are turbidites. The section reflects an evolution different from that of the Cape Verde Basin or of the North American Basin because strong terrigenous influence persists from the Early Cretaceous (Valanginian) through the Pleistocene. A hiatus of approximately 35 m.y. separates Cenomanian from early Paleocene sediments. This hiatus might result from erosion by bottom currents. No well-defined black shales were found in Aptian-Cenomanian sediments, although the claystones from this interval are darker colored and have organic carbon contents reaching up to 5%. Rosettes of barite partly replaced by calcite, as at Site 369, might indicate migration of sulfate-rich solutions originating from nearby evaporites (see Dean and Schreiber, this volume).

EVOLUTION OF THE CENTRAL NORTHEASTERN ATLANTIC

Introduction

In order to attempt a synthesis of the evolution of the eastern basins of the central North Atlantic it is necessary to consider the regional extension of the different facies which have been recognized. This enables distinguishing between facies which are related to basinwide, oceanwide, or even worldwide significance and those which are indicative only of regional evolution. Therefore the five sites drilled during Leg 41 must be compared with results obtained during previous cruises. Comparisons between eastern and western basins of the North Atlantic as well as between northern and southern basins of the east side are essential. Furthermore, comparison between sites drilled within the deep basins and sites drilled on relatively shallower areas should provide vertical control.

Comparison Between Eastern and Western Basins

Such a comparison shows that there is a basic similarity in the sedimentary evolution in the basins on both sides of the Mid-Atlantic Ridge. This similarity is based on (1) the general tectonic evolution of both flanks of that ridge within concepts of sea-floor spreading; and (2) the same gross environmental conditions, at least during the Mesozoic, with regard to the circulation of water masses.

Asymmetry is evident as far as the terrigenous deposits are concerned. This is not unexpected if one considers that while the general evolution of the ocean basins reflects primarily tectonic and oceanographic conditions that can be extrapolated over large areas because of the nature of the controlling factors. The terrigenous overprint, on the other hand, is more directly related to the evolution of adjacent land masses where possibly diversified climates and regional tectonics can play an important role in the delivery of terrigenous materials into the oceanic basins.

Comparison Between Northern and Southern Basins

There is apparently an important difference between the basins located north and south of the Canary Islands. Our results are too scanty to estimate the extent of this difference, but the basin located north of the Canary Islands appears to be characterized by particularly abundant terrigenous deposits, probably related to the evolution of the Atlas fold belt.

Comparison Between Deep Basins, Rises, and Continental Slope

This comparison is limited essentially to the Cenozoic, which is particularly well sampled on the Sierra Leone Rise. Here it consists mainly of carbonates which are not present at greater water depths in the basins. Cenozoic carbonates have also been sampled except on the continental slope off Spanish Sahara. At the latter site, however, the occurrence of Lower Cretaceous sediments also provides elements for a discussion of the environments of deposition of the so-called "black shale" sediments.

We will now review the different stages of evolution of the eastern Atlantic, starting with the basement, and try to place our interpretations of Leg 41 reports in the general framework of the evolution of the North Atlantic. Figure 3 summarizes the distribution of the various lithologic units described below. Detailed descriptions can be found in Gardner et al. and Jansa et al. (this volume). Stratigraphic control was generally relatively good except for the Late Cretaceous-Oligocene record in the basin (see Cepek et al.; Cepek; Foreman; Gradstein; Johnson; Krasheninnikov and

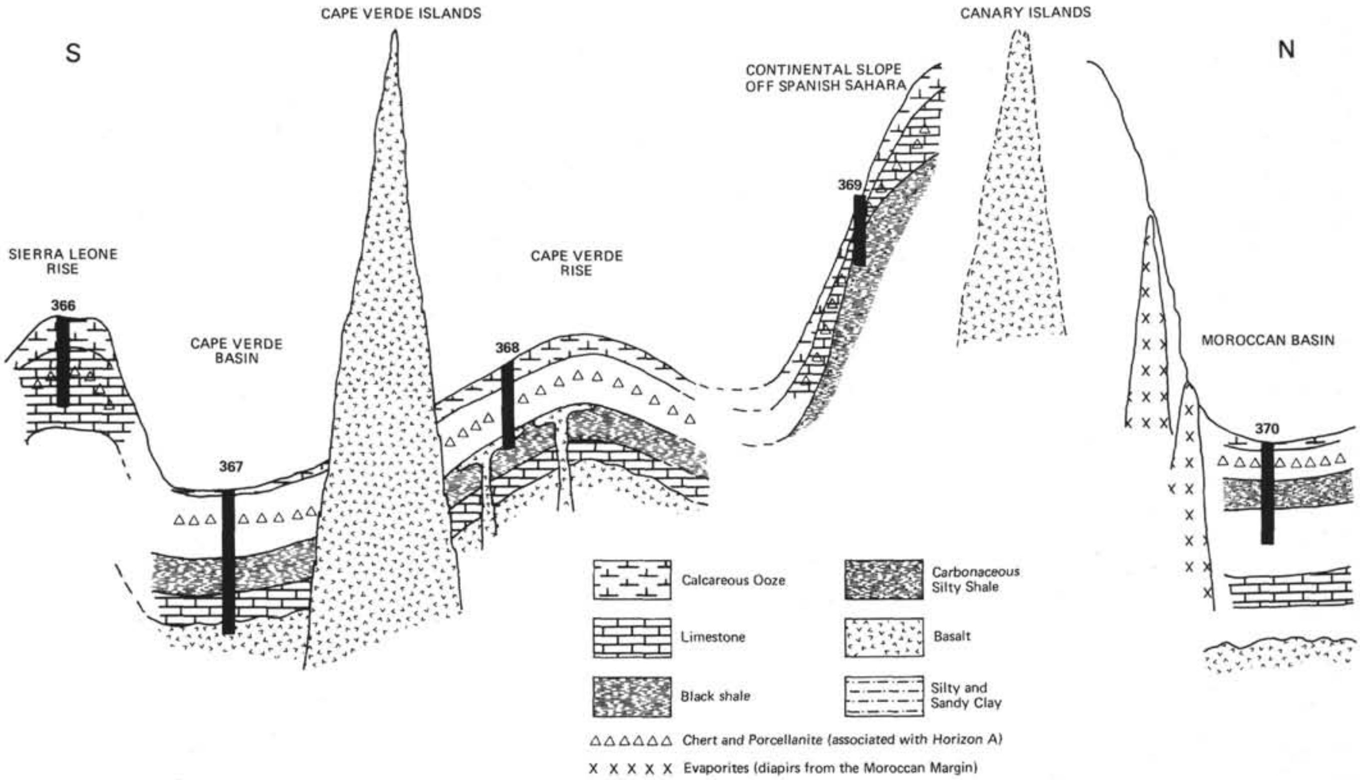

Figure 3. *Schematic distribution of lithologic units sampled at Leg 41 drill sites.*

Pflaumann, this volume). Several attempts were made at filling gaps in the stratigraphy by use of palynomorphs and dinocysts (see Kotova; Williams; Zaklinskaya, this volume), calcisphaerulids and calcareous dinoflagellates (see Fütterer; Pflaumann and Krasheninnikov, this volume) as well as paleomagnetics (see Keating and Helsley; Kent; Hailwood, this volume).

The Basement

Rocks believed to correspond with the acoustic basement were sampled only at the base of Site 367 in the Cape Verde Basin. At that site all data seem to indicate that these rocks represent basaltic flows extruded at the sea floor on a ridge-crest of Jurassic age. Evidence supporting this interpretation comes from other investigations such as regional geophysics, petrology, and isotope geochemistry. Radiometric age determinations disagree with this interpretation, but their reliability is subject to debate (Duncan and Jackson, this volume).

The geophysical data will be discussed first as they give a broader view of the problems posed by the nature of the basement in the eastern basins of the North Atlantic while sparse sampling of the basement achieved during Legs 14 and 41 only confirms its nature in the vicinity of the magnetic quiet zone boundary.

Geophysical Data

Magnetics

Leg 41 sites are located either within the Jurassic Quiet Zone (JQZ) or close to its boundary as defined by Hayes and Rabinowitz (1975) (Figure 1). Site 366 on Sierra Leone Rise is an exception; it is located in an area where magnetic data are of extremely poor quality owing to very low latitude. Site 367 is about 70 km landward of the JQZ boundary. Site 368 is an area where magnetic lineations are badly defined, probably because of the presence of numerous intrusions beneath the Cape Verde Rise. It is believed to be in the vicinity of anomalies M 22 to M 23 by extrapolation from nearby well-identified anomalies. Site 369, on the west African continental slope off Cape Bojador, and Site 370, in the Moroccan Basin, near the base of the margin, are located well within the JQZ (about 300 km and 320 km landward from the boundary, respectively).

There is no doubt about the oceanic nature of the basement underlying Site 368 and very little doubt about a crust of the same nature being at Site 367. It is worth mentioning that, because of its location, Site 367 apparently yielded the only existing samples of oceanic crust that are within the Jurassic magnetic quiet zone. The only comparable settings so far were those of Sites 100 and 105 in the North American Basin and both of them are thought to be just at the quiet zone boundary (Larson and Hilde, 1975).

Seismic Profile Information

Abundant single-channel seismic profile coverage in the eastern North Atlantic comes from numerous Lamont-Doherty Geological Observatory cruises and WHOI cruises of *Atlantis* II. Multichannel data have been obtained mainly by Bundesanstalt fur Geowissenschaften und Rohstoffe Meteor cruises and also by Shell Internationale Petroleum Maatschappij, B.V., Den Haag. Most of the prime data remain presently unpublished, but some of the available data in the vicinity of Sites 367 and 368 have been compiled by G. Wissman (personal communication) and appear in Figure 4. They provide an estimate of the depth to basement. This interpretation of the basement depth differs slightly from those of Uchupi et al. (1976), Beck and Lehner (1974), and Grunau et al. (1975).

Cape Verde Basin

Whenever the acoustic basement can be clearly seen on profiles crossing the quiet zone boundary, no change in its geometry and acoustic properties can be observed. Usually, on single-channel profiles, basement identification becomes spotty in the Cape Verde Basin landward of the longitude of Site 367 (See Figure 9) and only multichannel data can be used. Acoustic basement within that basin gently deepens to slightly over 8 seconds and appears to keep an acoustic character similar to that observed near the seaward edge of the quiet zone.

Cape Verde Rise

Beneath most of the Cape Verde Rise the acoustic basement shows a broad elevation culminating at about 6 seconds beneath the summit of the rise.

The basement is rather smooth in the eastern part of the rise and becomes rough in the western part, particularly in the region where numerous diapiric structures are observed on the profiles. A broad terrace-like rise is observed between the Cape Verde Rise proper and the continental margin (Figure 4). The rise is smooth, roughly oriented northwest-southeast, has an average depth of 7 seconds below the sea surface, and appears to connect the top of the rise with the Dakar area. Both in the Cape Verde Basin and in the Cape Verde Rise area numerous basement peaks that often reach the sea floor are observed. Their distribution does not seem to follow any particular pattern and attempts to connect them with the trace of old fracture zones were unsuccessful.

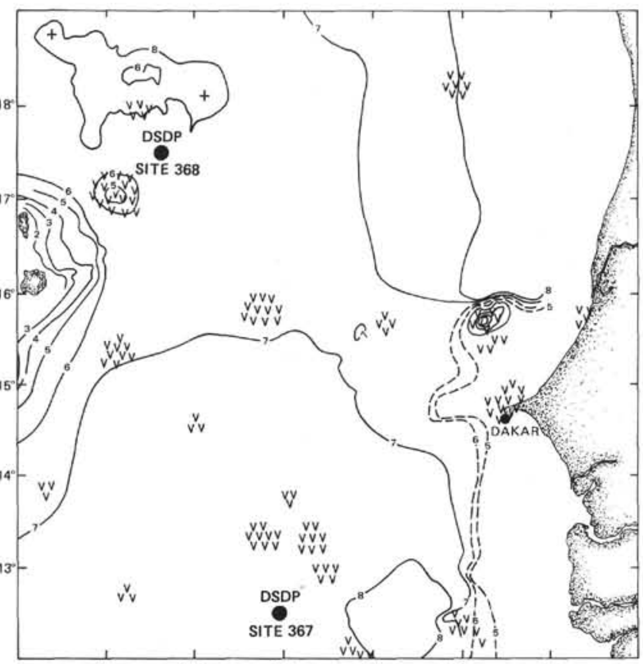

Figure 4. *Depth to basement (in seconds from the sea surface) between Africa and the Cape Verde Island region, contoured by G. Wissmann (Bundesanstalt fur Geowissenschaften und Rohstoffe, personal communication) from* Valdivia, Meteor, Atlantis II, *and* Vema *cruises.*

Moroccan Basin

North of the Canary Islands, in the Moroccan Basin, the basement is observed on both single-channel and multichannel seismic profiles from the magnetic quiet zone boundary to the westernmost diapirs that rim the continental margin and extend beneath the Seine Abyssal Plain. No significant change can be observed in the acoustic characteristics of the basement beneath the entire basin.

Refraction data have been reviewed by Uchupi et al. (1976). The results do not provide definite evidence as to the nature of the crust beneath the areas studied here. Therefore the exact location of the boundary or transition between oceanic and continental crust remains subject to speculation.

Drilling Results

Basement From the Cape Verde Basin (Site 367)

Basalt was reached at Site 367 at a subbottom depth of 1146 meters. Only 7 meters could be sampled before failure of the drill bit that prevented further penetration and terminated the hole. The rocks consist of nearly aphyric fine-grained vesicular basalt rich in plagioclase and pyroxene. The basalt is altered and its absolute age of about 105 m.y., obtained by the K-Ar method, is considered unreliable (Duncan and Jackson, this volume).

Several lines of evidence lead us to interpret these rocks as representing the uppermost part of the oceanic crust (layer 2) that were extruded at the sea floor during the Oxfordian (Upper Jurassic).

First, the nature and structure of the basalt are comparable to what has been generally interpreted as basaltic flows in many previous DSDP holes. In particular the basalt compares well with basement rocks, believed to be only slightly younger, which were recovered at Site 105 in the western North Atlantic (Hollister, Ewing, et al., 1972). For example, the glassy and altered texture of the rock, calcite-filled veinlets, and glassy selvages suggest basaltic flows and/or pillow lavas. The comparison with an undisputable intrusion observed at Site 368 is particularly significant. At the latter site the rock is very massive, coarse-grained, fresh, and homogeneous. It seems difficult to consider a single mode of implacement for the two very different looking rocks.

Furthermore the contact between the basalt and the sediment appears devoid of any thermal alteration (contact metamorphism). The contact was actually recovered in a single core. Of course some of the contact zone might have been destroyed during the coring but probably not enough so that nothing would have been left of a metamorphosed sediment contact layer.

Additional evidence suggesting an extrusive origin for the basalts from Site 367 comes from the oxygen isotope analyses performed on the calcite-filled veinlets within the basalt as well as on the sediment immediately above (Brenneke, this volume). The results of these analyses show that calcite from the veinlets crystallized only after considerable weathering of the basalt had occurred, probably after exposure at the sea floor. They also show the absence of thermal alteration in the calcareous sediments resting directly on the basement.

In conclusion, all evidence derived either from direct sample analysis or from geophysical data—especially the good continuity of the basement reflector as well as the "draping" of sediment over that reflector observed across Site 367—supports the interpretation that the basaltic rocks recovered from the base of Site 367 are indeed the top of the oceanic crust and that the sediments immediately overlying the basalt are the oldest to have been deposited at that site.

Sills From the Cape Verde Rise (Site 368)

The occurrence of diabase at the base of Hole 368 was totally unexpected. There cannot be any doubt about the intrusive origin of these rocks because of the following evidence:

Geophysical evidence: Seismic reflection profiles recorded at, and in the vicinity of, Site 368 (Figure 5) show parallel reflections beneath the level of the sills. As a matter of fact, now that sills have been discovered by direct observation through drilling, it is relatively easy to identify them on several seismic profiles recorded on Cape Verde Rise (Figure 6). Their characteristic features—strong, abruptly interrupted, parallel reflectors—compare well with those observed elsewhere, for example, in the central Pacific where their occurrences have also been proven by drilling (Winterer, Ewing, et al., 1973). Moreover, multichannel seismic reflection profiles from the immediate vicinity of Site 368 clearly show that the actual basement lies at about 1.2 seconds below the level of the sills (personal communication, courtesy of Shell Internationale, Den Haag).

