36. NORTH ATLANTIC CRETACEOUS BLACK SHALES: THE RECORD AT SITE 398 AND A BRIEF COMPARISON WITH OTHER OCCURRENCES

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INTRODUCTION

Drilling during Leg 47B at Site 398 on the south flank of Vigo Seamount recovered "black shales" and associated relatively organic-rich upper Hauterivian through mid-Cenomanian sediments. This and the recovery of Aptian-Albian "black shales" at two sites on the northern margin of the Bay of Biscay (Scientific Staff—Leg 48, 1976) extends the known area of black shale deposition on the deeper sea floors of the Early Cretaceous North Atlantic. However, the lithology, paleoenvironment, and preservation and source of organic matter in the black shales of the northern North Atlantic (north of the New Foundland fracture zone) differ in important respects from those of dark-colored, organic-rich sediment deposited in other areas of the Early Cretaceous North Atlantic and Tethys. The purpose of this paper is to discuss some of the salient aspects of lithology and paleoenvironment of the Lower Cretaceous sediment of Site 398 and to briefly compare and contrast them with Lower Cretaceous black shale sections in some North Atlantic DSDP sites and Tethyan exposures on land. Although similar organic-rich sedimentary sequences were distributed globally during the Early to Middle Cretaceous (Schlanger and Jenkyns, 1976; Fischer and Arthur, 1977), it is important to avoid general application of a model for paleoenvironment derived from any one region to explain all other occurrences.

In this paper, the term "black shale" is used in a general sense to refer to relatively organic carbon-rich (i.e., >0.5 wt. % C_{org}), dark-colored (dark gray, greenish black, and black) mudstone and marlstone which may or may not be "shale" in the classical sense. "Black shale" sequences rarely consist entirely of dark-colored lithologies; they are often rhythmically interbedded with lighter colored (green to gray) mud, marl, or limestone. The use of Early Cretaceous and Middle Cretaceous here refers to the periods Valanginian-Hauterivian through Albian and Cenomanian-Turonian, respectively.

CRETACEOUS SEDIMENTARY ENVIRONMENTS AT SITE 398

Site 398 is located about 20 km south of Vigo Seamount at the southern end of Galicia Bank on the continental margin of western Iberia (Figure 1). A 740-meter-thick sedimentary section was recovered with nearly continuous coring; the site was terminated after recovering sediment of the upper Hauterivian. Lower and Middle Cretaceous (upper Hauterivian through middle Cenomanian) sediments are 793 meters thick and rapidly deposited (up to 75 m/m.y. sedimentation rate). These Cretaceous deposits are unconformably overlain by Santonian(?) and younger, more slowly deposited pelagic clays, marls, and chalks. The lithologic features of the Lower to Middle Cretaceous sediments have been detailed in the Site 398 Report (this volume) and in papers by Sigal, de Graciansky and Chenet, and Réhault and Mauffret (all, this volume); Upper Cretaceous and Cenozoic sediments are treated in detail in this volume by Maldonado, by Réhault and Mauffret, as well as in the Site Report. A brief overview and description of the lithostratigraphy and sedimentary evolution during Cretaceous time is presented here (Table 1; Figures 1B and 2). Of primary interest in this paper are the oceanic paleoenvironment of this part of the North Atlantic during Cretaceous time, particularly conditions of deep-water oxygenation and of surface productivity, and certain diagenetic aspects (formation of pyrite, siderite, preservation of carbonate, and organic carbon) of the sediment related to the initial depositional conditions. The discussion of sedimentation at Site 398 presented here is based on visual observation of all Cretaceous core material from Site 398, study of over 150 smear slides and thin sections from selected intervals, 40 supplemental analyses of total organic carbon (using standard preparation techniques and a LECO 70-second analyzer), and the data and discussions of several colleagues including G. Blechschmidt, D. Habib, P.C. de Graciansky, and J. Sigal. Major lithologic types and interesting sedimentary features are shown in Plates 1 through 6 and discussed in separate sections below.

ORGANIC MATTER IN BLACK SHALES

The study of the amount, composition, and maturity of organic matter in Cretaceous organic-rich sediment recovered in North Atlantic Deep Sea Drilling sites has become an increasingly popular and important aspect of studies of the black shales. A number of such studies using various techniques have been reported in this volume (e.g., Habib, Johnson et al., Kendrick et al., Doerenkamp and Robert, Deroo et al., Dow and Pearson). Figure 2 summarizes data on measurements of total organic carbon in Lower to Middle Cretaceous sediments obtained during the aforementioned investi-

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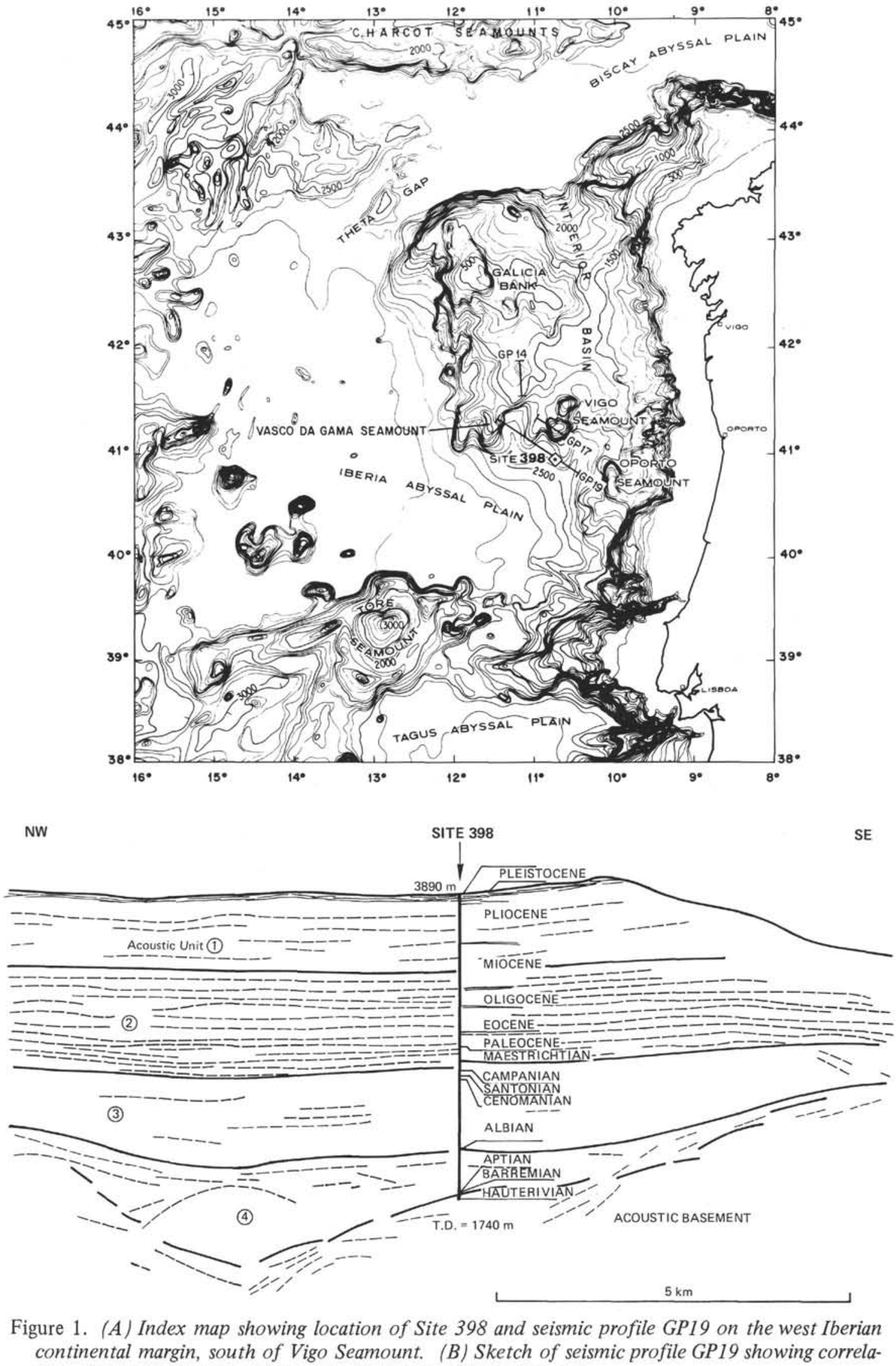


Figure 1. *(A) Index map showing location of Site 398 and seismic profile GP19 on the west Iberian continental margin, south of Vigo Seamount. (B) Sketch of seismic profile GP19 showing correlation of major reflectors with age (see Table 1 for lithologic units).*

TABLE 1

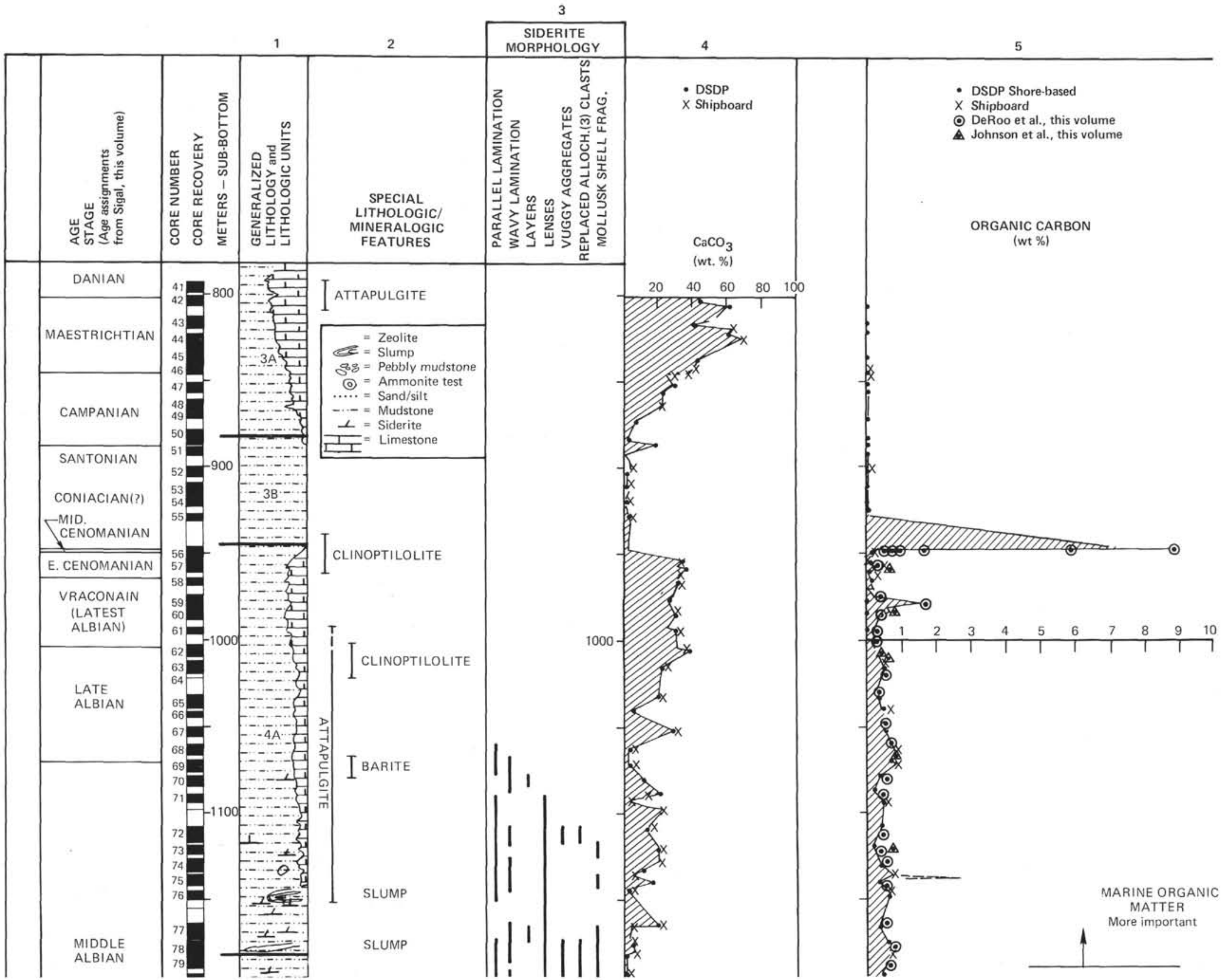
Lithologic Succession and Paleoenvironment of Cretaceous Sediment at Hole 398D, Leg 47B

