60. LATE APTIAN TO RECENT SEDIMENTOLOGICAL HISTORY OF THE LOWER CONTINENTAL RISE OFF NEW JERSEY, DEEP SEA DRILLING PROJECT SITE 603[1]

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ABSTRACT

Deep sea drilling off the east coast of North America provided valuable information on the development of the continental rise in a region that has been influenced by the deposition of both continentally derived and pelagic sediments. Site 603 is interpreted to overlie Jurassic oceanic crustal basement. Based upon the oldest sediment recovered, Site 603 was only influenced by pelagic sedimentation during the late Berriasian to Valanginian, with terrigenous sediment not appearing until the late Valanginian to Aptian. The first evidence of clastic sedimentation is the development of a large turbidite system during a time when deltas were being built on the shelf. From the Hauterivian through the Late Cretaceous, black shale turbidites were intermittently deposited at this site. The maximum abundance of the carbonaceous claystone occurs interbedded with red and green claystone, and some silt and sand turbidites, in the Aptian–Albian interval. Sea level rose during the Albian, and as a consequence redeposition of terrigenous sediment waned, then ceased. The site then dropped below the calcite compensation depth. Less extensive terrigenous turbidite deposits are found associated with multicolored noncalcareous claystone that represents pelagic sedimentation during the Late Cretaceous. A turbidite containing dark green spherules of montmorillonite, and anomalously high concentrations of Ni, Co, and As, is interpreted to represent exotic sediment that was reworked from the Cretaceous/Tertiary (K/T) boundary sediment, based on its sedimentological and geochemical similarities to a biostratigraphically dated K/T boundary lamina cored at DSDP Hole 390B on the Blake Plateau. Late Paleocene to early middle Eocene pelagic claystone is disconformably overlain by middle Miocene hemipelagic claystone. Turbiditic silts and clays accumulated at this site, followed by the development of the lower continental rise hills of the Hatteras Outer Ridge. This constructional feature formed from muddy contourites deposited from the Western Boundary Undercurrent. Terrigenous turbidites ponded landward of Site 603 and formed the adjacent continental rise terrace.

INTRODUCTION

The continental rise off the east coast of North America has been of great interest recently because it records the evolution of the Atlantic passive margin and the ocean basin in its depositional record. Changes in sea level (Vail et al., 1980) and changes in terrigenous sediment input from the continents, as well as changes in the deep-water circulation (Tucholke, 1981), leave their signatures in the sedimentary rocks underlying the continental rise. Petroleum exploration has also tried to evaluate the strata beneath the continental rise for their hydrocarbon source and reservoir potential (Jansa and MacQueen, 1978).

Deep Sea Drilling Project Site 603 is located in the western North Atlantic Basin, on the Hatteras Outer Ridge, in 4633 m water depth, approximately 435 km due east of Cape Hatteras, North Carolina. The site is immediately adjacent to the lower continental rise terrace, located in the most landward valley of the continental rise hills. Numerous DSDP drill sites are located to the east in the oceanic realm of the North Atlantic and to the west on the continental slope (Fig. 1). Site 603 was chosen because of the potential of penetrating Upper Jurassic oceanic basement and, in the process, recovering strata that record the history of the development of the continental rise in a region that responds as the basin margin interface between continent-influenced sedimentation and pelagic sedimentation from the oceanic realm.

The recovery of a total of 1025.26 m of sediment (a DSDP record for any one drill site), and the location of the site, make Site 603 better suited than previous DSDP sites for recording the Mesozoic to Recent signature of coastal events related to sea-level change and oceanic events related to deep-water circulation. Site 603 received more terrigenous sediment from the adjacent North American continent than the eastward DSDP sites in the oceanic realm. Based upon the oldest sediment recovered, Site 603 was primarily influenced by pelagic sedimentation during the late Berriasian to Valanginian, with continentally derived sediment not appearing until the late Valanginian to Aptian. This chapter focuses on the relationship of continent-influenced sedimentation with pelagic sedimentation from the late Aptian to the Recent at Site 603 in an attempt to interpret the sedimentological history that recorded the development and evolution of the continental rise.

During DSDP Leg 93, four drill holes (603 to 603C) were cored at varying sub-bottom depth intervals. A 9.5-m surface core of Pleistocene sediment was collected from Hole 603, which was then washed to a sub-bottom depth of 573 m, followed by rotary coring continuously from 573 m to a total sub-bottom depth of 833 m located in middle Miocene sediment. Hole 603A did not

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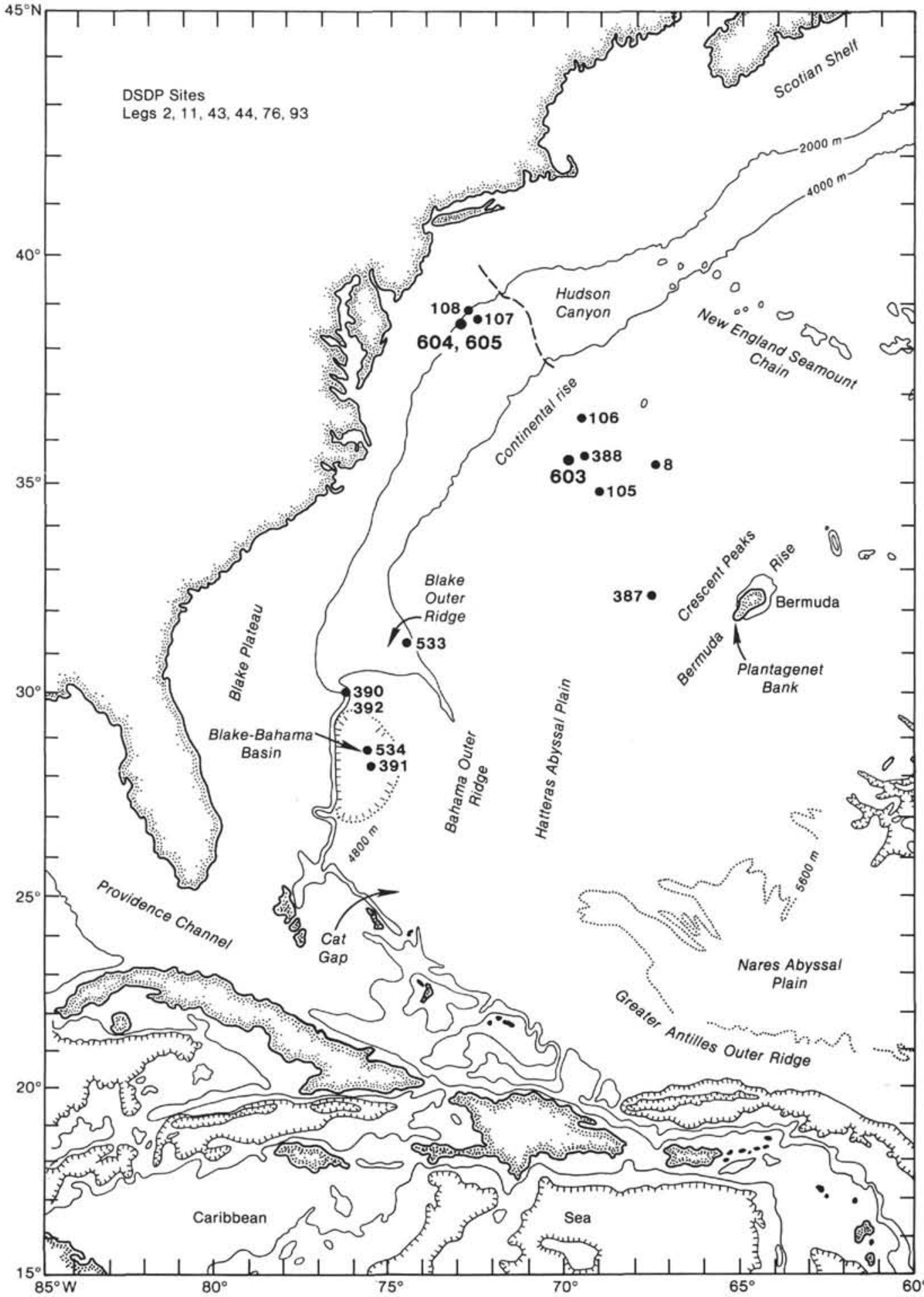

Figure 1. Location map with physiographic features of the North American Basin and location of DSDP sites from Legs 2, 11, 43, 44, 76, and 93. During Leg 93, Site 603 was drilled on the lower continental rise in 4633 m water depth; Site 604 (2340 m water depth) and Site 605 (2197 m water depth) were drilled on the continental slope. Bathymetry after Uchupi, 1971.

recover any sediment owing to a failure in setting the re-entry cone. Hole 603B was washed to 927 m sub-bottom depth and then rotary cored continuously to a depth of 1576 m. As a result of technical problems at Hole 603B, Upper Jurassic oceanic crust was not recovered (see Site 603 chapter, Operations Report, this volume). From Hole 603B, 484.44 m of middle Miocene to upper Berriasian strata were recovered from a 1576-m section that was cored. Hole 603C was drilled by using a hydraulic piston corer and extended core barrel, and recovered 314.44 m of strata that are found to record the development of the continental rise during the late Cenozoic. Notwithstanding the difficulties encountered in Hole 603B, an excellent lower Pleistocene to Lower Cretaceous section was recovered from Site 603. DSDP Leg 95 later returned to Site 603, and three unsuccessful attempts (Holes 603D, E, and F) were made to deepen the cored record at Site 603.

The purpose of this chapter is to summarize the sedimentological history of the lower continental rise from the post-early Aptian at Site 603. It should be noted that Leg 95 focused on recovery of Valanginian and older strata, and for this reason there is no discussion of those results in this chapter. See Ogg et al. (this volume) for a synthesis discussion of the Berriasian to Aptian strata (Blake-Bahama Formation) at Site 603, Sarti and von Rad (this volume) for a detailed account of Early Cretaceous turbidite sedimentation of the "Hatteras deep-sea fan," and Haggerty (this volume) for a discussion of the petrology and stable isotopic composition of macrofossils and sediments from Lower Cretaceous pelagic limestones at Site 603.

LITHOSTRATIGRAPHY

The sedimentary section recovered at Site 603 is divided into five lithologic units (I through V, see Fig. 2 and Table 1) based on composition, color, and degree of lithification. The five lithologic units penetrated at Site 603 can be correlated with the oceanic formations proposed for the western North American Basin by Jansa et al. (1979). Slight facies differences exist between the units recovered at Site 603 and the "type sections" of the "oceanic formations" at other DSDP sites, because Site 603 has received more terrigenous sediment derived from the adjacent North American continent. Also, Subunits IB to IVC at Site 603 were deposited near or below the calcite compensation depth (CCD), thereby enhancing the character of the noncarbonate components in the sediment. The majority of the carbonate grains contained in Subunits IB to IVC were transported downslope and were rapidly buried.

This chapter focuses on the sedimentological history recorded in Units I through IV at Site 603 in an attempt to interpret the development and evolution of the continental rise since the late Aptian. These four lithologic units are described in the sequence drilled from the sediment/water interface to 1215 m sub-bottom depth. A brief discussion of Unit V (upper Berriasian–lower Aptian strata) is also included to maintain perspective on the depositional history at Site 603, progressing from strictly pelagic sedimentation to an interaction with continent-influenced sedimentation. A detailed lithologic description of the units is provided in the Site 603 chapter (this volume). In this section, we summarize the interesting and characteristic features of each unit and describe important features not discussed in detail in the site chapter or in the speciality papers.

Unit I (Blake Ridge Formation)

Lithologic Unit I is composed of 960 m of hemipelagic clay–claystone that is slightly to moderately bioturbated with well-preserved ichnofossils (Fig. 3). Pyrite, siderite, and manganosiderite occur as nodules, burrow fills, and layers in the hemipelagic sediment (see von Rad and Botz, this volume, for details). The strata are dated as early Pleistocene to middle Miocene using foraminifers, nannofossils, radiolarians, and fish teeth. Some watery mud trapped by the core liner above the sediments recovered in Core 603C-1 is dated as Holocene on the basis of the foraminiferal assemblage.

Unit I is divided into four subunits on the basis of minor constituents contained in the clay–claystone. All of the subunits contain trace to rare amounts (1–5% by smear slide analysis) of heavy minerals, glauconite, and pyrite framboids.

Subunit IA

Subunit IA is composed of greenish gray to dark greenish gray nannofossil-bearing clay–claystone, and is differentiated from Subunit IB, composed of quartz-mica-bearing claystone, by the abundance of calcareous microfossils throughout Subunit IA. There is no color or textural difference between Subunit IA and the underlying claystone of Subunit IB.