Petrographic evidence: The structure of the rocks is strongly different from that of the basaltic flows or pillow lavas. In particular in the thickest of the three diabase layers, which reaches 14 meters, one can clearly see a change in grain size away from the contact with the sediment. The grain size in the central part of the layer is much larger than in the tholeiitic flow basalts. It is also very homogeneous and no fractures or brecciation are visible. The texture, in thin sections, is typical of a diabase (see Duncan and Jackson, this volume).

The chemical composition of the rock is similar in some samples to that of an oceanic tholeiite, which is quite unusual for an oceanic intrusion (Natland, this volume). Other samples exhibit a composition comparable to that of the alkaline rocks of Iceland and other Atlantic islands (Eremeev, this volume).

Sedimentological evidence: The analyses of sediments near the upper and lower contact with the diabase clearly show evidence of thermal alteration both above and below the intrusion. Such alteration is recorded in the clay mineralogy (Mêlières, this volume) and its effects on the diagenesis of organic matter are even more pronounced (see, for example, Baker et al., and Erdman and Schorno, this volume). These effects are observed both above and below the diabase, thus demonstrating its intrusive nature.

Geochronological evidence: Duncan and Jackson (this volume) have obtained reproducible age determinations from three unaltered samples. The three different methods used (K-Ar; $^{40}Ar/^{39}Ar$, total fusion; and $^{40}Ar/^{39}Ar$ incremental heating) indicate an age of about 19 m.y. for the formation of the diabase. This age confirms the intrusive nature of the igneous rocks.

The occurrence of intrusives at Site 368 was unexpected on the basis of seismic reflection data. However, sedimentological interpretation of the overlying section, as well as the possible occurrence of basalts plugs on the western flank of the rise (Hayes, Pimm, et al., 1972), show that intrusion of basaltic material can be related to (1) the formation of the nearby Cape Verde volcanic complex during the early Miocene, and (2) the contemporaneous uplift of Cape Verde Rise that will be discussed later in this paper.

Jurassic-Neocomian Basal Carbonates

One of the main objectives of Leg 41 was to study the early history of the eastern North Atlantic. There appeared to be a good opportunity to reach and sample sediments older than Oxfordian at the two sites located in deep basins within the magnetic quiet zone (Site 367 and 370). Such a prospect was particularly attractive because such sediments would allow not only the study of the early history of the eastern basins but also of the entire North Atlantic. The oldest sediments ever cored in the deep ocean were sampled in the North American Basin near the base of the continental rise at Sites 100 and 105 (Leg 11, Hollister, Ewing, et al., 1972), both located at or very close to the magnetic zone boundary. The oldest sediments reached at these sites were Oxfordian limestones resting directly on basaltic basement. The eastern basins (Cape Verde Basin and Moroccan Basin) appeared to offer opportunities to obtain part of the older record because of their location farther within the quiet zone, and closer to the continental margin.

At Site 367, located on the Cape Verde Basin, some 70 km within the quiet zone (Figure 1) sediments as old as late Middle Jurassic could be expected just above the basement. A precise prediction based on simple extrapolation of spreading rates within the quiet zone was very difficult because the age of the Jurassic Quiet Zone boundary is based on sediments from the base of Sites 100 and 105 where paleontological age determinations are not precise enough to determine exactly where the boundary lies within the Oxfordian. Seismic profiles in the Cape Verde Basin were rather encouraging in that respect, showing the presence of a reflecting zone (reflector C) making contact with the basement in the vicinity of the quiet zone boundary and thickening

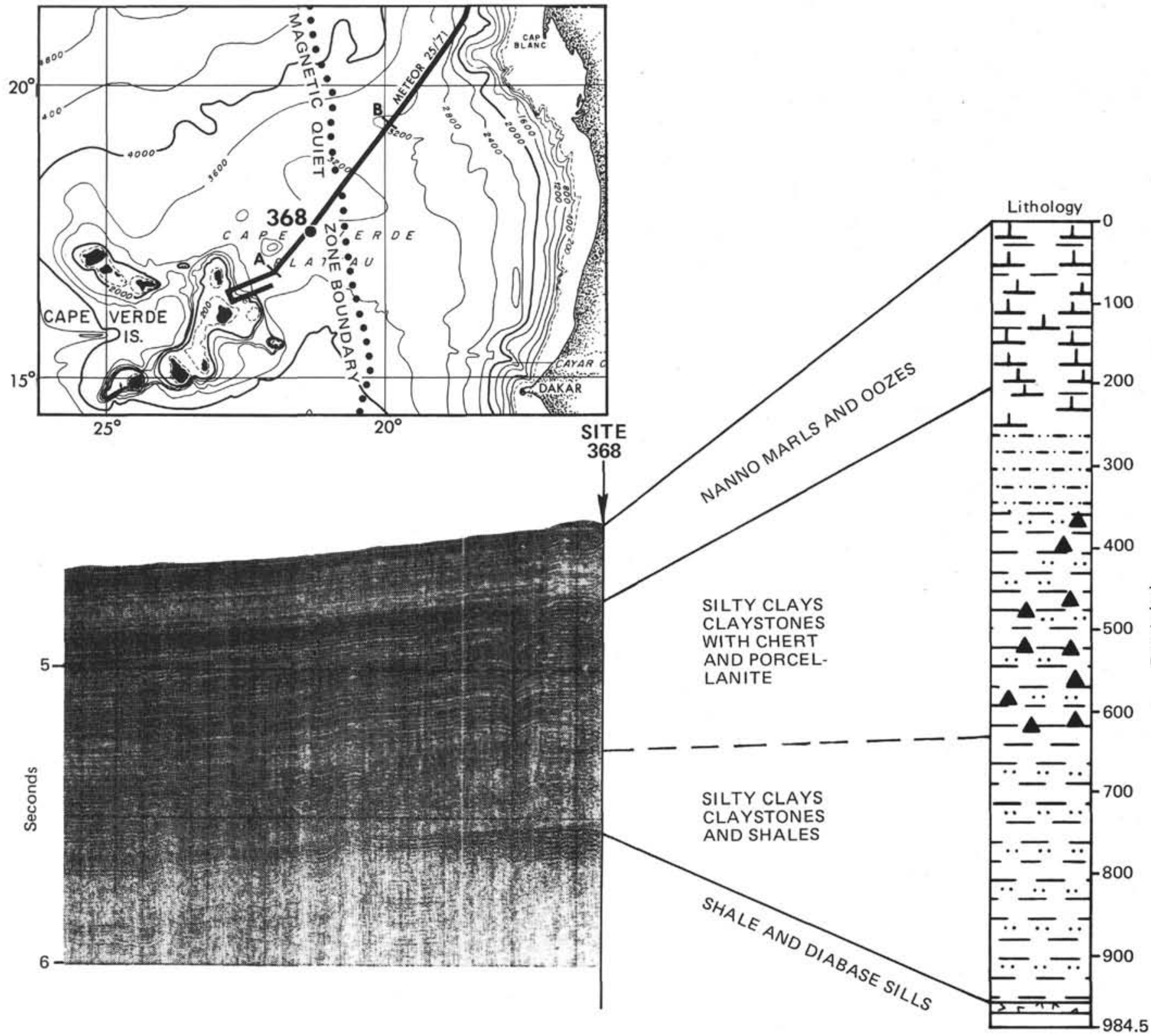

Figure 5. *Correlation of* Meteor *25-1975 seismic profile with drilling results at Site 368. Note the parallel reflections below the level of the diabase sills.*

landward, toward the southeast (Figure 7). Site 367 was located in one of the only regions where this reflector was close enough to the sea floor, because of a basement high, to offer a good target for *Glomar Challenger*.

Site 370, in the Moroccan Basin, is located farther within the Jurassic Quiet Zone in an area where a reflector, believed to be the equivalent of reflector C, was expected to correlate with sediments lying around 1500 meters below the sea floor. This reflector also reaches the basement near the quiet zone boundary.

Interpretation of Drilling Results

At Site 367 limestones, ranging in age from Oxfordian (Kuznetsova and Seibold, this volume) at the base to upper Neocomian at the top, were sampled. The base of that section lies directly on basaltic basement. At Site 370 the hole did not reach sediments lower than the Valanginian and the facies is strikingly different. The sediments consist of a thick Early Cretaceous flysch sequence. Detailed descriptions of the rocks and their fossils are given in the Site Chapters and in separate contributions in this volume. Lithological and mineralogical composition is given in Jansa et al. and Mélières (this volume). A description of the abundant aptychi found in these layers appears in Renz (this volume).

Oxfordian-Neocomian Limestones in the Cape Verde Basin

The limestones of Site 367 are strikingly similar to those sampled in the North American Basin at Sites 99, 100, and 105 (Hollister, Ewing, et al., 1972) in the same stratigraphic interval. The lower third of the interval consists of Oxfordian-Kimmeridgian red and green argillaceous nodular limestones ("Ammonitico Rosso" type), and the upper two-thirds consist of alternations of white limestones and dark gray marls which are also similar to the sediments outcropping on the island of Maio (Cape Verde Islands) and described by Stahlecker (1934). The similarity of the facies from the eastern and western basins of the North Atlantic can be observed in details of the mineralogical composition, sedimentary structure, and lithostratigraphy (Jansa et al., this volume). It confirms the wide extension of these facies, as already recognized in the North American Basin by Lancelot et al. (1972). It not only documents the perfectly symmetrical evolution on both sides of the Mid-Atlantic Ridge during the Upper Jurassic and Lower Cretaceous, but also confirms the widespread distribution of the peri-Mediterranean facies into the North Atlantic at that time (see discussion in Bernoulli, 1972; Bernoulli and Jenkyns, 1974; Jansa et al., this volume). The occurrence of calcareous sediments just above the basalt was expected following the sea-floor-spreading models. "Backtracking" of Site 367, following the method of Berger (1972) provides an estimate of the level of the CCD at the time when carbonate deposition ceased because of the subsidence of the oceanic crust. It shows that the CCD in the eastern North Atlantic must have been at about 3800 to 3900 meters during the upper Neocomian. This relatively shallow level compares well with tentative estimates made by Van Andel (1975).

As already noted by Lancelot et al. (1972), the low amounts of terrigenous components in these limestones is intriguing. It indicates that on both sides of the young North Atlantic Ocean and south of the New England seamounts and Canary Islands, terrigenous material either must have been trapped beneath continental shelf areas or reduced in volume. The nature of the time-equivalent facies north of the Canary Islands is still unknown as only the uppermost Jurassic was reached during subsequent drilling efforts (Lancelot, Winterer, et al., 1977). The occurrence of a well-documented and generalized transgression on the North Atlantic margins during the Oxfordian could explain the great reduction of the terrigenous input into the basins at that time. The presence of Upper Jurassic to Lower Cretaceous carbonate banks and probably reefs also suggests that the edge of the continental areas might have been devoid of terrigenous accumulations which were restricted to the inner shelf and coastal plains.

Lower Cretaceous Terrigenous Turbidites in the Moroccan Basin

In the Moroccan Basin (Site 370) the evolution is different and is more directly related to regional influences. The absence of pelagic carbonates during the Neocomian is not surprising in view of the location of Site 370 overlying crust which, if it is oceanic, can be as old as Sinemurian. If we assume that the level of the CCD has remained approximately the same during the Late Jurassic and Early Cretaceous, then the area of Site 370 would have subsided below that level some time during the Oxfordian-Kimmeridgian. The occurrence of Lower Cretaceous massive terrigenous

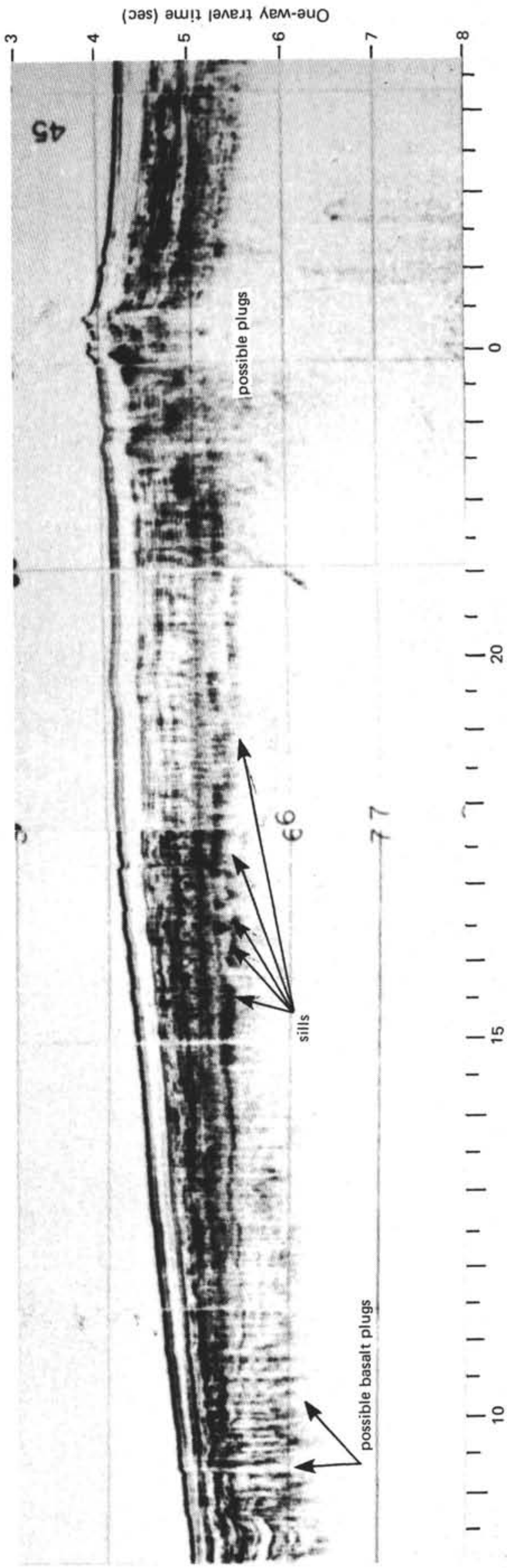

Figure 6. Vema 30 seismic reflection profile showing the occurrence of sills and plugs on Cape Verde Rise.

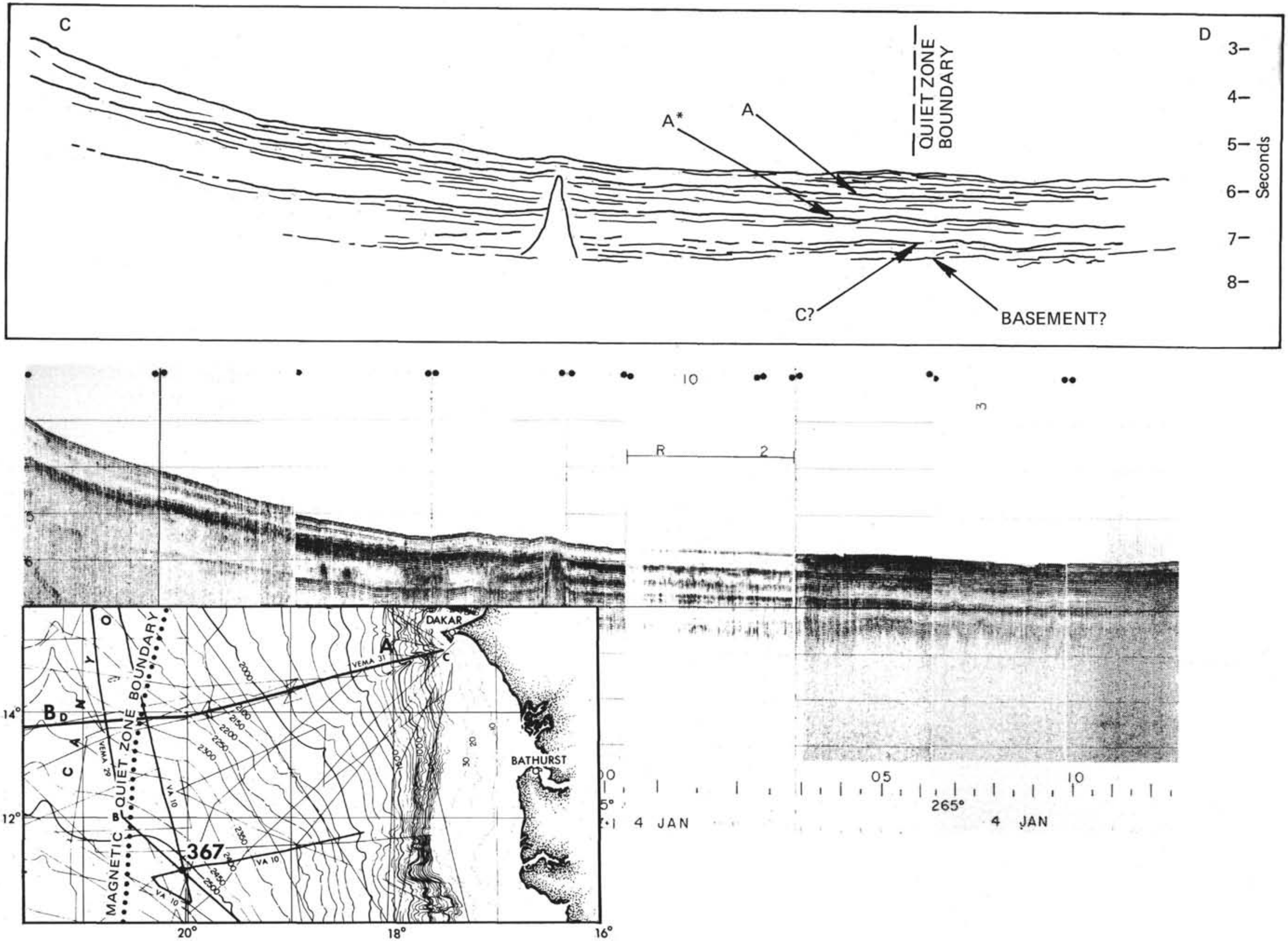

Figure 7. Vema-*31 seismic reflection profile off Dakar. Note how reflector C reaches basement west of the quiet zone boundary.*

influx at that site, on the other hand, contrasts dramatically with the pelagic carbonates of Site 367. Such a massive delivery of terrigenous detritus can be best explained by the occurrence of a tectonic uplift on the continent nearby. It could indeed correlate with the first major tectonic phase in the Western Atlas in southern Morocco, dated Latest Jurassic-Early Cretaceous (Choubert and Faure-Muret, 1962). Knowing that such a tectonic phase is the first to be recorded in the Atlas region and that the preceding times (Oxfordian) were characterized by a major transgression and the development of extensive carbonate platforms along the outer shelf off Morocco (Renz et al., 1975), it appears reasonable to assume that Oxfordian pelagic sediments, deposited while Site 370 was still above the CCD and just prior to the massive deposition of uppermost Jurassic to Early Cretaceous flysch in the Moroccan basin (Lancelot, Winterer, et al., 1977), could be responsible for the major reflector observed in that area (reflector C).

