39. SEDIMENTATION-RATE-DEPENDENT DISTRIBUTION OF ORGANIC MATTER IN THE NORTH ATLANTIC JURASSIC-CRETACEOUS[1]

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ABSTRACT

The kind, sedimentation rate, and diagenesis of organic particles delivered to the North Atlantic seafloor during the Middle Jurassic–Early Cretaceous were responsible for the presence of carbonaceous sediments in Hole 534A. Organic-rich black clays formed from the rapid supply of organic matter; this organic matter was composed of either abundant, well-preserved, and poorly sorted particles of land plants deposited in clays and silty clays within terrigenous turbiditic sequences (tracheal facies) or abundant amorphous debris (xenomorphic facies) generated through the digestive tracts of marine zooplankton and sedimented as fecal pellets. Evidence for the fecal-pellet origin of xenomorphic debris is illustrated.

Black clays were also produced in sediments containing less organic matter as a result of the black color of carbonized particles composing all or most of the residues (micrinitic facies). Slowly sedimented hematitic Aptian clays contain very little carbonized, organic debris that survived diagenetic oxidation. In the red calcareous clay sequence of the Late Jurassic, larger amounts of this oxidized debris turned several clay layers black or blackish red. Carbonized debris also dominates the residues recovered in interbedded black and green Albian clays. Carbonization of organic matter in these sediments either turned them black or provided the diagenetic environment for reduced iron. Carbonized debris is also appreciable in burrow-mottled black-green Kimmeridgian clay.

The study of Hole 534A organic matter indicates that during the middle Callovian there was a rapid supply of terrigenous organic matter, followed by a late Callovian episode of rapidly supplied xenomorphic debris deposited as fecal pellets. The Late Jurassic–Berriasian was a time of slower sedimentation of organic matter, primarily of a marine dinoflagellate flora in a poorly preserved xenomorphic facies variously affected by diagenetic oxidation. Several intervals of carbonized tracheal tissue in the Oxfordian and Kimmeridgian suggest episodes of oxidized terrigenous matter. The same sequence of Callovian organic events is evident in much of the Early Cretaceous: rapid supply of terrigenous organic matter followed by rapid sedimentation of fecal debris and morphologically sorted pollen grains. During the middle Albian to Vraconian, smaller terrigenous carbonized particles were more slowly sedimented. According to this history, the North Atlantic need never have undergone widespread basinal anoxia during the middle Callovian–Vraconian. It could have been oxic throughout this time, with anoxia produced in the sediments whenever there was a sufficiently rapid supply of organic matter.

INTRODUCTION

The palynology of the Lower Cretaceous–Jurassic sequence of Hole 534A, drilled by the Deep Sea Drilling Project in the Blake-Bahama Basin and located 22 km northeast of Hole 391C (Fig. 1), was undertaken to determine the stratigraphic occurrence and origin of particulate organic matter. Hole 534A penetrated a subbottom depth approximately 1666 m thick, terminating in basalt (Site 534 report, this volume). The palynological investigation covered the lowermost 875 m of the sedimentary section (Fig. 2), which includes the Hatteras Formation, Blake-Bahama Formation, and Cat Gap Formation, formally described and named by Jansa et al. (1979) in a study of the western North Atlantic, and a lowermost new and unnamed lithostratigraphic unit resting directly on basalt. In Hole 534A, this sequence ranges from Vraconian Albian at the top of the Hatteras Formation to middle Callovian at the base of the unnamed unit, on the basis of stratigraphic ages determined by dinoflagellates (Habib and Drugg, this volume).