Subunit IB

Subunit IB cores are primarily claystone and silt-bearing claystone, but below Core 603-37 (660 m sub-bottom depth) the amount of silt-sized terrigenous material increases. Calcareous microfossils are almost completely absent from Subunit IB. Microfossils diminish in numbers and diversity downhole in this subunit, indicating deposition in the vicinity of a fluctuating CCD. Calcareous benthic foraminifers are rare or absent, and only a few agglutinated foraminiferal species are representative of the sporadically occurring benthic assemblages. Nannofossils are found in extremely rare thin laminae of nannofossil-bearing to nannofossil-rich claystone in Cores 603-26 to -31, and Cores 603-33 to -41. The majority of the carbonate found in Subunit IB is siderite as burrow fills, thin layers, and nodules or concretions (Fig. 4). The authigenic siderite may have derived its source of carbonate ions from dissolution of *in situ* biogenic calcite from the microfossils. Below a sub-bottom depth of 120 m, siderite is found throughout Unit I; however, it is most abundant in Subunits IB and IC. The base of Subunit IB is placed above the uppermost occurrence of radiolarians.

Subunit IC

In Subunit IC, a slightly paler green color is associated with the claystone that contains more biogenic silica. Calcareous microfossils are almost completely absent from Subunit IC; the exception is the presence of dissolution-resistant discoasters. A moderately preserved radiolarian assemblage is used for determining the middle to late Miocene biostratigraphic age.

In addition to the biogenic silica as a characteristic feature of Subunit IC, this subunit also contains evidence of turbidite or sandy contourite deposition during the middle Miocene. These thin laminated deposits are rare in Subunit IC (a total of 12 occurrences in 11 cores) but are key primary sedimentary structures used for interpreting the evolution of the continental rise. As these

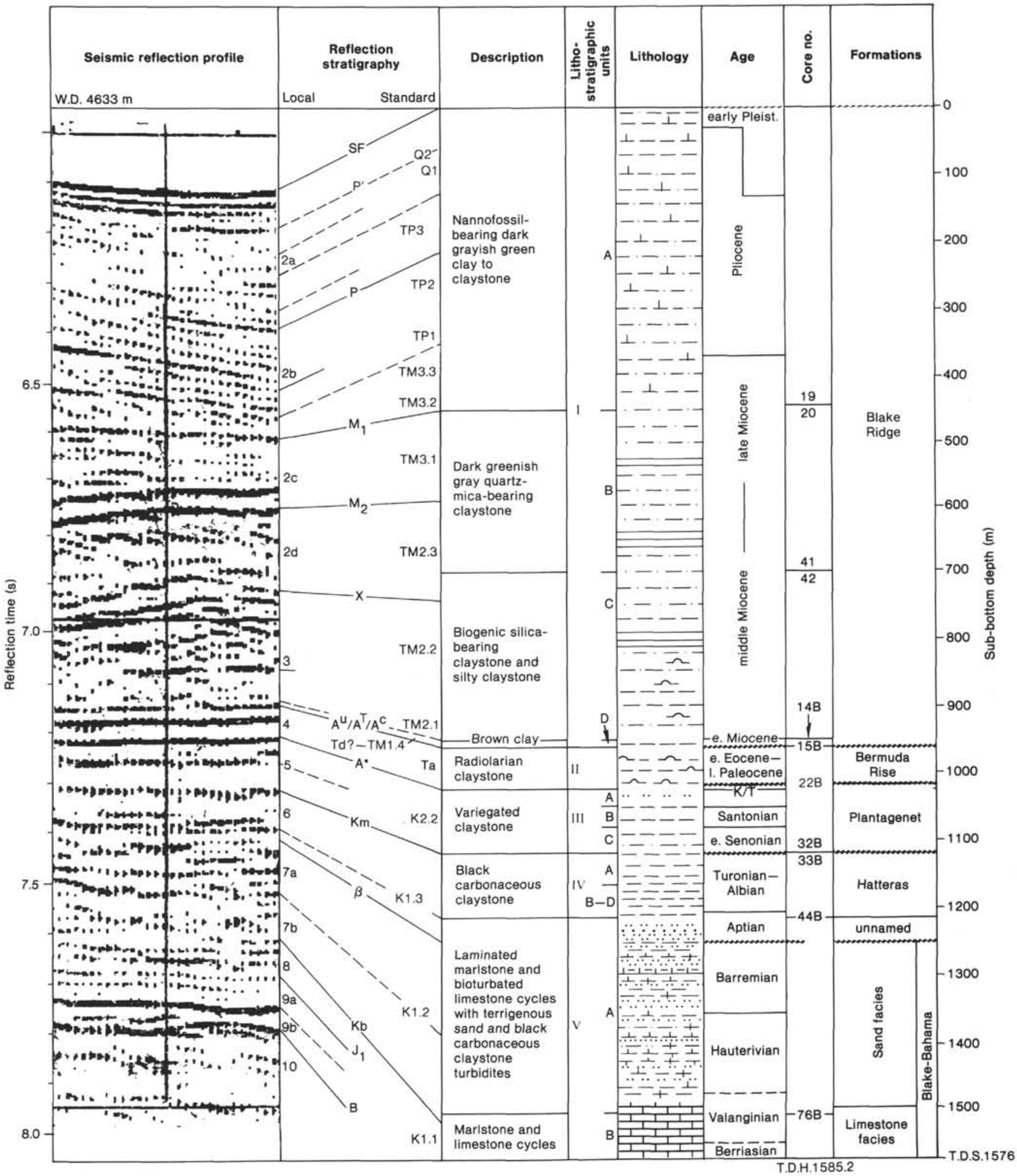

Figure 2. Stratigraphic summary of Site 603 (Holes 603, 603A, 603B, 603C). Units I to V are local lithostratigraphic units. Units 1 to 10 are local seismostratigraphic units; standard seismic sequence notation after Vail et al. (1980).

Table 1. Site 603 lithostratigraphy.

Unit	Subunit	Lithology	Hole-Core-Section, cm level	Sub-bottom depth (m) (Hole)	Age
I		Hemipelagic clay–claystone	603-1 to 603-54,CC 603B-1 to -15-4, 45 cm 603C-1 to -40,CC 603D-1 603E-1 603F-1M to 2M	0–960.75 (603B)	Pleistocene–middle Miocene
	IA	Nannofossil-bearing clay–claystone	603-1 to 603-19,CC 603B-1 to 603B-2,CC 603C-1 to 40,CC 603D-1 603F-1M	0–419.8/448.6 (603)	early Pleistocene–late Miocene
	IB	Quartz-mica-bearing claystone	603-20 to 603-41,CC 603B-3 to 603B-4-5 603F-2M	419.8/448.6–698.2 (603)	late Miocene
	IC	Biogenic silica-bearing clay–claystone and silt-bearing or silt-rich claystone	603-42 to 603-54,CC 603B-4-5 to -14-3, 65 cm 603E-1	698.2 (603)–949.85 (603B)	late Miocene–middle Miocene
	ID	Silt-rich claystone	603B-14-3, 65 cm to -15-4, 45 cm	949.85–960.75 (603B)	middle Miocene–middle early Eocene?
II		Radiolarian claystone	603B-15-4, 45 cm to -22-2, 68 cm 603F-3M	960.75–1022.78 (603B)	middle early Eocene–late Paleocene
III		Variegated claystone	603B-22-2, 68 cm to -33-1, 60 cm	1022.78–1119.1 (603B)	late Paleocene?–early Senonian
	IIIA	Variegated claystone without carbonaceous claystone	603B-22-2, 68 cm to -23,CC	1022.78–1038.6 (603B)	late Paleocene?–Santonian
	IIIB	Variegated claystone (greenish gray, reddish brown) and carbonaceous claystone	603B-24 to -29-2	1038.6–1083.8 (603B)	Santonian–late Coniacian?
	IIIC	Variegated claystone (reddish brown, greenish gray) and some carbonaceous claystone	603B-29-3 to -33-1, 60 cm	1083.8–1119.1 (603B)	early Senonian
IV		Black carbonaceous claystone	603B-33-1, 60 cm to -44-1, 32 cm	1119.1–1214.72 (603B)	Turonian–Aptian
	IVA	Black carbonaceous and pelagic greenish gray claystone, lacking any reddish brown color	603B-33-1, 60 cm to -38-2	1119.1–1166.5 (603B)	Turonian–Cenomanian
	IVB	Less black carbonaceous, more pelagic (greenish gray and reddish brown) claystone	603B-38-3 to -41-4	1166.5–1196.5 (603B)	Albian
	IVC	Black carbonaceous and pelagic (greenish gray only) claystone	603B-41-5 to -42,CC	1196.5–1204.8 (603B)	early Albian
	IVD	Pelagic greenish gray, reddish brown claystone with less black carbonaceous claystone	603B-43-1 to -44-1, 32 cm	1204.8–1214.72 (603B)	Aptian
V		Interbedded laminated marlstone and bioturbated limestone with sandstone to claystone turbidites	603B-44-1, 32 cm to -82,CC 603E-2M to 4M 603F-4M to -9,CC	1214.72–1576.2 (603B)	Aptian–late Berriasian
	VA	As above with the turbidites	603B-44-1, 32 cm to -76-1, 120 cm 603E-2M to 4M 603F-4M to 5M	1214.7–1512.3 (603B)	Aptian–late Valanginian
	VB	As above without the turbidites	603B-76-1, 120 cm to 603B-82,CC 603F-6 to -9,CC	1512.3–1576.2 (603B)	late Valanginian–late Berriasian

Note: M indicates mixed sediment from washed core; see Site 603 chapter (this volume).

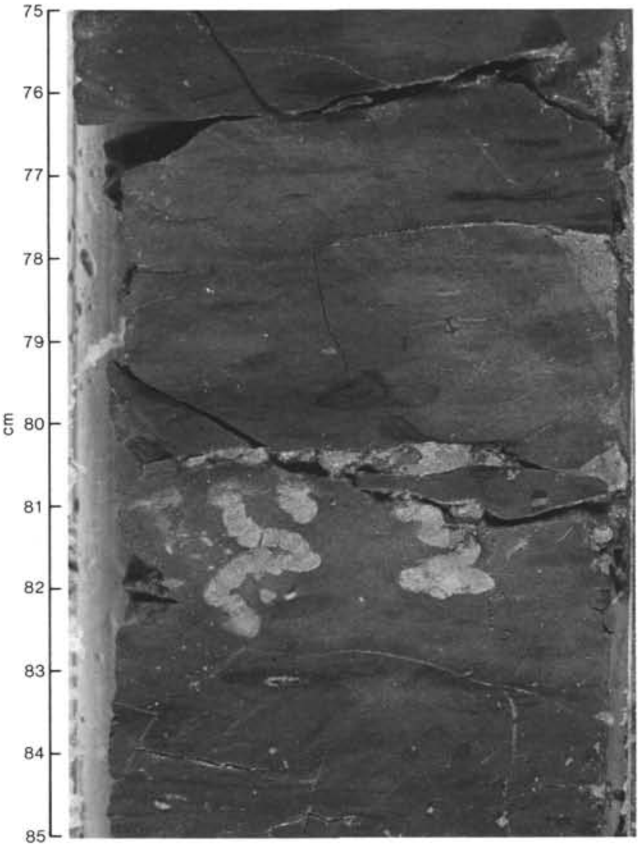

Figure 3. Well-preserved burrows in lithologic Unit I (Sample 603B-12-3, 75–85 cm).