Acoustic Expression and Geographical Extension of the Basal Carbonates

The correlation of seismic profiles with the results obtained at Site 367 (Figure 8) allows for a discussion of the acoustic stratigraphy observed in the Cape Verde Basin. This correlation is certainly not as well established here as in the western Atlantic (Hollister, Ewing, et al., 1972) where the top of the carbonates was found to correspond with Horizon β. Here the main reflector within the lower interval of the sediment section (reflector C) correlates with some of the layers within the limestone interval and is located quite low in the section. The top of the limestones is only marked by a moderate to faint reflector. This reflector is probably the equivalent of Horizon β and is not as strong as in the North American Basin because it corresponds to a relatively small change in acoustic impedance between the chalky limestones and overlying relatively well-lithified claystones. Actually if Horizon β should correlate with the top of the carbonate everywhere in the deep basins, it should be time transgressive and could not remain parallel to the stratification over large regions. Time transgressive reflectors, cutting across the stratification and related only to time transgressive facies changes are very rare, except in the northern Pacific where they correspond to an exceptionally abrupt facies change from clays to chert (Lancelot and Larson, 1975). It is reasonable to assume that Horizon β is clearly identifiable only where it correlates with the direct contact between the black shales and the underlying limestones as in the North American Basin. Here Horizon β is almost invisible because of the intercalation of claystones between the black shales and the limestones. This makes the determination of the lateral extension of the carbonate facies difficult. Reflector C can be followed toward the west until it approaches the basement in the vicinity of the quiet zone boundary (Figure 7). This indicates that the age of the boundary on the eastern side of the North Atlantic is approximately the same as on the western side. Certainly the Neocomian white and gray limestones extend further west, but apparently the transition from these carbonates to younger black shales might be gradual enough, both vertically and laterally, so that it is not marked by a well-defined reflector on the profiles. Toward the east, reflector C is seen to separate more and more from the basement (Figure 7), indicating the presence of older sediments beneath the Oxfordian, but sediment thicknesses beneath the continental rise rapidly prevent penetration of acoustic waves down to that level and the reflector disappears on single-channel profiles. To the north the occurrence of a relatively thick series of parallel reflectors near the base of the continental rise also masks the lower reflectors which are generally not visible beneath the Cape Verde Rise and the eastern part of the Canary Basin. North of the Canary Islands in the Moroccan Basin, a major reflector, believed to correspond with reflector C (as discussed above), is clearly visible. Drilling results from Site 370, however, show that the overlying sediments in that basin are different from those from the Cape Verde Basin. It is probable that Lower Cretaceous carbonates are present in most of the deeper part of the Canary Basin, but as they were never sampled and because of the difficulty in obtaining a good signature from single-channel profiles, their geographical distribution remains uncertain.

Lower to Middle Cretaceous Anoxic Environments

Carbonaceous Cretaceous sediments from the deep basins of the North Atlantic were first observed in piston cores from the Cat Gap area, off the Bahamas (Habib, 1970; Windisch et al., 1968). They were sampled more extensively and their importance was recognized during Leg 11 of the Deep Sea Drilling Project (Hollister, Ewing, et al., 1972). It was discovered at that time that the "black shale" facies was spanning the Barremian-Cenomanian interval, and they were interpreted as resulting from stagnation in the deep parts of the North American Basin (Hollister, Ewing, et al., 1972; Lancelot et al., 1972). Since then comparable facies have been recovered from middle Upper Cretaceous sections in various oceanic basins of the world and in particular in the South Atlantic (Bolli, Ryan, et al., 1975). Their origin is still controversial although a wealth of new analytical data, part of which is published in this volume, provides some clues regarding their environment of deposition.

Drilling Results

During Leg 41, carbonaceous sediments of the "black shale" type were recovered at Site 367 (Cape Verde Basin) and at Site 368 (Cape Verde Rise). Although typical "black shales" were not present at Sites 369 and 370, Middle Cretaceous sediments at these sites were found to be enriched in organic matter. Black shales at Site 367, unlike what was observed at Site 105 (Hollister, Ewing, et al., 1972), do not directly overlie the Neocomian white and dark gray limestones. They are separated from this facies by an intercalation of red and green claystones of Barremian age. This intercalation breaks the continuity of what had been interpreted by Lancelot et al. (1972) as the progressive development of stagnant conditions in the North

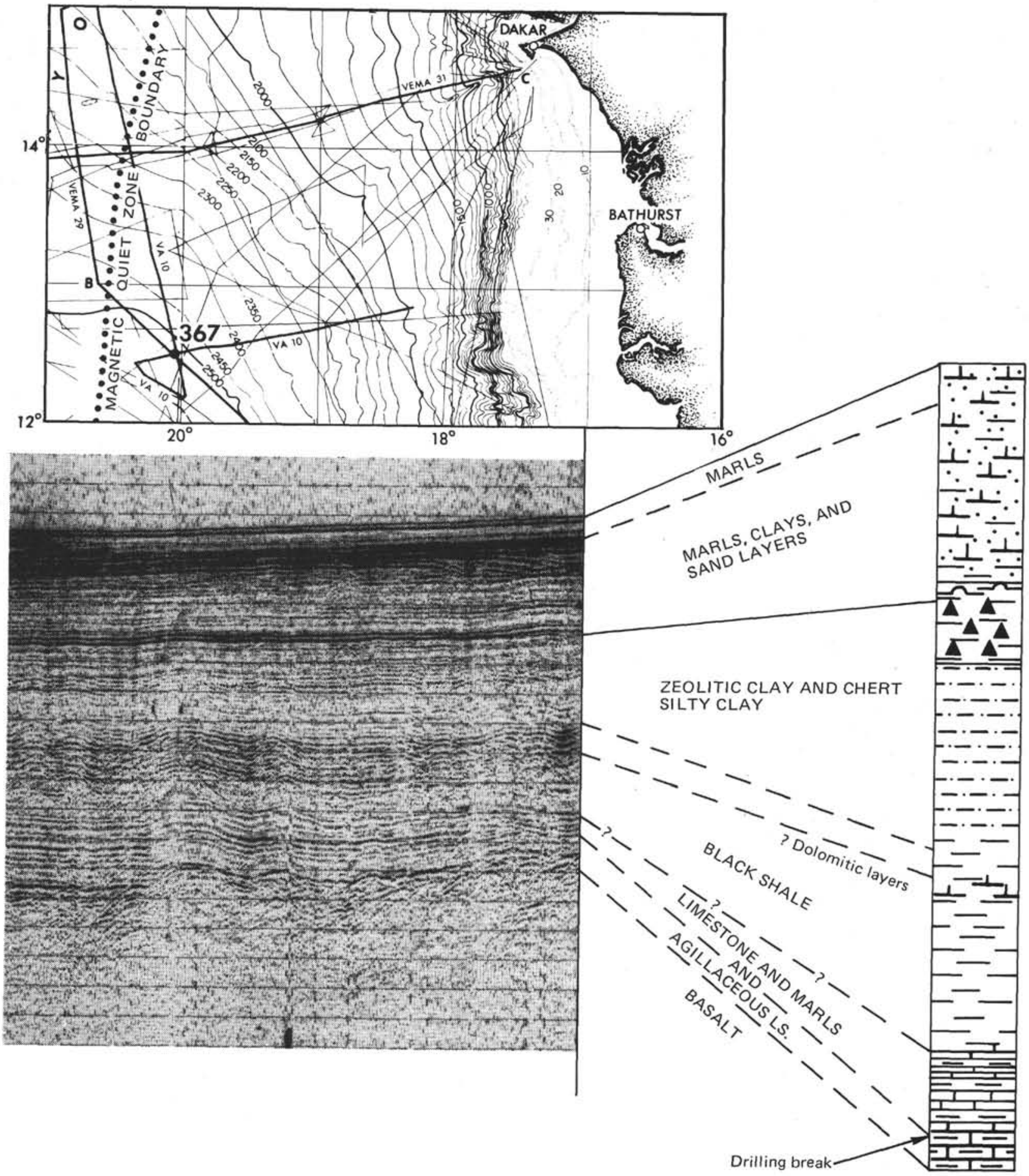

Figure 8. *Correlation of drilling results with seismic reflection profile at Site 367 (*Valdivia *10-1975 seismic profile).*

American Basin. Such a gradual transition was indeed suggested by the upward increase of the amount of dark gray marly layers intercalated within the white limestones. At Site 367, similar dark gray marlstones are also intercalated within the Neocomian white limestones and suggest alternations of oxidizing and reducing conditions on the bottom. The Barremian variegated claystones, clearly indicative of oxidizing conditions, might correspond with a longer interval of circulation of bottom waters before the definitive development of Aptian-Cenomanian reducing environments. Thus they would be the equivalent to the well-oxygenated white limestone intervals, but would correspond to a time when the sea floor had already subsided below the CCD.

The base of the black shale at Site 367 is not very well dated because of sparse sampling as well as poor preservation and scarcity of age-diagnostic microfossils. It is apparently Aptian, that is, of about the same age as in the North American Basin. The upper limit of that sedimentary unit at this site is also not well dated but is apparently Cenomanian. It shows a transition to very poorly dated (Upper Cretaceous) clays. That transition is very gradational compared with the truncation observed at Site 105 in the North American Basin. At that site multicolored clays overlie the black shales with a very sharp contact that seems to indicate a very abrupt cessation of the stagnant conditions and the onset of circulation of well-oxygenated bottom waters during the Cenomanian. On the eastern side the end of the black shale episode is probably more transitional, except in the Moroccan Basin where a major hiatus occurs as discussed later. Mildly reducing conditions are still encountered in green clays (Upper Cretaceous) overlying the black shales at Site 367. At Site 368 also, the upper age boundary of the "black shale" environment is poorly dated (? Turonian-Albian), and it is not known at present if it differs strongly from what has been observed in the North American Basin. In any case it seems that these environments do not extend much into the Upper Cretaceous, which shows a definite contrast with the evolution of the South Atlantic where black shales or comparable sediments are found at higher stratigraphic levels in the Upper Cretaceous (Campanian as indicated by Bolli, Ryan, et al., 1975).

The lithology of these sediments is described in the Site Chapters and separate chapters by Jansa et al., in this volume. Their mineralogical and chemical composition is discussed by Mélières, and Lange et al. (this volume). The composition of the black shales and related sediments is rather varied, not only from one basin to another, but also within the same basin and even at a given site from one layer to another. In general at Leg 41 sites, the bulk of the sediment consists of detrital elements (clay minerals and terrigenous silt) with variable amounts of carbonate and organic matter. Diagenetic imprint is characterized by the regular presence of abundant pyrite and small amounts of gypsum. At the two northern sites (369 and 370) barite also occurs in unusually large amounts, generally concentrated in rosettes. Its origin might be related to the proximity of evaporites (Couture et al., this volume), or alternatively, it could have formed diagenetically from oxidation of sulfides within the sediments (Dean and Schreiber, this volume). Carbonates are generally rare and often diagenetically transformed in dolomite, siderite, ankerite, or nodular calcite. Calcite is also present in some thin layers of probably displaced foraminifers at Site 367.

Organic matter from the "black shales" recovered during Leg 41 has been intensively studied, and the main results are reported elsewhere in this volume. These studies show that (1) the sediment is a potential source rock for hydrocarbons, and (2) the organic matter from several selected samples is of marine origin. The latter observation contrasts with the recorded occurrence of abundant plant debris in these layers.

Environment of Deposition

The main problems posed by the occurrence of "black shale" types of sediments are the depth of deposition and the cause and vertical extension of the reducing environments. We will briefly discuss here a possible interpretation derived from the study of Leg 41 "black shales."

The depth of deposition is not easy to determine directly from the composition of the sediments. The relative rarity of carbonates can be caused by dissolution of calcite of biogenic origin on the sea floor below the CCD, or it can result from dissolution within the sediment after burial in the presence of CO_2 released during sulfate reduction. For these reasons reducing environments are poor water-depth indicators. In the case of Leg 41 sites, however, indirect evidence suggests that, in the Cape Verde Basin (Site 367) and by inference in the Cape Verde Rise area (Site 368), the black shales were deposited probably quite close to the CCD. The presence of red and green claystones, devoid of carbonates except for probably redeposited foraminifers in thin layers beneath the black shales, indicates that oceanic subsidence had already brought the site below the level of the Neocomian CCD prior to the deposition of the black shales. The presence of some carbonate layers within the black shales (usually a few per cent but with occasional concentrations reaching 30% and even up to 60% in rare cases), however, might be explained either by redeposition or by a deepening of the CCD subsequent to the deposition of the Barremian carbonate-free claystones. Again, the generally poor state of preservation of the calcareous microfossils does not provide very useful indications in that respect because it might be related to post-depositional processes.