Lithologic Unit	Core Numbers	Sub-Bottom Depth (m)	Time-Rock Unit	Lithology	Paleoenvironment	Average Sedimentation Rate[a]
3	(38-56)	(774-945)	Mid-Cenomanian-Paleocene			
3A	38-50	774-880	Campanian-Paleocene	Light red to brown and tan with some greenish gray; interbedded nannofossil chalk, marl, and claystone	Slow pelagic deposition with deepening of the CCD in Maestrichtian-Danian time; well-oxygenated conditions on sea floor; some reworking of sediment by slumping and currents	
3B	50-56, 2	880-944	Mid-Cenomanian through upper Santonian(?)	Brown, yellow-brown, red, and reddish gray unfossiliferous homogeneous mudstone and claystone; rhythmic intercalation of 1-cm-thick silt and sand beds at 10 to 100 cm intervals	Slow pelagic clay sedimentation below CCD with periodic terrigenous silt input (distal source). Well-oxygenated conditions; hiatus between mid-Cenomanian and Santonian sediment, possible deep current erosion slight angular discordance between Sub-units 3B and 4A in seismic profiles; marks onset of well-oxygenated conditions and strong deep circulation	~8 m/m.y.
4	(56-130)	(947-1667)	Late Barremian through mid-Cenomanian		Unit 4 fills depressions and grabens, smooth topography on upper surface	
4A	56-79	947-1183	Middle Albian-mid-Cenomanian	Gray-green marly nannofossil chalk to calcareous mudstone interbedded with dark gray to gray-black claystone; a few radiolarian sands in upper part of unit; also some graded calcareous mudchip siltstones and sandstones and quartzose sandstones. Sediment bioturbated to homogeneous and laminated; pyritic, zeolitic, sideritic, with occasional barite, gypsum	Hemipelagic-pelagic deposition, rhythmic bedding with fluctuating carbonate and organic carbon contents periodic anoxia or very low bottom water oxygenation; sea floor probably above CCD but redeposition of carbonate from slopes does occur; possibly three sediment sources: (1) terrigenous input-mud turbidites, hemipelagites; (2) pelagic carbonate input; (3) downslope redeposition of older and penecontemporaneous carbonate. Mixture of terrigenous and marine organic matter	< 25 m/m.y.
4B	79-102	1183-1401	Early to middle Albian	Very dark gray to black laminated to homogeneous claystone interbedded with dark greenish gray and green-gray mudstone to calcareous mudstone; lighter interval commonly burrowed; carbonate contents generally low, organic carbon values relatively high; siderite common; ammonites and other mollusk debris common; a few debris flow or slump units	Deposition in outer deep-sea fan possibly below CCD, but rapid sedimentation rates and terrigenous dilution make this analysis difficult; low oxygen levels in bottom waters, probably occasionally anoxic; primarily terrigenous (higher plant) organic matter	~75 m/m.y.
4C	102-130	1401-1667	Late Barremian through late Aptian	Black to dark gray to olive-green gray mudstone, claystone and calcareous claystone, interbedded mud and limestone pebble debris flows (mud-supported conglomerates) turbiditic mudstones, and turbiditic quartzose to calcareous sandstone and siltstone	Prodelta or submarine fan deposition with various sediment sources including nearby slopes and scarps from which calcareous mudchip sands and silts, carbonate-pebble conglomerates and debris flows and slump units were derived; quartzose sands, silts, and mud from continental source, pelagic carbonate content diluted; deposition possibly at or below CCD but this interpretation is difficult to make; terrigenous (higher plant) organic matter prevalent; sand content wanes during upper Aptian	> 25 m/m.y.
5	131-138	1667-1740	Late Hauterivian-early Barremian	Bluish white to white nannofossil limestone (radiolarians abundant) interbedded with thinly laminated medium dark to dark gray, black and olive-gray mudstone or calcareous mudstone; some thin turbiditic quartzose sandstone and siltstone beds	Pelagic carbonate sedimentation with periodic terrigenous influx; rapid transition upward to Subunit 4C probably related to faulting and subsidence in response to extensional tectonics at this time; bottom-water oxygen levels are low to moderate	< 15 m/m.y.

[a]Calculated using biostratigraphic zonation and time scale of Sigal (this volume).

gations, by DSDP, and in this study. The data show peaks in organic carbon concentrations in Barremian through lower Aptian, lower to middle Albian deposits, and some high values within uppermost Albian to middle Cenomanian sediments. Gradually declining organic carbon values occur in middle to upper Albian deposits. Highest values (up to 7.2 wt. %) occur in the middle Cenomanian. Upper Cretaceous sediments are well oxidized and contain less than 0.1 wt. per cent organic carbon.

The amount of organic carbon is not always a good indicator of sources of organic matter, paleoenvironmental conditions of preservation, or extent of diagenesis of organic components. Therefore, information derived from palynological, vitrinite reflectance, pyrolysis, and other studies of kerogen and extractable organic matter must be used to evaluate these aspects. Such studies have shown that nearly all of the organic matter in Lower Cretaceous dark-colored sediment in Site 398 was derived from terrestrial higher plants with some contribution of second-cycle organic carbon, possibly derived from eroded coal deposits or black shales. The multicycle organic matter exhibits a much higher than average reflectance (e.g., Kendrick et al.; Doerenkamp and Robert; both papers, this volume) and a very high oxygen and very low hydrogen index (Deroo


AGE
STAGE
(Age assignments from Sigal, this volume)
CORE NUMBER
CORE RECOVERY
METERS – SUB-BOTTOM
1
GENERALIZED LITHOLOGY and LITHOLOGIC UNITS
2
SPECIAL LITHOLOGIC/ MINERALOGIC FEATURES
3
SIDERITE MORPHOLOGY
PARALLEL LAMINATION
WAVY LAMINATION
LAYERS
LENSES
VUGGY AGGREGATES
REPLACED ALLOCH.(3) CLASTS
MOLLUSK SHELL FRAG.
4
• DSDP
X Shipboard
CaCO3 (wt. %)
20 40 60 80 100
5
• DSDP Shore-based
X Shipboard
⊙ DeRoo et al., this volume
▲ Johnson et al., this volume
ORGANIC CARBON (wt %)
1 2 3 4 5 6 7 8 9 10
DANIAN
MAESTRICHTIAN
CAMPANIAN
SANTONIAN
CONIACIAN(?)
MID. CENOMANIAN
E. CENOMANIAN
VRACONAIN (LATEST ALBIAN)
LATE ALBIAN
MIDDLE ALBIAN
41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79
800
900
1000
1100
3A
3B
4A
ATTAPULGITE
= Zeolite
= Slump
= Pebbly mudstone
= Ammonite test
= Sand/silt
= Mudstone
= Siderite
= Limestone
CLINOPTILOLITE
CLINOPTILOLITE
ATTAPULGITE
BARITE
SLUMP
SLUMP
MARINE ORGANIC MATTER
More important

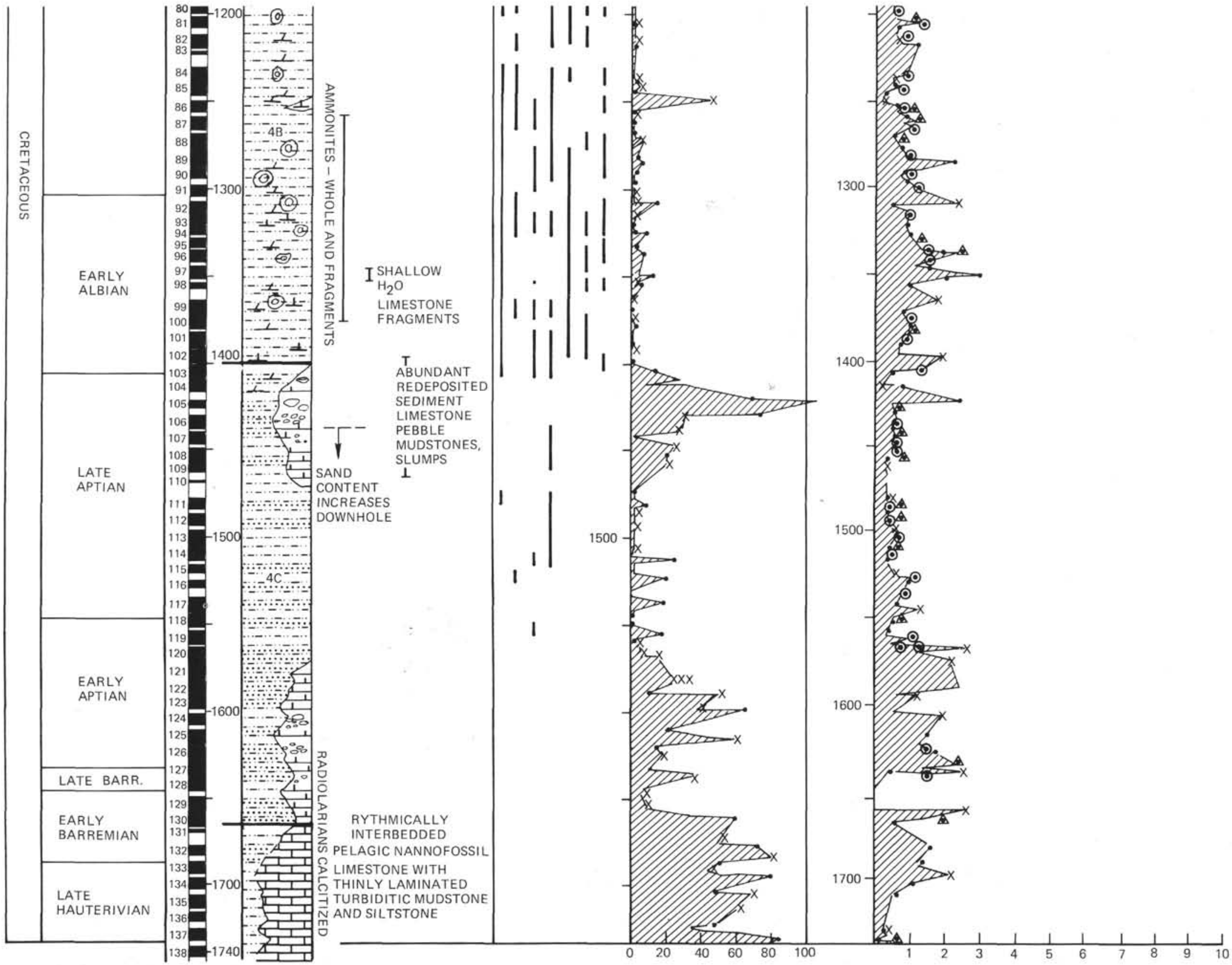


Figure 2. *Chart of sediment characteristics of the Cretaceous at Site 398: data in column 3 from this study; column 4 from DSDP, shipboard measurements, and this study; column 5 from DSDP, shipboard measurements, this study, and references cited.*

et al., this volume). Furthermore, studies of the land-derived organic matter of higher plant origin all agree in their suggestion that only the more stable organic compounds are preserved in Hauterivian to upper Albian sediments. Only in upper Albian to Cenomanian dark-colored muds does more hydrogen-rich organic matter of marine derivation comprise a significant part of the total organic material. The thermal maturity and hydrocarbon potential of the Lower Cretaceous black shale section in Site 398 is low (see references cited above).

Habib (this volume) has also shown that peak organic carbon values in sediment correspond to the highest proportion of land plant-derived sporomorphs and that marine carbonaceous material (dinoflagellates and acritarchs) is an insignificant component, except possibly in middle to upper Albian and Cenomanian sediment. Hauterivian through middle Albian sedimentation is characterized by high terrigenous influx and very high sedimentation rates (Table 1, Figure 2; also, see de Graciansky and Chenet; Sigal; Réhault and Mauffret; all, this volume). The sedimentary sequences, especially sand and silt turbidites which are Barremian-lower Aptian, suggest build-up of a deep-sea fan, possibly related to regional deltaic progradation. It is not surprising, therefore, that most of the organic matter indicates a terrigenous source. It is puzzling, however, that the Lower Cretaceous black shale facies at Site 398, which represents sedimentation under periodic anoxic or very low oxygen conditions elsewhere in the North Atlantic, does not represent enhanced preservation of more hydrogen-rich organic matter (so-called liptinite or amorphous kerogen) under anoxic conditions which some of the features of the sediment suggest might have existed at least periodically. There are one or more possible reasons for this: (1) overall sea-surface productivity in this part of the North Atlantic in Barremian to middle Albian time was very low; this, coupled with the masking effects of dilution by terrigenous detritus (average sedimentation rates up to 75 m/m.y. and locally up to 100 m/m.y.), leads to the diminished expression of the pelagic marine contribution. This argument can be made for carbonate as well (see below); (2) conditions were not anoxic in bottom waters in this portion of the North Atlantic and reactive organic matter was oxidized on the sea floor before and during the early phases of burial; therefore, only inert organic matter was preserved; or (3) the high rate of influx of terrigenous organic matter and its subsequent oxidation led to anoxic or very oxygen-depleted conditions in the water column; however, nearly all reactive organic matter was consumed in the process. These possibilities require discussion because they influence interpretations of paleoenvironment as well as comparison with conditions in adjacent ocean basins.

Other DSDP sites in the North Atlantic have encountered Lower to Middle Cretaceous black shales (Figure 3) which range from Hauterivian through mid-Cenomanian over most of the North Atlantic. Organic-rich facies persist into the Upper Cretaceous in some parts of the eastern and southern North Atlantic and through the Caribbean Sea (Edgar, Saunders et al., 1973). Tethyan sections from southern France (de Boer et al., in preparation) and Italy (Arthur, 1978) show best development of black shale facies during the Aptian-Albian, but thin black shales are interbedded with pelagic limestones as old as Hauterivian-Valanginian. Patterns of organic carbon concentration at many DSDP sites and at Gubbio are similar to those from Site 398, but absolute values of organic carbon are generally greater (Figure 4; these values should be converted to accumulation rates for better comparison). Highest values occur in Cenomanian to lowermost Turonian sediment as at Site 398. The major difference between other North Atlantic sites and Site 398 is that marine organic matter is more prevalent in the other North Atlantic sequences. Mixtures of marine and terrigenous (or predominantly terrigenous) organic matter are common in sediments below the upper Albian; the marine organic component dominates the upper Albian (and above) at many sites. The details vary from region to region and according to analytical techniques used (see Dow, 1978; Kendrick et al., 1978; Deroo et al., 1978; Simoneit, 1978; Simoneit et al., 1972, 1973; Kendrick, 1979; Erdman and Schorno, 1979; Stuermer and Simoneit, 1978). Deposition of many of the organic carbon-rich layers probably occurred under anoxic conditions, based on sedimentary and geochemical criteria (e.g., Simoneit, 1977; Kendrick, 1979; McCave, 1979). The intensity and duration of intervals of oxygen depletion in the water column also probably varied with time and local rates of organic carbon input. Sedimentation rates in many of these sequences were relatively low except at sites located near continental margins and active deltas. The large amount of terrigenous organic matter in the sediment during the Hauterivian although Albian is most likely due to the input from large deltas fringing both sides of the Atlantic during the Early Cretaceous (e.g., Jansa and Wade, 1975; Bhat et al., 1975; Einsele and von Rad, in press).