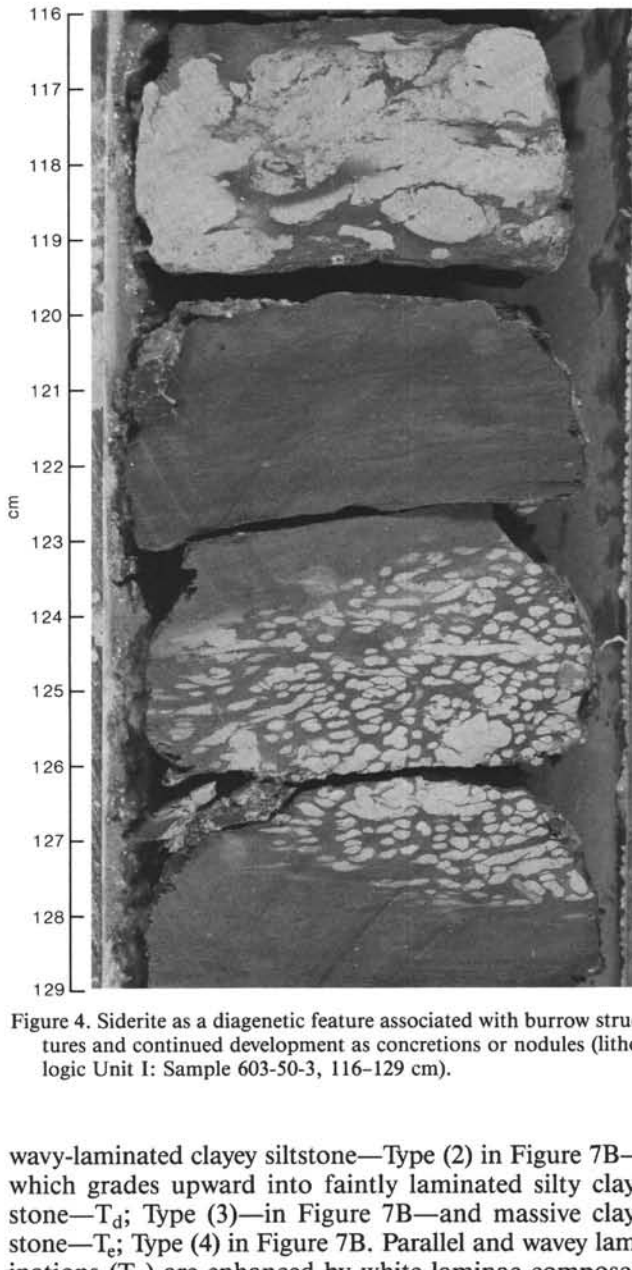

Figure 4. Siderite as a diagenetic feature associated with burrow structures and continued development as concretions or nodules (lithologic Unit I: Sample 603-50-3, 116–129 cm).

structures are not described in detail in the site chapter or in the speciality papers, we include the following account.

In the upper part of Subunit IC, at 719.5 m sub-bottom depth (Sample 603-44-2, 63–64 cm), we found a silt-rich claystone exhibiting a basal scour feature. This claystone is overlain by a rippled, cross-laminated, silt layer that grades upward into bioturbated claystone (Fig. 5). The core catcher of Core 603-48 contains a "drilling biscuit" (757.4 m sub-bottom depth) exhibiting a parallel-laminated silt layer, 1 cm thick, with a sharp basal contact, and a gradational upper contact that is ultimately obscured by drilling disturbance (Fig. 6). Although two 1-cm-thick layers in Subunit IC from Hole 603 are questionable evidence of turbidity current deposition, these layers do provide evidence of some form of scour and redeposition in these sediments from the continental rise.

The evidence of turbidite deposition is less ambiguous in Subunit IC below 827 m sub-bottom depth in Hole 603B than in Hole 603. Turbidites occur sporadically throughout this subunit in Cores 603B-5, -7, -8, -12, and -13. Sample 603B-5-4, 14–32 cm contains a series of drilling biscuits of more indurated material separated by softer sediment (Fig. 7A), which display at least two distinct turbiditic layers (15–22 cm, and 22–31.5 cm). The identification of a Bouma sequence is ambiguous because of intense drilling disturbance. Each bed consists of parallel-laminated—T_b; Type (1) in Figure 7B—and wavy-laminated clayey siltstone—Type (2) in Figure 7B—which grades upward into faintly laminated silty claystone—T_d; Type (3)—in Figure 7B—and massive claystone—T_e; Type (4) in Figure 7B. Parallel and wavey laminations (T_b) are enhanced by white laminae composed primarily of quartz silt. Rare bioturbation has occurred in the wavey laminated siltstone at 21 cm in Figure 7. Oblique laminated ripples consisting of white, clean, well-sorted silt are isolated within the laminated siltstone. White siltstone laminae and lenses might represent the product of current reworking and sediment sorting. These laminations appear to be slightly inclined (Fig. 7), but this could be the result of draping around siltstone lenses or a slight change in orientation of the drilling biscuit. This sequence (Fig. 7B) is repeated with a finer grain size and then appears to be overlain by a pelite interval (T_e, or mud interval of a turbidite).

Sample 603B-7-1, 70–87 cm contains another possible turbidite with sharp basal scouring into the underlying claystone (Fig. 8). The base is composed of parallel-laminated, clay-rich, quartz siltstone (T_b, Fig. 8B, 82–

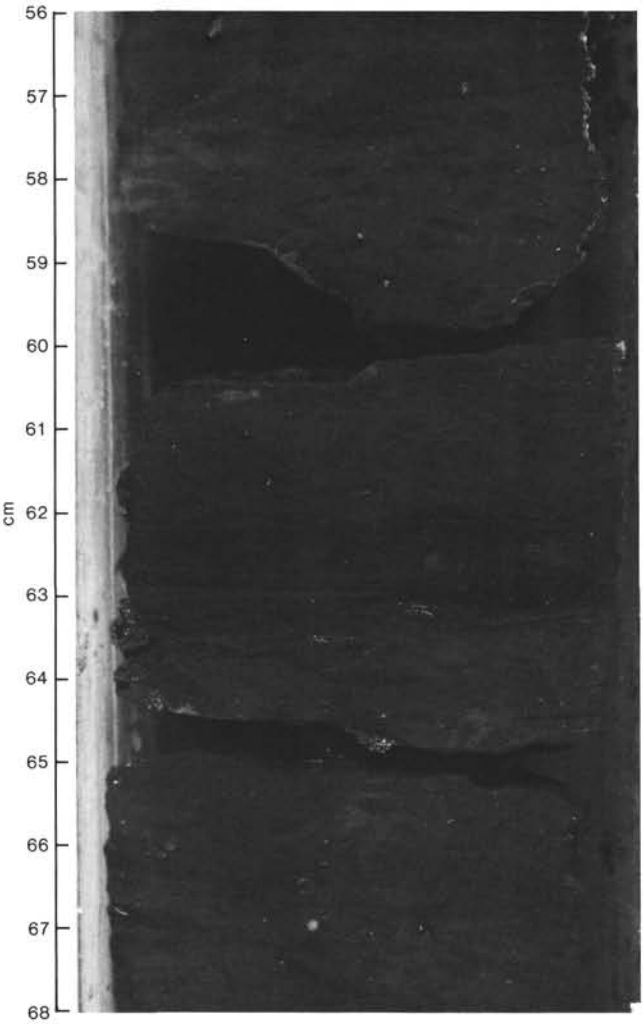

Figure 5. Thin turbidite layer located at 62–64 cm (Subunit IC, Sample 603-44-2, 56–68 cm).

86 cm) overlain by faintly laminated silty (or silt-rich) claystone (T_d, Figure 8B). Above these laminations, from 70 to 77 cm, is structureless organic matter- and quartz-bearing dark gray claystone, possibly the mud interval (T_e) of a turbidite. No bioturbation is present throughout this turbidite sequence.

In Core 603B-12, four small-scale (less than 10 cm in thickness) turbidites occur in the grayish green claystone. These typically are dark gray in color, with parallel laminations and a sharp base (Fig. 9). Within the area of laminations are rare wavy laminations. In Core 603B-12, these four layers are interpreted as mud turbidites and occur interbedded with hemipelagic mud. This phenomenon of mud turbidites interbedded with hemipelagic mud has been previously noted at Site 368 on the Cape Verde Rise by Dean et al. (1978) and at other DSDP sites in the Blake-Bahama Basin (Sheridan, Gradstein, et al., 1983).

The remainder of the turbidite deposits in Subunit IC from Hole 603B are similar to one of the three above-illustrated examples. These thin-laminated deposits are uncommon but characteristic of Subunit IC. A total of 12

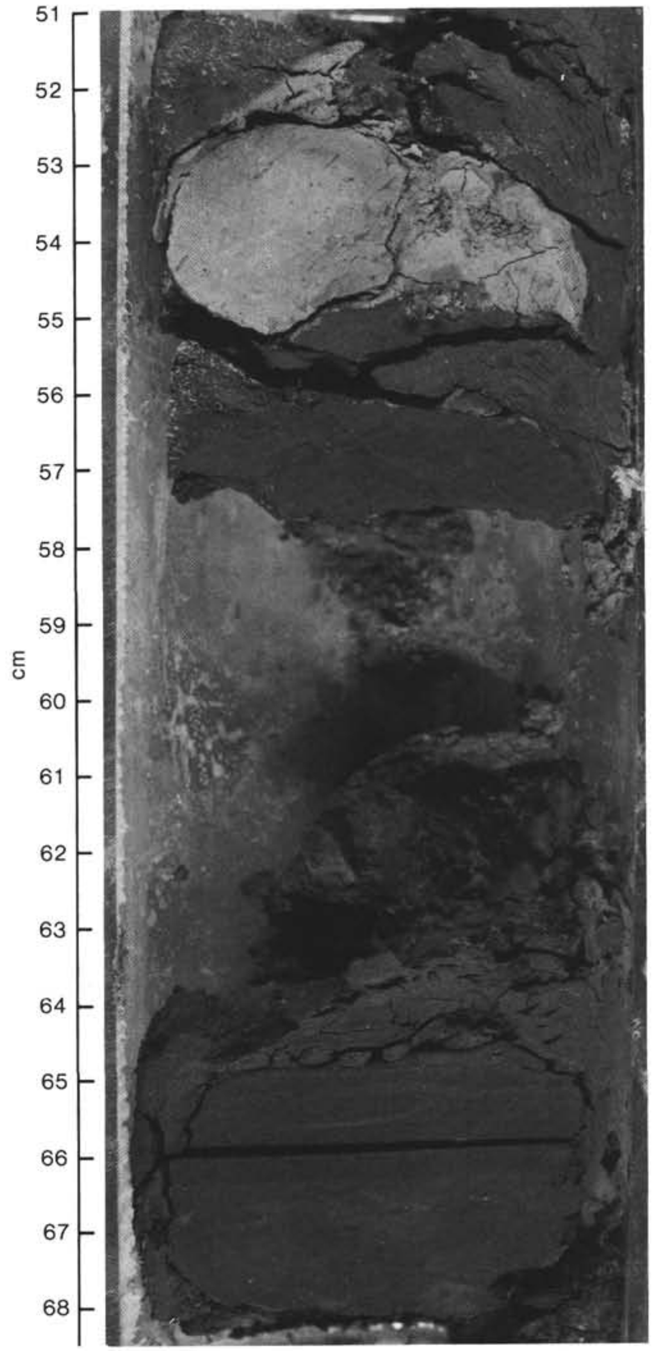

Figure 6. Turbidite below siderite nodule in Subunit IC, located in a "drilling biscuit" at the interval marked 64.5–66.5 cm (Sample 603-48,CC).

such occurrences in 11 cores is interpreted as deposition from sporadic turbidity currents.

The deposits in Subunit IC do not appear to fit the definition of a sandy contourite (Hollister and Heezen, 1972): that is, clean, well-sorted, fine-grained sands or silts in well-defined layers from 0.1 to 10 cm thick (generally less than 5 cm) with sharp upper and lower contacts, have either normal or reverse grading, are commonly cross-bedded, and have significant concentrations of heavy minerals along the oblique laminae (see discus-