The cause for the reducing conditions and concomitant preservation of organic matter in these sediments has been and is still under debate. The first question to solve is to determine if reducing conditions occurred in the water column or if they were restricted to the sediments. The second question, which arises only if it has been determined that reducing conditions were present within the water, is to determine if they were caused by total (or intermittent) stagnation of the bottom waters in the deep part of the basins, or by the presence of an intermediate water mass strongly depleted in oxygen (oxygen minimum layer). Organic geochemistry analyses of Leg 41 samples provide valuable elements for answering the first question. Deroo et al. (this volume) have demonstrated the marine (planktonic) origin of the organic matter of several selected samples that correspond to some of the most typical black shales of Site 367. The samples come from homogeneous to finely laminated very dark layers. It is reasonable to interpret these layers as pelagic in origin by contrast with other layers that show discrete turbidite structures and contain abundant plant debris. The co-existence of two types of organic matter, having two different origins—marine in the first case, continental in the second one—is particularly remarkable. It shows that the presence of abundant organic matter in the sediments cannot merely reflect massive input of continental plant debris, but that organic matter, whatever its origin, was preserved instead of being oxidized at the sediment-water interface. If massive input of plant debris provides the only explanation for the rapid burial of organic matter, thus preventing its oxidation, within turbidite environments (Dean et al., this volume), it is extremely difficult to explain the absence of oxidation of the organic matter of pelagic origin which was accumulating more slowly on the sea floor unless bottom waters were depleted in oxygen. It is remarkable that whenever "atypical" black shales have been described, where dilution with detrital terrigenous components is evident, such as at Site 370 in the Moroccan Basin, or further north along the European margin off Portugal and off the Bay of Biscay (Ryan and Sibuet, 1976; Montadert, Roberts, et al., 1976) the organic matter appears always of continental (higher plants) origin. This observation often leads observers to challenge the "bottom water stagnation model," whereas analyses of the organic matter from selected "typical" black shales from some layers of Site 367 or Site 105 (Leg 11) confirm its marine origin and favor stagnation of the bottom water as the most plausible explanation (Lancelot et al., 1972). Because in both cases the stratigraphic interval is generally the same, it appears probable that a single cause must be invoked. The simplest interpretation is that organic matter of both origins has been preserved on the sea floor because of generalized stagnation or much reduced circulation at the water-sediment interface during the Aptian-Cenomanian in most of the North Atlantic, while regionally the same conditions might have persisted slightly longer in more or less isolated basins. Another piece of evidence lending support to this interpretation lies in the relatively low to moderate rates of accumulation of the carbonaceous sediments of Site 367 that remained always below 20 m/m.y., even for intervals characterized by plant debris in series of turbidites. By comparison, rates of accumulation as high as 100 to 190 m/m.y. occurred in hemipelagic Tertiary sediments of the Blake-Bahama Outer Ridge (Hollister, Ewing, et al., 1972) and maintained reducing conditions very close to the sediment-water interface even in the presence of vigorous bottom circulation. In normally well-oxygenated high productivity environments where pelagic sediments accumulate at rates of up to 40 to 50 m/m.y. organic matter of planktonic origin is generally not preserved in substantial amounts.

If, therefore, the solution to the problem should be found in the water column rather than in the sediments themselves, present data do not allow us to decide if the reducing conditions at the sediment-water interface could be attributed to the presence of an oxygen-minimum layer interstratified within normally oxygenated water masses (Thiede and Van Andel, 1977), or if they resulted from general stagnation in the deepest parts of isolated or partially isolated basins. In the latter case, however, stagnation would have been intermittent or even possibly cyclic, as evidenced by the occurrence of dark green to black burrowed layers interstratified within black finely laminated layers.

Acoustic Expression and Geographical Extension of the "Black Shales"

The correlation between the base of the carbonaceous sediment interval and the acoustic reflector β was discussed above. It seems clear now that the beginning of the black shale environment was indeed caused by a synchronous oceanographic event that occurred during the early Aptian. In that case, Horizon β, correlated in the North American Basin with the contact between the black shales and underlying carbonates (Hollister, Ewing, et al., 1972), probably also was synchronous over large parts of the basins, whereas it would probably be diachronous and therefore more difficult to identify if it merely correlated with the time transgressive top of the carbonates deposited on the flanks of the Mid-Atlantic Ridge.

The top of the carbonaceous sediment interval is well identified by a strong reflector on seismic profiles in most of the eastern North Atlantic basins. That reflector corresponds with reflector D_1 in the Canary Basin and Cape Verde Rise (Seibold and Hinz, 1974). Prior to Leg 41 it had been tentatively correlated with Horizon β from the North American Basin. Such a correlation now appears untenable and, because that reflector was found to correlate with the top of the black shale unit at least in the deep basins south of the Canary Islands, a correlation with Horizon A* observed in the North American Basin in a similar situation (Ewing and Hollister, 1972) is most plausible. Based on seismic profiles recorded in the northeast Atlantic, it should be possible to actually map the geographical extension of the carbonaceous facies in the basins from the extension of Horizons β and A*. This should often require multichannel records, however, because of the presence of highly reflective layers in the upper part of the sedimentary section in most of the eastern Canary Basin and Cape Verde Rise areas. In any case, the results of Leg 14 provide an estimate of the westward extension of the carbonaceous sediments on the flank of the Mid-Atlantic Ridge (Hayes, Pimm, et al., 1972). Carbonaceous layers were regularly found in the Aptian-Cenomanian sediments during that cruise. They generally contain more carbonate than the black shales from older (hence deeper) parts of the basins because of their relatively shallow depth at the time of deposition. These sediments are often very close to, or at contact with, the basement so that the water depth at that time can be estimated to be about 2700 to 3000 meters. It appears reasonable to place the westward limit of the carbonaceous facies in the vicinity of the Cenomanian basement horizon. This limit is of course rather difficult to map precisely because no magnetic anomalies can be used directly for that purpose. Based on spreading rates indicated by Larson and Pitman (1972), the limit can be traced tentatively as a line parallel to anomaly MO and located at about 200 km to the west of that anomaly (Figure 9). On the basis of the results of Sites 135 and 136, located north of the Canary Islands-Atlas trend, the westward limit of these facies can also be extended into the Moroccan Basin. At Site 370 in the deep part of that basin reducing conditions are indicated by sediments enriched in organic matter in the Aptian-upper Albian although dilution by terrigenous material is such that no "typical" black shales are present.

The vertical extension of the reducing environments can be estimated from the results of sites drilled in

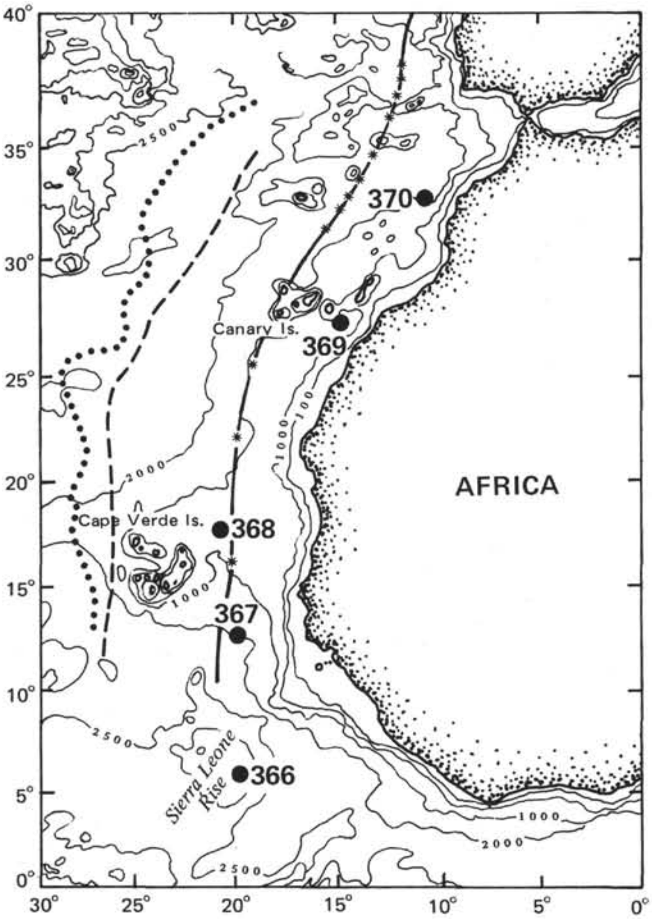

Figure 9. *Seaward extension of Horizon A (dotted line) from Uchupi et al. (1976), and theoretical maximum seaward extension of the black shale facies (dashed line) corresponding with a Cenomanian basement isochron obtained by extrapolation of magnetic data. The easternmost line (interrupted with stars) is the magnetic quiet zone boundary from Hayes and Rabinowitz (1975).*

relatively shallow areas such as the African continental slope (Site 369) or the flanks of the Mid-Atlantic Ridge in regions that were close to the ridge crest at the time of the stagnation; such regions correspond with oceanic crust of Aptian-Cenomanian age. At Site 369 on the continental slope off Spanish Sahara, Aptian-Albian dark green and brown marls have been recovered in water depth believed to be comparable to those of the present times at that location (1800-2100 m). The sediments are not "typical" black shales because of dilution by carbonate and clay, but they show a definite enrichment in organic matter (more than 2% in some samples). These sediments compare well with those deposited at the same time near the ridge crest and samples at Sites 135, 136, and 137 close to the basement (Hayes, Pimm, et al., 1972) at depths that can be estimated to be 2700-3000 meters. It is possible that during the Aptian-Albian reducing environments could have reached almost up to the sea surface as suggested from preliminary interpretation of results from a site drilled along the European margin off Portugal (Ryan and Sibuet, 1976). Again, the diversity of environments and lithologies associated with carbonaceous sediments contrast with the consistency of the stratigraphic interval in which they are observed. This contrast strongly suggests that reducing conditions in the sediments resulted from anoxic environments within the water column during the Aptian-Cenomanian rather than from excess of input of organic matter in normally oxygenated basins.

Reoxygenation and Carbonate Depletion in the Basins During the Late Cretaceous and Paleogene

Termination of the Anoxic Conditions

The upper limit of the carbonaceous facies is not as abrupt in the eastern North Atlantic as in the North American Basin. At Sites 367 (Cape Verde Basin) and 368 (Cape Verde Rise) corresponding with deep basin environments the passage from the black shales to overlying green silty clays appears gradational. It is rather well marked, however, in the mineralogical composition of the sediment by the upward abrupt disappearance of pyrite and gypsum. Unfortunately at the same time the already scarce microfossils become extremely rare, and the end of the anoxic conditions could not be assigned an age more precise than Upper Cretaceous. In both cases, however, carbonaceous sediments were found to reach at least up to the Cenomanian (and possibly the Turonian at Site 368).

By contrast the upper limit of the black shales in the northwest Atlantic, as observed at Site 105 (Hollister, Ewing, et al., 1972) is extremely sharp. That limit, however, is probably related to erosion by vigorous bottom circulation. Such an erosional phase cannot be easily dated because the first sediments deposited on top of the lower Cenomanian black shale are barren of microfossils and it is impossible to determine how much sediment has been removed through erosion.

On the African continental slope (Site 369) the upper part of the carbonaceous sediment interval is truncated by an unconformity which places Coniacian-Santonian white marly chalks directly on top of Albian olive-black marls enriched in organic matter. An unconformity (between upper Albian and Paleocene) also marks the upper limit of the carbonaceous sediments in the Moroccan Basin.

The results from Site 369 combined with those of Leg 14 sites show that, at least on the continental slope and on the flanks of the Mid-Atlantic Ridge, the carbonaceous facies may reach up to the Turonian and that by the Coniacian-Santonian, conditions were back to normal with respect to oxygenation of the bottom water.

Carbonate-poor Sediments in the Basins

In the Cape Verde Basin, the Cape Verde Rise (still a basin at the time), and the Moroccan Basin the sediments overlying the "black shales" are green terrigenous clays and silty clays containing almost no carbonates except at Site 370 (Moroccan Basin) where these are clearly redeposited. These deposits are indicative of deep basin conditions, below the CCD, dominated by terrigenous influences. Occasional pelagic influences are visible, however, and are especially well marked by the occurrence of chert and/or porcellanite in the lower Tertiary. The same kind of environment prevailed in the basins up to the early Neogene. Sediments often exhibit well defined cycles having periods in the order of tens of thousand years. Different mechanisms responsible for such cyclicity are discussed in Dean et al. (this volume).

The mineralogical composition of the sediment (Mélières; Timofeev, et al., this volume) confirms the predominance of the terrigenous contribution in that interval. It also shows the striking occurrence of massive output of palygorskite (attapulgite) and sepiolite in the lower Tertiary, and to a lesser degree in the Upper Cretaceous layers. The occurrence of large amounts of these minerals in the African coastal basins (Millot, 1964) in the lower Tertiary strongly suggests a detrital origin at Leg 41 sites (Melières; Timofeev et al., this volume).

Although the sediments of this stratigraphic interval are predominantly terrigenous, and often exhibit distal turbidite sedimentary structures, the rates of accumulation remain always relatively low (10 to 20 m/m.y.). This results from a combination of factors, of which the more important is the general Upper Cretaceous transgression. Such a transgression had two main consequences: (1) it prevented the delivery of massive detrital elements from the shelf areas to the basins. In addition it is possible also that most of the sediments delivered to the ocean remained trapped in the shelf area; and (2) it favored the accumulation of large amounts of carbonates in epicontinental seas (e.g., the Upper Cretaceous chalks of northern Europe) and as a consequence led to a general shoaling of the CCD in the World Ocean (Berger, 1970, Berger and Winterer, 1974) thus preventing pelagic carbonates from reaching the deep basins.

A combination of relatively high sea level and favorable climate probably caused the accumulation of palygorskite and sepiolite in coastal basins during the Late Cretaceous and early Tertiary (Millot, 1964). These clay minerals were then released into the deeper basins during some subsequent relatively small-scale oscillations of the sea level.

During the Paleogene the sea began to retreat slowly from the high levels reached during the Late Cretaceous and an abrupt drop occurred during the Oligocene (Vail et al., in press). That lowering is not recorded in the basins by any increase in the volume of terrigenous deposits. On the contrary, Oligocene sedimentation appears to be generally characterized by a hiatus, although age determinations are very poor for that interval because of the rarity of microfossils preserved in the deep basins. This hiatus might be the result of erosion by bottom currents related to the major Southern Hemisphere's high latitude cooling recorded near the Eocene-Oligocene boundary which produced a general increase in deep water circulation (Shackleton and Kennett, 1975; Boersma and Shackleton, this volume), but it is still difficult to explain the almost total lack of deposition in basins adjacent to the margins during such a major regression. In any case, even if the volume of terrigenous deposits did not increase substantially around the Oligocene, the mineralogical composition of the sediments (Mélières, this volume) indicates that sedimentation becomes definitely more terrigenous in character after that time.

Because of the high level of the CCD, biogenic sedimentation is represented almost exclusively by siliceous microfossils. They are particularly abundant in the lower Tertiary sediments where most of them have been transformed into chert and porcellanite (see von Rad and Rösch, this volume). This input of biogenic silica is probably responsible, for a large part, for the relatively high rates of sedimentation observed at that time at most sites (Figure 10). The mineralogical composition of the sediments confirms this observation as the terrigenous contribution remains very low except for palygorskite and sepiolite found only in the finer fraction of the sediment and which dominate largely the clay mineral assemblage. The occurrence of these clay minerals, reflecting high-silica environments, and of chert and porcellanite in the same interval is probably not fortuitous. This co-occurrence reflects a general increase in the amounts of silica being delivered to the ocean at that time, thus suggesting that continental runoff might have been a primary source of silica (Millot, 1964). It is also possible that the occurrence of silica-rich clay minerals within the sediment layers might have altered the balance of silica between the pore-water and the mineral phase, and favored diagenetic reprecipitation of silica (Lancelot, 1973). In any case, even if continental runoff was the primary source of silica, the generalized development of large amounts of siliceous microfossils must also be related to conditions of circulation especially favorable for high productivity in the surface waters. Such conditions could have been found in upwelling zones related to the presence of an active westward flowing equatorial current connecting Atlantic and Pacific tropical areas (Cita, 1971). Of course the existence of such a current pattern would also have favored the immediate dispersal of silica from the African continent toward the equatorial Pacific upwelling zone where it would have been readily available together with nutrients coming from the deeper water layers thus favoring massive development of siliceous organisms.

The northwestern Atlantic sediments contrast markedly with the eastern basins in that chert is often absent in the deep parts of the western basin. This absence results from erosion or nondeposition caused by strong bottom currents flowing along the American margin. The opening of a deep seaway between Greenland and Spitsbergen about 50 m.y.B.P. was probably responsible for the initiation of the circulation of North Atlantic deep water into the North American Basin (Berggren and Hollister, 1974). This water mass was channeled along the American margin by the Coriolis force and either prevented deposition of the siliceous oozes or eroded them before they had time to be transformed into hard chert layers and nodules. This explains why Horizon A, which is generally correlated with lower Tertiary cherts in many parts of the world, often corresponds with a hiatus in the North American Basin.