The preservation of this material under at least partly anoxic conditions is not unlike that of the Black Sea, where terrigenous lipids (Simoneit, 1977) comprise most of the organic matter in sediments deposited during the period of intense anoxia existing during the last 7000 years (Degens and Ross, 1974). The contribution of marine organic matter to black shales at any one site is a function of contemporaneous sea-surface productivity over the site and extent of anoxia in the water column, though not necessarily always related to the latter (i.e., anoxic conditions could occur without local input of marine organic matter, such that only terrigenous material would be present in sediment).

There is little doubt that reducing conditions (anoxia) were established within Hauterivian through Albian sediments shortly after deposition at Site 398; the persistence of authigenic pyrite and siderite throughout these sediments attests to this fact (Figure 2; Table 1). However, the lack of preservation of much reactive organic matter, some burrow mottling, and the presence of benthic foraminifers (Sigal, this volume) allow at least intermittent but possibly low oxygen levels at the sediment-water interface throughout deposition of

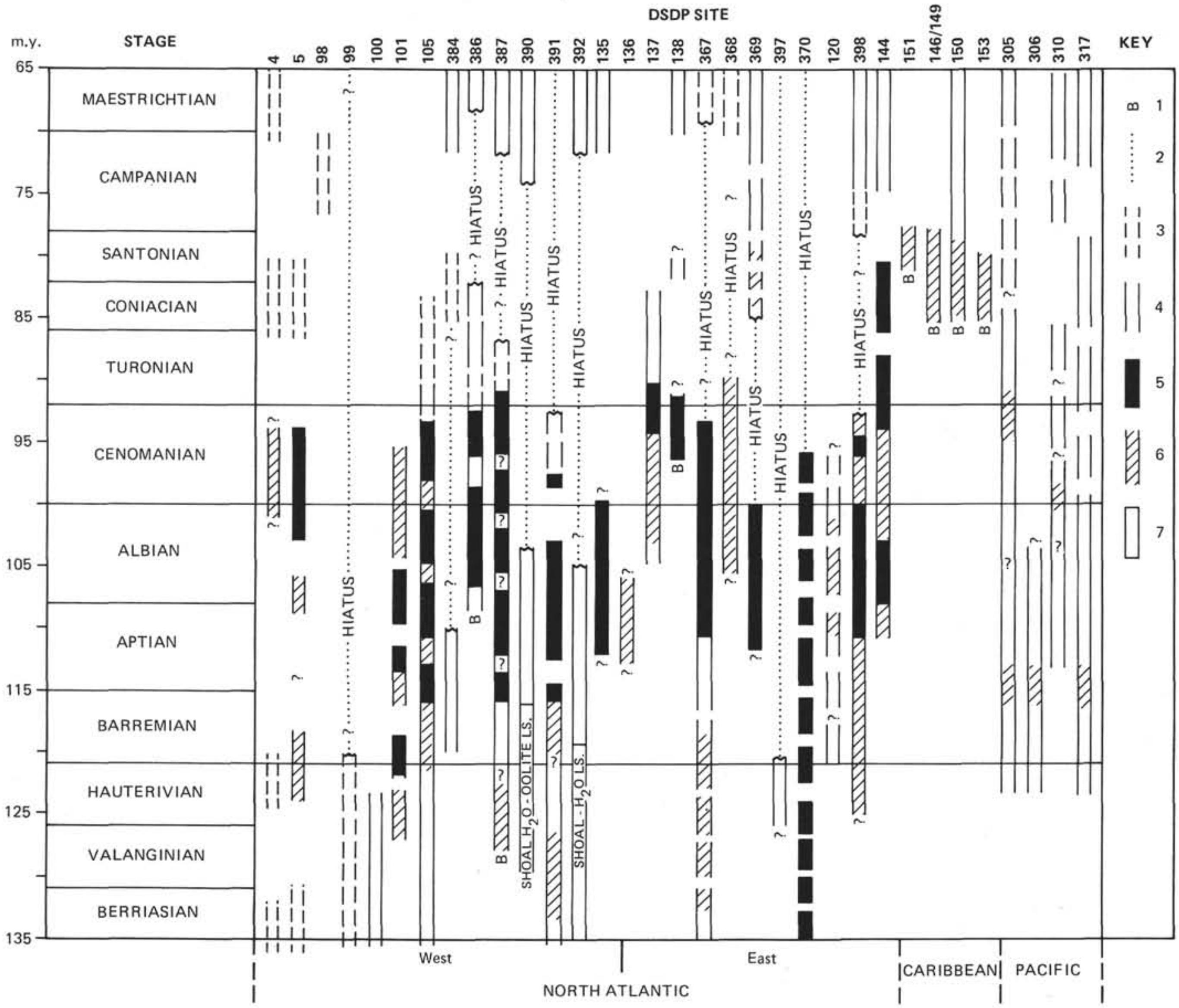
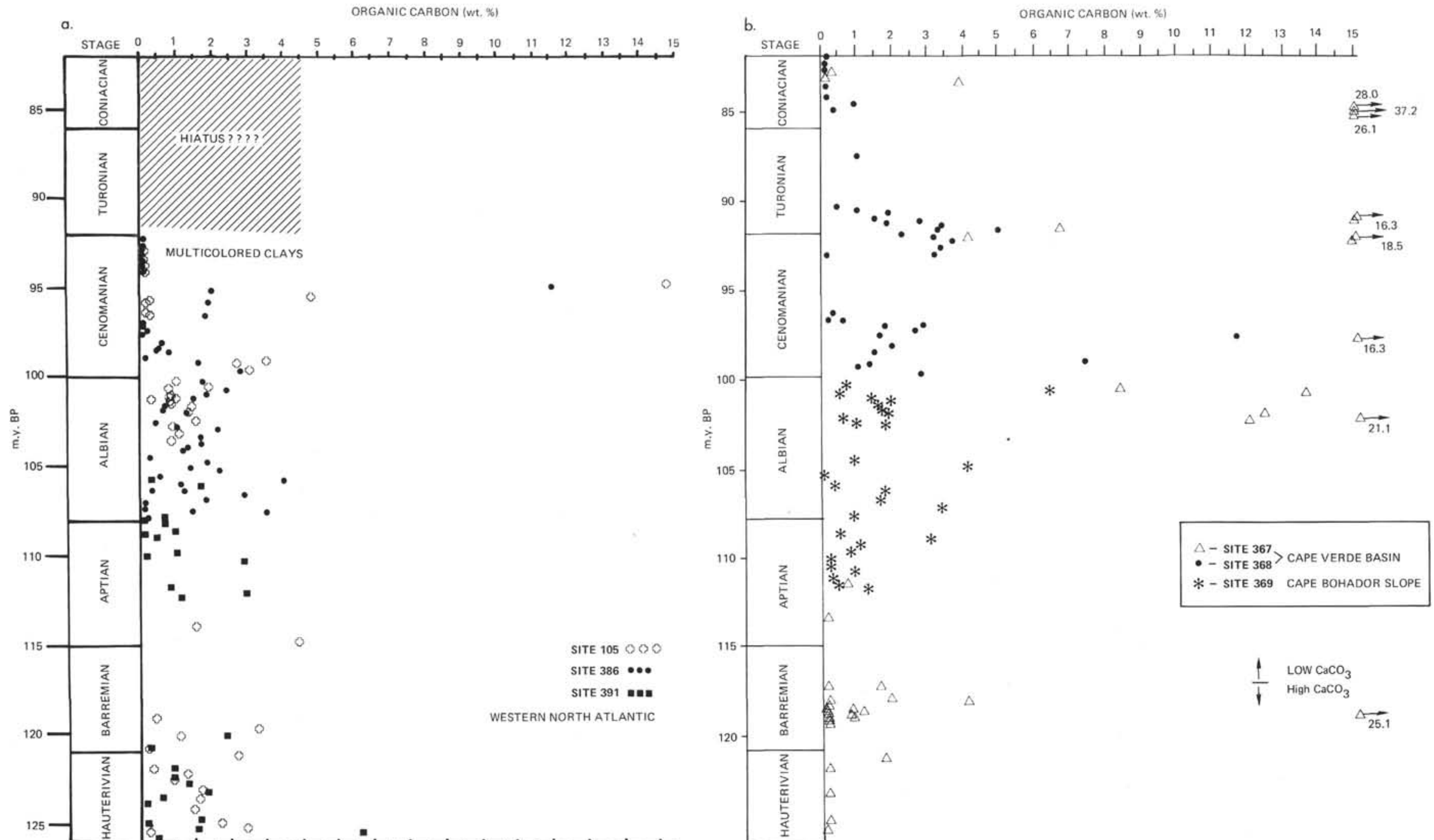


Figure 3. *Summary of ages of Cretaceous black shale or other organic-rich facies in North Atlantic, Caribbean, and selected Pacific JOIDES drill sites. Note concentration within Hauterivian through Cenomanian interval. Symbols: (1) Site reached basement. (2) Hiatus. (3) Age uncertain or inferred. (4) Cored interval with age documented. (5) Primarily dark-colored, relatively organic-rich sediment showing evidence of anoxic or very low oxygen conditions. (6) Primarily dark-colored organic-rich sediment showing evidence of low oxygen to oxygenated conditions. (7) Sediment evidencing well-oxygenated conditions.*

much of the sediment. The high sedimentation rates and input of terrigenous organic matter can be suggested as the cause for establishment of anoxic conditions within the sediment after burial. Under these conditions, one would expect at least some autochthonous marine organic matter to be preserved. Heath et al. (1977) have shown that the extent of preservation of organic matter under conditions of oxygenated sea bottoms is primarily a function of burial rate. Much of the metabolizable organic matter in the Cretaceous sediments at Site 398 may have been consumed during bacterial sulfate reduction. The abundance of siderite is evidence of complete reduction of sulfate (e.g., Berner, 1971); it has been estimated (see Goldhaber and Kaplan, 1975, and references within) that up to about 20 per cent of the organic matter initially present in sediment is required for complete reduction of sulfate, allowing for some diffusion of sulfate into sediment from the water column. Also, adequate consideration has not been given the possibility that surface fertility and productivity in the vicinity of Site 398 were very low during much of the Barremian through Albian. Although radiolarians, occasional planktonic foraminifers, and calcareous nannofossils are found in sediment, they are often in redeposited intervals and may have been derived from other areas of higher productivity along the continental


a.
ORGANIC CARBON (wt. %)
STAGE
m.y. BP
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
HIATUS ? ? ? ?
MULTICOLORED CLAYS
SITE 105
SITE 386
SITE 391
WESTERN NORTH ATLANTIC
b.
ORGANIC CARBON (wt. %)
STAGE
m.y. BP
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
28.0
37.2
26.1
16.3
18.5
16.3
21.1
25.1
△ – SITE 367
● – SITE 368
CAPE VERDE BASIN
✻ – SITE 369
CAPE BOHADOR SLOPE
LOW CaCO3
High CaCO3