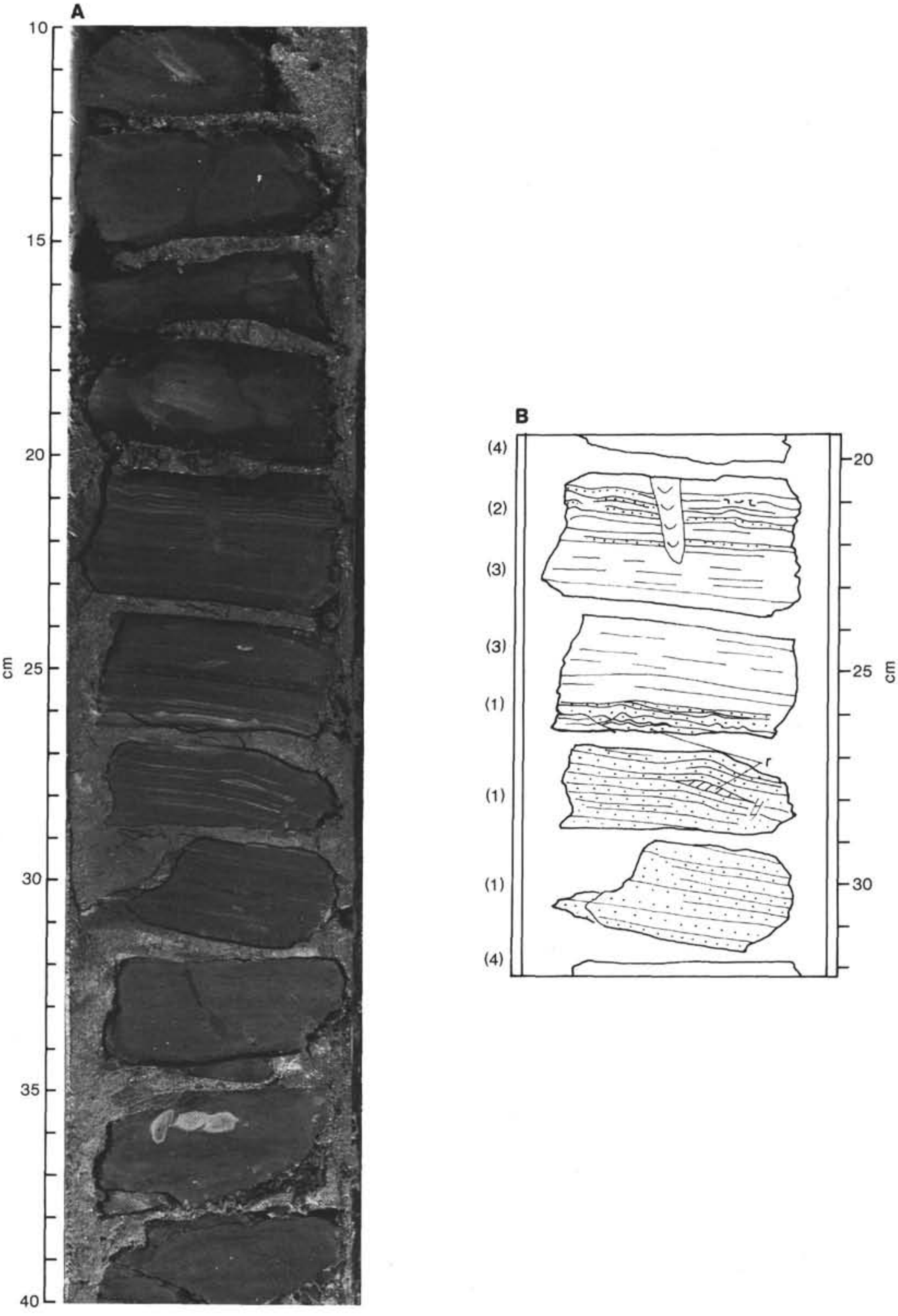

Figure 7. A. Turbidite sequence in Subunit IC (Sample 603B-5-4, 10–40 cm). B. Schematic representation of Figure 7A with centimeter notation for ease of identification with core photo. Type (1): parallel-laminated, clay-rich siltstone–fine-grained sandstone with isolated lenses of oblique laminated white siltstone; laminae are downwarped and contain wavy white draping siltstone lenses (r = ripples). Type (2): wavy laminated siltstone; locally disrupted at 21–23 cm by a vertical burrow. Type (3): faintly parallel-laminated silty claystone. Type (4): massive claystone; lamination is enhanced by white, well-sorted siltstone laminae. Types (1), (3), and (4) probably correspond to the intervals b, d, and e of the Bouma sequence, respectively.

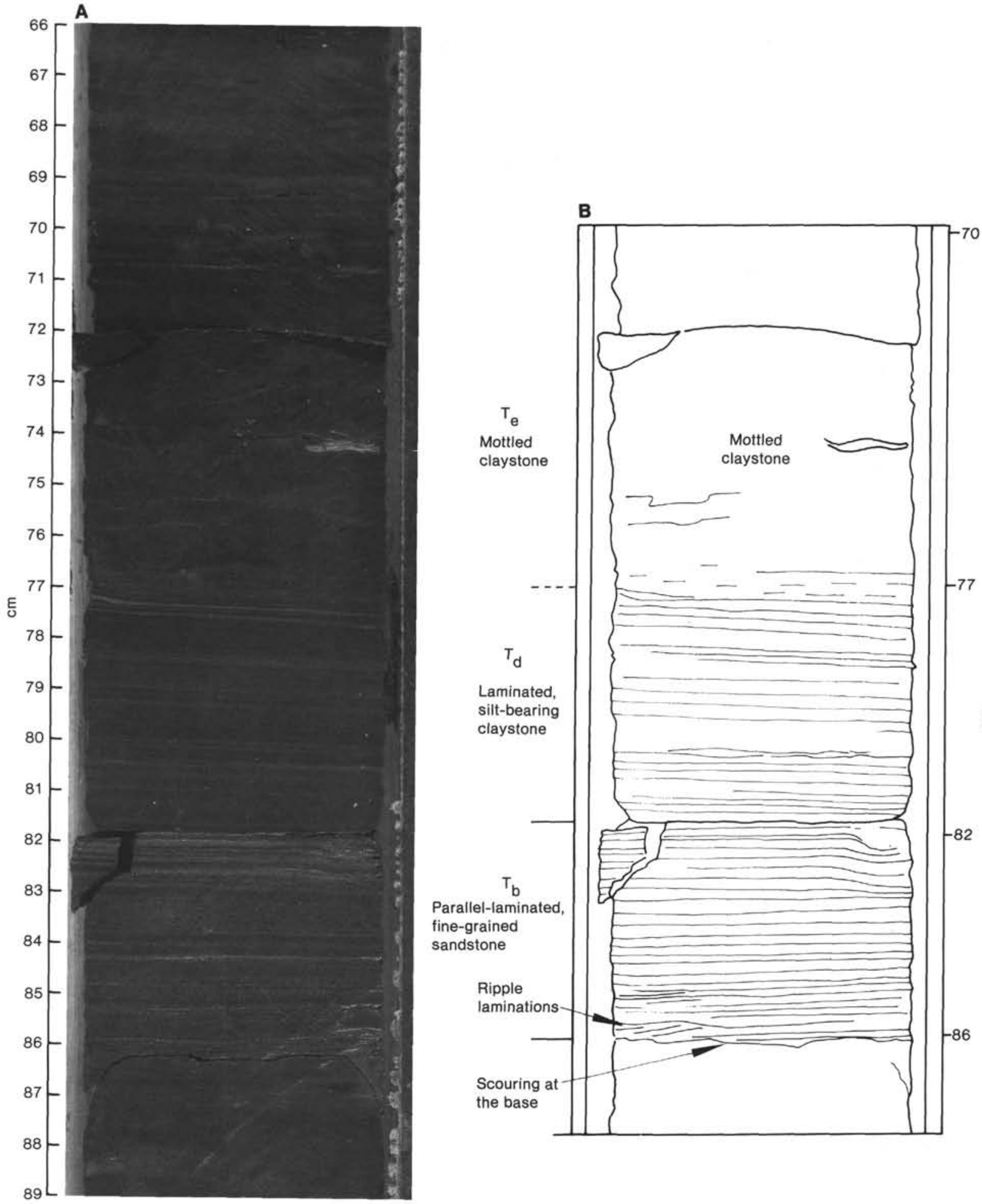

Figure 8. A. Distal turbidite sequence in Subunit IC (Sample 603B-7-1, 66–89 cm). B. Schematic representation of Figure 8A with centimeter notation for ease of identification with core photo. Bouma turbidite intervals are also marked.

sion of Bottom Current Deposits in Site 603 chapter, this volume). In the previous example from Section 603B-7-1 (Fig. 8), an interval (possibly T_e) is composed of organic matter- and quartz-bearing claystone. From smear-slide analysis, this mud interval contains significantly more organic matter than the hemipelagic intervals. It would be hard to conceive of a contour current retaining and enriching the resultant deposit in organic material. These uncommon deposits in Subunit IC consisting of siltstone/mudstone couplets, showing a Bouma-like type sequence, and interbedded with hemipelagic claystone, are indicative of deposition by turbidity currents. However, fea-

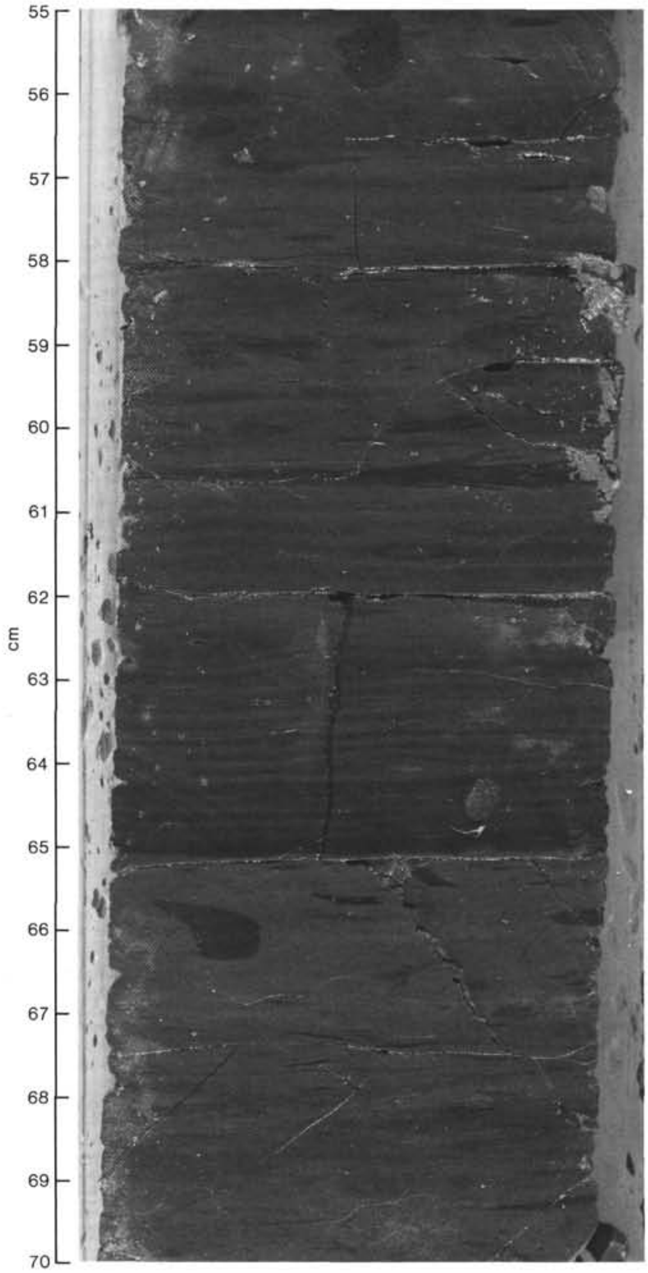

Figure 9. Turbidite of hemipelagic claystone in Subunit IC (Sample 603B-12-3, 55–70 cm).

tures such as sediment-starved ripples and laminae of white, highly mature silt, observed in Figure 7, might be the result of partial reworking of turbidite silt.

Subunit ID

Subunit ID is differentiated from the base of Subunit IC by a change in color to grayish brown associated with the mica-rich claystone of Subunit ID. In contrast to the overlying subunits, Subunit ID is barren of calcareous and siliceous microfossils, but contains fish teeth of possible early Miocene age (Section 603E-1-1; see Hart and Mountain, this volume). A rapid downhole decrease in bioturbation is also noted in the sediment of Subunit ID. Manganese concretions occur in Core 603B-14 in Section 3 at 90 cm, and in Section 6 at both 7 and 65 cm. These concretions are not noted in the overlying cores. Near the base of subunit ID (Core 603B-15), there is a slight color change from yellowish brown to brown, and the appearance of 1-mm laminations of a red, silt-rich claystone. Smear-slide analysis shows a trace amount of zeolites as a new component. The base of Unit I is easily differentiated from Unit II by the dramatic color change from brown to pale green and a lithologic change from silt-rich claystone to radiolarian claystone (at 47 cm in Fig. 10; Frontispiece Fig. A, this volume). This abrupt change between the middle Miocene brown, silt-rich claystone and the lower Eocene green, radiolarian claystone coincides with the seismic reflector A complex ($A^u/A^T/A^c$, see Fig. 2).

Discussion

Unit I drilled at Site 603 may be directly compared to the Blake Ridge Formation defined by Jansa et al. (1979) at DSDP Site 106. Unit I correlates with the upper part of the type section from the Blake Ridge Formation (Cores 106-1 to 106-6), consisting of lower Pleistocene -lower Miocene, greenish gray and brown hemipelagic muds that contain abundant mica and quartz. Additional mutual characteristics, found in the type section of the Blake Ridge Formation and Unit I of Site 603, are pyrite and siderite burrow fills. Also, Jansa et al. (1979) state that the seismic reflector Horizon A^u marks the base of the Blake Ridge Formation along the continental margin; farther seaward where the unconformity does not erode the underlying Bermuda Rise Formation, the base of the Blake Ridge Formation correlates with Horizon A^c. The seismic reflector A complex is located at the boundary between Unit I and Unit II at Site 603.