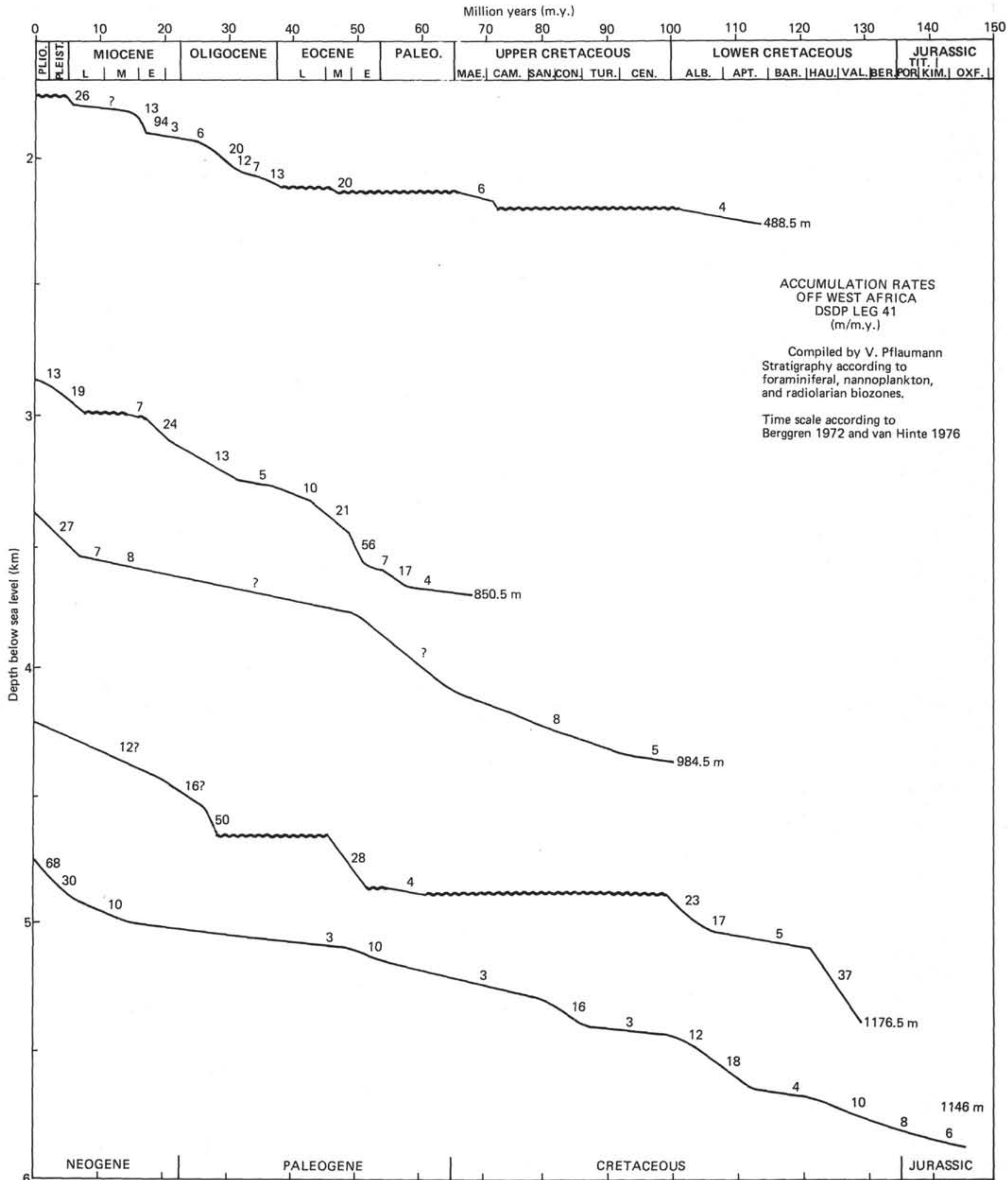

Figure 10. *Rates of accumulation at Leg 41 drill sites (compiled by U. Pflaumann). Sites have been arranged vertically as a function of their water depth.*

Although the Upper Cretaceous-Paleogene section is very comparable at each of the deep basin sites, the Moroccan Basin (Site 370) is characterized by slightly different features. A major (≈40 m.y.) hiatus spans the entire Upper Cretaceous and the lower Paleocene. The upper Paleocene corresponds with a short duration but notable deepening of the CCD. The rest of the section is comparable with that of the Cape Verde Basin and Cape Verde Rise (still a basin during that time). It is of course tempting to explain the major Upper Cretaceous-lower Paleocene hiatus, in the same manner as for the North American Basin, by a flow of North Atlantic deep water into the basin following opening of major seaways in northern areas. This explanation appears untenable here, however, because of the presence of upper Paleocene hemipelagic and pelagic sediments just above the unconformity. These deposits indicate that erosion occurred prior to about 60 m.y. and predates the onset of deep water circulation in the North American Basin. Furthermore it would be difficult to explain, for purely dynamic reasons, the presence of a strong southward-flowing bottom current along an eastern margin in the Northern Hemisphere.

The occurrence of upper Paleocene pelagic carbonates in the deep basin, on the other hand, might be of more than regional significance. Unfortunately because of both discontinuous sampling and poor stratigraphic control, it cannot be determined if similar deposits are present in the other basins of the eastern North Atlantic. However, the occurrence of upper Paleocene pelagic carbonates at several sites in the basins of the South Atlantic (Bolli, Ryan et al., 1975) as well as small but noticeable increase in the rate of accumulation observed at that time on Sierra Leone Rise (Site 366) suggest that a general lowering of the CCD occurred during the late Paleocene and is possibly related to changes in the general circulation pattern in the Atlantic. This problem will require further investigation on a global scale because a quick review of the drilling results in the Pacific indicates that Paleocene carbonates are generally missing or much reduced in that ocean except beneath zones of particularly high productivity. The study of possible fractionation between basins might help solve that question.

Acoustic Expression and Geographical Extension of These Facies

Two major seismic reflectors are observed in the sections correlating with this sediment interval. The lowermost one, discussed earlier, marks the limit between these facies and the underlying black shales (reflector D_1 of Seibold and Hinz, 1974) in the basins south of the Canary Islands. Our interpretation of the drilling results in the eastern North Atlantic basins suggests that it is the equivalent of Horizon A* correlated with the same lithologic boundary in the North American Basin (Ewing and Hollister, 1972). The second one, which in the Cape Verde Basin and Cape Verde Rise areas generally lies 0.4 to 0.6 second above A*, correlates well at most sites with the top of chert-rich layers and can be reasonably identified as Horizon A.

In the Moroccan Basin the picture is somewhat different. A major reflector was believed to correspond with reflector D_1 of the Canary and Cape Verde basins, but no direct correlation could actually be made along profiles across the Canary Island-Atlas tectonized region. Preliminary results of Leg 50 (Lancelot, Winterer, et al., 1977) demonstrate that in the Moroccan Basin, reflector D_1 does not correspond with the top of the "black shales" or with the top of layers associated with reducing conditions in the same stratigraphic interval. That interval is here interrupted by the major hiatus described above and, surprisingly, the reflector was found to correlate with a smaller and younger unconformity between the Paleocene and lower Eocene, hence situated slightly higher in the section. In our conclusions for this volume we do not attempt a detailed discussion of the acoustic stratigraphy of the Moroccan Basin which will be studied in much greater detail by the Leg 50 scientific party.

The upper limit of this interval lies somewhere in the lower Neogene and is not easy to correlate with any reflector on a basinwide basis. Around the Cape Verde Rise and in the Canary Basin, however, it seems to correlate rather well with the relatively strong reflector D_2 of Seibold and Hinz (1974). At several Leg 14 sites that reflector has been correlated with the transition from carbonate-poor sediments to nannofossil marls around the lower to middle Miocene. Drilling results of both Leg 14 and Leg 41 in that stratigraphic interval are too scanty to document more definitely such a correlation.

Although there is little doubt about the widespread distribution of these reflectors, they are relatively difficult to map except on a regional basis because of the occurrence of highly reflective layers high in the section in the lower continental rise area. Horizon A, for example, is often hidden in these layers which results from the deposition of turbidites during the Late Cretaceous and early Tertiary. Furthermore, these reflective layers prevent deep penetration of acoustic waves and mask the deeper reflectors on most single-channel profiles except in the Cape Verde Basin and Cape Verde Rise areas. Mapping the distribution of the sediments described above is also complicated because of lateral changes in facies. When going westward toward the flank of the Mid-Atlantic Ridge, the carbonate-poor Upper Cretaceous-Paleogene sediments pass laterally to carbonate chalks and oozes. This change does not leave a clear signature on the seismic profile. The only reflector that can be traced in almost all of the eastern basins in Horizon A (Uchupi et al., 1976) (Figure 9) because it corresponds generally with siliceous concentrations present in clays as well as in carbonates.

The Return of Carbonates in the Deep Basins During the Neogene

Lowering of the CCD

Calcareous pelagic sediments overlying layers devoid of carbonates have been sampled in the upper section of the Cape Verde Basin, the Cape Verde Rise, and the

Moroccan Basin. Similar situations have been encountered at several sites drilled in the Canary Basin and Cape Verde Rise area during Leg 14 (Hayes, Pimm, et al., 1972). They document a major lowering of the CCD during the late Tertiary when it reached a level comparable to that of today. A comparison between the deepest sites (Leg 14, Sites 137 and 138) and other sites drilled in shallower areas of the basin during both Leg 14 and Leg 41 provides a reasonably good estimate of the depth reached by the CCD. Sites 137 and 138, respectively, in 5360 meters and 5288 meters of water, are completely devoid of carbonates whereas the other sites (Sites 135, 136, 140, 141, 367, 368, and 370) in the basin (near the base of the continental rise), having water depths ranging from 3360 to 4480 meters, all show carbonates in the late Tertiary and Quaternary part of their record.

It is difficult to determine exactly the time of the lowering of the CCD because of incomplete sampling at most sites. Furthermore, during the Tertiary, some sites (Sites 135, 141, 368) have undergone vertical uplift that has brought them above the CCD at a time which therefore is independent from the lowering of the CCD. For the same reasons it is difficult to determine accurately the depth reached by the CCD. If we use exclusively the information from sites believed to have remained relatively stable, that is, having undergone only normal "oceanic" thermal subsidence along the age-depth curves of Sclater et al. (1971), and if we consider that depth variations at these sites are negligible for the last 20 m.y. because they overlie relatively old crust already almost stabilized, then the level reached by the CCD around the middle Miocene lies between 5288 meters (Site 138) and about 4150 to 4200 meters (Sites 136 and 370). The record of Site 140, located in nearly 4500 meters of water depth, suggests that the lowering of the CCD down to its present level was not accomplished in a single step because the transition from non-carbonate facies at that relatively deep site (4483 m) occurs somewhere between the middle Miocene and the Pliocene whereas it is substantially older at slightly shallower sites. Toward the upper continental rise the CCD clearly tends to be shallower, probably because of high fertility in upwelling areas (Berger and von Rad, 1972) so that the lowering of the CCD appears more or less synchronous at Site 139 (water depth 3047 m) and at Site 136 (water depth 4169 m). An alternative explanation would be an almost instant drop of the CCD from above 3000 meters down to about 4200 meters in the middle Miocene.

The lowering of the CCD during the late-early to middle Miocene was probably caused by global changes in the oceanic circulation, possibly related to major climatic changes in the latitudes of the Southern Hemisphere. Without a more precise estimate of the time of the lowering of the CCD, however, it is impossible to establish firmly such a relationship. In that respect the only reasonable connection between Antarctic glaciation and deep water vigorous circulation up to now seems to be the marked dissolution of calcareous microfossils and the occurrence of hiatuses in the basin during the middle Miocene. One evidence for major changes (general increase) in the circulation of probably both surface and bottom waters is the development or enhancement of upwelling along the African margin during the early Miocene (see Diester-Haass, this volume). It is possible that the narrowing of the Straits of Gibraltar area around the early-middle Miocene boundary, which is marked in the radiolarian record by the termination of faunal exchanges with the Mediterranean Sea (Johnson, this volume) played a role in reinforcing the Canary Current and associated coastal upwelling at that time.

Decrease of Terrigenous Influences

The occurrence of pelagic carbonates in the basin is also enhanced by the decrease of terrigenous influences caused by the climatic evolution of the North African continent during the Tertiary. With the exception of Site 367, located near the path of the Cayar Canyon system, and to a certain extent, Site 370, located close to a tectonically active area (Canary Islands-Atlas fold belt), terrigenous material and in particular sand and silt are rare in the Neogene sediments. Aridity in the Sahara region seems to have begun or at least increased dramatically with the early Miocene as shown by the occurrence of occasional eolian sands redeposited by turbidity currents in the deep basins (Sarnthein, this volume). These sands compare well with those observed in Pleistocene sediments off northwest Africa and suggest the presence of strong offshore trade winds already present during the early Miocene. Such strong winds might also have favored the development of coastal upwelling. The influence of the winds can be followed as far south as Site 366 (Sierra Leone Rise) where eolian quartz silt particles, freshwater diatoms, and opal phytoliths were observed (Fütterer, this volume). This major climatic change during the early Neogene seems to mark the onset of a climatic zonation comparable to that observed today, following the generalized tropical to subtropical conditions of the Paleogene, extending northward up to western Europe.

The Neogene evolution of the eastern North Atlantic basins contrasts markedly with that of their western counterparts. During the Neogene, sedimentation along the Atlantic margin of the North American continent was characterized by thick accumulation of terrigenous deposits. These sediments were laid down under the influence of strong bottom currents (Western Boundary Undercurrent) bringing terrigenous material from the northern part of the North American continent characterized by humid climates (Ewing and Hollister, 1972). The massive accumulation of these sediments that started probably around the early Miocene were responsible for the building of the continental rise off North America contrasting strongly with the "starved" African margin, resulting from arid climate on the adjacent continent.

Acoustic Expression and Geographical Extension of the Neogene Calcareous Layers

The uppermost part of the sediment section appears as an almost transparent interval of variable thickness (from 0 to about 0.3 sec) on seismic profiles. It generally thins out in the deeper parts of the basins, probably because the depth of the sea floor is approaching the depth of the CCD. In the Cape Verde Basin the occurrence of Pliocene and Pleistocene turbidites interbedded with the calcareous pelagic sediments complicates the picture. In any case, because of the poor definition of the age of the base of the calcareous layer, which is also probably time transgressive, the correlation of the transition from non-carbonate to carbonate-rich facies with the strong first sub-bottom reflector in the entire eastern North Atlantic remains uncertain. It is possible, for example, that the reflector could be the expression of a middle Miocene hiatus or condensed section. More continuous coring will be required to completely document and map the variations of the CCD during the Miocene and to understand fully their relation with mid-Miocene climatic events.

Cenozoic Carbonates on an Aseismic Plateau (Sierra Leone Rise)

Drilling results of Site 366 (Sierra Leone Rise) provide the means to compare the sedimentary record of an elevated area (2850 m) (Figure 11) separated from the continental margin, with that of the deep oceanic basins as well as of the continental slope. That comparison concerns exclusively the Tertiary because the older record of the Sierra Leone Rise could not be sampled during Leg 41.

The sediments are calcareous with carbonate contents generally above 60%, showing that the rise remained above the CCD during the entire Cenozoic. None of these sediments, not even the oldest sediment reached (uppermost Cretaceous), are indicative of shallow water conditions. Although the age and nature of the basement on the rise and in the surrounding basins is not precisely known, we can reasonably assume that most of the subsidence of the rise occurred during the Mesozoic and that water depth variations were relatively small during the Cenozoic. The composition of the sediment is, on a large scale, rather homogeneous. Pelagic calcareous microfossils and, to a certain extent, siliceous ones, form the bulk of the sediment (Figure 12). Terrigenous contribution is very low and consists almost exclusively of fine-grained elements (clay minerals). This observation confirms the permanent isolation of the rise from the nearby African continental margin. Therefore, the comparison of the record of the rise with that of the basins is limited to the pelagic sedimentation. It permits a discrimination of the factors controlling pelagic sedimentation at different levels in the water column. Essentially, the sediment column on the rise should have recorded the variations in the productivity of the surface waters while variations in the parameters influencing the preservation of the microfossils in greater water depths are to be found in the basins. Because of the relative homogeneity of the sediments the single most important element to take into consideration is the rate of accumulation of these sediments (Figure 10).

Variations observed in the rate of accumulation at Site 366 appear generally synchronous and parallel with those observed in the basins, although the rates remain generally higher on the rise. The highest rates, found in the lower Eocene, clearly correspond with an increase in productivity of the surface waters, which is marked in the sediment by the occurrence of very abundant siliceous microfossils. Correspondingly, relative increases in the rates of accumulation are observed in the basins during the early Eocene, and sediments of that age contain abundant silica, either as microfossils or diagenetically recrystallized into chert and porcellanite.