The lithostratigraphy (Fig. 2) of these units is described, with emphasis placed on the occurrence of organic matter and on the lithology of samples collected for palynological study (see the Site 534 report for a detailed lithologic description [this volume]). The sedimentology is described by Ogg et al. (this volume) and Robertson (this volume). One hundred and one cores were recovered in the palynologically studied interval. The Hatteras Formation extends from the level of Cores 534A-27 through 534A-48, and is approximately 200 m thick. Four main lithologies are evident. The uppermost consists of carbonaceous claystones interbedded with greenish gray, silty claystones in Cores 534A-27 through 534A-30, deposited in the Vraconian. Directly below is a mainly carbonaceous and lesser interbedded greenish claystone lithology (Cores 534A-31–534A-39, of the early to late Albian). The lowermost two lithologies occupy a stratigraphic interval between the mainly carbonaceous noncalcareous black shales of the Hatteras Formation and the predominantly limestone lithology of the Blake-Bahama Formation. The upper of the two is a variegated pale brown, yellow, or reddish brown claystone interval of the late Aptian (in part), and the lower a transitional lithology of carbonaceous claystones grading downward in sequence to calcareous nannofossil claystones of earliest Aptian to Aptian. The Aptian intermediate lithologies of Cores 534A-41 to 534A-48 are widespread at North Atlantic sites drilled by the Deep Sea Drilling Project, where red clays and/or transitional

[1] Sheridan, R. E., Gradstein, F. M., et al., *Init. Repts. DSDP*, 76: Washington (U.S. Govt. Printing Office).

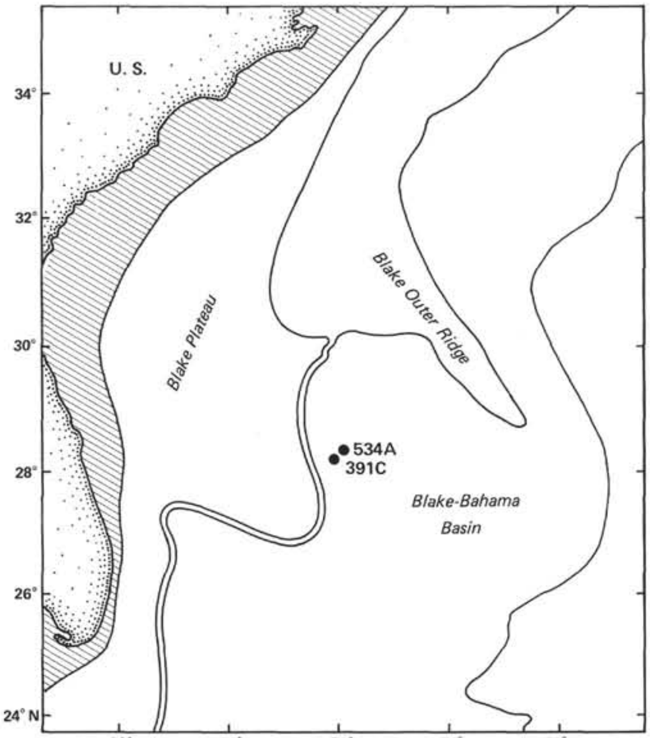

Figure 1. Location of Deep Sea Drilling Project Holes 534A and 391C in the Blake-Bahama Basin.