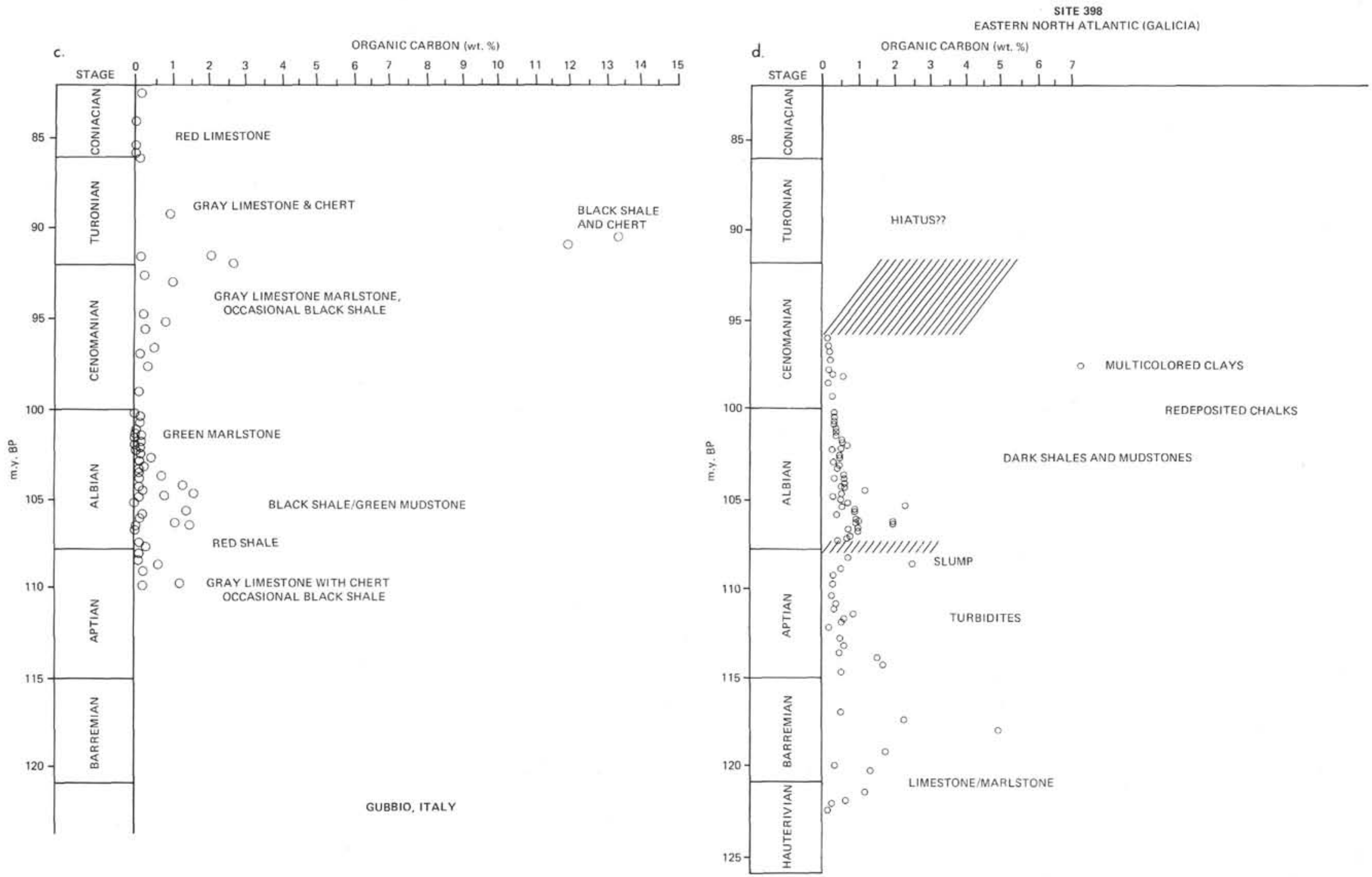


Figure 4. *Measurements of organic carbon content in Lower to Middle Cretaceous sediment from other North Atlantic DSDP sites and from Gubbio, Italy, to illustrate general trends. Site 398 for comparison. (A) Western North Atlantic: data and ages from Hollister, Ewing, et al. (1972) (Site 105); Tucholke, Vogt, et al. (1978) (Site 386); and Benson, Sheridan et al. (1978) (Site 391). (B) Eastern North Atlantic: data and ages from Lancelot, Siebold, et al. (1978). (C) Gubbio, Italy: data from Arthur (unpublished). (D) Site 398: Site Chapter.*

margin. Sigal (this volume), and de Graciansky and Chenet (this volume) appeal to dissolution of calcareous material because of the passage of the site below the CCD. However, I suggest that a record of some productivity is present but the paucity of calcareous microfossils is due to a combination of low productivity, dilution by terrigenous detritus, and diagenetic transformation of much biogenic calcite to siderite. Aspects of the carbonate problem will be argued further in the following section. Thus, the frequent fine lamination, apparent lack of bioturbation, alternation of relatively organic carbon-rich and -poor layers, and variations in abundance of benthic foraminifers could have been due to periodic anoxic or low-oxygen conditions in the bottom waters of this part of the North Atlantic. The apparent lack of preservation of marine hydrogenous organic matter then could be explained by terrigenous dilution, low productivity in surface waters, and consumption during anaerobic bacterial metabolism. Low productivity in surface waters of the northern North Atlantic may have resulted from large salinity variations caused by fluctuations in fresh-water input from deltas. Much of the terrigenous organic matter may have been oxidized in terrestrial shallow marine sites of initial deposition prior to transport to deeper waters. It is interesting to note that as sedimentation rates (and terrigenous influx) decline for the upper Albian-Cenomanian, the proportion of marine-derived organic matter increases as does pelagic carbonate, some of which may have been redeposited from local submarine highs.

RHYTHMIC SEDIMENTATION

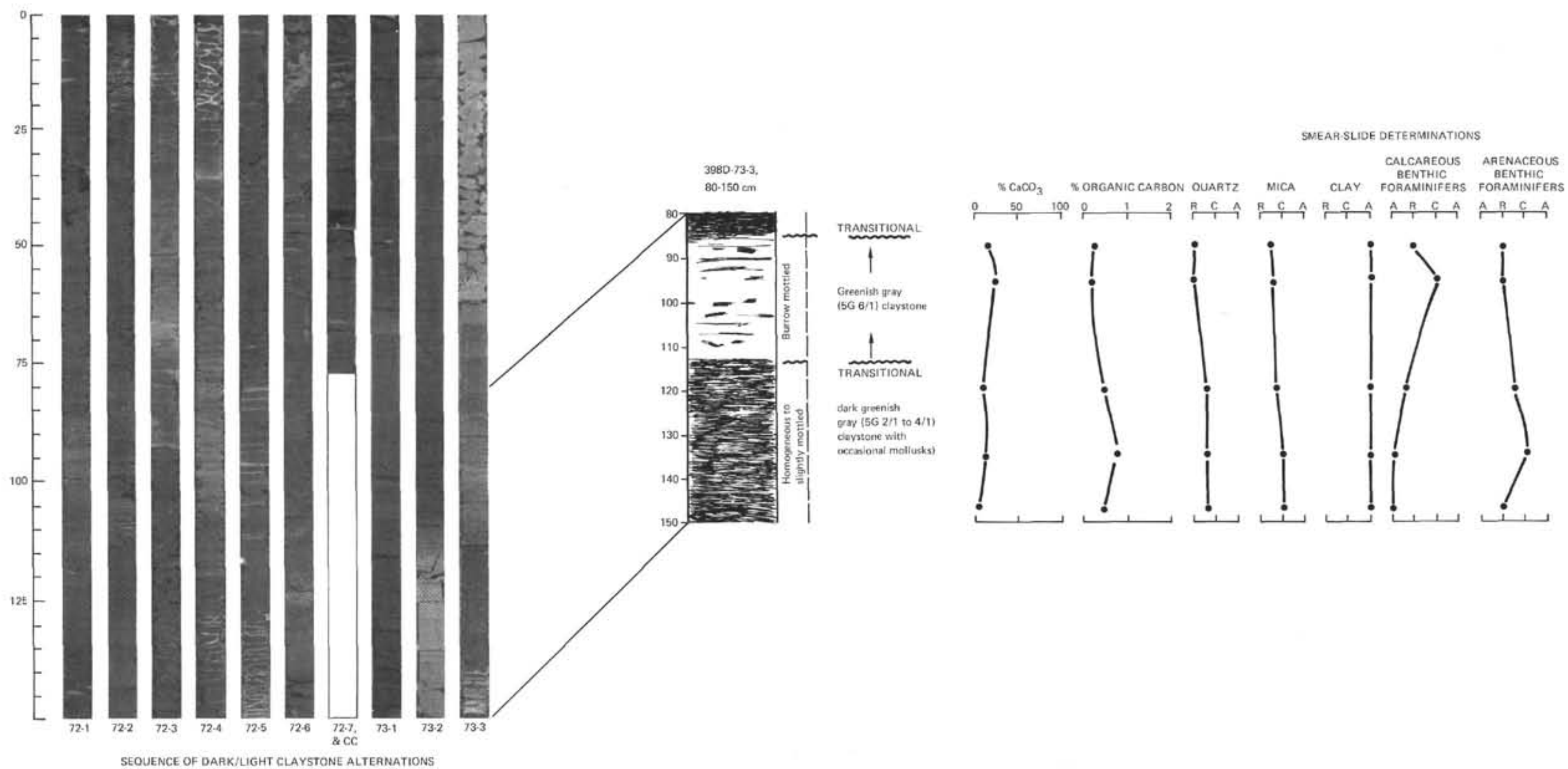
A conspicuous feature of all "black shale" sections is rhythmically interbedded light- and dark-colored sediment. This rhythmicity is generally expressed as an alternation of dark gray to black, homogeneous to laminated, organic carbon-rich clay or mudstone and dark green-gray, light greenish gray or blue-gray, burrow-mottled mudstone, marlstone, or limestone. The carbonate content depends on age and depth of deposition and the amount of terrigenous dilution: Neocomian rhythms generally consist of marl-limestone couplets, while Aptian-Albian rhythms are generally more carbonate depleted. This, of course, is a function of the relatively shallow CCD level (about 3000 m) in the North Atlantic during post-Barremian through much of the Late Cretaceous (e.g., Tucholke and Vogt, 1979). These marl-shale couplets seem to be present at nearly all paleodepths sampled in the North Atlantic (e.g., from shallower Sites 144 and 369 to deepest Aptian-Albian levels at Sites 386, 387, and 391) and in Tethyan sections such as Vergons, France (de Boer et al., in preparation; personal observation) and Gubbio, Italy (Arthur and Fischer, 1977). McCave (1979) and Dean et al. (1978) have discussed exemplary Lower Cretaceous sediments of the western and eastern North Atlantic basins, respectively. Estimates of the periodicity of these oxidation-reduction cycles are subject to several assumptions, but suggested periods range from 20,000 to 100,000 yr/cycle with an average of about 50,000 yr being the best estimate (Dean et al., 1978; Arthur and Fischer, 1977). This type of rhythmicity with approximately the same periodicity is seen to some extent in the Lower Cretaceous section at Site 398, especially Hauterivian (Figure 5B) and Albian-Cenomanian (Figure 5A) sediments, and also has been reported from Sites 400 and 402 of Leg 48 in both shallow- and deep-water black shale settings (Scientific Staff, Leg 48, 1976).

The lithologic expression of the cycles varies somewhat as shown in Figure 6 (also see Plate 6). In more pelagic sequences, the passage from the underlying light-colored portion of the cycle to black clay or mudstone above may be transitional to sharp, while the contact between dark-colored mudstone and overlying lighter colored marl is also sharp to transitional. The original nature of this contact can be blurred by bioturbation (as at Gubbio, Figure 6), but McCave (1979) has shown it is often quite sharp. In contrast, the cycles in more rapidly deposited sediment with a pronounced high terrigenous input generally show sharp contacts between light-colored, more calcareous layers and overlying, dark-colored, relatively organic carbon-rich layers (Dean et al., 1978). The passage from dark to light layers is generally more transitional. In oxidation-reduction rhythms from all settings, bioturbation is usually confined to the light-colored, relatively carbonate-rich and organic carbon-depleted intervals; dark gray to black layers are typically organic carbon-rich, relatively carbonate-poor, and homogeneous to finely laminated.

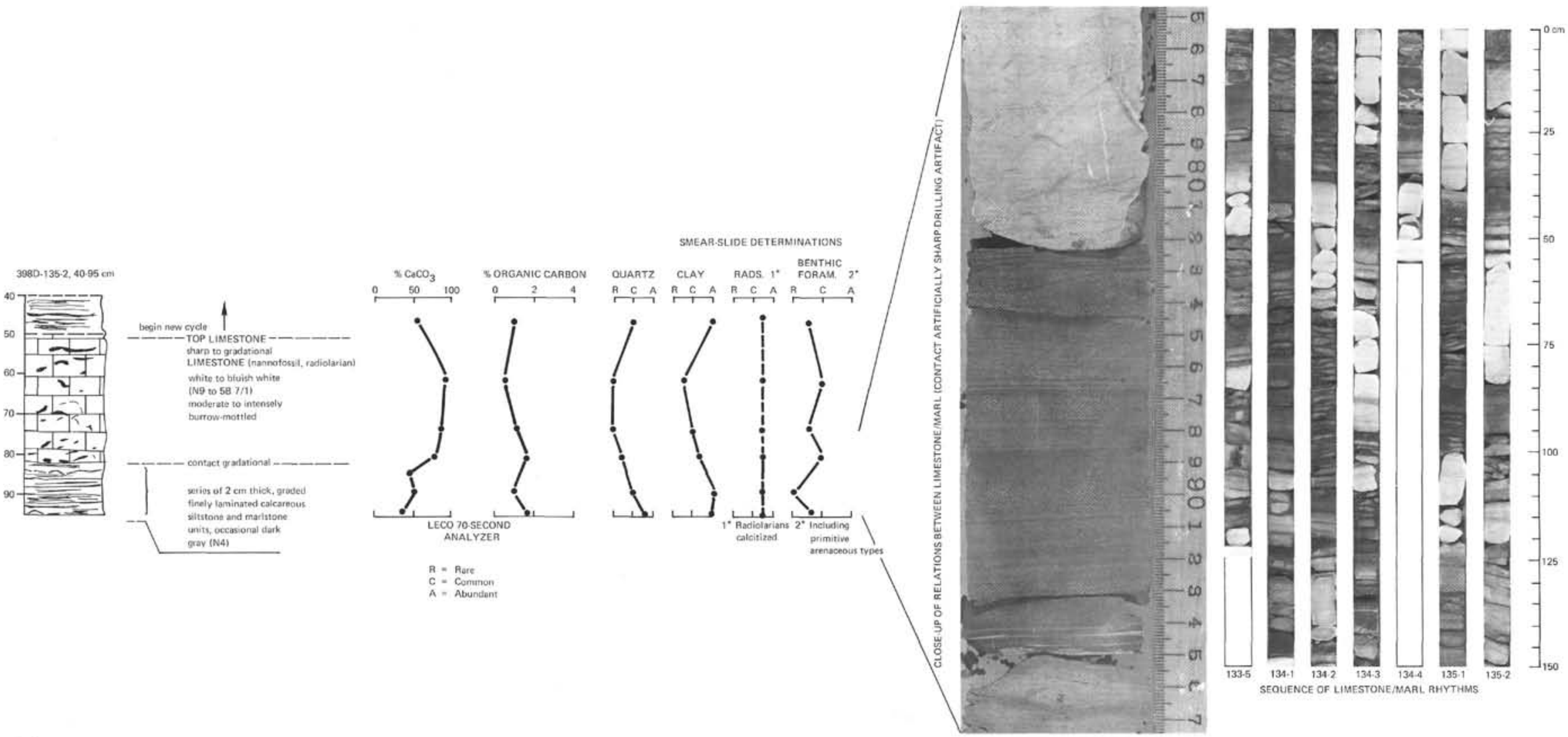
At Site 398, there are two intervals where oxidation-reduction cycles are outstanding (oxidation-reduction cycles also are sometimes carbonate cycles): in the Hauterivian (Figure 5B) and in the Albian-Cenomanian (Figure 5A). Cycles are not as apparent in intervening intervals, possibly because of very high sedimentation rates (up to 100 m/m.y.) and terrigenous dilution (where a 50,000-yr cycle would represent about 5 m of sediment), superimposed rapid sedimentation events (debris flow units, sand, and silt beds), and problems of core recovery. Carbonate contents are higher in Hauterivian-lower Barremian and upper Albian-Cenomanian lighter colored sediment than in the dark-colored Barremian to middle Albian interval (Figure 2). The peaks in carbonate correspond to lower terrigenous influx and consequent diminished sedimentation rates (about 8 to 25 m/m.y.). Therefore, the expression of the cycles is enhanced at these times.