The lowest rates of accumulation are found in the lower Paleocene, the lower Oligocene, and the middle Miocene. These three periods correspond also either to hiatuses or very low rates of accumulation in the basins. The processes responsible for these variations are not clear however. Dissolution cycles could provide an explanation as they seem to be present during most of the Miocene. A detailed study of the dissolution, dilution, and other cycles can be found in Dean et al. (this volume). Two minor hiatuses also occur at the upper and lower boundaries of the middle Miocene. They might have been caused by complete dissolution of the calcareous microfossils during periods of relatively low productivity and of circulation of aggressive bottom waters reaching up to a depth of about 3000 meters. They might also result from the removal of some of the sediments by bottom currents, or from a combination of the two factors. A shoaling of the CCD has indeed been observed during the middle Miocene in that region (Berger and von Rad, 1972), but in the case of Sierra Leone Rise the level reached by the CCD at that time would be considerably higher (3000 m or less) than what had been documented previously.

Sedimentation on the North African Slope Since the Middle Cretaceous

Site 369 was drilled on the continental slope off Spanish Sahara (see location in Figure 1) and penetrated sediments ranging from Aptian to Quaternary in age (Figure 13). The Aptian-Albian part of the record, which consists of carbonaceous marls and is abruptly truncated by a hiatus spanning the Albian-Coniacian interval, has been discussed earlier in this chapter. A more detailed discussion of the problems posed by the sedimentation on the slope and its relation with the adjacent basin will certainly be possible when the results of subsequent drilling (Leg 47A) and geophysical surveys will be analyzed. Therefore our discussion here remains very preliminary.

The entire section (about 490 m) consists primarily of marls and occasional marlstones or limestones. Sediments are more pelagic than hemipelagic, and, although terrigenous components (clay and some quartz silt) are generally present, rates of accumulation remain relatively low (Figure 10). The highest rates do not seem to correspond with times of high terrigenous output but rather represent increased pelagic biogenic contribution into the sediment. These intervals are

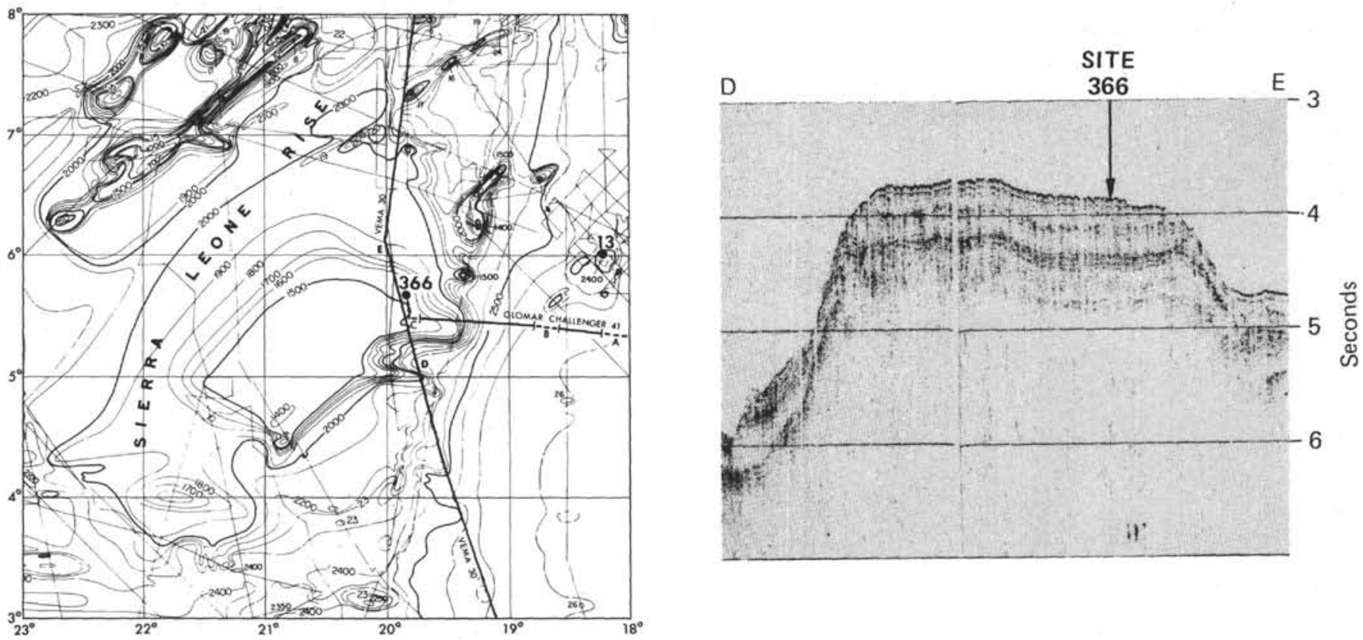

Figure 11. Vema *30 seismic reflection profile recorded on the eastern part of the Sierra Leone Rise and location of Site 366.*

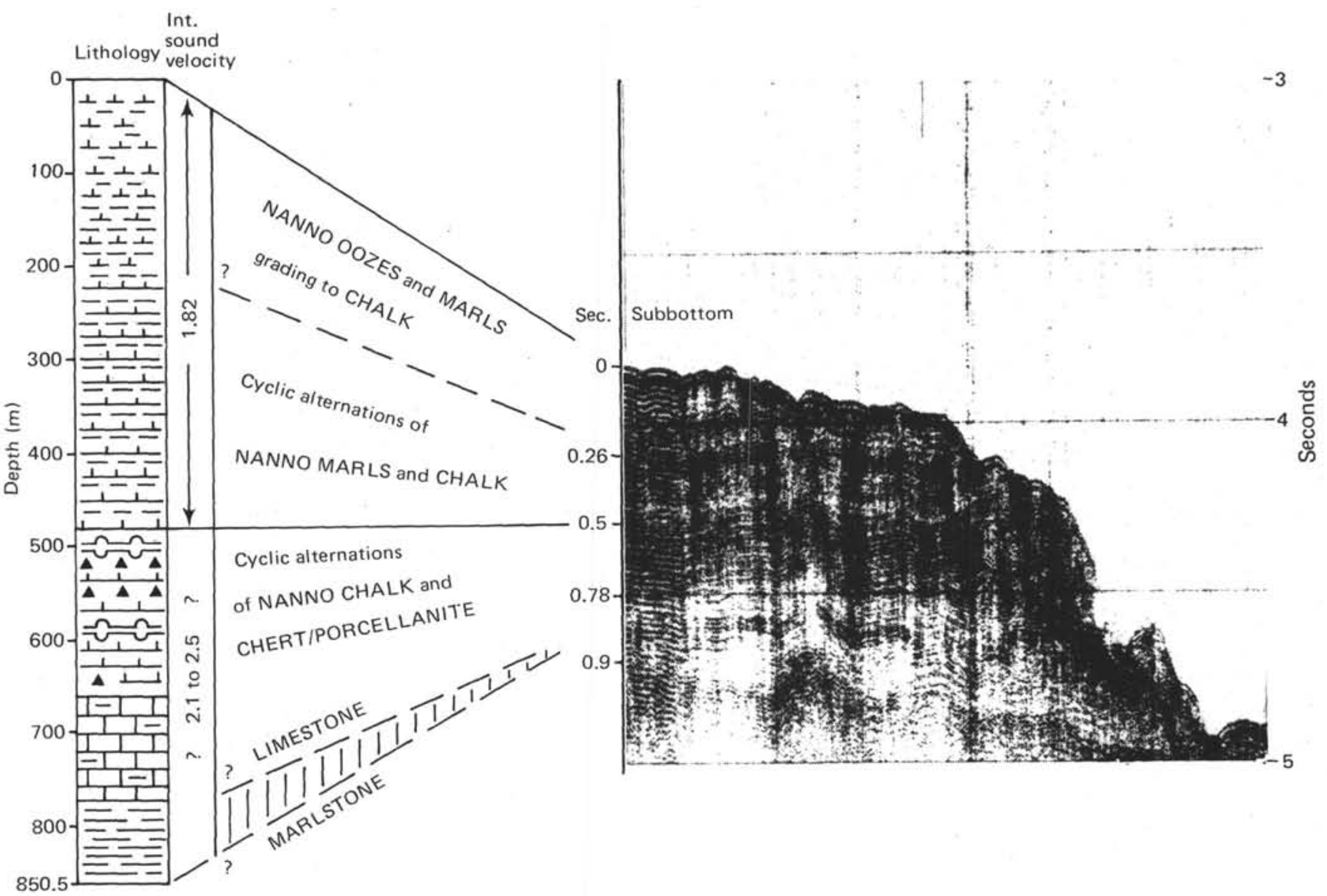

Figure 12. *Correlation of seismic profile and drilling results at Site 366.*

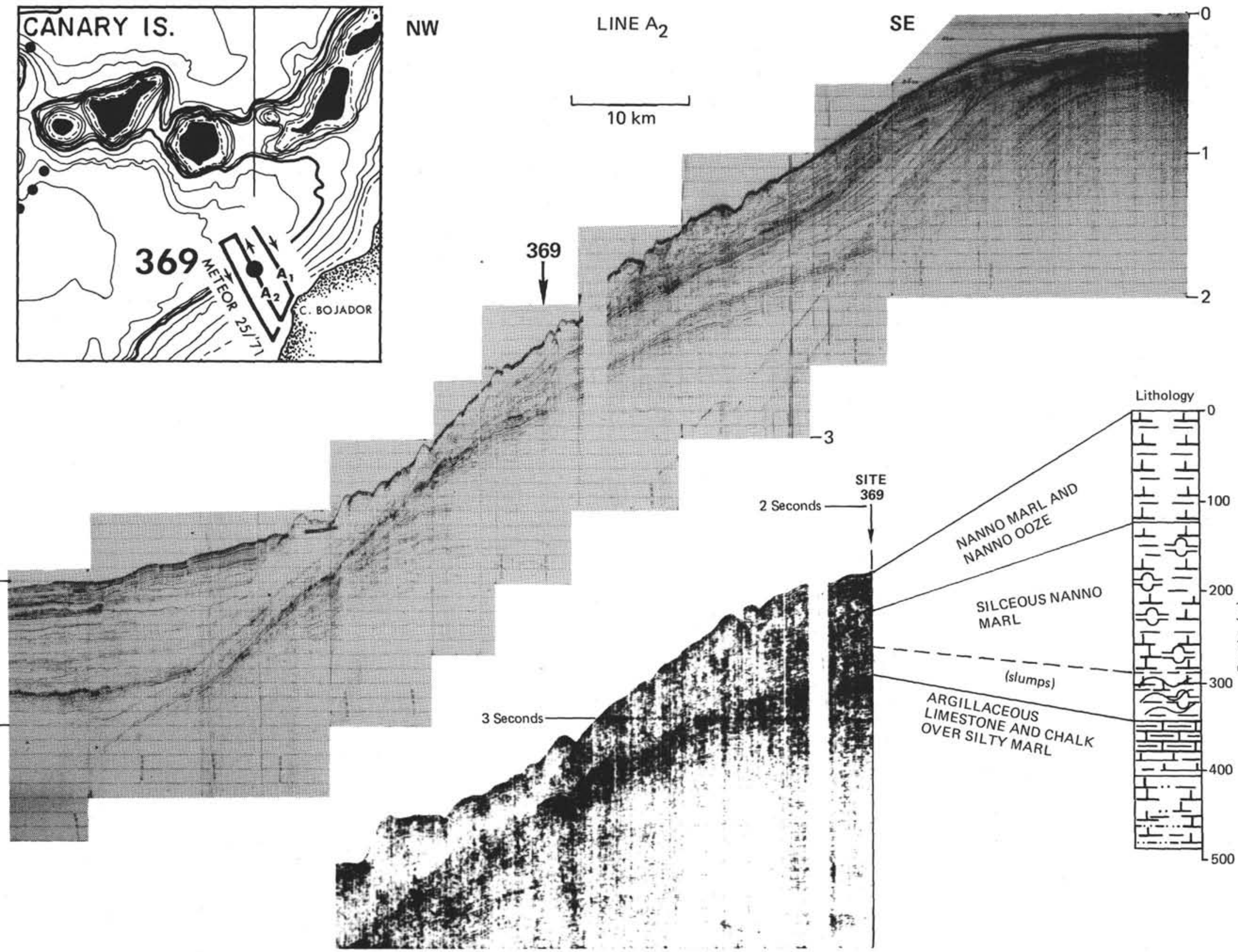

Figure 13. *Correlation of seismic reflection profile and drilling results at Site 369.*

particularly enriched in siliceous microfossils, indicating a strong influence of upwelling-induced high productivity.

Hiatuses observed in the section are not synchronous with those recorded in the basins or on Sierra Leone Rise. Their origin is probably purely mechanical and is mostly related to occasional mass-wasting and slumping along the relatively steep slope as observed in several cores. The generally very good state of preservation of the calcareous microfossils also confirms that hiatuses are probably not associated with dissolution. The nature of the microfossils also indicates that relatively little water depth changes occurred in the area of Site 369 at least since the Aptian.

Discussion

The continental slope off North Africa is essentially characterized by relatively limited influence of the nearby continent on the nature of the sedimentation, low rates of accumulation except during active upwelling, occasional mass-wasting, and relative stability since mid-Cretaceous times with regard to the general subsidence of the margin. These conditions might be reasonably extended to most "starved" margins. A more detailed discussion of the problems posed by the sedimentation on the slope and its relation with the adjacent basin will certainly be possible when the results of subsequent drilling (Leg 47A) and geophysical surveys will be analyzed. Therefore our discussion here remains very preliminary.

The limited influence of terrigenous components in the sedimentation reflects both the absence of progradation on the slope and the role played by submarine canyons in channeling the flow of coarse detrital material down to the basins. The low rates of accumulation also reflect the limited supply of terrigenous detritus. The relative stability of the water depth conditions since the Aptian indicates that most of the subsidence of the slope area must have taken place during the early history of the margin. It suggests that such a subsidence is parallel to that of the oceanic crust and contrasts markedly with the extended subsidence of the inner continental shelf area. A very tentative and schematic reconstruction of the evolution of the margin appears in Figure 14. It shows that the "slope anticline" of Seibold and Hinz (1974) might be of entirely passive origin and might result from differential subsidence on each side of the continental slope area. The subsidence of the edge of the continent, which is probably now under the slope, would have followed that of the adjacent oceanic crust to which it was coupled. Thus, most of that subsidence would have taken place during the first 50 m.y. of sea-floor spreading in the Atlantic Ocean. Meanwhile the inner shelf area would have also subsided in a flexured manner around a hinge line located somewhere on the continent. Sediment load would have kept increasing the subsidence of the inner shelf, even after thermal subsidence of the slope area would have stopped. The subsequent transfer of the zone of maximum subsidence from the outer to the inner shelf might have flexed the sediment layers below the slope, forming the "slope anticline." This interpretation is obviously very tentative and the critical isostatic implications will not be discussed here except to point out that more detailed modeling has to be made in light of the recent studies of Watts and Ryan (1976) in order to test the validity of our explanation.

Tertiary Volcanism and Related Tectonics

Two major volcanic complexes are present in the eastern North Atlantic, namely the Cape Verde Islands and the Canary Islands. Both are known to be of Neogene age on the basis of radiometric dating of the volcanic rocks (Abdel-Monem et al., 1971; Grunau et al., in press). Evidence for the Neogene volcanic activity in these areas has been found at several Leg 41 sites, either in the form of volcanic glass and zeolites in the sediments, or of diabase intrusions intercalated within sediment layers. The origin of the "intra-plate" volcanism is not completely understood, but it must be pointed out that a relation between volcanism and tectonics appears here rather well established. Figure 15 indicates the correlation between Leg 41 data and evidence for volcanic activity in and around the northeastern Atlantic region off Africa.

Volcanic Detritus in the Sediments

Ash layers and zeolites dispersed within the sediments were observed at Sites 367 and 368 in the Cape Verde area, and at Sites 369 and 370 in the Canary area. At Site 367 (Cape Verde Basin) evidence for volcanic activity in the Cape Verde Islands areas was found in the form of zeolites in Eocene and middle to upper Miocene sediments. Reworked fresh volcanic elements (pumice) were also found in middle Pliocene turbidites at the same site (Sarnthein, this volume). The middle-upper Miocene volcanic activity is contemporaneous with that documented near Dakar (Cantagrel, 1976; Uchupi et al., 1976). Volcanogenic particles were redeposited in the Cape Verde Basin through turbidity currents flowing from the Dakar area along the Cayar Canyon system and other valleys running over the lower continental rise off that region. The Eocene zeolites of Site 367 are difficult to link directly with any volcanic event as no Eocene activity either in the Cape Verde Islands or in the Dakar area has been described so far. They might indicate earlier phases of volcanism in one or both of these areas. At Site 368 (Cape Verde Rise) ash layers and zeolites found in lower-middle Miocene sediments are easy to correlate with volcanic activity occurring at the same time in the Cape Verde Islands (Grunau et al., in press).