Unit II (Bermuda Rise Formation)

Lithologic Unit II, from 961 to 1023 m sub-bottom depth, is composed primarily of a colorful radiolarian claystone and is the local equivalent of the Bermuda Rise Formation. The biostratigraphic age of this strata is middle early Eocene to late Paleocene. Manganese nodules characteristically occur in the reddish brown (well-oxidized) facies, and rhodochrosite nodules are sporadically disseminated in the greenish gray, more organic-carbon-rich (partially reduced) facies (von Rad and Botz, this volume). The colorful nature of this unit is also the expression of an enrichment in transition elements. Geochemical analysis revealed high concentrations of Co (150 ppm) and Ni (210 ppm) in one sample, and two samples had high concentrations of Cu (160 and 210 ppm). These transition elements are interpreted to have diffused upward from the underlying black claystone in Unit IV (Dean and Arthur, this volume).

The uppermost 10 m of this strata are bioturbated and extremely colorful, with hues ranging from pale green, reddish brown, yellow brown, pale orange, to dark brown and black. Core 603B-16 has been informally named "The Halloween Core" (see Frontispiece Fig. B, this volume) because of these vivid orange and brown colors. The reddish brown claystones contain more hematite and iron

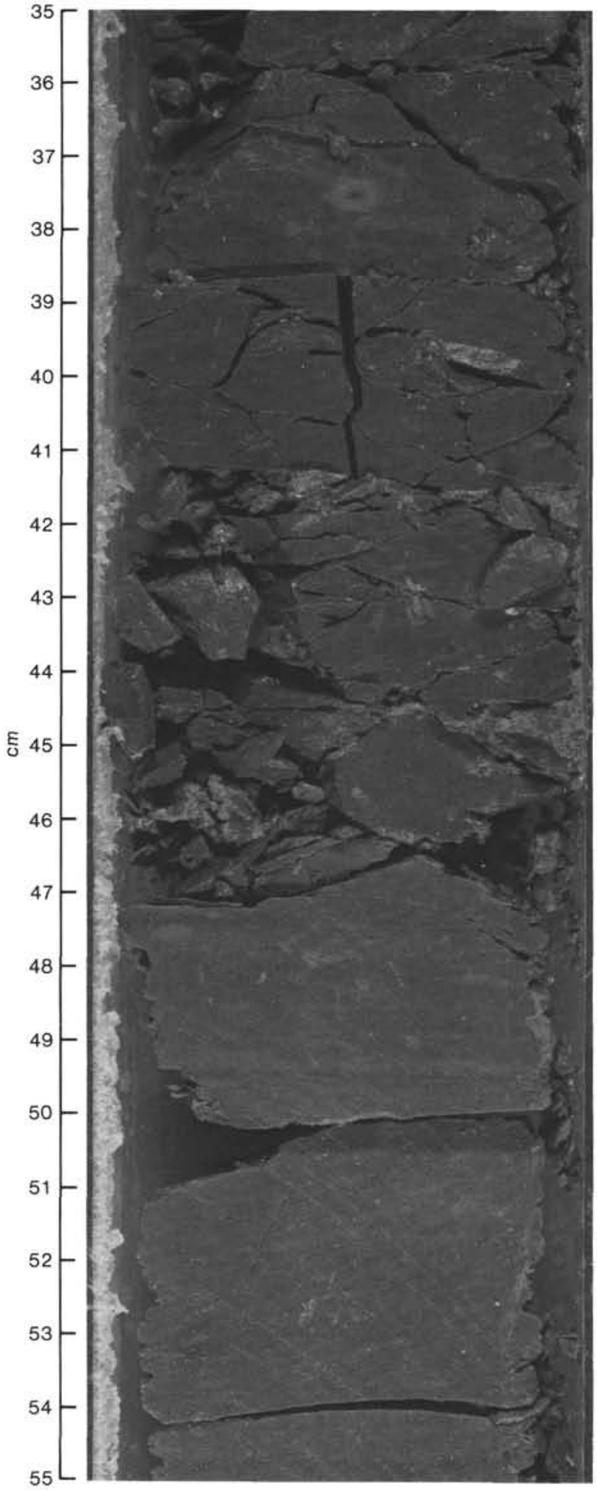

Figure 10. Boundary between Units I and II at Site 603 is located at 46 cm. (See Frontispiece Fig. A, this volume, for color photo.) Interval 603B-15-4, 35–55 cm.

oxides than the grayish green claystones. Millimeter-thick black layers, in Cores 603B-15, 603B-16, and 603B-18, appear as discrete layers of iron-manganese crusts or iron-manganese impregnated claystone. The black layers are not concentrations of organic matter. A sample of black claystone in Core 603B-16 that was analyzed for manganese has an enriched concentration of 1.67% manganese oxide (Dean and Arthur, this volume).

Below Core 603B-16, some centric diatoms appear sporadically in the sediment, and bioturbation is rare. Faint laminations containing laminae with concentrations of recrystallized radiolarians alternate with laminae practically devoid of radiolarians (Fig. 11). Some of the laminations change to lenses (3–5 mm in length) filled with radiolarians displaying incipient diagenesis. The diagenesis converted a small portion of the biogenic opal to opal-CT (porcelaneous radiolarian claystone), but not in a sufficient amount for the rock to be classified as a porcellanite. Toward the base of the unit, diffuse concentrations of scattered tiny rhodochrosite crystals (mostly twins) appear as if sprinkled in the core (Fig. 12; see von Rad and Botz, this volume). Zeolites are also present in the strata below Core 603B-16, and they occur in sufficient quantities to form white lenses of zeolitic silt in Core 603B-19. The only strong evidence of turbidity-current deposition in Unit II occurs at the very base of the unit; two graded siltstone layers are overlain by radiolarian-rich claystone.

Discussion

Unit II drilled in Hole 603B is the local equivalent of the Bermuda Rise Formation that is characterized by sediment enriched in biogenic silica and porcellanite. At

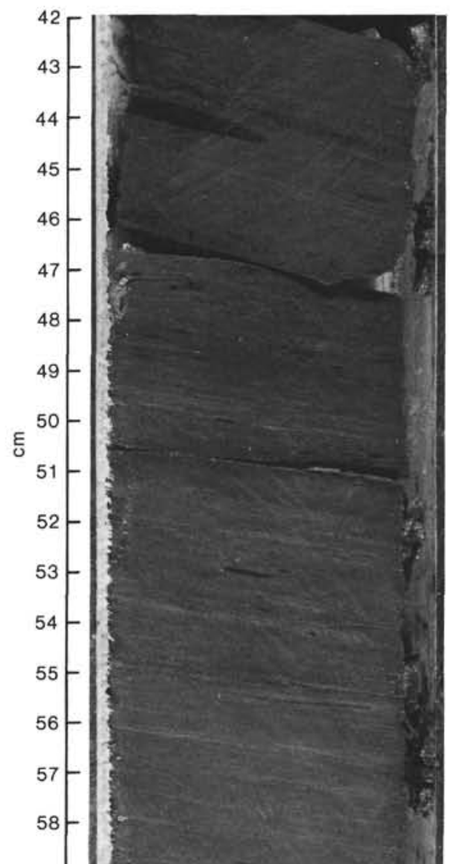

Figure 11. Faint parallel laminations are the characteristic primary sedimentary structure in Unit II (Sample 603B-18-3, 42–59 cm).

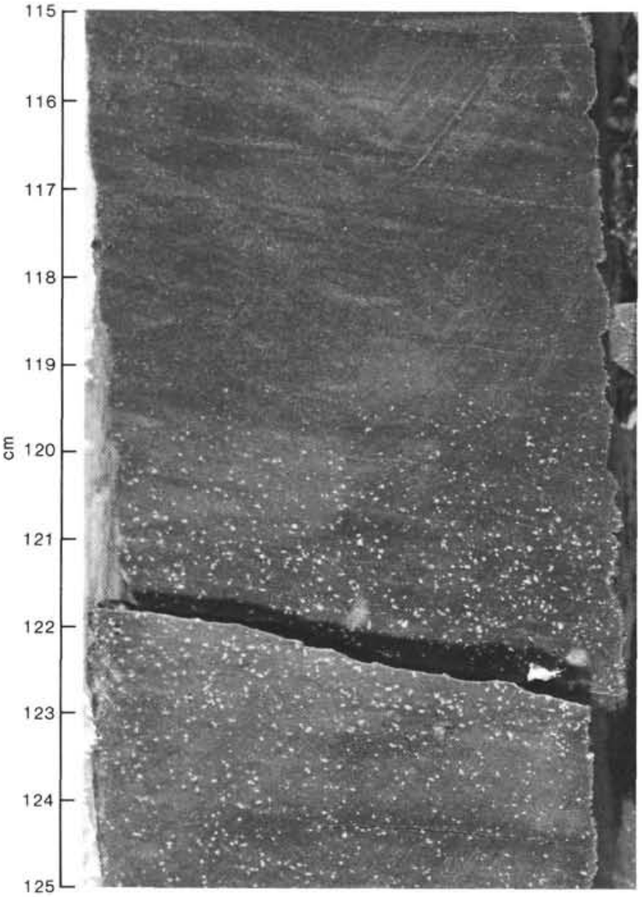

Figure 12. Diffuse concentrations of rhodochrosite crystals (mostly twins) alternating with layers practically devoid of recrystallized radiolarians in Unit II (Sample 603B-21-4, 115-125 cm).

the type locality of DSDP Site 387, the formation consists of 200 m of porcellanite, silicified claystone, radiolarian mudstone, and calcareous mudstone. The type locality also has "primary sedimentary structures and compositional variations (that) define cycles that are reminiscent of Bouma sequences" (Jansa et al., 1979, p. 33). At Site 387, the middle to upper Eocene siliceous turbidite and radiolarian mud sequence, which directly overlies the type Bermuda Rise Formation, exhibits no opal-CT but does contain up to 25% biogenic silica in some horizons (Benson, Sheridan, et al., 1978). A comparison of Unit II at Site 603 with Site 387 reveals that Unit II has no calcareous mudstone and only a few porcellanite layers, although porcelaneous mudstone-claystone and radiolarian claystone are present. The lack of well-developed, thick porcellanite layers is probably the result of inhibited silica diagenesis from the strong dilution of the biogenic silica with clays. Unit II therefore does not have as high an opal-CT content as the type section of the Bermuda Rise Formation drilled at DSDP Site 387 (see Thein and von Rad, in press). The radiolarians in the claystone at Site 603 are not opal-A preserved radiolarians, but appear only as radiolarian "ghosts" (Thein and von Rad, in press). Only the type section of the Bermuda Rise Formation at Site 387 has porcellanite as a common characteristic with Unit II at Site 603. Primary sedimentary structures such as parallel laminations are found throughout Unit II, but only two turbidite deposits are noted at the base of Unit II, similar to the characteristics of the type section at Site 387. During sediment deposition in the late Paleocene to early Eocene, the biogenic contribution was predominantly siliceous rather than calcareous because Site 603 was located below the CCD.

From the drill site data available in 1979, Jansa et al. (1979) interpreted that the Bermuda Rise Formation is missing beneath a major unconformity under the continental rise and in the Blake-Bahama Basin. Since 1979, DSDP Leg 76 (Sheridan, Gradstein, et al., 1983) drilled at Site 534 in the Blake-Bahama Basin (see Fig. 1) and recovered 48 m of strata that belongs to the Bermuda Rise Formation. This formation was not recovered at Site 391 (Sheridan, Enos, et al., 1978), only 22 km northwest of Site 534 in the Blake-Bahama Basin. Robertson (1983) therefore concluded that the discovery of this interval of the Bermuda Rise Formation at Site 534 points to less extensive seafloor erosion than previously suggested by Jansa et al. (1979). Robertson also noted that the distribution of the Bermuda Rise Formation is usually between the outer continental rise and the upper Eocene Mid-Atlantic Ridge. The recovery of the Bermuda Rise Formation beneath the lower continental rise at Site 603 confirms that the deep seafloor erosion associated with Horizon A^u was not as extensive as previously suggested by Jansa et al. (1979). The seismic reflector A complex is located at the boundary between Units I and II at Site 603.

Unit III (Plantagenet Formation)

Lithologic Unit III, from 1023 to 1119 m sub-bottom depth, is composed of Upper Cretaceous (early Paleocene?) variegated claystone, organic-rich claystone, and sand and silt turbidites. The boundary between the radiolarian claystone of Unit II and the variegated claystone of Unit III is marked by the color change to reddish brown and greenish gray, as well as the absence of microfossils in the claystone of the upper part of Unit III. Biostratigraphic ages of the subunits are based upon their contained microfossils: agglutinated foraminifers, radiolarians, and dinoflagellates. Discrete rhodochrosite layers formed by diagenesis are rare in this unit (e.g., Section 603B-29-2; von Rad and Botz, this volume).