The Hauterivian cycle at Site 398 (Cores 398D-131 to 398D-138) is an alternation of bluish white to very light gray (5B 8/1 to N8) recrystallized nannofossil limestone and marly nannofossil limestone with typical burrow-mottling, and of dark gray to medium dark gray homogeneous to laminated (N3 to N4) calcareous silty claystone (see Figure 5B). Radiolarians replaced by calcite are common in the light-colored limestone; fine lamination is also common, but burrow mottling is more typical. Contacts with dark-colored, more clay-rich sediment are transitional both above and below. The two lithologies are often finely interlaminated at their upper and lower margins. The dark-colored part of each bedding rhythm typically contains less carbonate, more organic carbon (especially land-plant material and wood fragments), and has a more terrigenous character overall. Multiple, apparently fine-grained, graded sedimentation units of 1 to 2 cm thickness often comprise these intervals. The nannofossil limestones have a variable clay content and contain a significant amount of other terrigenous components, primarily silt-sized quartz and mica; organic carbon contents are usually low relative to the dark-colored layers. The cycle described above apparently represents a periodic increase in terrigenous influx superimposed on deposition of pelagic nannofossil carbonate. Quartz-silt layers of mud-chip turbidite units are occasionally associated with the dark calcareous mudstone intervals. These types of turbidites become more prevalent upward beginning in Core 398D-129. The dark mudstone is rarely burrowed, suggesting either rapid deposition or bottom-current activity which prevented or destroyed a record of much bioturbation, or anoxic conditions on the sea floor which periodically eliminated benthic fauna. It is difficult to determine the possible occurrence of the latter, but evidence of current activity is certainly present. Estimated periodicity is about 50,000 yr/cycle, with a possible range of 30,000 to 100,000 yr. Distinct rhythmic bedding appears again, beginning in Core 398D-87, and becomes prominent from Cores 398D-77 through 398D-56 in upper-middle Albian to middle Cenomanian sediment. The sediment in both parts of the rhythm in this interval is more carbonate rich overall than in the preceding Aptian through middle Albian dark-colored mudstones. The diminishing amount of terrigenous dilution (lower sedimentation rates) is certainly one reason for this. The rhythm is expressed mainly as an alternation of greenish gray to gray (5GY 2/1-4/1 and N2 to N3) calcareous mudstone, marlstone, or marly nannofossil chalk with dark gray to medium-dark gray and medium gray (N2 to N4) mudstone and calcareous mudstone. Colors lighten upsection as carbonate content increases. Organic carbon contents are relatively low, averaging about 0.5 wt. per cent; dark-colored parts of the rhythm often contain more organic carbon than the lighter colored, more carbonate-rich intervals. The dark layers are laminated to homogeneous and usually unburrowed, while light layers commonly exhibit burrow mottling and are rarely laminated. The proportion of the sand-silt fraction estimated from smear slides differs only slightly between light and dark portions of the rhythm, and the mineralogy in each is similar. The main difference appears to lie in carbonate and organic carbon contents; authigenic pyrite is present in both types of sediment. de Graciansky and Chenet (this volume) have suggested that the chalks and marls represent carbonate redeposited from higher levels to the sea floor at Site 398, which was below the CCD during this time. They imply that the dark-colored carbonate-depleted sediment is the hemipelagite or the autochthonous part of each rhythm (see discussion of carbonate diagenesis below). Some carbonate-rich intervals certainly originated as redeposited sediment, because graded bedding and sharp basal contacts can be observed (Plate 1, Figure 2; Section 398D-56-3), and some intervals may exhibit current laminations. However, many of the contacts between dark and light units are very gradational (Figure 5) and the limier portions are nearly always burrow-mottled (Plate 1, Figure 3) while dark mudstones apparently are not. All of these relations suggest that periodic, more rapid, terrigenous input (dark, carbonate-poor, organic-rich clays) was superimposed on generally autochthonous pelagic carbonate sedimentation (primarily calcareous nannofossils preserved). The dark muds are similar to but less organic carbon-rich than those considered to be mud turbidites lower in the section. The importance of this sediment type decreases upsection. Sigal (this volume) has shown that the preserved benthos in dark muds are primarily refractory elements, i.e., arenaceous foraminifers, while more carbonate-rich parts of each cycle do contain some calcareous benthic and planktonic foraminifers. Radiolarians are present in both portions. It is difficult to determine whether or not anoxic conditions prevailed during deposition of the apparently unburrowed relatively organic carbon-rich dark muds. Near anoxic conditions in the water column may have prevailed at times, thus inhibiting the existence of a burrowing infauna and allowing preservation of more reactive organic matter. Benthic foraminifers in the dark layers may have been transported from more oxygen-rich environments or reworked from sediment representing oxygenated periods. They also may have lived in sediment under low-oxygen conditions; Phleger and Soutar (1973) have shown that productivity of recent benthic foraminifers along the California borderland is very high even when bottom-water oxygen levels reach values of less than 0.1 ml/1. Conditions were apparently not as intensely oxygen depleted on the sea floor at Site 398 as in other parts of the North Atlantic.

A rhythmicity, then, is apparent in the variation of carbonate and organic carbon concentrations and the extent of bioturbation in many portions of the Lower Cretaceous black shale section. The estimated periodicity of the rhythm, which in this setting may represent fluctuations in terrigenous influx to the basin in response to climatic cycles, is about 50,000 yr (with a possible range of 20,000 to 100,000 yr). This "average" estimate depends on several assumptions. The cycle is similar to those recognized in many other Lower Cretaceous "black shale" or multicolored clay sequences. In the central North Atlantic sequences mentioned earlier (e.g., those described by McCave, 1979), such cycles may represent periodicity in renewal of oxygen to bottom water, possibly by climatically induced sinking of saline surface waters from evaporative shelf settings. Depletion of oxygen would occur gradually so that the transition from burrowed light-colored portions of cycles to dark-colored, typically unburrowed, and organic carbon-rich portions would be transitional; nearly


72-1
72-2
72-3
72-4
72-5
72-6
72-7, & CC
73-1
73-2
73-3
SEQUENCE OF DARK/LIGHT CLAYSTONE ALTERNATIONS
398D-73-3, 80-150 cm
TRANSITIONAL
Burrow mottled
Greenish gray (5G 6/1) claystone
TRANSITIONAL
Homogeneous to slightly mottled
dark greenish gray (5G 2/1 to 4/1) claystone with occasional mollusks)
% CaCO$_3$
% ORGANIC CARBON
SMEAR-SLIDE DETERMINATIONS
QUARTZ
MICA
CLAY
CALCAREOUS BENTHIC FORAMINIFERS
ARENACEOUS BENTHIC FORAMINIFERS

(A)



(B)

Figure 5. *(A) Typical Albian-Cenomanian cycle or rhythm from Site 398 (398D-73-3) showing variation in lithology, organic carbon, carbonate, and selected mineralogic and fossil constituents (see text). (B) Example of rhythm from Hauterivian at Site 398 (398D-135-2) (see text).*

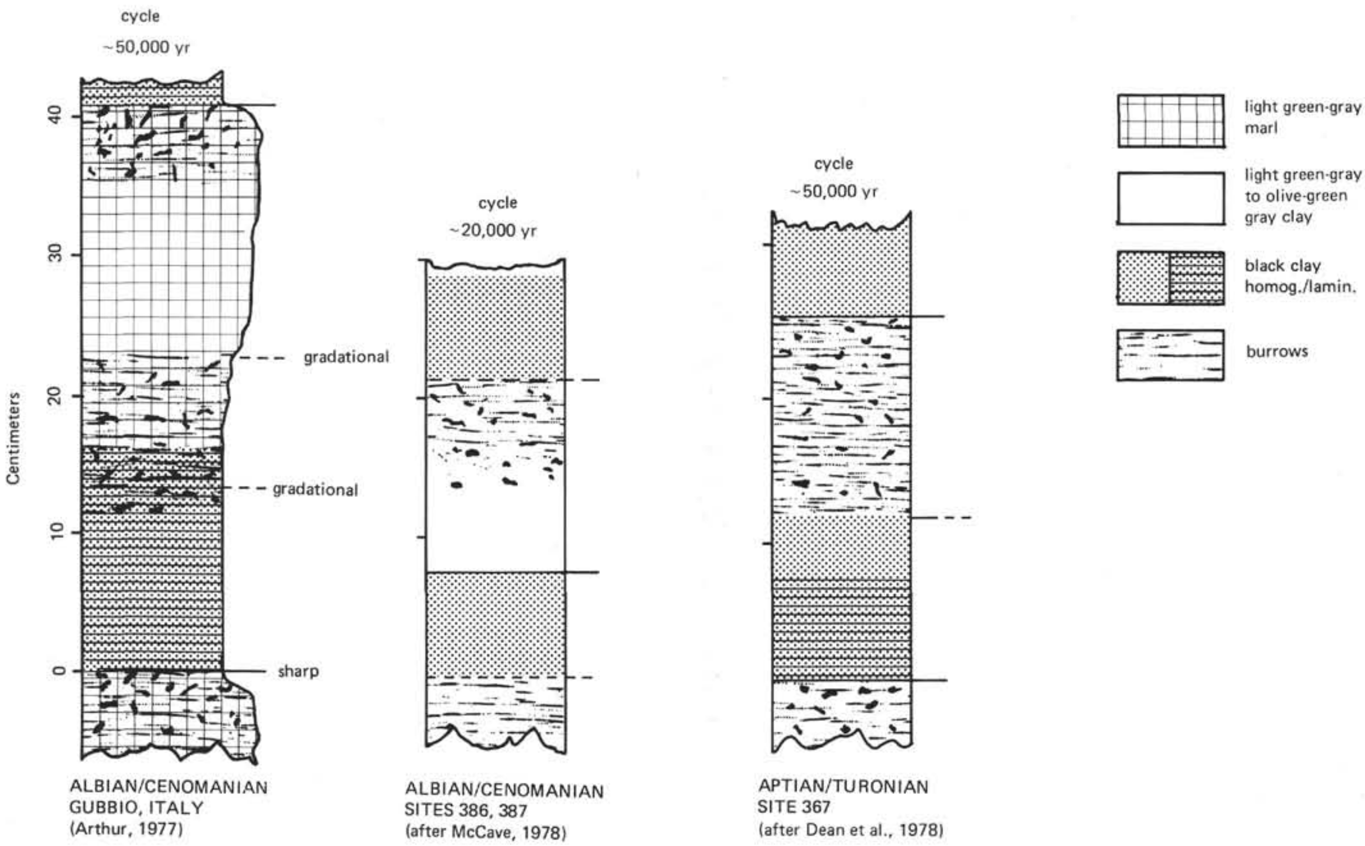


Figure 6. *Examples of Early to Middle Cretaceous oxidation-reduction cycles in multicolored clays from the North Atlantic and Gubbio, Italy.*

total depletion of oxygen might ensue for several thousand years. The oxygenation pulse would be expected to be fairly rapid, hence a sharp upper contact to the black clay part of the cycle (Figure 6). Alternations in carbonate preservation could also result from these periodic exchanges in deep water; preservation would be enhanced during the oxygenated pulse where saline surface waters of high carbonate alkalinity sink to the bottom. During oxygen depletion, CO_2 would be produced and the pH would be expected to fall within the sediment resulting in dissolution of carbonate until saturation again was reached. Of course, cyclic fluctuations in surface productivity cannot be excluded as a cause of the rhythms (McCave, 1979).

CARBONATE SEDIMENTATION AND DIAGENESIS

An interesting aspect of the paleoenvironment at Site 398 concerns the apparent subsidence of the sea floor at the site below the CCD level (or rise of the CCD) during the early Aptian (Sigal; de Graciansky and Chenet; both, this volume). The observation is based on the standard criteria of etching and dissolution of calcareous nannofossils and foraminifers and the near-absence of carbonate in bulk sediment within the lower Aptian through middle Albian interval (see Figure 2). There are a number of problems with this interpretation; I argue here that one cannot sufficiently evaluate the CCD depth during deposition of hemipelagic sequences such as that at Site 398. First, sedimentation of pelagic carbonate occurs within the Hauterivian to upper Barremian section and again from upper Albian to mid-Cenomanian, with a relatively carbonate-depleted interval interposed. This requires either a lowering of the CCD during the late Albian and resumption of carbonate preservation at Site 398, or rapid and coeval redeposition of carbonate originally sedimented on slopes above the CCD. The latter interpretation is consistent with the features seen in some but not all carbonate beds of the upper Albian to mid-Cenomanian interval. Many of the carbonate beds are bioturbated and rhythmically (often gradationally) interbedded with dark shales, as previously discussed. This may suggest that at least some of the light-colored pelagic limestone beds resulted from enhanced preservation of pelagic carbonate on the sea floor with continuing periodic influx of terrigenous sediment typical of the preceding time period, but at much lower rates. Terrigenous dilution is one important facet of the CCD problem at Site 398. As the terrigenous influx and overall sedimentation rate decline, the carbonate content of bulk sediment increases and marl or chalk beds become more pronounced.