In the Canary Islands region, volcanogenic material has been found in sediments from the continental slope off Spanish Sahara (Site 369) and in the Moroccan Basin (Site 370). Volcanic ash layers from middle-upper Miocene sediments of Site 369 correspond with a peak of volcanic activity in the islands (Diester-Haass, this volume). The composition of the volcanic glass suggests that it originated from Miocene eruptions on Gran Canaria Island (Rothe and Koch, this volume).

Diabase Sills and the Uplift of Cape Verde Rise

At Site 368 (Cape Verde Rise) several diabase sills, one of them 13 meters thick, have been found

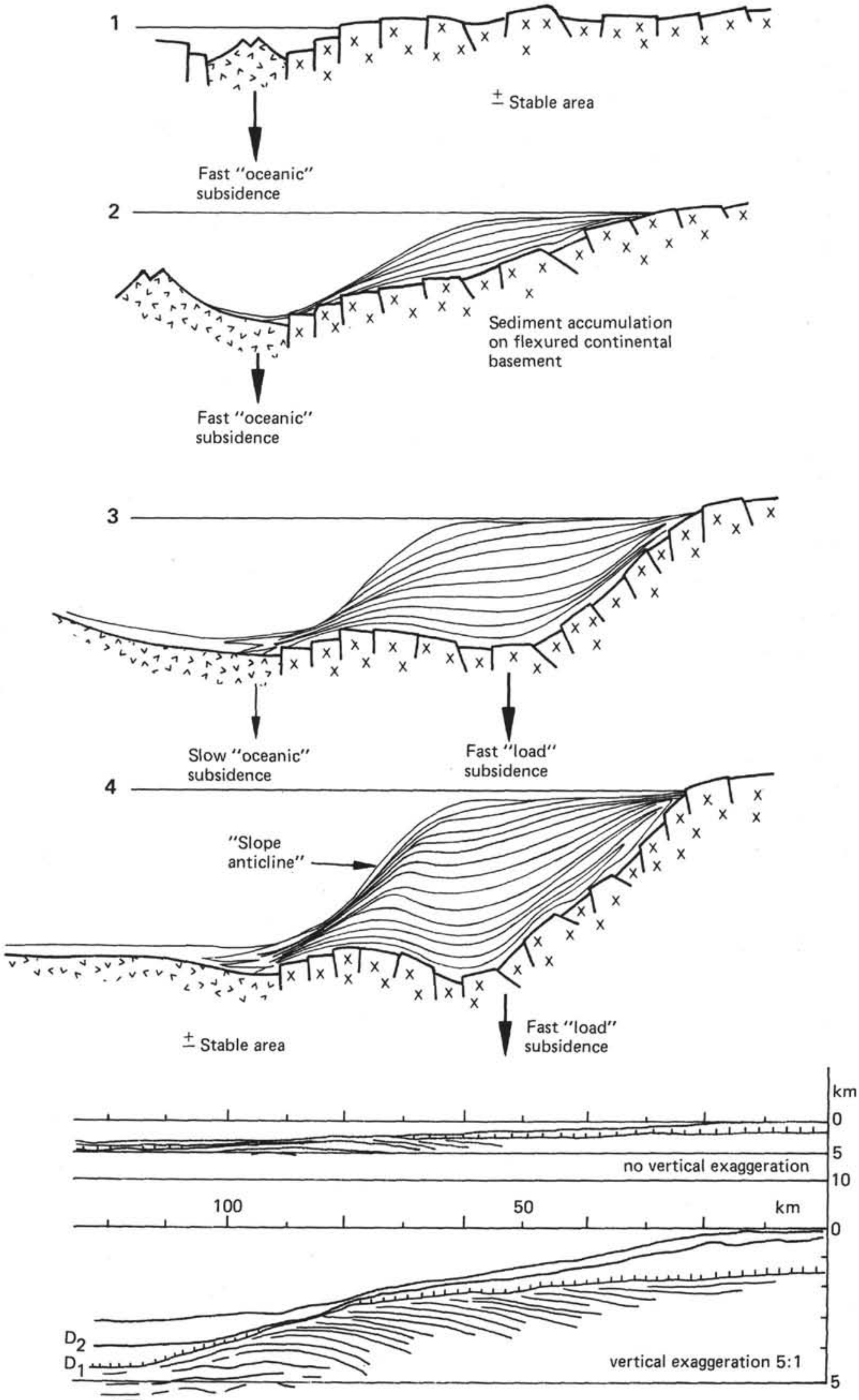

Figure 14. *Four successive phases in the schematic evolution of the continental margin off Cape Bojador. Lower line drawings interpreted from actual seismic profiles.*

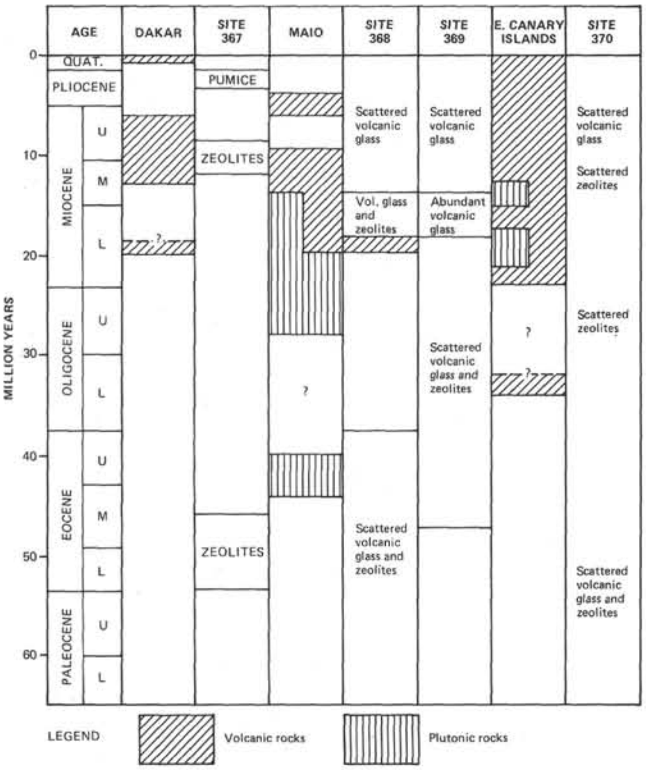

Figure 15. *Summary of occurences of volcanic rocks and volcanogenic elements at and around Leg 41 drill sites. Data on volcanism on Cape Verde and Canary Islands are from Cantagrel et al. (1976), Grunau et al. (1975), and Schmincke (1976).*

interbedded with Albian-Turonian black shales. Their radiometric age of 19 m.y., determined with good precision by Duncan and Jackson (this volume), places them in the lower Miocene. They are probably related to a major volcanic phase in the Cape Verde Islands. The vertical uplift of the Cape Verde Rise is certainly related to that Miocene volcanic activity. This Tertiary uplift was determined based on sediment nature and the presence of the sills brought a confirmation of the discovery. The Miocene sediment record of Site 368 shows an upward transition from terrigenous turbidites to calcareous oozes. Detailed mineralogical studies by Mélières (this volume) demonstrate that the lowering of the CCD predates the cessation of the turbidite regime. The distribution of calcitic versus terrigenous components (Figure 16) shows that, during the middle and lower-upper Miocene, pelagic calcareous components reached the sea floor while turbidites were still accumulating in a basin setting. Then during the upper Miocene the terrigenous input into the sediment dropped abruptly, indicating that the sea floor had been uplifted so that the area was out of reach of turbidites. Turbidity currents at that time were deflected probably toward the south in the Cape Verde Basin where they continued to accumulate until at least the Pliocene. These results indicate that the intrusion of the 19-m.y. old sill probably predates the uplift of the rise by some 10 m.y. Figure 17 summarizes schematically the evolution of the Cape Verde Rise.

Relations Between Volcanism and Tectonics

The origin of the Cape Verde and Canary Island volcanoes is still an unresolved problem. In fact, intraplate volcanism remains one of the puzzling questions in the plate tectonic concept. Basically two different theories have been invoked to explain this sort of volcanism. Either the volcanic activity results from deep-seated plumes of concentrated heat rising from the lower mantle and causing the development of "hot spots" in the overlying lithosphere (Morgan, 1971), or it is associated with cracks within the lithosphere through which magma can rise at times of tectonic activity. Both theories have been invoked to explain the origin of the Cape Verde and Canary archipelagos. Morgan (1971) and Burke and Wilson (1972) have applied the "hot spot" theory to these islands because the clustered distribution of volcanoes in these islands, opposed to linear seamount chains of the Pacific, suggests limited motion of the African plate with respect to the asthenosphere during the Tertiary. Le Pichon and Fox (1971) have proposed that both archipelagos correspond to volcanic complexes roughty aligned along old fracture zones created during the early opening of the North Atlantic. In that case, the volcanoes would have been created in a much later phase, during the Neogene, probably in relation to rearrangement of plate motion following a major collision in the Alpine orogenic belt.

The question remains unresolved but geological data from the islands lend more support to the fracture zone rather than the "hot spot" theory. Deep-sea sediments crop out in both the Cape Verde and the Canary Islands. Some of these sediments, on the island of Maio (Cape Verde Islands) have been studied in detail by Stahlecker (1934). They consist of alternation of Lower Cretaceous pelagic limestones and marlstones that appear quite similar to those recovered from the Cape Verde Basin in the same stratigraphic interval (Site 367). Pelagic deep-sea limestones of probable Jurassic age, overlain by Lower Cretaceous flysch, have been observed on Fuerteventura in the Canary Islands (Bernoulli, personal communication). In both cases, the sedimentary rocks appear in highly tectonized contexts. Such occurrences of uplifted deep-sea sediments are to our knowledge unknown in "classical" seamounts or volcanic islands that are not associated with tectonic zones. For example, nothing comparable to these occurrences is found in the Hawaiian or Polynesian islands. In contrast, uplifted blocks of oceanic crust such as the Gorringe Bank or Ampere seamount, along the Azores-Gibraltar tectonic zone, or the clearly faulted seamounts of the Bay of Biscay, all show uplifted sediments that have been sampled either by dredging or drilling. Faulting and uplifting is not enough to explain the volcanism in the Cape Verde and Canary Islands, but we can tentatively suggest that tectonic activity occurred along old fracture zones during the Tertiary and that it favored the eruption of lava at about the same time. The apparent absence of old (Upper Jurassic to Lower Cretaceous) oceanic crust on these islands, however, is surprising if this suggestion is correct.

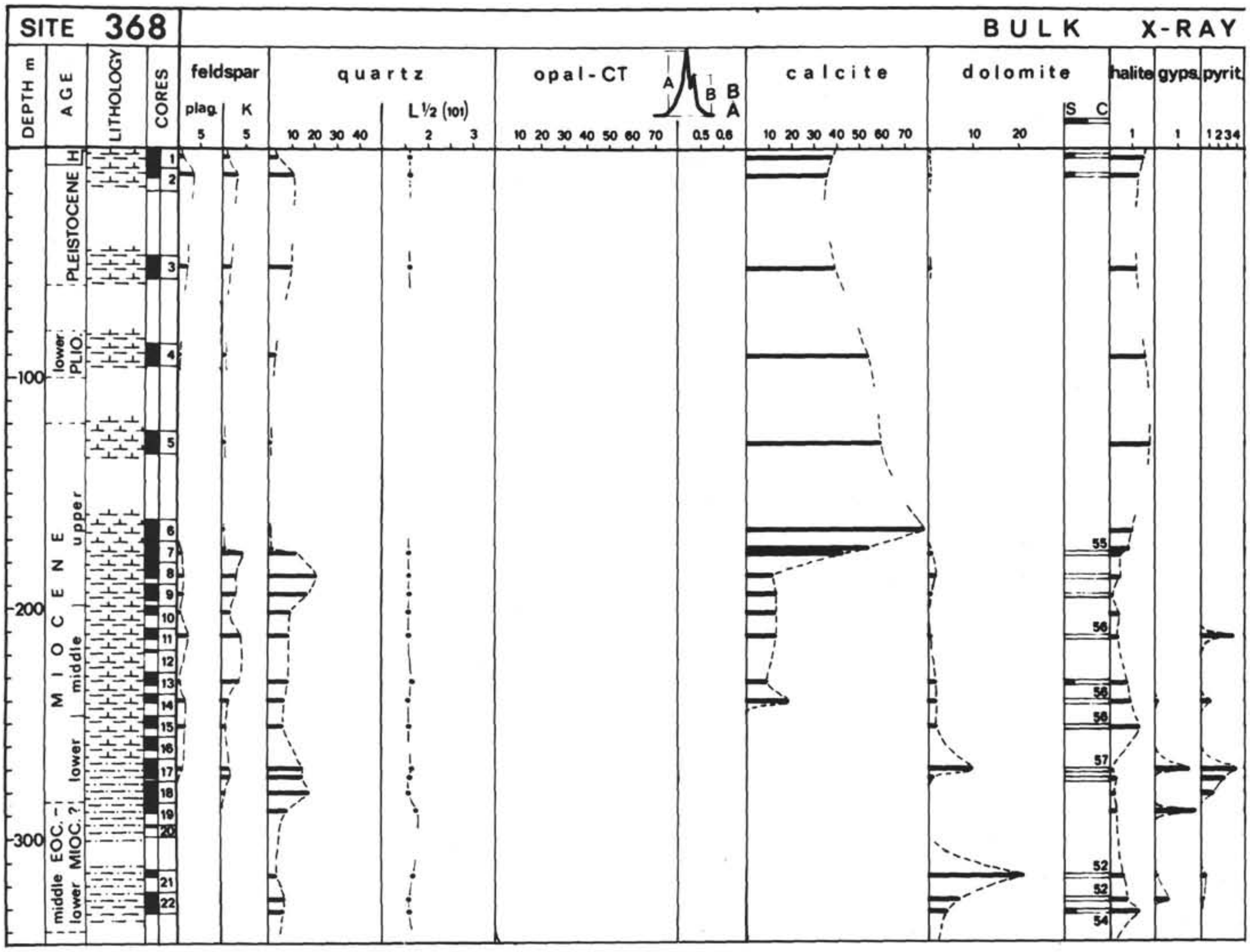

Figure 16. *Bulk X-Ray mineralogy from Neogene sediments at Site 368 (from Melieres, this volume). Note occurrences of calcite below the level of the abrupt decrease in terrigenous components.*

SUMMARY

The sedimentation in the eastern Atlantic off North Africa has been dominated by its tectonic evolution, the pattern and changes of the water circulation, and partially by the evolution of the adjacent continent. The tectonic evolution has two aspects playing a different role in the sedimentary evolution. The first one concerns the regular subsidence of the oceanic sea floor derived from a sea-floor-spreading type of evolution since the Jurassic. The second one deals with renewed tectonic activity during the Tertiary.

The Mesozoic history of the basins shows that from the Oxfordian to the end of the Neocomian carbonates were deposited on the flanks of the Mid-Atlantic Ridge, in a well-oxygenated basin. This oxygenation implies a connection not only with the Tethys, as demonstrated by the remarkable similarity of facies, but also probably with the Pacific in order to maintain a steady flow of well-oxygenated bottom water. Confirmation for this connection should be found in the nature of the deep-sea pelagic Jurassic-Lower Cretaceous sediments of Central America. The deepest part of the early basins, below the CCD, was probably characterized by sedimentation of deep-sea clays, but it has not been sampled because the only area where the basement was old enough eventually to obtain these facies was the Moroccan Basin, which was under the influence of regional tectonics at that time so that massive redeposition of flysch-type of sediments was present. The Aptian-Turonian black shale episode indicates a stagnation in the basins, probably in relation to a restriction of the deep seaway connecting the North Atlantic and the Pacific, and in the absence of a deep-sea connection between the North Atlantic and the young South Atlantic (also stagnant at that time). Too large a part of the Upper Cretaceous record is missing, because of erosion, lack of sampling, or poor identification in nearly barren sediments, to enable us to draw definite conclusions about the evolution in the deep basins at that time. The main characters of that period are probably the general transgression and its two main consequences: shoaling of the CCD because of shelf-basin fractionation of the carbonates and reduced terrigenous supply in the ocean.