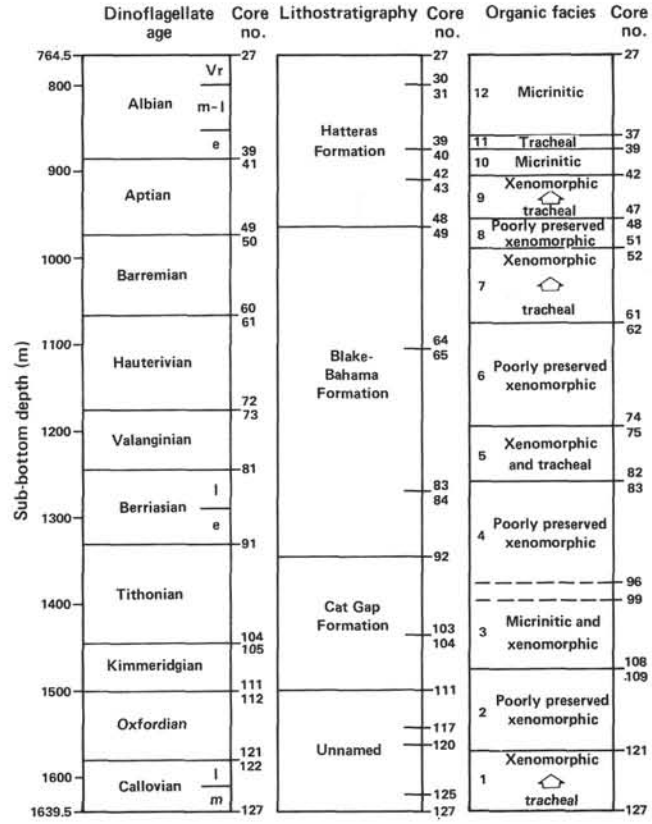

Figure 2. Lithostratigraphy of the lower 875 m of the Hole 534A sedimentary section. (Age and sequence of organic facies are illustrated).

carbonaceous-calcareous claystones mark the lowermost part of the Hatteras Formation (Jansa et al., 1979). In this chapter the base of the Hatteras Formation is located between Cores 534A-48 and 534A-49, based on precise dinoflagellate correlation with the geographically close section at Hole 391C.

The Blake-Bahama Formation is 383 m thick, and ranges from the stratigraphic level of Core 534A-49 into Core 534A-92. Three major, predominantly calcareous lithologies are identified. The uppermost, in Cores 534A-49 to 534A-64, consists of limestones with intercalated quartzose and calcareous siltstone and sandstone turbidites, of which the terrigenous turbidites possess typical Bouma structures. This uppermost lithology is Hauterivian to earliest Aptian and is 143 m thick—37% of the thickness of the Formation. The middle lithology, from Cores 534A-65 to 534A-83, ranges from late Berriasian to Hauterivian. It consists of finely laminated nannofossil chalks and marls intercalated with bioturbated chalks. Minor intercalations of terrigenous carbonaceous siltstones and claystones occur throughout.

The lowermost unit of the Blake-Bahama Formation, from Cores 534A-84 to 534A-92, Section 2, consists of uniform limestones and chalks characterized by calcitized radiolarians and nannofossil micrites. The distinguishing feature of this unit is the absence of parallel-laminated chalks. The sediment is burrowed and contains stylolites. Several thin red calcilutite layers or streaks occur in Cores 534A-84 and 534A-90. This unit is approximately 79 m thick. The base of the Formation lies in core 534A-92, Section 2, where the highest red calcareous claystones typical of the Cat Gap Formation occur. The Cretaceous/Jurassic boundary is placed within Core 534A-91 (Habib and Drugg, this volume), indicating that in Hole 534A the lowest part of the Blake-Bahama Formation is Tithonian.

The Cat Gap Formation occurs in the interval from Core 534A-92 into Section 1 of Core 534A-111. It is 153 m thick and ranges from the Kimmeridgian to the Tithonian. Two major lithologies occur. The upper, entirely Tithonian, from Cores 534A-92 to 534A-103, is a hematitic, pale, reddish, calcareous claystone lithology, which darkens toward its base. Moderate burrowing is evident. The lower lithology, primarily Kimmeridgian, consists of greenish gray calcareous claystones in which there are intervals of darker gray limestone turbidites. Where there are only few turbidites, the claystones remain reddish gray.

The lowermost, unnamed lithostratigraphic unit is 140 m thick and extends from Core 534A-111 to the base of the sedimentary section. It is the oldest unit thus far recovered from the western North Atlantic. The uppermost lithology (Cores 534A-111–534A-117) consists of dark variegated claystones that are pale red to blackish red, greenish gray, olive black, and dark gray. The next lithology, from Core 534A-117 to the top of Core 534A-120, is distinguished by gray limestones interbedded with variegated claystones. In the interval from Cores 534A-120 to 534A-125, the lithology consists of dark green radiolarian claystones and greenish gray limestones. The lowermost lithology consists of greenish black and reddish brown calcareous nannofossil claystones.