The lower Aptian through middle Albian interval (Cores 127 to 79) at Site 398 has a very high sedimentation rate (>50 m/m.y., locally 75 m/m.y. to 100 m/m.y) and is characterized by carbonate values in bulk sediment of less than 5 wt. per cent (Figure 2). The calcareous foraminifer and nannofossil preservation is poor in this interval, yet mollusk debris and (especially) whole ammonites are preserved, and aragonitic epistominids may be found (Sigal, this volume). Foraminifers and nannofossils are abundant enough to allow biostratigraphic zonation of sediment. Therefore, calcareous microfossils have not been completely dissolved; but redeposition, terrigenous dilution, and diagenesis in such a sequence has substantially altered the record of carbonate sedimentation. The diagenetic aspect of carbonate alteration in the sediment within the Aptian through middle Albian interval is seen in the presence of abundant siderite as layers, lenses, laminae, and pods or concretionary lumps (Figure 2; Plates 2 and 3). In fact, the occurrence of siderite is limited exclusively to the carbonate-poor intervals supposedly sedimented below the CCD. Thin-section and smear-slide examination shows that some of the siderite occurs as replacement of calcareous nannofossil-rich layers or laminae, but much of the siderite occurs as cemented aggregates of 10 to 20 micron-sized euhedral to anhedral grains, the origin of which is uncertain. Boundaries of siderite layers and lenses with surrounding dark claystones are sharp to gradational. Some structures suggest obvious dissolution, migration, and redeposition of carbonate in concentrations as siderite, sometimes in association with molluskan shell fragments. Other sedimentary structures within hard, dense siderite layers (such as lamination and burrow mottling) imply replacement of original carbonate-rich layers. Most layers or lenses are about 1 to 2 cm thick (or less) and fairly abundant within dark claystone or mudstone intervals, but some may be as thick as 6 cm. The presence of this siderite is not reflected in measurements of carbonate in bulk sediment, nor has it been considered with reference to aforementioned discussions of the CCD depth. Most of the siderite layers are fairly pure and probably represent dissolution of calcium carbonate and growth of siderite during early diagenesis. Oxygen and carbon isotope values of siderite (4 samples; see Arthur et al., this volume) and de Graciansky and Chenet (this volume), may have been in response to equilibration with anaerobic interstitial waters of rapidly deposited carbonate-poor above and below. Thus, the occurrence of much of the carbonate dissolution, as suggested by Sigal (this volume) and de Graciansky and Chenet (this volume), may have been in response to equilibration with anaerobic interstitial waters of rapidly deposited carbonate-poor terrigenous sediment, rather than entirely in response to an elevated CCD. The requirements for formation of siderite over calcite are generally a high carbonate alkalinity, very low dissolved sulfide contents, and Fe^{2+}/Ca^{2+} of >0.05 (Berner, 1971). Sulfide resulting from anaerobic bacterial sulface reduction may have been completely exhausted by formation of metal sulfides during early diagenesis; pyrite is a common constituent of the reducing sediments at Site 398. The reduced iron: calcium ratio was probably high in the terrigenous sediment. Siderite is present to abundant in a number of other North Atlantic "black shale" sequences (e.g., Sites 105, 386, and 397).

It can be demonstrated that there are many difficulties in interpreting the Lower Cretaceous sequence at Hole 398D in terms of relative changes in the CCD depth. There seems little doubt that the site was well below the CCD after the middle Cenomanian and until at least late Campanian time, as evidenced by the sequence of slowly deposited barren red clays within that interval. The CCD level appears to have again been depressed below the depth of the site from Campanian through late Maestrichtian-Paleocene time. However, the problems of dilution and of carbonate diagenesis in the rapidly deposited Lower Cretaceous terrigenous section cast doubt on attempts to ascertain the relative CCD depth during deposition at this earlier time. This is not to say that the site did not subside below the CCD during Aptian time, but only to call attention to the problems of interpretation and to suggest the likelihood that it did not. An estimate of the paleodepth during that interval, based on the thermal subsidence depth backtracking method and assuming an initial depth and time of rifting of about late Hauterivian (Sibuet and Ryan, this volume), allows for sedimentation at Site 398 in less than 3000 meters of water during pre-Cenomanian time. Tucholke and Vogt (1979) have suggested that the Early to Middle Cretaceous CCD in the western North Atlantic could have been as shallow as 2500 meters; if this estimate holds for the northern North Atlantic, which is uncertain, then the site could have been just below the CCD during Aptian and later time. An interesting observation is that late Albian sedimentation represents an amelioration of the preceding low oxygen conditions and sedimentation of pelagic carbonate becomes more widespread in the northern North Atlantic during and following that time (e.g., Hart and Tarling, 1974; Hart and Carter, 1975; Jansa and Wade, 1975). The coincidence of gradual marine transgression with decline in sedimentation of terrigenous materials in marine basins, better oxidation of oceanic deep waters, and spread of carbonate sedimentation during late Albian and Cenomanian time suggests that these events are somehow linked. It is possible that the paucity of carbonate in northern North Atlantic sites prior to the late Albian is due, in addition to dilution and diagenetic factors, to low sea-surface fertility, fluctuating salinities, and turbidity because of the major deltaic influx into a somewhat restricted high latitude basin (Figure 7; see also Sibuet and Ryan, this volume, their fig. 4). By late Albian-early Cenomanian time, marine transgression and possibly climatic changes had resulted in cessation of most deltaic outbuilding and trapping of terrigenous materials on shelves and in interior basins (see Jansa and Wade, 1975; Bhat et al., 1975; Einsele and von Rad, in press). Sea-floor spreading, which began in the latest Aptian in the northern North Atlantic (Sibuet and Ryan, this volume), had widened this seaway and probably brought about good connections for surface circulation with the remainder of the North Atlantic. The combination of these two effects possibly led to widespread

Figure 7. *Location of North Atlantic sites recovering Cretaceous sediment (shown on Figure 3) on reconstruction of Sclater et al. (1977) for 110 m.y.B.P. Note paleolatitudes of ocean basins discussed in text.*

chalk sedimentation in the northern North Atlantic region. The spread of chalk seas and extraction of large amounts of carbonate in shelf settings may have then led to the rise of the CCD in the post-Cenomanian Cretaceous.

PALEOENVIRONMENTAL MODELS

The overall explanation for these widespread organic-rich and carbonate-poor facies, many of which exhibit evidence of anoxic conditions or extreme oxygen depletion in bottom waters above the sediment-water interface, can be found in conditions of paleoclimate and in sea-level changes (e.g., Schlanger and Jenkyns, 1976; Ryan and Cita, 1977; Fischer and Arthur, 1977). Stability of water mass stratification leading to establishment of deep-water anoxia can be a function of several parameters (salinity-temperature) which may vary latitudinally and regionally within latitudinal envelopes. These parameters certainly depend on such factors as average air temperature, the balance of evaporation versus precipitation over a sea and adjacent land areas, and the amount of restriction of an ocean basin (landlocked, silled, or open to exchange). For example, restricted high-latitude ocean basins having an excess of precipitation over evaporation and surrounded by high-standing landmasses can develop a stable salinity stratification with a low salinity surface-water layer. Organic productivity in surface waters within such a basin may be relatively low; anoxic or near-anoxic conditions may develop in deep waters of the basin, but mainly terrigenous-derived organic matter will be preserved in sediments. Organic material is derived mostly from deltas and low-lying coastal plains in this climatic regime (Habib, this volume; Simoneit, 1977). This is probably an explanation for the origin of "black shales" in the northern North Atlantic (e.g., those cored in Site 398 and during Leg 48), and similar to the Middle Cretaceous situation described by Kauffman (1975) for the Western Interior Seaway of North America. Another end-member of stably stratified basin types is a restricted low-latitude basin where evaporation exceeds precipitation. In this type of basin, a stable salinity stratification develops by the sinking of dense, saline surface or shelf waters. Again, "black shales" would result as anoxic conditions developed, possibly in association with evaporites. Both terrigenous and marine organic matter would be preserved in such a basin (Figure 7) which is similar to the Early Cretaceous Angola Basin of the South Atlantic (e.g., Natland, 1978). An intermediate situation can develop in sluggishly circulating but open ocean basins. Here again, anoxic or low-oxygen conditions may develop in deep waters due to a salinity-density stratification and low latitudinal thermal gradients. Variations on the oxygen-minimum model (Schlanger and Jenkyns, 1976; Thiede and van Andel, 1977; Fischer and Arthur, 1977) can be applied to the vertical oxygen distribution in some such basins (e.g., Early Cretaceous Equatorial Pacific, Indian, and South Atlantic oceans), and, in addition, some basins periodically could become entirely anoxic (e.g., Cretaceous central North Atlantic). Intensity, duration, and depth distribution of anoxia would depend on the size of the basin, age and sources of bottom waters, upwelling, fertility, and, therefore, the amount of degradable organic matter entering the system. The Early Cretaceous central North Atlantic basin was probably intermittently anoxic or nearly so throughout its changes in depth (Ryan and Cita, 1977; Arthur, 1978; Tucholke and Vogt, 1979; Kendrick, 1979; Simoneit, 1977). These periodic oxygen-depleted intervals led to the preservation of both marine (phytoplanktic) and terrigenous (higher plant) organic matter in the "black shales." Large deltaic systems added sediment and organic material to both the east and west basins of the central North Atlantic (Jansa and Wade, 1975; Einsele and von Rad, in press) during much of the Early Cretaceous. Marine organic matter in Lower Cretaceous black shales (Deroo et al., 1978; Tissot, 1978) resulted from enhanced preservation under areas of upwelling of nutrient-rich deep waters such as around the continental margins of Africa and along oceanic divergences. The particularly extensive development of stable stratification and anoxic waters in the central North Atlantic can possibly be attributed to several factors acting in concert: (1) stable salinity stratification due to sinking of dense, saline waters derived from evaporative shelf settings (e.g., Gulf of Mexico region-Florida-Bahamas Platform; Bryant et al., 1969; Khudoley, 1967; Applin and Applin, 1965); (2) mixing of these saline waters with old, already oxygen-depleted deep waters derived from adjoining ocean basins along an equatorial track; (3) sluggish surface-water circulation and relatively poor exchange of gases between surface waters and atmosphere due to equable climate and high surface temperatures; and (4) possible periodic enhancement of stable salinity stratification by incursion of low salinity surface waters due to extensive outflow from delta systems.

Therefore, each basin, although characterized by a Lower Cretaceous black shale facies, has a significantly different hydrologic balance and, hence, different expression of the relatively organic-rich deposits shown in depth range and intensity of oxygen depletion and amount and type of organic matter preserved. The sequence and timing of events in many basins are similar, as discussed in the next section.

DISCUSSION AND CONCLUSIONS

Deposition of black shales in marine environments was widespread during much of the Early Cretaceous. Amounts and sources of organic matter preserved in anoxic or near-anoxic ocean basins varied areally and temporally. Relatively organic carbon-rich black shales were deposited in the northern North Atlantic (cored at Site 398 of Leg 47B, and Sites 400 and 402 of Leg 48) at water depths ranging from less than 200 meters (Scientific Staff—Leg 48, 1976) to over 4000 meters. Organic contents in these sequences are generally low for black shales and consist almost entirely of land-derived higher plant debris (references cited above), except within upper Albian and Cenomanian strata. High sedimentation rates of terrigenous detritus (25 to 100 m/m.y.) and reducing conditions within the sediment column prevailed during most of the Early Cretaceous; conditions were also periodically anoxic or very oxygen depleted within deeper waters of the basin. The following factors probably led to the development of a "black shale" facies in the northern North Atlantic: the tectonic restriction, a high latitude position and apparent excess of precipitation over evaporation, an uplifted hinterland (Wilson, 1975) and development of coastal vegetation belts with consequent large outpourings of terrigenous clastics and land-plant detritus, and a climatically modulated stable salinity stratification. However, proposals to apply to this model to explain all occurrences of "black shales" (e.g., Scientific Staff—Leg 48, 1976; Tissot, 1978; Habib, this volume) appear premature if based on study of only one region. Global climate and sea level were undoubtedly two of the mechanisms controlling development of the black shales, but these controls were manifested in different ways in the various ocean basins, as briefly discussed above. The changes in global climate may have been partly influenced by variations in the atmospheric CO_2 content and geologic extent of ocean basins and shelf seas. Patterns of black shale facies in all North Atlantic basins do show similarities in the development of three major stages as:

1) Intercalations of dark, organic-rich, laminated mudstone and occasional thin sands or silts within light-colored, typically bioturbated pelagic limestone that is Valanginian-Hauterivian and Barremian. Deposition of pelagic limestones ceased at most sites as they subsided below the CCD and as the CCD apparently abruptly arose in Barremian time (e.g., Tucholke and Vogt, 1979).

2) Development of typical "black shale" facies in the Barremian through middle Albian, with pronounced terrigenous imprint including sand, silt, and land-plant derived organic matter. Variations in sedimentation rate, amount of terrigenous detritus, and the ratio of terrigenous: marine organic matter depends on paleodepth, proximity to deltaic influx, and local sea-surface fertility. Anoxic or near-anoxic conditions in the water column were periodic throughout most of the North Atlantic. Analogous Tethyan examples are common.