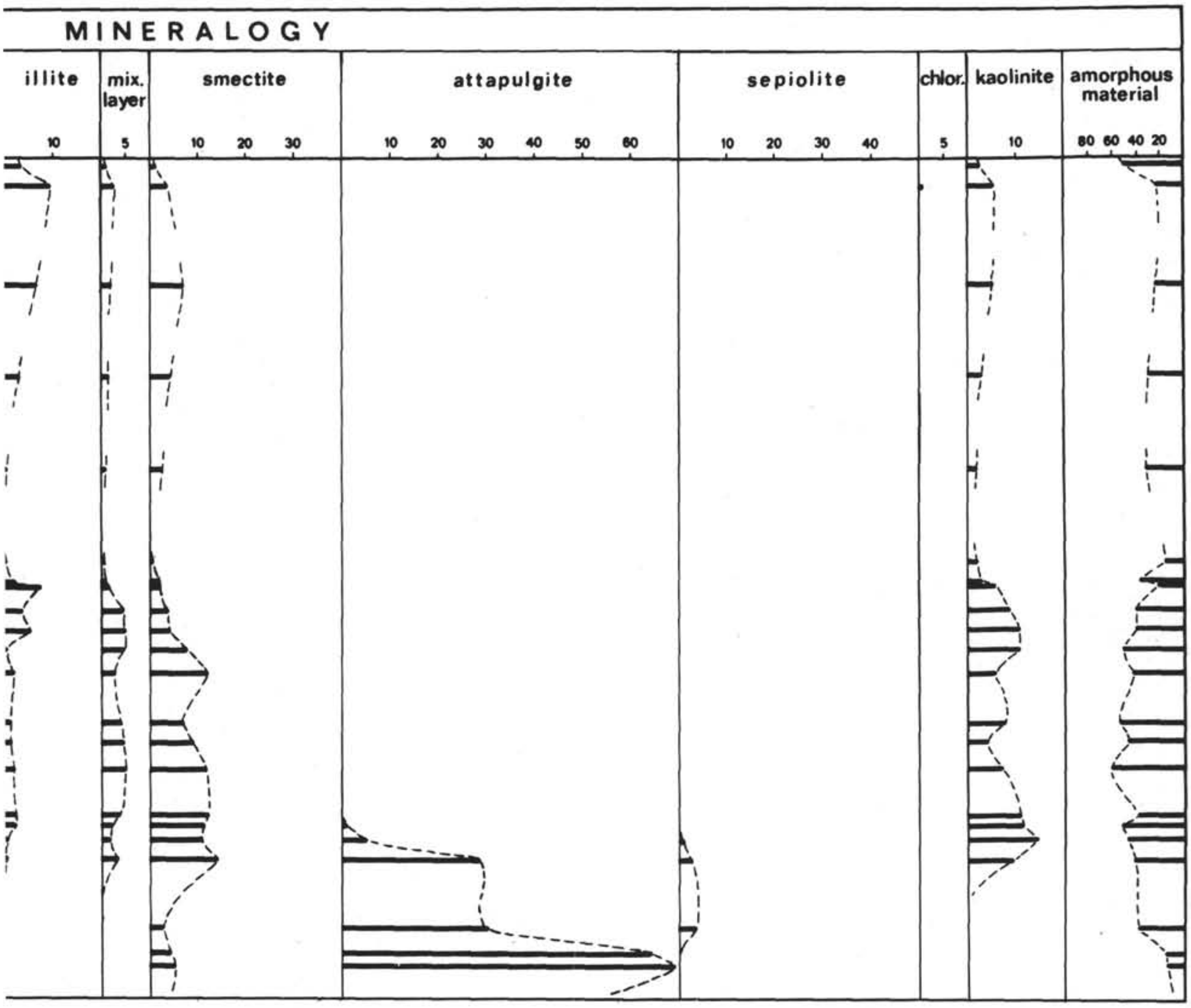

Figure 16. *(Continued).*

The Cenozoic history is characterized by fluctuations in the conditions of circulation and by volcanism and tectonic activity. It is also a time when sedimentation appears to follow well defined short-period cycles or rhythms (with a periodicity in the order of tens of thousand years) that might be related to climatic fluctuations. The evolution of the circulation is probably related to global climatic changes. Such changes are poorly documented in the Paleocene and better known from the Eocene-Oligocene boundary up to the Quaternary. Figure 18 summarizes the evolution of the northeast Atlantic region during the Cenozoic. The main consequences of this evolution have been: (1) the lowering of the CCD to its present level after important fluctuations, and (2) variations in the upwelling conditions along the African margin. Tectonic activity, possibly related to a major collision between the African and Eurasian plates, triggered volcanism in the Canary and Cape Verde Islands and in the surrounding regions. One striking result of this activity is the uplift of Cape Verde Rise during the Miocene.

REMARKS ON THE HYDROCARBON POTENTIAL OF THE OUTER NORTH AFRICAN MARGIN

Some of the results of Leg 41 provide new insights with respect to the possible generation and accumulation of hydrocarbons near the base of the Atlantic margin of North Africa. Hydrocarbon accumulation in the sediments requires these basic elements: organic-rich source rocks, maturation of organic matter into hydrocarbons, and accumulation in reservoirs. We will briefly review here the contribution of Leg 41 to the evaluation of the possibility of encountering these elements in deep water along the margin.

Source Rocks

Sediments rich in organic matter were found regularly in the Aptian-Cenomanian stratigraphic interval. Geochemical studies have shown that they represent good to very good potential source rocks although the state of maturation of the organic matter remained always very low. (See Baker et al.; Deroo et

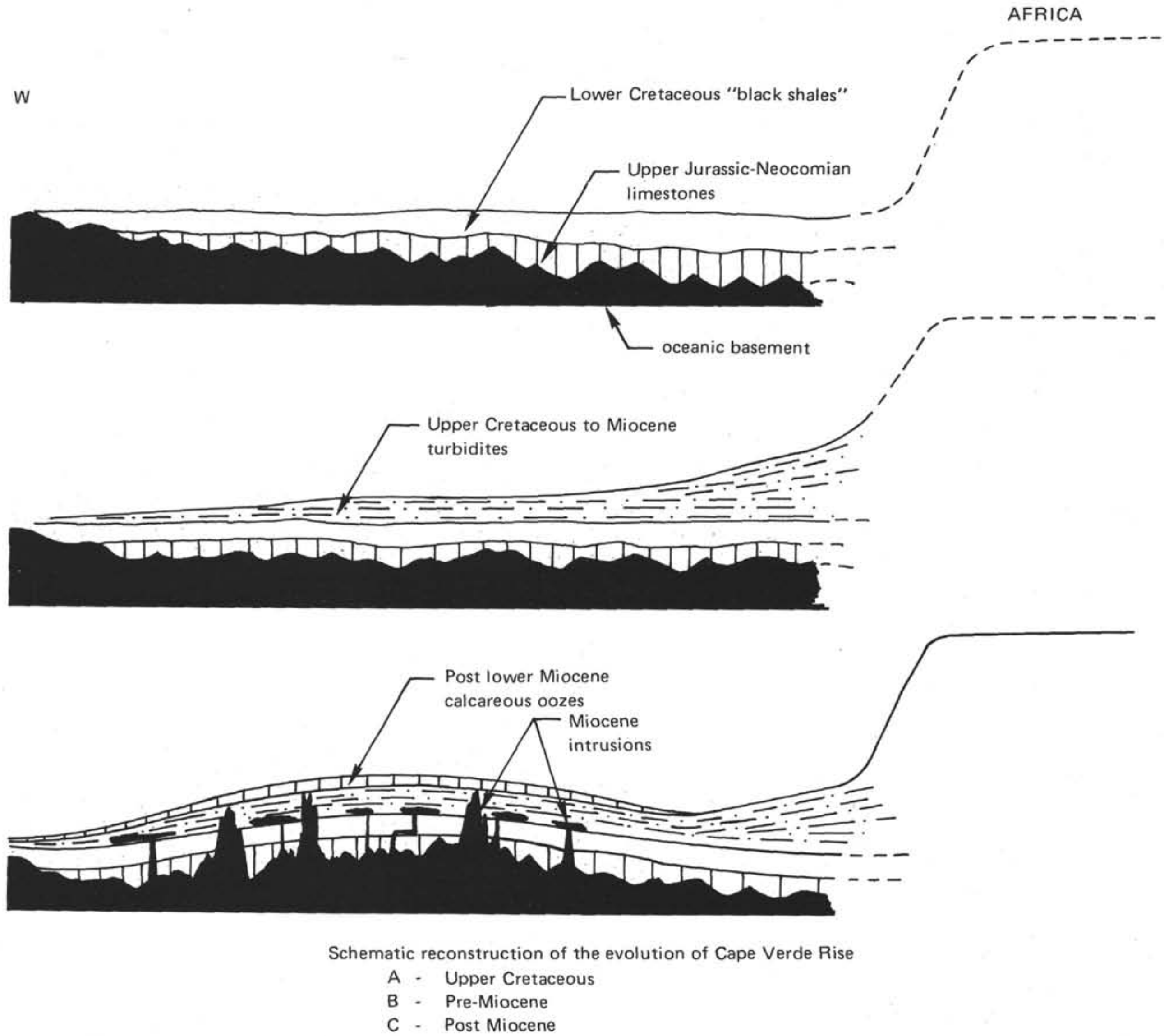

Figure 17. *Schematic reconstruction of the evolution of the Cape Verde Rise.*

al.; Dow; Erdman and Schorno; Hunt and Whelan; Kendricks; Kvenvolden; Simoneit; all this volume.) The organic carbon contents often reach several percent and hydrocarbon yields by pyrolysis are consistently above 0.3% at Sites 367, 368, and 369. They are lower at Site 370 because of dilution by terrigenous components. The analyses also demonstrate the dual origin of the organic matter: marine (phytoplankton) and continental (higher plants). One important consequence of this result, as discussed earlier in this paper, is the occurrence of generalized reducing conditions within the water column during the Early-Middle Cretaceous. This suggests that conditions remained favorable for preservation of the organic matter on the sea floor during that time and that accumulations could be sought independently from regional source considerations.

The intrusion of a diabase sill within the black shales of Site 368 demonstrated the hydrocarbon potential of these sediments. Extractable hydrocarbons were found in the sediments close to the sill, owing to the high temperatures reached during the intrusion. Various analyses described in the papers cited above confirm the thermal generation of these hydrocarbons and provide an estimate of the temperature reached in the vicinity of the sill (about 550°C at 2 m from the site). The alteration effect, however, was restricted to within a few meters above and below the sill.

Maturation of the Organic Matter

At all sites organic-rich sediments were present, and with the exception of the sediments very close to the diabase sill at Site 368, organic matter was found to be in a very low state of maturation.

Maturation results primarily from temperature. In old oceanic basins of relatively low heat flow, the geothermal gradient derived mainly from burial, favors maturation. It was found recently by Boutefeu, Galimov, and Taguchi during Leg 50 (reported in Lancelot, Winterer, et al., 1977) that the earliest stage

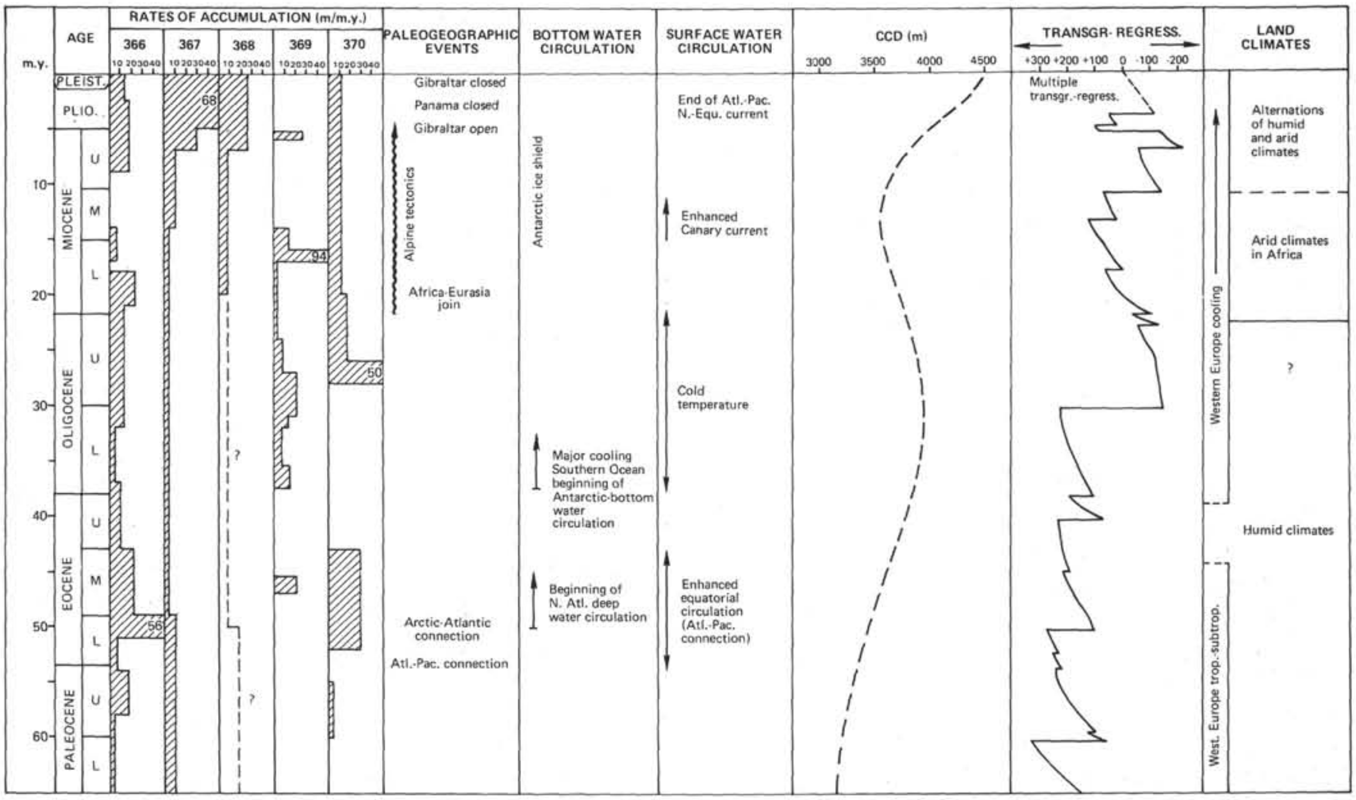

Figure 18. *Correlation of rates of accumulation at Leg 41 drill sites with paleogeographic and paleo-oceanographic events in and around the northeast Atlantic during the Cenozoic. Paleogeographic and circulation data modified after Berggren and Hollister (1977). CCD curve adapted from van Andel (1975). Transgression-regression curve adapted from Vail et al. (in press).*

of maturation into liquid hydrocarbon in these conditions requires a minimum of 1500 meters of overburden.

Instant maturation of the organic matter, locally limited however, can be produced by volcanic intrusion into organic-rich layers. In general, the most favorable areas for such a maturation have to be looked for in regions where the organic matter was deposited close to the basement, while the heat flow was still high on the flanks of the Mid-Atlantic Ridge. Then the organic-rich sediments should have been rapidly covered by a thick blanket of sediment so that the decrease in temperature, caused by the increasing distance from the high heat-flow areas of the upper ridge flank, would be compensated for by burial temperature. Such conditions are probably quite rare in the eastern Atlantic where the black shales are covered with thick blankets of sediments only in the vicinity of the margin, that is, in regions where, because of the old basement age, black shales were deposited considerably above the top of the oceanic crust in rather low heat-flow conditions. The presence of numerous intrusions in the Cape Verde Rise area, beside the immediate but limited effect of the hot lavas, might be related to regionally high values of the heat-flow during the Miocene. It is uncertain, however, that the increase in heat flow would have been high and long-lasting enough to produce general and substantial maturation under moderate sediment overburden.

Potential Reservoirs

Deep-sea sediments are generally characterized by relatively low permeabilities and porosities except for turbidites. Sediments overlying the black shales generally consist of clays or silty clays and do not represent good potential reservoirs. At Site 370, in the Moroccan Basin, coarser grained turbidites are present in most of the sedimentary column, but they seem to be generally well cemented. Cementation appears to be particularly enhanced in coarser grained layers where several generations of cement have been recognized (Meyer, this volume). Thus, the prospect is not very encouraging as far as the post-Middle Cretaceous deep-sea sediments are concerned. The situation is comparable higher on the continental slope (Site 369) where cementation appears exceptionally high in some limestones, possibly in relation to the presence of nearby evaporites. It is possible, however, that higher permeabilities and porosities could be found toward the inner shelf where shallow water deposits might occur.

The above discussion deals only with the potential of the post-Jurassic record. The occurrence of older restricted environments, eventually associated with evaporites, is still an open possibility.

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