HYPOTHESIS AND CLASSIFICATION

Previous palynological studies of black shales in the North Atlantic Cretaceous have shown the close relationship between the sedimentology of mineral matter and that of organic matter and, thus, the close correspondence between lithostratigraphy and the stratigraphy of palynologically defined organic facies (Habib, 1979a; 1979b; 1982a). Because geochemical evidence (Tissot et al., 1979) indicates that the organic matter in the North Atlantic Cretaceous is thermally immature, the occurrence of the organic matter must be the result of biological, sedimentological, and geochemical processes operating in the source area, water mass, and/or in the shallow buried sediment. The occurrence of widespread black-shale intervals has been attributed to Cretaceous oceanic anoxic events (Schlanger and Jenkyns, 1976). Several ocean-basin models involving geographic configuration of the Early Cretaceous North Atlantic, widespread stratification of the water column, or density current transported oxygen-minima zones of shelf origin have been proposed to account for anoxia in the water column through which organic matter, regardless of its supply, was preserved on the deep ocean floor (e.g., Arthur and Natland, 1979). An alternative hypothesis (Habib, 1982a) attributes the origin of black shales to the kind of organic matter and its rate of supply to the seafloor. According to this model, the water column above the sediment/water interface could have been initially oxic throughout the Early Cretaceous (and through the early Late Cretaceous marine carbon event). The rapid influx of organic matter produced anoxia in the buried sediment (and possibly ephemeral anoxic conditions in the immediately overlying waters as well, as proposed by Gardner et al. [1978]) in organic-rich black shales geochemically and palynologically identified (Deroo et al., 1978) as containing terrigenous or oceanic organic matter, respectively. Slower rates of supply in organic-poor black shales contributed partially oxidized, small, carbonized tracheal particles, which produced the black color in the overall sediment despite the smaller organic matter content.

Based on this sedimentary-supply hypothesis, Habib (1982a) classified the following organic facies according to their sedimentary history. Large amounts (on the order of 80,000–100,000 specimens/gram) of biologically recognizable and well-preserved land-plant particles, distinguished by the greater abundance of larger (>50 μm) and schizaeaceous pteridophyte spores, tracheids, and cellular cuticles, occur in organic-rich graded black clays in intervals of distal turbidites (Hole 398D—Ryan, Sibuet, et al., 1979) and in prodeltaic terrigenous black clays (Hole 397A—Einsele and von Rad, 1979). This is the exinitic facies. Its palynological composition, poor morphological sorting, and sedimentological association indicate rapid burial on the seafloor (and rapid production of anoxic buried sediment).

Assemblages similar to the exinitic facies also contain abundant (30,000–80,000/g) land-plant detritus. These assemblages, called the tracheal facies, are distinguished, however, by an admixture of marine dinoflagellates and fewer larger pteridophyte spores and schizaeaceous fern spores. Although land-derived organic matter remains abundant, there is now a concentration of pollen grains in *Classopollis* and *Pinuspollenites* which, in addition to the fewer larger pteridophyte spores and admixture of dinoflagellates, indicates some morphological sorting. Sedimentological evidence indicates that the tracheal facies was also emplaced during rapid, terrigenous, turbiditic sedimentation. The episodes of tracheal and exinitic sedimentation were penecontemporaneous at both margins of the Early Cretaceous North Atlantic (Habib, 1979b). The concentration of the tracheal facies near the western Atlantic margin may reflect a somewhat longer transit time, perhaps within deltas prograding across a wider outer continental shelf.