3) Upper Albian through Cenomanian pelagic "black shales" or multicolored clays typified by primarily marine organic matter preserved in black mudstone layers and interbedded oxidized pelagic carbonates and radiolarian sands. This implies overturn of nutrients and increase in sea-surface productivity over much of the North Atlantic and distinct waning of the terrigenous input. Periodic anoxia still occurred in deep-water masses.

Hiatuses and/or condensed sedimentation of oxidized red or multicolored clays characterize post-Cenomanian Upper Cretaceous sediments at most North Atlantic sites. Sea-floor erosion or low rates of deposition and well-oxygenated conditions were probably related to the destruction of stable stratification and increased circulation, overturn, and oxygenation of deep waters, while a Cenomanian sea-level rise led to entrapment of terrigenous material in shallow-shelf seas and possibly resulted in the destruction of sites of production of dense saline sea water by drowning of rudistid reef complexes and associated shallow-water evaporite settings (e.g., Matthews et al., 1974).

Rhythmic sedimentation characterizes most black shale sections. Interbedded dark, typically laminated, relatively organic-rich mudstones and lighter colored, bioturbated, sometimes more calcareous layers occur with a period of about 50,000 yr. The precise lithologic relationships vary depending on the basin of deposition and paleodepth, but the pronounced rhythmicity suggests a cyclic climatic control of oxygen depletion, input of terrigenous sediment and organic matter, sea-surface productivity, and carbonate preservation. Trends in apparent oxygenation or oxygen depletion on a scale greater than individual cycles can be examined as possible basin-wide events and may indicate something more about the causes of oxygen depletion.

The "black shale problem" is a complex one which will be resolved as more detailed sedimentologic and organic geochemical studies of individual sequences are made on a global basis. The heterogeneity of such deposits necessitates that care be taken to examine individual bedding cycles in detail for faunal and floral composition (especially benthic faunal elements), degree of bioturbation, development of sedimentary structures (such as fine lamination), mineralogy, stable isotopic composition, and amount and type of organic matter (such as those undertaken by various investigators for this volume). These parameters must also be considered with respect to time, as shown above. Only then will we be able to select between the various models of paleoenvironment proposed for black shale deposition and reconstruct a global paleoceanography for the Early and Middle Cretaceous.

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PLATE 1

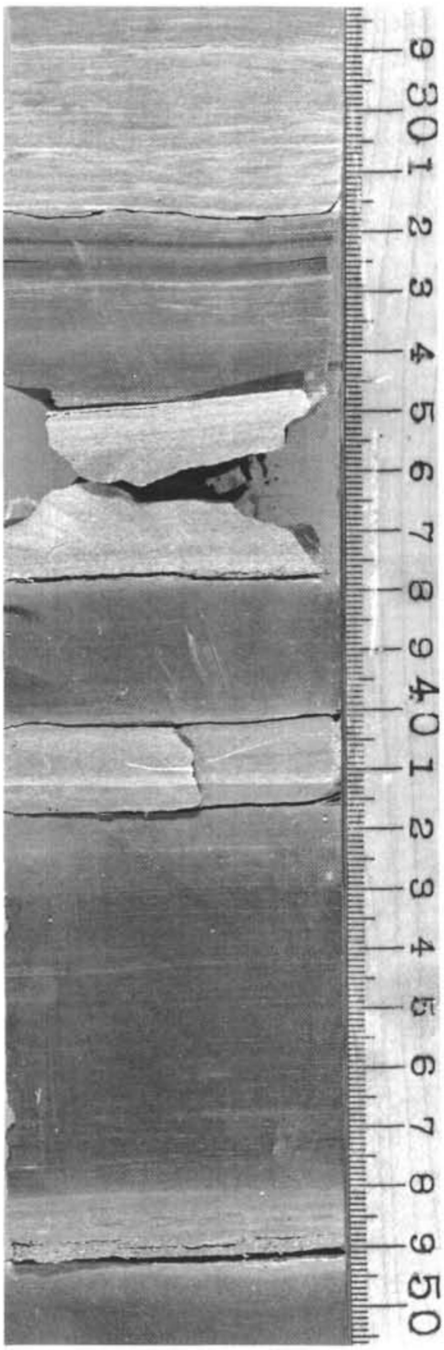
Upper Part of Lithologic Sub-unit 4A

Figure 1 — Sample 398-56-1, 30-50 cm. Laminated grayish green to reddish brown zeolitic claystone with interbedded faintly graded calcareous mudchip siltstones. Note absence of burrowing. This sediment is of middle Cenomanian age and represents the top of Sub-unit 4A at the contact between red claystones and darker mudstones.

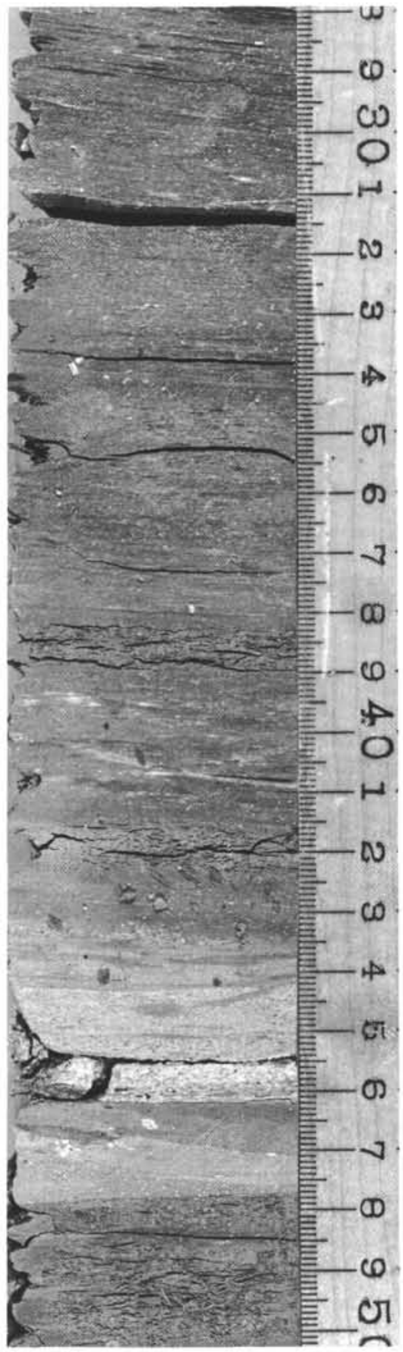
Figure 2 — Sample 398D-56-3, 28-50 cm. Laminated, greenish gray zeolitic claystone showing some bioturbation. Uppermost organic carbon-rich Cenomanian layers were recovered in Sections 2 and 3 of this core. Note evidence of stretching of clasts at base of graded sand at 48 cm. Much material in this core (gypsum, radiolarian sands, marine organic matter) may have been redeposited.

Figure 3 — Sample 398D-59-6, 35-38 cm. Burrowed bluish gray (5B 6/1) marly nannofossil chalk. This is interbedded with homogeneous dark gray-black (N2, N3) marly nannofossil chalk. Contacts are sharp or interlaminated.

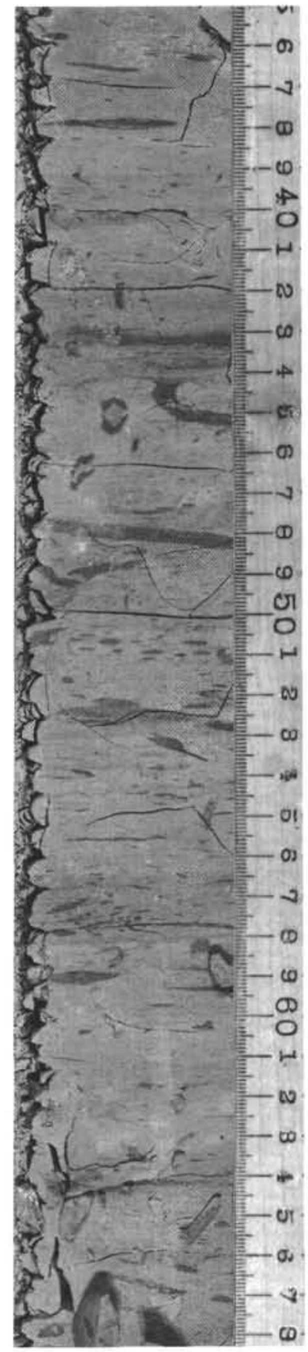
PLATE 1



398-56-1, 30-50 cm



398-56-3, 28-50 cm



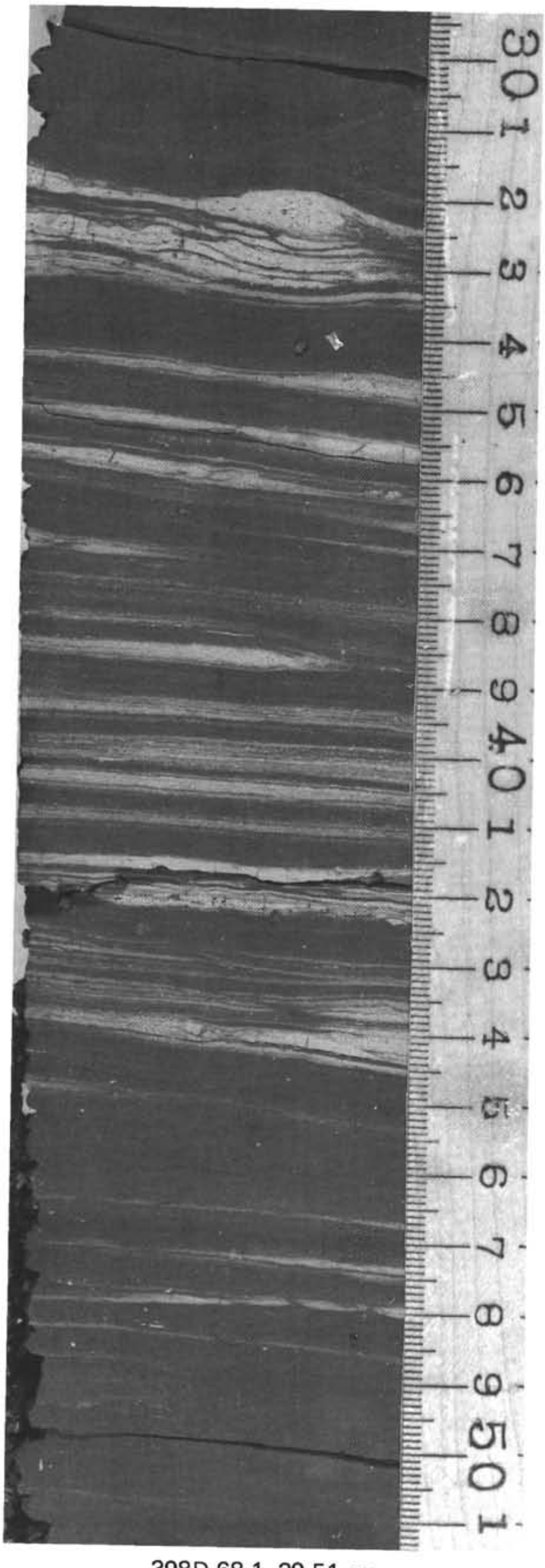
398D-59-6, 35-38 cm

PLATE 2

Lithologic Sub-unit 4A; Dark Mudstones

Figure 1	Sample 398D-68-1, 29-51 cm. Grayish black to olive-black (N2 to 5Y 2/1) laminated claystone with lenses, laminae, and irregular thin beds of (5Y 2/1) siderite, typical of interval from Core 68 to 103; some bioturbation in interbedded lighter colored intervals of greenish black claystone.
Figure 2	Sample 398D-69-4, 100-120 cm. Dense barite nodule in black, very faintly laminated claystone.

PLATE 2



398D-68-1, 29-51 cm

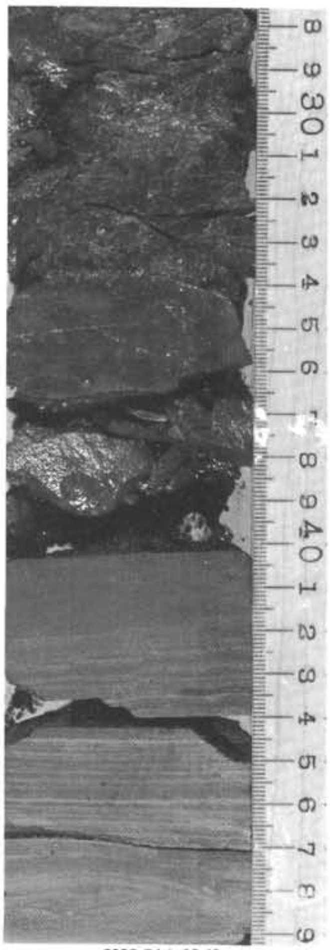
398D-69-4, 100-120 cm

PLATE 3

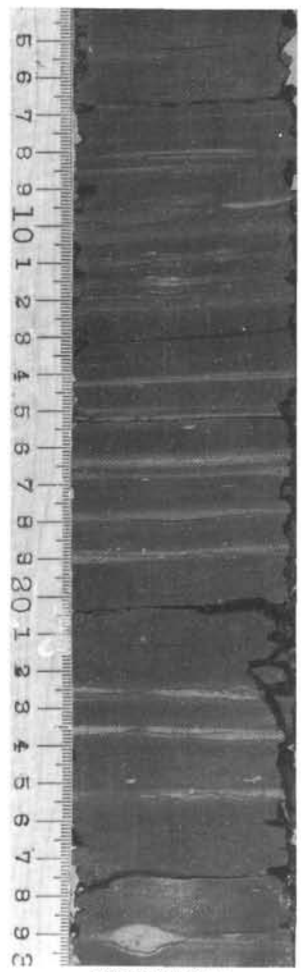
Black Claystone and Slumped Calcareous Intervals, Sub-units 4A and 4B

Figure 1	Sample 398D-74-1, 28-49 cm. Lamination, contorted lamination, and microfaults in dark gray (N3) claystone. Laminations are more calcareous; sedimentary structures indicate some redeposition of carbonate.
Figure 2	Sample 398D-95-2, 4-40 cm. Black claystone (N1, N2) with thin siderite stringers; some siderite blebs may fill small infrequent burrow mottles. In some cores, vuggy siderite fills in upper portion of an upturned concave ammonite fragment.
Figure 3	Sample 398D-105-1, 21-64 cm. Slumped interval consisting of upper Aptian, medium gray to bluish white marly limestone to limestone interbedded in black to dark gray mudstone sequence. Slumped unit is over 3.5 meters thick.