The multicolored claystone of Unit III has a slight enrichment in the concentrations of several trace transition elements (Co, Cu, Ni, and Cr) but otherwise is similar in composition to red pelagic clay from the adjacent Hatteras Abyssal Plain (Dean and Arthur, this volume). The multicolored claystone is not enriched in iron or manganese. The slight enrichment in the transition metals may be caused by diffusion of these elements from the interbedded carbonaceous claystones of Unit III, or from the abundant underlying carbonaceous claystones of Unit IV (Dean and Arthur, this volume).

Unit III is divided into three subunits on the basis of the relative abundance of the carbonaceous claystone. The uppermost occurrence of these organic-rich claystones is in Subunit IIIB and continues downhole in Units

IV and V. Unit III (as well as Units IV and V) contains terrigenous silt and sand deposited by turbidity currents. Trace to rare amounts of organic matter (as plant debris), glauconite, and zeolites are contained in the variegated claystones that are interpreted to be *in situ*.

Subunit IIIA

In Subunit IIIA at 1023.3 m sub-bottom depth, a 3.5-cm-thick layer is composed of small bluish black and dark green spherules that are approximately 1 mm in diameter (Fig. 13). Geochemical studies (Klaver et al., this volume) indicate that these spherules are composed primarily of montmorillonite and that the spherules did not form in the sediment. Parallel and oblique laminae (Fig. 13B) suggest that these spherules were transported by a turbidity current. The original Cretaceous/Tertiary boundary clay apparently has been redistributed in the overlying silty claystone of the same turbidite (Fig. 13A). The spherules in Hole 603B contain nomalously high concentrations of Ni, Co, and As (Klaver et al., this volume). They are structurally and geochemically similar to montmorillonite spherules found in DSDP Hole 390B on the Blake Plateau, which were cored in a Cretaceous/Tertiary boundary section with abundant microfossils. The exotic bed containing green spherules at Site 603 is therefore interpreted as a turbidite bed that is composed

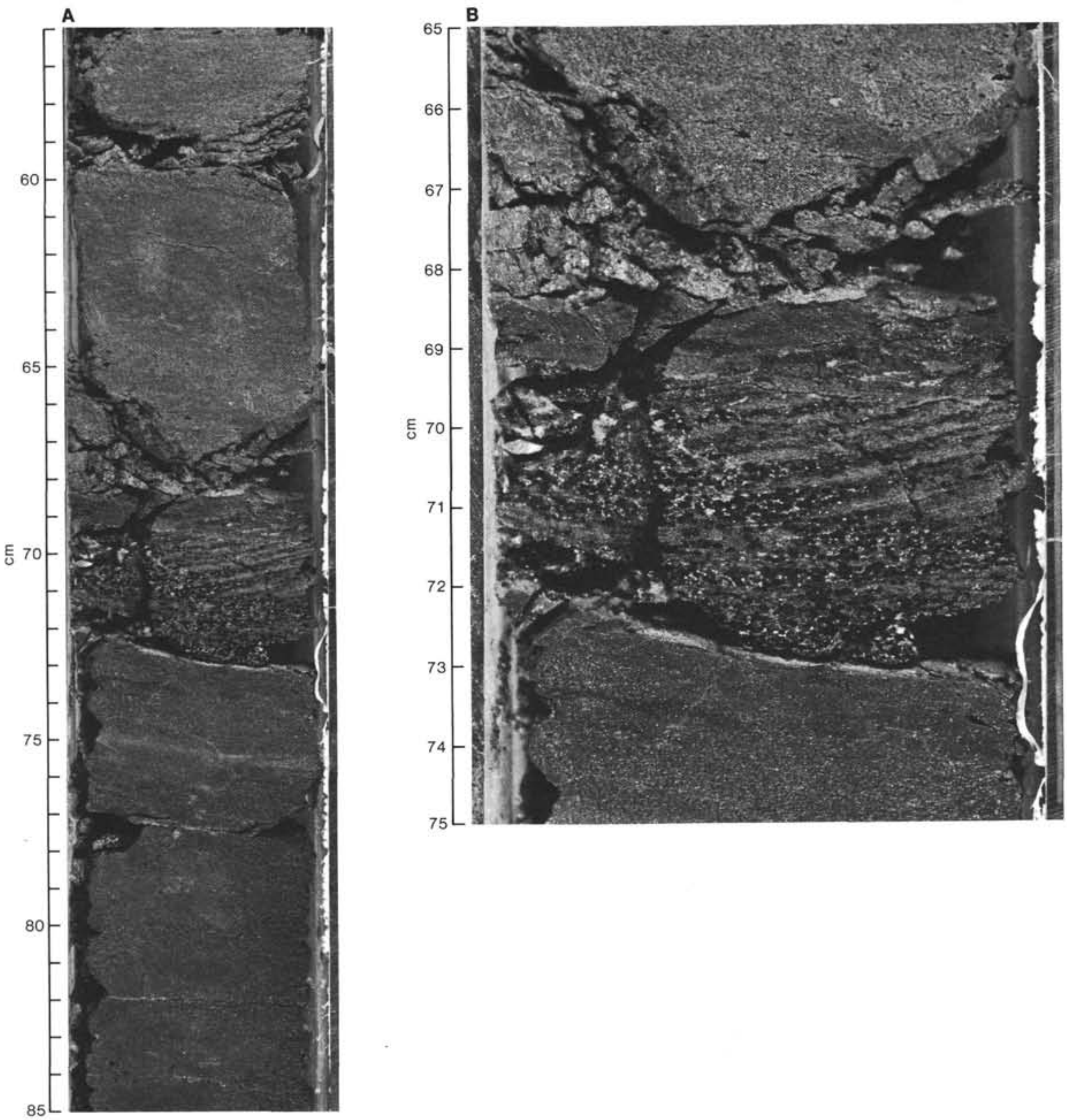

Figure 13. A. The 3.5-cm-thick layer (from 69.5 to 73 cm), at 1023.3 m sub-bottom depth, of current-deposited, small bluish black and dark green spherules in Subunit IIIA. The strata surrounding this layer are composed of a clayey, silty, fine-grained sandstone (Sample 603B-22-3, 56–85 cm). B. Close-up of Figure 13A. The spherules are approximately 1 mm in diameter and clearly associated with a current deposit (Sample 603B-22-3, 65–75 cm).

of reworked Cretaceous/Tertiary boundary sediments. (Klaver et al., this vol.). However, further geochemical analysis is necessary to determine if the Cretaceous/Tertiary global iridium anomaly is present in Hole 603B sediments.

Subunit IIIB

Subunit IIIB contains interbedded variegated claystone and carbonaceous claystone. Dinoflagellate stratigraphy indicates an age from late Coniacian or early Santonian to Santonian in Cores 603B-28 to -26 (Habib and Drugg, this volume). The uppermost occurrence of the carbonaceous claystone is in Santonian strata, and the organic matter in the claystone is predominantly terrigenous in origin (Habib and Drugg, this volume). Terrigenous silt layers are found in this subunit, as well as manganese-stained thin laminae (Fig. 14). The subunit also contains a 4-cm-thick zeolitic claystone (Fig. 15) that is interpreted as evidence of ash from nearby volcanic activity during the Late Cretaceous.

Subunit IIIC

Subunit IIIC is characterized by the predominance of variegated claystone containing some sand and silt turbidites. The biostratigraphic age of early Senonian is determined from assemblages of agglutinated foraminifers and radiolarian fauna (Biostratigraphy section, Site 603 chapter, this volume). Carbonaceous claystone is absent from this subunit. Rare thin black layers (<1 mm thick), which appear to be manganese stained, are also found in Subunit IIIC.

Discussion

Unit III is the local equivalent of the Plantagenet Formation of Jansa et al. (1979). This unit is condensed or is composed of hiatus-rich strata (manganese hardgrounds?) because it has the lowest sedimentation rate (3 m/m.y.) for the total section drilled at Site 603. The type locality at DSDP Site 386 has a 100-m-thick section, whereas DSDP Sites 7, 9, 105, 382, 385, 387, 391, and 534 (Hollister, Ewing, et al., 1972; Benson, Sheridan, et al., 1978; Sheridan, Gradstein, et al., 1983) have correlative sections that are about 20 m thick. Site 603 is the first site with a continuously cored, 100-m-thick section with a high recovery rate of this formation. Jansa et al. (1979) state that this formation lacks terrigenous input into the deep basin. As the result of the landward location of Site 603, this is the only DSDP site in the western North Atlantic that has terrigenous clastics reported from the Plantagenet Formation. Site 603 is also the first location to have carbonaceous claystone, containing terrigenous organic matter, reported from this formation.

Mechanisms for metal enrichment in the multicolored claystones of the Plantagenet Formation of the western North Atlantic have been previously addressed by many authors proposing different hypotheses. Lancelot et al. (1972) suggested that this metal enrichment was from volcanic exhalations; Murdmaa et al. (1978) proposed that the metal enrichment was related to slow sediment accumulation; and Arthur (1979) suggested that the enrichment was the result of upward diffussion of the elements from the underlying black shales of the Hatteras Formation. Robertson (1983) analyzed multicolored claystones from the Plantagenet Formation recovered at Site 534 in the Blake-Bahama Basin. He concluded that slow accumulation of sediment in strongly oxidizing bottom

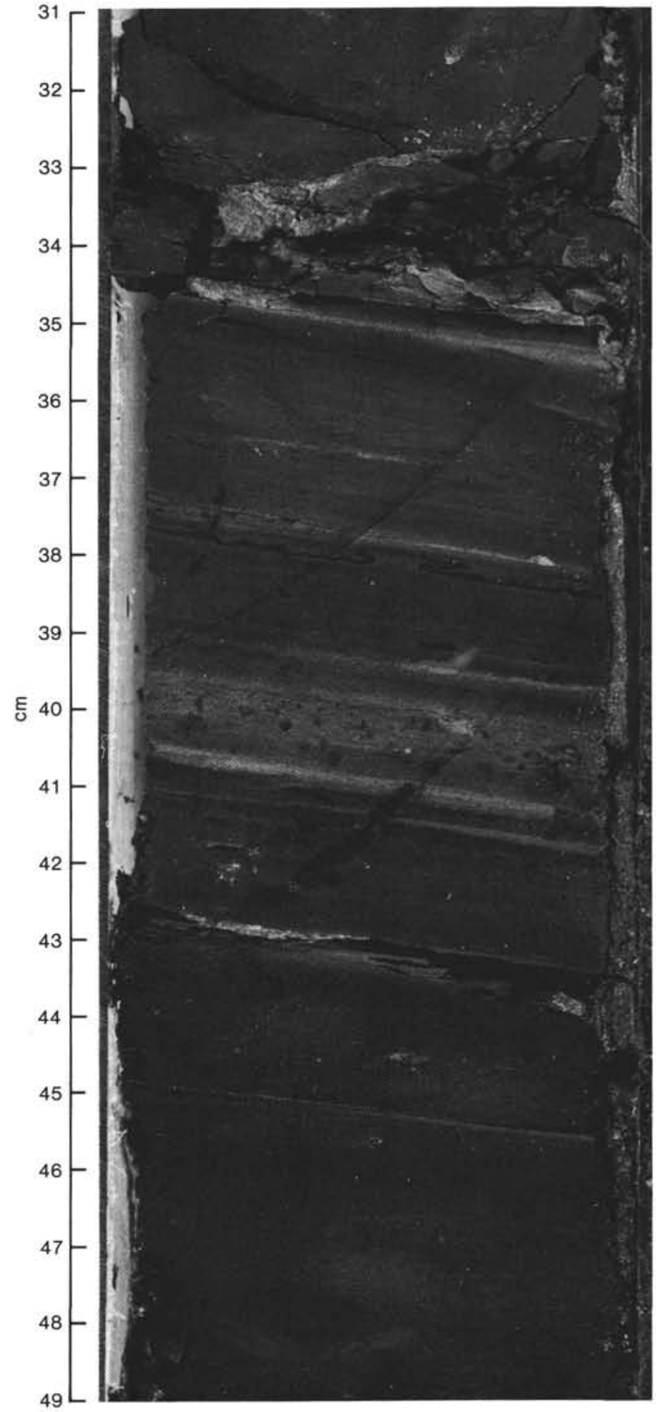

Figure 14. Subunit IIIB composed primarily of variegated claystone interbedded with carbonaceous claystone (not shown in photo) and numerous layers of terrigenous silt. Rare occurrence of manganese layer (<1 mm thick) is located at 38.5 cm (Sample 603B-28-4, 31–49 cm).