Tracheids, the primary conductive tissue of land plants, occur in almost all sediments containing pollen grains and spores. Where they are abundant, they help to identify the exinitic and tracheal facies. Two categories are distinguished. The first consists of larger (>50 μm) fragments that are both well-preserved and carbonized. When abundant, both the well-preserved and carbonized fragments were buried relatively rapidly, with the admixed carbonized particles evidently partially oxidized at the source prior to transportation and deposition. The second category consists of smaller, comminuted, carbonized debris of tracheids that occur ubiquitously in the various organic facies, but are concentrated in those intervals where biostratigraphic and sedimentological evidence indicates reduced rates of sedimentation. The concentration of these particles, along with only few of the larger and also carbonized tracheids, few (5000 to less than 500/g) morphologically sorted pollen grains (*Classopollis*), and diverse dinoflagellates occurring in smaller numbers but in high relative percentages, was termed the micrinitic facies. Cross et al. (1966) showed that this debris is concentrated in offshore surface sediments of the southern Gulf of California. The micrinitic facies represents the smaller partially oxidized tracheal particles and few pollen grains deposited in lower-energy environments; the carbonized debris would have survived slower settling in an oxic water column and oxic diagenesis.

The last class of organic matter consists of amorphous, noncarbonized and presumably relatively hydrogen-rich debris which, in well-preserved residues, is of pale yellow to orange yellow color and shows red safranin stain well. Where it is the most abundant organic matter, it is classified in the xenomorphic facies. Well-preserved xenomorphic debris occurs as larger (>50 μm) aggregates admixed with smaller xenomorphic debris in marine carbon-rich intervals, such as in the Cenomanian at Site 105 and Hole 398D. Dinoflagellates and morphologically sorted pollen may be numerous or few and are well-preserved. Darker-colored and more poorly preserved xenomorphic debris occurs as smaller particles in the poorly preserved xenomorphic facies and is associated with poorly preserved pollen and dinoflagellates; also, it is admixed with micrinitic debris (xenomorphic–micrinitic organic residue of Table 1).

Table 1. List of samples, Hole 534A.

Sample (core-section, interval in cm)	Organic residue	mm level/g
27-1, 66-68	Micrinitic	0.38
27-2, 66-68	Micrinitic	—
27-3, 66-68	Micrinitic	—
28-2, 20-22	Micrinitic	2.00
29-1, 14-16	Micrinitic	1.75
30-1, 15-17	Micrinitic	1.00
32-1, 21-24	Micrinitic	1.43
33-2, 10-12	Micrinitic	1.17
34-3, 22-24	Micrinitic	0.51
35-1, 108-110	Micrinitic	2.69
36-1, 20-22	Micrinitic	1.03/2.40[a]
36-1, 59-61	Micrinitic	0.92
36-1, 62-64	Micrinitic	2.26
36-1, 88-90	Micrinitic	0.12
*36-2, 88-90	Micrinitic	0.11
36-3, 88-90	Micrinitic	0.91
37-1, 25-27	Micrinitic	0.24
37-3, 25-27	Carbonized tracheal	2.27
38-5, 4-6	Tracheal	1.36
*39-1, 26-28	Micrinitic	0.45
39-4, 46-48	Tracheal	1.75
39-6, 0-2	Carbonized tracheal	0.24
*41-1, 42-44	Micrinitic	0.21
*41-2, 42-44	Micrinitic	0.40
41-3, 42-44	Micrinitic	0.21
41-6, 42-44	Micrinitic	0.83
*42-1, 15-17	Micrinitic	0.12
*42-2, 15-17	Micrinitic	0.20
42-3, 15-17	Xenomorphic	1.25
43-1, 92-94	Xenomorphic	2.25
44-3, 94-96	Tracheal	1.11
45-2, 34-36	Tracheal	1.50
45-4, 78-80	Tracheal	1.09
45-5, 6-8	Tracheal	1.60
46-1, 68-70	Tracheal	1.74
47-1, 66-68	Tracheal	0.86
47-4, 2-4	Tracheal	1.80
48-2, 19-21	Carbonized tracheal	2.17
48-6, 19-21	Carbonized tracheal	1.15
49-3, 30-32	Micrinitic	1.30
49-4, 30-32	Micrinitic	—
49-7, 30-32	Micrinitic	1.40
50-1, 50-52	Xenomorphic	—
50-2, 50-52	Xenomorphic	0.21
50-5, 50-52	Micrinitic	0.26
51-1, 30-32	Micrinitic	0.11
52-3, 2-4	Xenomorphic	1.09
53-3, 128-130	Xenomorphic	0.76
54-2, 41-43	Xenomorphic	0.81
55-3, 11-13	Xenomorphic	0.08
56-1, 34-36	Tracheal	0.95
58-4, 59-61	Carbonized tracheal	0.29
59-2, 30-32	Tracheal	1.09
60-3, 76-78	Tracheal	1.67
61-2, 73-75	Tracheal	1.43
62-1, 41-42	Micrinitic	0.13
63-2, 38-40	Xenomorphic-micrinitic	0.10
64-1, 70-72	Xenomorphic-micrinitic	0.25
65-5, 40-42	Xenomorphic-micrinitic	0.21
66-5, 81-82	Xenomorphic-micrinitic	0.30
67-1, 131-133	Carbonized tracheal	0.43
68-1, 39-41	Xenomorphic-micrinitic	0.91
69-1, 50-52	Xenomorphic-micrinitic	1.36
70-6, 30-32	Xenomorphic-micrinitic	1.20
71-1, 29-31	Xenomorphic-micrinitic	0.90
72-2, 34-36	Xenomorphic-micrinitic	1.80
73-1, 125-127	Xenomorphic-micrinitic	0.38
74-6, 54-56	Xenomorphic-micrinitic	0.42
75-1, 43-44	Tracheal	0.91
76-3, 10-12	Xenomorphic	0.91
77-2, 43-45	Xenomorphic	0.43
78-1, 104-106	Xenomorphic	0.60
79-2, 55-57	Xenomorphic	0.75
80-2, 27-28	Xenomorphic	1.54