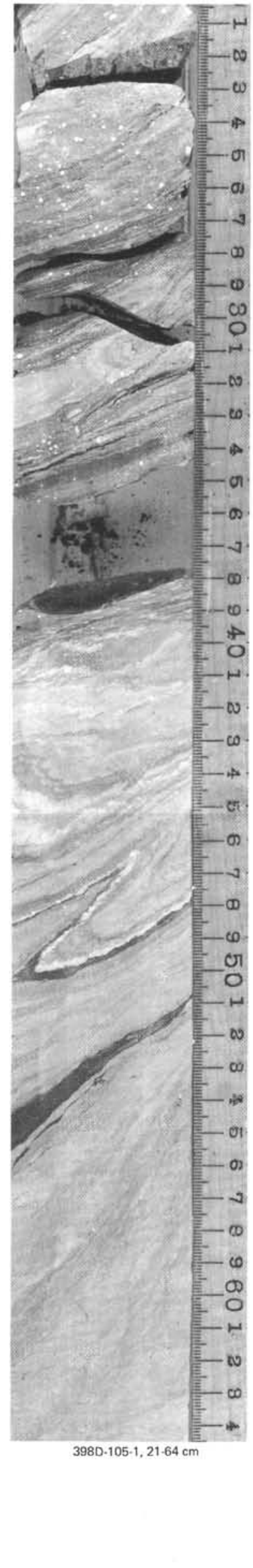
PLATE 3



398D-74-1, 28-49 cm



398D-95-2, 4-40 cm



398D-105-1, 21-64 cm

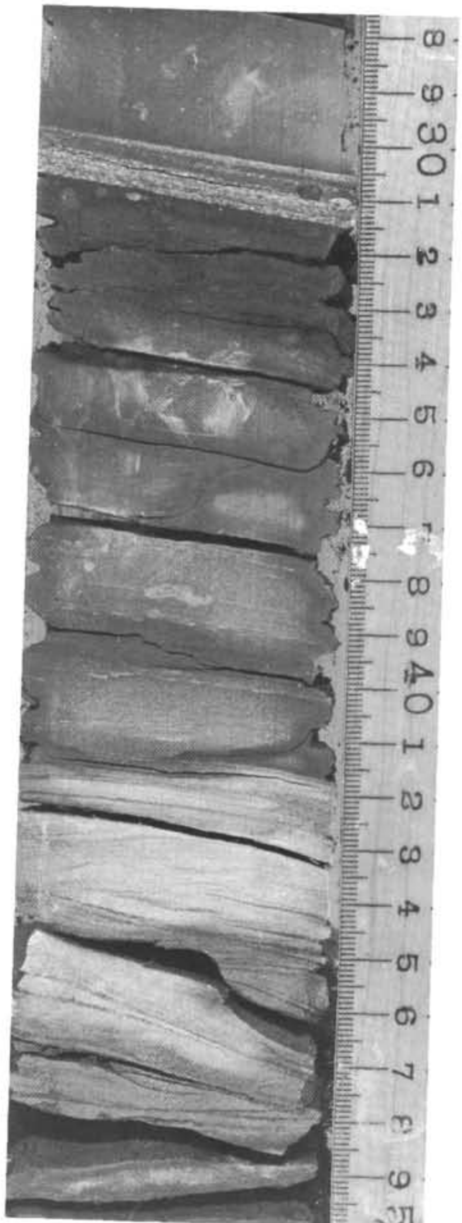
PLATE 4

Turbiditic Sandstones and Siltstones of Sub-unit 4C

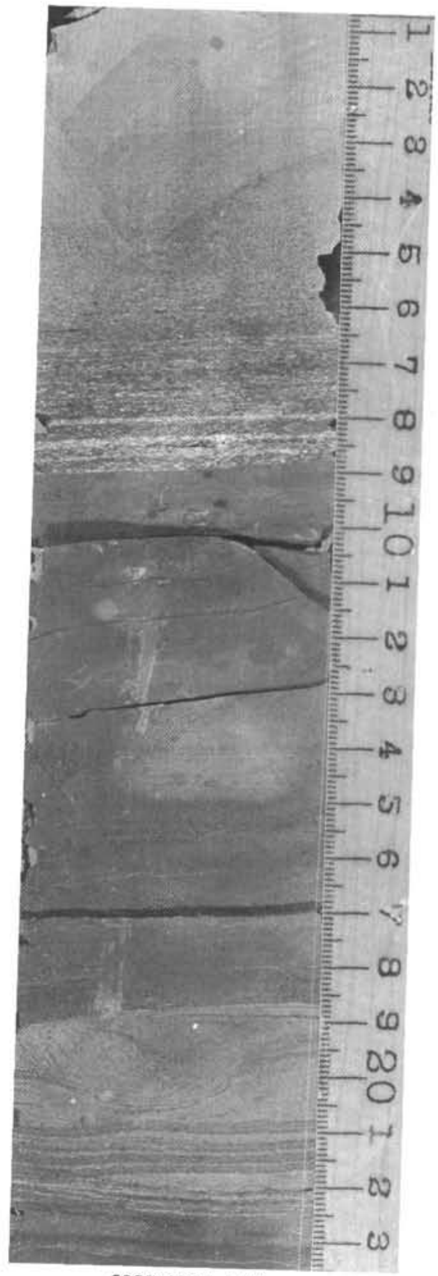
Figure 1	Sample 398D-117-2, 71-100 cm.
Figure 2	Sample 398D-123-1, 28-50 cm.
Figure 3	Sample 398D-123-4, 1-23 cm. Lower to lower-upper Aptian thin-bedded turbidites; ''base cut-out'' sequences with primarily T_{cde} divisions. Cross laminated fine-grained sandstone and siltstone is light gray (N7), grading upward to grayish black claystone (N3). Sands and silts are quartz and calcite rich. Also note the graded muddy calcareous mudchip sands at 31 cm (Figure 2) and 9 cm (Figure 3).

PLATE 4

398D-117-2, 71-100 cm



398D-123-1, 28-50 cm



398D-123-4, 1-23 cm

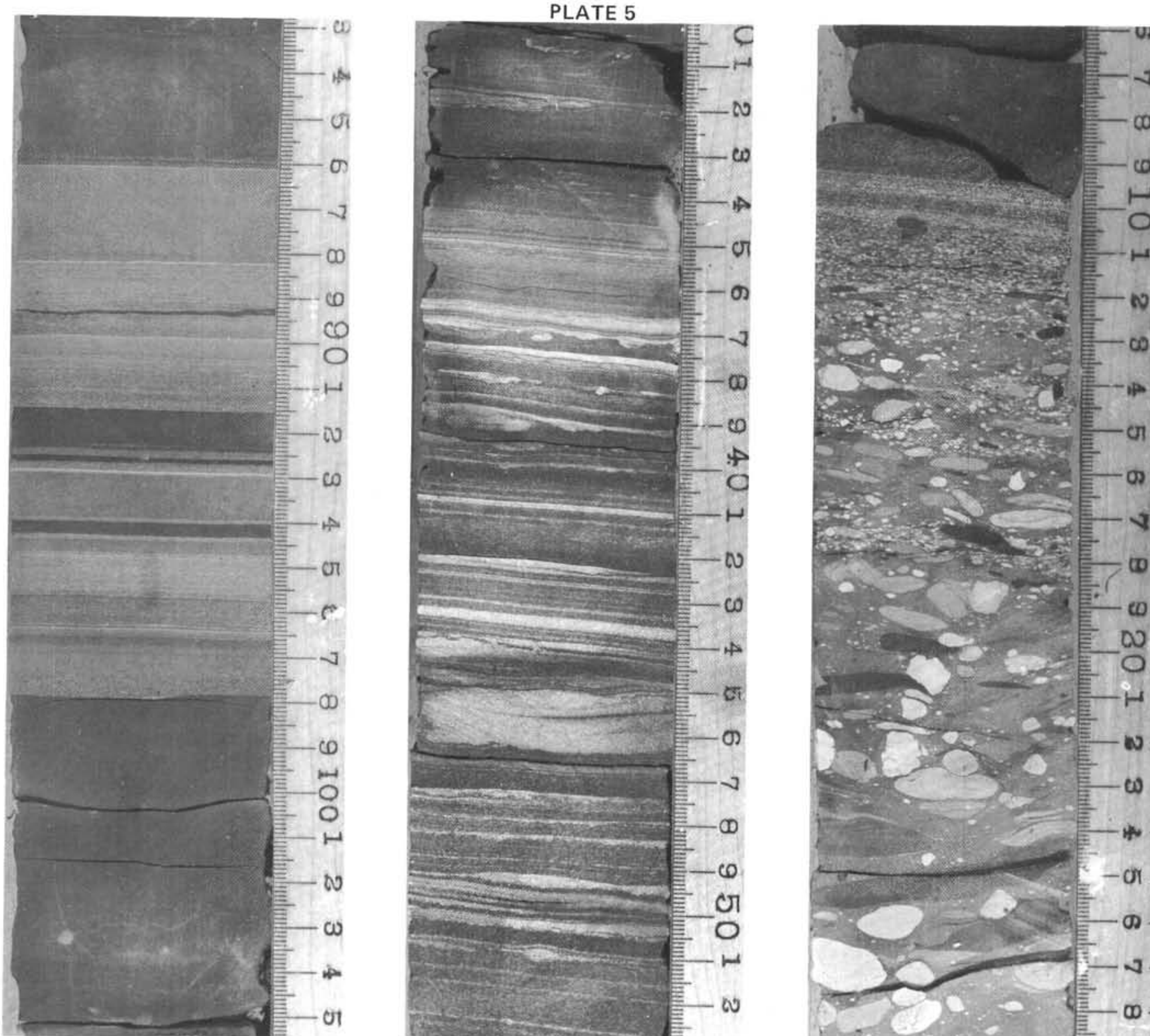
PLATE 5

Figure 1 Sample 398D-127-4, 83-105 cm. Upper Barremian gray-black claystone with very thin, laminated fine-grained faintly graded and superimposed calcareous mudchip turbidites in predominantly fine-grained sand-silt sequence. Pelecypod fragments are commonly found in this interval.

Figure 2 Sample 398D-127-5, 30-53 cm. Upper Barremian, thin-bedded quartzose turbidites.

Figure 3 Sample 398D-124-4, 6-29 cm. Lower Aptian matrix-supported pebbly mudstone. Pebbles consist of white oolitic limestone, deformed white gray to brown chalks and limestones (originally poorly indurated), black claystone, green claystone, pyrite blebs and crystals, and some graded (?) gray siltstone clasts.

PLATE 5



398D-127-4, 83-105 cm

398D-127-5, 30-50 cm

398D-124-4, 6-29 cm

PLATE 6

Similar Appearing Facies and Rhythms in Other North Atlantic DSDP Sites

Figure 1A Section 41-370-28-2, upper Aptian-lower Albian (eastern North Atlantic).

Figure 1B Section 43-387-34-4, Albian(?), (western North Atlantic). These "black shale" facies, deposited at lower rates than the Aptian-Albian "black shales" at Site 398D, exhibit the same dark-light rhythms (see Figure 5A in text). These consist of alternations of silty clay (10G 6/2 and N3) and carbonaceous silty clay (5Y 2/1) at Site 370, and greenish black to black claystone and radiolarian mudstone interbedded with dark green-gray bioturbated radiolarian mudstone at Site 387. At Site 370, organic carbon contents in Core 28 are 2.1 wt. per cent in black, laminated layers and 0.3 wt. per cent in bioturbated light-colored intervals.

Figure 1C Section 43-387-30-1 and Sample 43-387-30, CC (Cenomanian?). This facies occurs near the top of the black shale interval in the western North Atlantic and consists of very organic carbon rich black shale (up to 11 wt. per cent C_{org}) with interbedded radiolarian sands. The interval is overlain by younger oxidized red clays. Similar lithologic relations can be round in many North Atlantic DSDP sites including 398D (see Plate 1, Figure 1).

Figure 2 Section 41-370-41-2 (this example: upper Valanginian-lower Hauterivian). Grayish green nannofossil marlstone (5G 5/2) interbedded with grayish olive 5GY 3/2) argillaceous calcareous siltstone and sandstone. These thin-bedded turbidite sands are somewhat similar to and occur during the same time-rock interval as the Barremian-Aptian in Hole 398D.

Figure 3A Section 41-367-26-2 (Barremian).

Figure 3B Section 43-387-49-5 (Lower Valanginian). Examples of light-colored burrowed pelagic nannofossil Early Cretaceous marlstone rhythmically interbedded with darker, laminated, more terrigenous claystone marlstone and silty claystone. Darker intervals contain higher C_{org} (up to 1.8 wt. per cent) while bioturbated limestones contain <0.2 wt. per cent. These are rhythms similar to the Hauterivian ones of Hole 398D.

PLATE 6