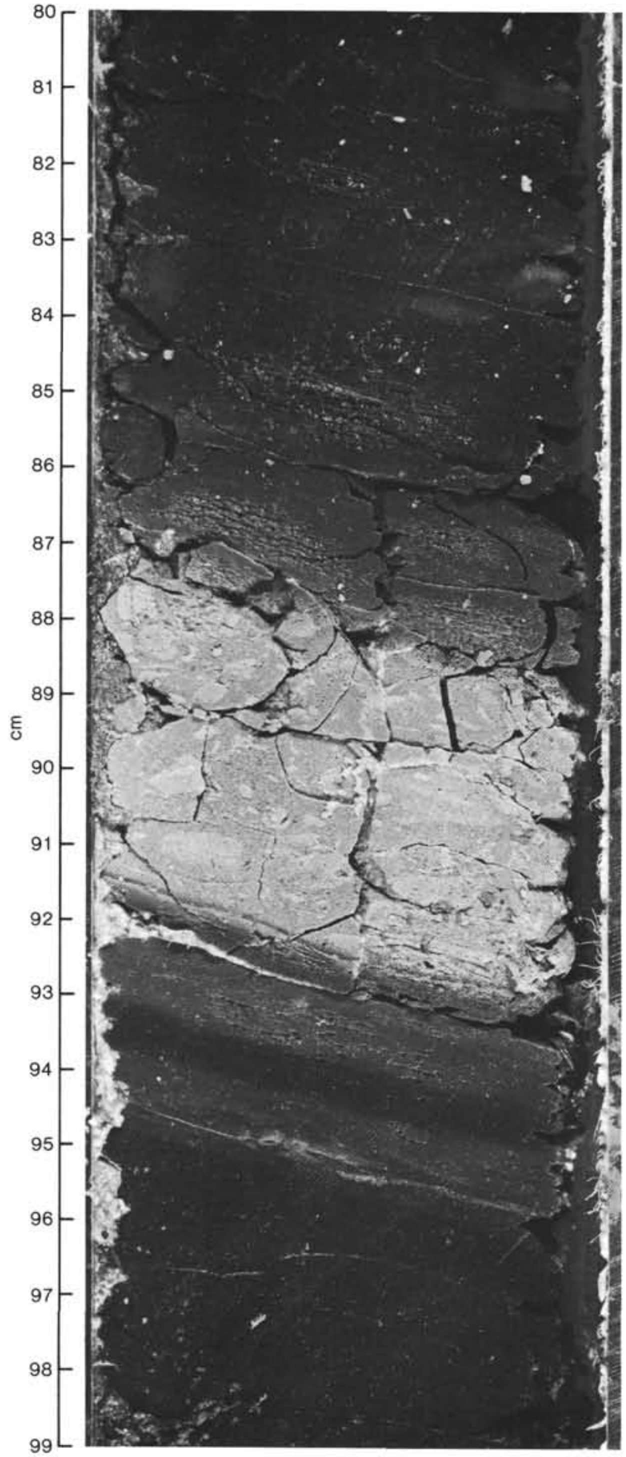

Figure 15. A 4-cm-thick layer (from 89 to 93 cm) of zeolitic claystone in Subunit IIIB. This layer may represent the diagenetic remnants of an ash layer contained in Subunit IIIB (Sample 603B-29-2, 80–99 cm).

waters may have been sufficient to allow metals to be scavenged from the seawater, and subsequent local diagenetic conditions within the sediment would alter the sediment chemistry, yielding color banding and mottling. Dean and Arthur (this volume) analyzed the multicolored claystones from Site 603 for metal enrichment, and have evaluated the various potential mechanisms of enrichment. Their research showed that the multicolored claystone of Unit III has an enrichment in the concentrations of several trace transition elements, but otherwise is similar in composition to red pelagic clay from the adjacent Hatteras Abyssal Plain. The claystone is not enriched in iron or manganese from Unit III. Although this unit has the lowest sedimentation rate for the section (3 m/m.y.), and includes a 4-cm-thick layer of zeolitic claystone that is interpreted to be derived from volcanic ash, they concluded that the slight enrichment in transition metals may be caused by diffusion of these elements from the interbedded carbonaceous claystones of Unit III, or from the abundant underlying carbonaceous claystones of Unit IV.

Unit IV (Hatteras Formation)

Lithologic Unit IV, from 1119 to 1215 m sub-bottom depth, is composed of Turonian–Aptian, interbedded carbonaceous claystone ("black shales"), variegated claystone, and terrigenous silt turbidites (Figs. 16 and 17). Pyrite concretions, rare occurrences of rhodochrosite, and a manganosiderite nodule were observed in this unit (von Rad and Botz, this volume).

Calcareous and agglutinated benthic foraminifers are rare and appear to represent a residual assemblage from which calcareous forms were dissolved (Biostratigraphy section, Site 603 chapter, this volume), probably after transport downslope. Rare calcified and/or pyritized radiolarians that are poorly preserved are distributed irregularly in this unit. Biostratigraphic age determination of this unit is based upon dinoflagellate stratigraphy (Habib and Drugg, this volume).

The unit contains a mixture of marine and continentally derived organic matter (Dunham et al., this volume), and the carbonaceous claystone contains more than ten times the concentration of organic carbon than the interbedded green claystone (Dean and Arthur, this volume). Layers of "black shale," however, occur in the overlying Unit III and the underlying Unit V. Therefore, "black shales" specifically occur in: (1) Hauterivian to Barremian (2) Albian to Turonian, and (3) Coniacian? to Santonian strata at Site 603.

Unit IV is divided into four subunits on the basis of the occurrence or relative abundance of pelagic, reddish brown claystone. The reddish brown claystone is present in Subunits IVB and IVD. The black shales are more abundant in this unit than in Unit III or V, and have the highest reported organic carbon contents (4.1–13.6%) from the western North Atlantic. Wood fragments are very common. Many of these "black shales" have sharp basal contacts and silty claystone bases that fine upward, and are best explained as mud turbidites. Another textural type of black claystone is a faintly to distinctly laminated carbonaceous claystone with pyrite or thin (< 1 mm thick) quartz silt laminae. The laminations are parallel or sometimes cross-laminated (Figs. 16 and 17) and therefore indicate bottom current activity. The greenish gray and reddish brown claystones in Unit IV are interpreted as the background pelagic sedimentation. It is

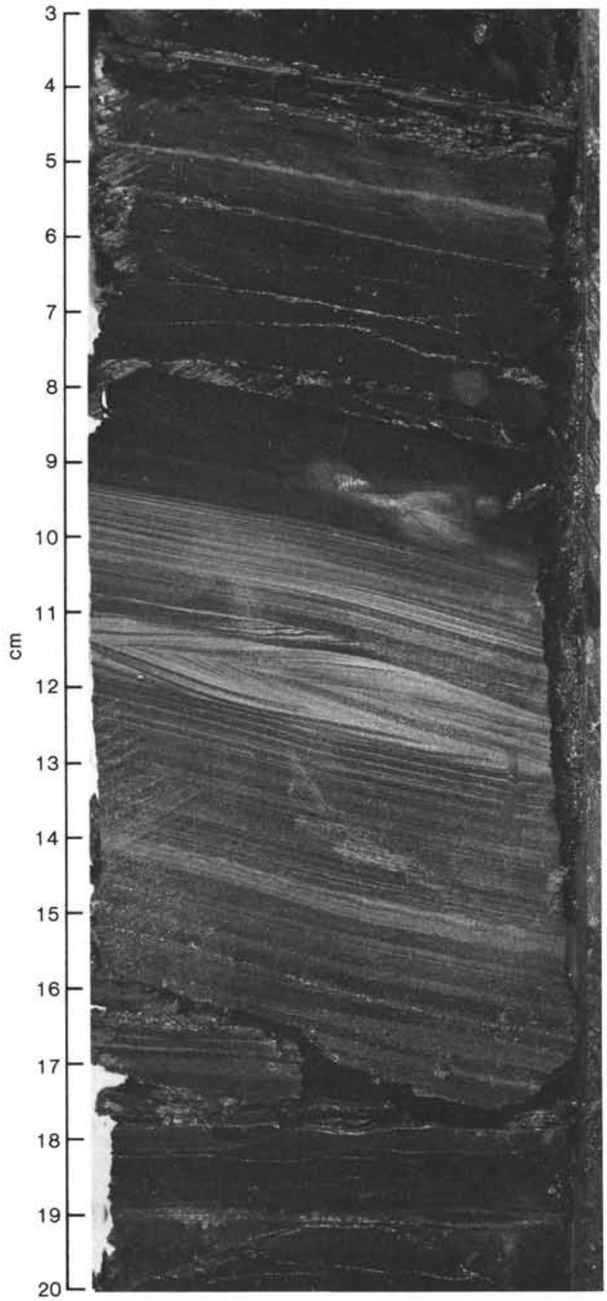

Figure 16. Terrigenous silt turbidite associated with the carbonaceous claystones of Subunit IVA. Fine detail of the turbidite is easily noted because of the strong contrast of the white quartz silt against the dark clay; this feature is typical for all of Unit IV (Sample 603B-36-2, 3-20 cm).

not uncommon in this unit to find a gradation between greenish gray claystone and black claystone.

Subunit IVA

Subunit IVA contains interbedded black carbonaceous claystone and pelagic greenish gray claystone. Sporadic blooms of a monospecific assemblage of the nannofossil genus *Nannoconus* were recorded in this Cenomanian–Turonian strata (Biostratigraphy section, Site 603 chapter, this volume). In Subunit IVA, the organic mat-

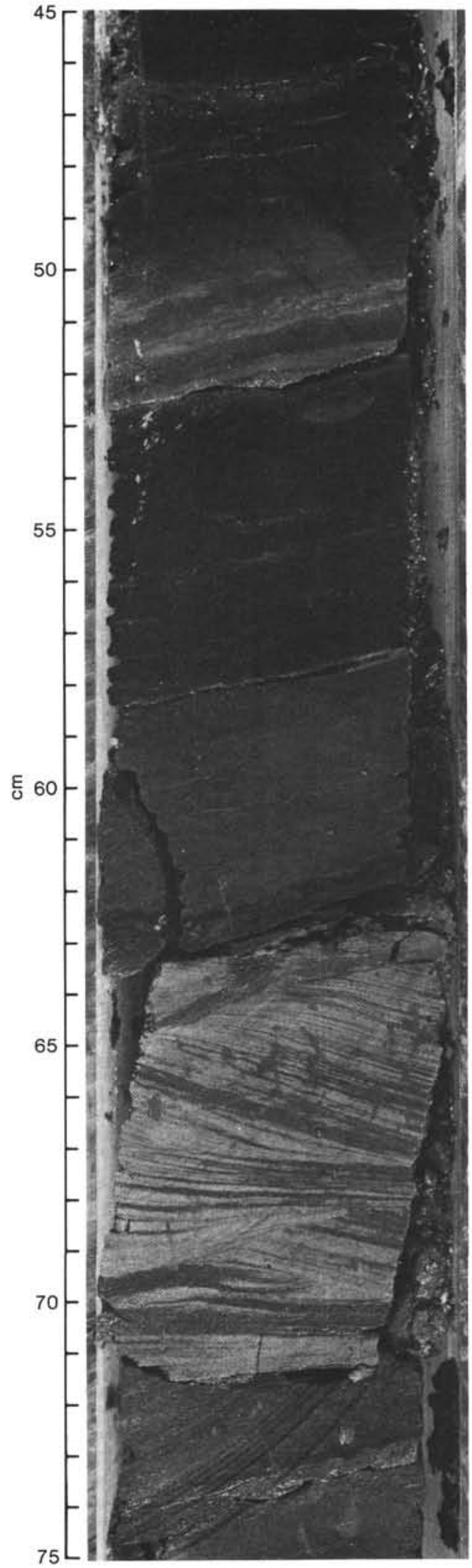

Figure 17. Terrigenous silt turbidite overlain by pelagic claystone from Subunit IVD (Sample 603B-43-5, 45–75 cm). Many of these cross-laminated, quartz-rich siltstones are cemented with siderite in Unit IV. The carbonaceous claystone is not as abundant in this subunit as in the overlying subunits of Unit IV.

ter in the carbonaceous claystone is predominantly of pelagic origin (Dean and Arthur; Dunham et al.; and Habib and Drugg, this volume). Habib and Drugg (this volume) suggest that Subunit IVA correlates in age with Cenomanian marine sapropels found at other sites in the North Atlantic.

Subunit IVB

Subunit IVB contains less carbonaceous claystone interbedded with more pelagic claystone than Subunit IVA. The pelagic claystone ranges in color from greenish gray to reddish brown. The color change can be gradual or sharp and may indicate changes in the reducing or oxidizing conditions of the benthic environment. The intervals of reddish claystone that are interbedded with minor amounts of carbonaceous claystone (turbidite deposits) are interpreted as evidence of periods of strongly oxidizing bottom-water conditions in the deep basin.