Table 1. (Continued).

Sample (core-section, interval in cm)	Organic residue	mm level/g
81-1, 61-62	Tracheal	1.48
82-1, 53-55	Xenomorphic	0.43
*83-4, 90-91	Micrinitic	0.12
84-7, 0-2	Xenomorphic-micrinitic	0.21
85-5, 48-49	Micrinitic-xenomorphic	1.15
86-1, 148-150	Micrinitic-xenomorphic	0.40
87-6, 7-8	Micrinitic-xenomorphic	0.16
88-2, 107-108	Micrinitic-xenomorphic	0.87
89-1, 81-82	Xenomorphic-micrinitic	0.10
90-1, 24-25	Xenomorphic-micrinitic	0.36
90-3, 52-53	Xenomorphic-micrinitic	0.47
90-4, 30-31	Xenomorphic-micrinitic	0.53
90-5, 49-50	Xenomorphic-micrinitic	0.65
90-2, 0-1	Xenomorphic-micrinitic	0.48
90-4, 30-31	Xenomorphic-micrinitic	0.30
*91-1, 103-104	Xenomorphic-micrinitic	0.33
91-2, 57-58	Xenomorphic-micrinitic	0.33
91-3, 40-41	Xenomorphic-micrinitic	0.39
91-4, 107-108	Xenomorphic-micrinitic	0.44
*92-2, 9-10	Xenomorphic-micrinitic	0.19
93-2, 99-10	Xenomorphic	1.82
*94-4, 68-70	Xenomorphic-micrinitic	0.08
95-4, 46-47	Xenomorphic-micrinitic	0.10
96-2, 35-36	Micrinitic	0.17
99-3, 79-80	Micrinitic	0.36
100-2, 127-128	Micrinitic	1.67
101-4, 71-73	Micrinitic	0.86
*102-4, 68-70	Micrinitic	0.10
102-5, 78-80	Micrinitic	0.50
103-1, 95-96	Xenomorphic-micrinitic	1.03
*103,CC	Micrinitic	0.40
104-2, 59-61	Xenomorphic-micrinitic	1.03
*104,CC	Micrinitic	0.23
105-2, 92-94	Xenomorphic-micrinitic	1.00
106-1, 3-4	Xenomorphic-micrinitic	1.50
107-2, 98-100	Micrinitic	1.04
*108-1, 23-25	Micrinitic	0.23
*109,CC	Xenomorphic-micrinitic	0.11
*110,CC	Xenomorphic-micrinitic	0.95
111-1, 27-29	Xenomorphic-micrinitic	0.24
112-1, 69-71	Xenomorphic-micrinitic	0.32
113-1, 0-2	Xenomorphic-micrinitic	0.22
114-1, 22-24	Xenomorphic-micrinitic	0.22
*115-1, 73-74	Micrinitic	0.16
116-1, 44-46	Xenomorphic-micrinitic	0.22
116-1, 76-78	Xenomorphic-micrinitic	0.42
*117-1, 9-10	Micrinitic	1.43
118-1, 5-7	Xenomorphic-micrinitic	0.11
118-1, 100-102	Xenomorphic-micrinitic	—
119-1, 120-121	Micrinitic	1.19
120-1, 31-33	Xenomorphic-micrinitic	—
120-1, 43-45	Xenomorphic-micrinitic	0.17
121-1, 8-10	Xenomorphic-micrinitic	0.74
121-1, 46-48	Xenomorphic	0.68
122-2, 68-70	Xenomorphic	0.24
123-1, 90-92	Xenomorphic	0.50
123-1, 92-94	Xenomorphic	—
124-1, 8-10	Xenomorphic	—
124-1, 54-56	Xenomorphic	0.25
125-1, 13-14	Tracheal	0.80
125-1, 64-66	Tracheal	1.00
125-3, 144-146	Tracheal	0.90
125-3, 146-147	Tracheal	1.21
125-5, 88-89	Tracheal	1.16
125-6, 91-92	Tracheal	1.20
126-1, 63-65	Tracheal	1.16
126-1, 74-77	Tracheal	1.25
126-2, 23-26	Tracheal	1.00
126-3, 74-75	Tracheal	0.90
126-4, 93-95	Tracheal	0.73
127-2, 33-35	Tracheal	0.73

Note: Asterisk (*) indicates that the sample is barren of palynomorphs; — indicates data were not available.
[a] 1.03 refers to green clay; 2.40 refers to black clay on either side of the sharp contact in this single sample.

It is difficult to explain the survival of xenomorphic debris settling in a deep oxic water column (e.g., Habib, 1982a). However, recent studies (Porter and Robbins, 1981; Honjo, 1980) indicate that amorphous organic matter is being generated through the digestive tract of living copepods fed a mixed phytoplankton diet and that in the modern deep and oxic oceans it is depositing rapidly as zooplanktonic fecal pellets. This amorphous debris is visually very close to the xenomorphic debris of this study (K. Porter, personal communication, 1982). Study of ancient fecal pellets (N. Robbins, personal communication, 1982) shows that they contain xenomorphic debris, terrigenous mineral matter, and preserved palynomorphs. Thus the fossil xenomorphic facies of the North Atlantic may have been rapidly deposited in much the same way, similar to that of fecal pellets containing calcareous nannoflora in the modern open and oxic oceans and in the Cretaceous North Atlantic (Habib, 1982b).

The sedimentary-supply hypothesis emphasizes the sedimentation rate, kind of organic matter, and shallow burial diagenesis parameters, which are interrelated. For example, Curtis (1980) indicated that diagenetic change in the early burial environment is sensitive to an adequate supply of organic matter and rate of sedimentation, particularly in finer-grained sediments.