Subunit IVC

This subunit contains the characteristic black carbonaceous claystone interbedded with only the greenish gray pelagic claystone. In Subunit IVC, the carbonaceous claystone contains organic matter that is primarily of terrigenous origin (Dean and Arthur; Dunham et al.; and Habib and Drugg, this volume). The organic geochemical studies (Dean and Arthur; and Dunham et al., this volume) note that the organic matter is more degraded in the black claystone than in the green claystone, and that the terrestrially derived organic matter in the black claystone was probably deposited in well-oxygenated bottom water. The green claystone is not interpreted as having been deposited during anoxic bottom-water conditions, because it contains evidence of extensive bioturbation.

Subunit IVD

Subunit IVD contains less carbonaceous claystone than Subunit IVC but more pelagic claystone of both the greenish gray and reddish brown colors. The intervals of reddish claystone that are interbedded with minor amounts of carbonaceous claystone (turbidite deposits) are interpreted as evidence of periods of strongly oxidizing bottom-water conditions in the deep basin.

Discussion

The primary sedimentary structures associated with the carbonaceous claystone indicate that the black claystones in Subunits IVB, IVC, and IVD are predominantly turbidite deposits. Geochemical studies (Dean and Arthur; and Dunham et al., this volume) reveal that the turbidites contain continentally derived organic matter that underwent enhanced burial in an environment that had moderately to strongly oxygenated bottom-water conditions. From research with Lower Cretaceous strata composed of organic-rich graded black clays containing terrestrial organic matter, Habib (1983) drew a similar conclusion of deposition by turbidity currents in an oxygenated bottom-water environment.

Unit IV is the local equivalent of the Hatteras Formation. The type section of the Hatteras Formation consists of black to dark greenish gray noncalcareous carbonaceous claystone (Jansa et al., 1979). At several sites in the western North Atlantic, the lower boundary of the Hatteras Formation with the Blake-Bahama Formation is transitional with interbedded carbonaceous claystone and calcareous claystone or reddish brown claystone (Hollister, Ewing, et al., 1972; Sheridan, Gradstein, et al., 1983). The lower boundary of Unit IV at Site 603 is defined by the lowermost occurrence of black carbonaceous claystone, the uppermost appearance of nannofossil claystone, and the uppermost occurrence of coarse-grained, sand-sized, redeposited sediments.

Unit V (Blake-Bahama Formation)

Unit V is composed of 261 m of upper Berriasian to Aptian interbedded laminated limestone and bioturbated limestone with sandstone to claystone turbidites. The unit is divided into two subunits on the basis of the presence or absence of turbidites. Unit V is characterized by cycles of laminated marlstone or limestone, and bioturbated limestone. Biostratigraphic age determination of this unit is based upon nannofossils, foraminifers, and ammonites.

Macrofossils found in this unit are impressions of flattened ammonites, ammonite aptychi, or fragments of *Inoceramus*. The macrofossils are not abundant in these limestones, but their occurrence is usually associated with the laminated limestones; they are rarely found in the bioturbated limestone (Haggerty, this volume).

The decline in the dissolved oxygen content of the bottom waters associated with each onset of laminated limestone deposition is documented by the decrease in the burrow size and ichnofaunal tiering relationship in the bioturbated limestone (Haggerty, this volume). The association of *Inoceramus* with the laminated limestone supports the interpretation that this is a dysaerobic facies.

Subunit VA

Subunit VA is upper Valanginian to Aptian and contains numerous turbidites interbedded with laminated limestone and bioturbated limestone. There are two distinct types of turbidites: siltstone-sandstone and organic-rich claystone. The presence of intermediate types and complete graded-sandstone to claystone sequences indicate that the two textural types are related. In addition to these turbidites, there are meter-thick clayey sandstone beds containing shale clasts, which suggest that extensive erosion of the seafloor occurred during transport of the sands prior to their redeposition (Sarti and von Rad, this volume). These clastic turbidites and thick beds of sand are interpreted to be from a submarine fan (see Sarti and von Rad, this volume, for details).

Subunit VB

Subunit VB is upper Berriasian to upper Valanginian and lacks turbidites. The laminated limestone is enriched in organic matter with respect to the bioturbated limestone. This organic carbon is predominantly plant debris. The same statement is true for the limestones in Subunit VA.

Discussion

The periodic influx of clay, very fine-grained sand, and terrigenous organic matter is interpreted to have resulted in the interbedded nature of the laminated limestone with the bioturbated limestone at Site 603. Similar conclusions were drawn from Site 534 in the Blake-Bahama Basin (Robertson and Bliefnick, 1983) for the cycles of laminated marlstone or limestone, and bioturbated limestone.

The deposition of intervals of laminated limestone associated with the bioturbated limestone (Subunit VB) anteceded the deposition of claystone turbidites (Subunit VA) and perhaps indicates the progradation of the Tithonian–Barremian deltas that developed on the inner and middle continental shelves (Haggerty, this volume). A submarine fan complex containing a channel–levee complex followed by an extensive sand lobe complex is interpreted to have been deposited within Subunit VA at Site 603 (Sarti and von Rad, this volume).

Unit V is the local equivalent of the upper portion of the Blake-Bahama Formation as defined by Jansa et al. (1979) from the type locality at DSDP Site 391 (Benson, Sheridan, et al., 1978). A more complete section was recovered at Site 534 (Sheridan, Gradstein, et al., 1983; Robertson and Bliefnick, 1983). During the early Barremian and Hauterivian at Sites 391 and 534, the turbidity currents were actively redepositing carbonate sediment, whereas at Site 603, terrigenous sediment was being redeposited by turbidity currents. The presence of terrigenous turbidites in Subunit VA makes the Blake-Bahama Formation at Site 603 different from other DSDP sites.

DEPOSITIONAL HISTORY

The oldest sediment recovered at Site 603 is characterized by cycles of laminated marlstone or limestone, and bioturbated limestone of Valanginian and Berriasian age (Subunit VB; see Ogg et al., this volume). This strata may represent periods of alternating aerobic and dysaerobic bottom-water conditions, and/or fluctuating bottom-current intensity in a youthful North Atlantic Ocean basin (Haggerty; Ogg et al., this volume). The Hauterivian to Aptian strata contain evidence of a deep-sea fan complex (Subunit VA; see Sarti and von Rad, this volume). These terrigenous clastics were deposited during a major progradation of the continental shelf from an increase in sediment supply. The redeposition of clastic sediment was greatly intensified by a low stand of sea level during the middle Aptian (Sarti and von Rad, this volume; Vail et al., 1980. See Wise and van Hinte, this volume, for an updated discussion of the recalibration of this event).

With the sea-level rise in the Albian, the redeposition of clastic sediment waned and ceased (Unit IV) because of the flooding of the sediment source. When sea-level rose, the CCD shoaled at the same time, as exhibited by the disappearance of calcareous nannofossils in the strata. The intervals of reddish claystone that are interbedded with minor amounts of carbonaceous claystone (turbidite deposits) in Subunits IVD and IVB are interpreted as evidence of periods of strongly oxidizing bottom-water conditions in the deep basin. The cyclic red and green claystone in Subunit IVD was probably related to changes in the bottom-water conditions from strongly oxic to less oxic. The green claystone is not interpreted as having been deposited during anoxic bottom-water conditions, because it contains evidence of extensive bioturbation. During the intense development and redeposition of carbonaceous claystone containing pelagic organic matter (Subunit IVA), sporadic blooms of a monospecific assemblage of the nannofossil genus *Nannoconus* were recorded in Cenomanian–Turonian claystone.

The emplacement of the dark carbonaceous claystone, which is interpreted as primarily the result of redeposition from the upper continental slope, continued into the Upper Cretaceous strata of Unit III. Therefore, anoxic conditions necessary for the initial deposition and formation of these organic-rich strata are proposed to have persisted on the continental slope during the Late Cretaceous.

The recovery of lower Eocene to upper Paleocene radiolarian claystone from beneath the continental rise, Unit II of Site 603, was unexpected because strata of that age was thought to have been eroded from the North American continental rise by the Oligocene erosional event that produced seismic Reflector A^u. The erosional event that produced seismic reflector A^u was not as extensive as previously suggested by Jansa et al. (1979). Deposition of the sediment took place below the CCD; silica diagenesis was therefore inhibited as the result of the high clay content of the lower Eocene radiolarian claystone. Consequently, no thick porcellanite layers developed, and thus no distinct and separate A^c horizon was produced by an acoustic impedance contrast (Thein and von Rad, in press). The middle and upper Eocene strata at this site were either removed or not deposited, resulting in the obvious disconformity between Units I and II.

The middle Miocene to Pleistocene sediment cored at Site 603 (Unit I) is a monotonous succession of more than 900 m of thick, homogenous gray green silty claystone, faintly banded and heavily bioturbated. Faint banding is the one type of sedimentary structure recognized throughout Unit I. The turbiditic character of the silt layers in Subunit IC (deposits from decelerating turbulent suspension and not from a purely tractive current) suggest that deposition occurred in the absence of contour currents during the middle Miocene. The inference that no contour currents were active along the North American continental rise in the pre-middle-Miocene (Thiede, 1979) supports such a conclusion. The occurrence of discrete turbiditic silt layers in Subunit IC might be an indication that turbiditic deposition occurred in the absence of the mixing effect with the Western Boundary Undercurrent in the middle Miocene.

The upper part of the Neogene section at Site 603 (Subunits IA and IB) is devoid of any silt or sand layers but instead has sand and silt dispersed into the claystone. Discrete beds bearing small-scale sedimentary structures that are diagnostic of transport by purely tractive currents, and that fit the definition of a sandy contourite given by Hollister and Heezen (1972) and Lovell and Stow (1981), are absent. However, large-scale features, such as the wavy pattern of the seismic reflectors, the lack of horizontal layering typical of many turbiditic sequences, the hilly seafloor morphology and the "antidunal-like" internal structure of these hills, which are recognized in the seismic sections (Seismic Stratigraphy section, Site 603 chapter, this volume; Asquith, 1979; Tucholke and Mountain, 1979), correspond better to the characteristics of muddy contourites summarized by Stow et al. (1984) and Stow and Piper (1984). The inference that bottom currents have been active along the North American continental rise since the middle Miocene (time of initiation of Arctic deep-water circulation in the North Atlantic; Thiede, 1979) supports such interpretation. The downslope flow of silt and mud by dilute turbidity currents and ultimately their incorporation into the contour-following bottom current might represent the two mechanisms—feeding and redistribution—which acted together since the middle Miocene in building up the ridges and hills of the lower continental rise. Possibly in special circumstances of high sedimentation rates, and high supply of fines, controlled by current regime (velocity, turbulence) and by seafloor morphology, clays and silts may be preferentially deposited as massively bedded, elongate sediment drifts rather than clearly bedded sequences with the typical contouritic characteristics of sandy contourites. Precursor turbiditic facies could ultimately control contouritic facies.

Given an adequate supply of fine-grained material, the continuous process of "plastering" (Asquith, 1979; Tucholke and Mountain, 1979) of muds against the upcurrent sides of slopes might be an efficient mechanism of depositing homogenous, almost structureless muddy sequences as seen in Subunits IA and IB. Subunit IB is interpreted as marking the beginning of deposition under the influence of the Western Boundary Undercurrent. This strata evolved into the modern Hatteras Outer Ridge (Tucholke and Laine, 1982) as a constructional product of the Western Boundary Undercurrent (Asquith, 1979) and the subsequent addition of sediment from Subunit IA.

In the early stages of development, the Hatteras Outer Ridge was a constructional ridge parallel to the current along the east coast of North America (Tucholke and Mountain, 1979). This bathymetric feature acted as a barrier to turbidites coming downslope and consequently ponded the sediment (Tucholke and Laine, 1982). The lower continental rise hills grew to their present morphology as the result of the interaction of the shifting position of the Western Boundary Undercurrent (Ledbetter and Balsam, 1985) and turbidite deposition from the margin yielding antidunelike sediment waves. No coarse clastics associated with glacial times are found in the monotonous mixture of green clay and silt of Subunit IA, because the clastic turbidites were dammed up on the landward continental rise terrace. Instead, only muddy contourites (Stow and Lovell, 1979), composing Subunit IA, were deposited at a high rate of sedimentation from the Pliocene to the early Pleistocene. There is no evidence from the studies of piston cores by Ledbetter and Balsam (1985) nor from our cores at Site 603 to suggest that stagnation of the western North Atlantic occurred during glacial time. The uppermost core recovered at DSDP Site 603 is dated as early Pleistocene; some watery mud trapped by the core liner above the sediment is dated as Holocene. This suggests that a thin layer of Holocene mud may overlie lower Pleistocene sediments, and therefore current activity may have eroded or prevented deposition of upper Pleistocene strata.

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