The palynological evidence stresses the changes that take place in the buried sediment as a function of sedimentation rate (Habib, 1982a, Curtis, 1980). A sufficiently rapid supply of organic matter produces anoxic interstitial waters in fine-grained sediment regardless of the Eh environment above the sediment/water interface, and the organic residue that survives oxic diagenesis (as in the hematitic red clays of Hole 534A) should reflect the Eh chemistry of the interstitial waters as well as that of the overlying water column. For example, biological oxidative processes continue within slowly deposited red clays and pelagic carbonate oozes underlying the oxic deep-water column of the central equatorial Pacific (Murray and Grundmanis, 1980). Oxic processes just below the sediment/water interface require that the overlying water be oxic as well. On the other hand, anoxia within sediment should not be used to indicate that the overlying water must also be anoxic. Although anaerobic microbial activity operates both within anoxic buried sediment and in the anoxic waters of the Black Sea Basin (Jannasch et al., 1974), there are also good examples where organic matter survives and accumulates in oxic oceanic waters. Organic matter of marine origin accumulates in the open ocean in areas where phytoplankton (and grazing zooplankton) productivity is high (Tissot and Pelet, 1981). Abundant terrigenous organic matter accumulates on oxic ocean floors, such as in the deep Amazon fan (Tissot and Pelet, 1981), in the Gulf of Mexico, and in the submarine delta of the Colorado River (Cross, et. al., 1966).

DESCRIPTION OF ORGANIC FACIES

MATERIALS AND METHODS

One hundred and forty-five samples were processed for sedimentological study (Table 1). Of these, 39 were analyzed from the Hatteras Formation. These include noncalcareous blackish (N1, N2, N3) carbonaceous clays in the Vraconian Albian interbedded silty claystone unit and in the early–late Albian carbonaceous-green claystone unit. Within the latter unit, green (56Y 6/1) clays were sampled in Core 534A-36 to compare the organic residues with those of the interbedded black clays. For example, Sample 534A-36-1, 20–22 cm shows a sharp contact between green and black clay. Each color lithology was studied in this sample. Other samples in Core 534A-36 are either entirely green or entirely black. In the late Aptian variegated unit, brown (5YR 3/4), reddish (10R 4/2), and pale green (6GY 6/1) lithologies were sampled, including one, Sample 534A-41-6, 42–44 cm, which is greenish black (10Y 4/2). In the lowermost unit, of earliest Aptian (early Bedoulian) to Aptian, graded carbonaceous clays of dark gray (N3) to blackish (5Y 2/1) color were analyzed.

Fifty-five samples representing the Blake-Bahama Formation were analyzed, including the lowest sample (534A-92-2, 9–10 cm), situated just 30 cm above the base of the Formation. Within the Hauterivian–Barremian turbiditic interval blackish (N1, 5Y 2/1), calcareous claystone was the only lithology analyzed. In the lower, Valanginian–Hauterivian interval, the samples are mostly laminated dark gray and light gray calcareous sediments, as well as blackish graded carbonaceous clays. In the lower-most Tithonian–Berriasian interval, all the samples are pale gray (N8), calcareous nannofossil chalks and hard limestones, with the exception of Sample 534A-85-5, 48–49 cm, which is darker gray, and Sample 534A-90-1, 24–25 cm, which is pale red.

Nineteen samples from both lithologic units of the Cat Gap Formation were analyzed. In the upper unit, samples in Cores 534A-94, 534A-95, and 534A-96 vary from dark red (10R 3/4) to brownish (5YR 2/2), calcareous clays in the pale red Tithonian unit. However, Sample 534A-93-2, 99–101 cm is a gray (N3) calcareous clay. In Cores 534A-99 through 534A-103, of the Tithonian, most of the samples are blackish red (10R 2/2) calcareous claystones. In the lower lithologic unit, of the Kimmeridgian, the samples range from dark gray (N4) to greenish black (5GY 2/1) calcareous claystones. However, Sample 534A-104-2, 44–45 cm is a hard blackish (N2) calcareous claystone, Sample 534A-107-2, 98–100 cm is a black-green mottled calcareous claystone, and Sample 534A-108-1, 23–25 cm is a blackish red (10R 2/2) claystone. None of the limestone turbidites in this unit was sampled.

Thirty-two samples from the lowermost unnamed formation, of the middle Callovian to the Oxfordian, were analyzed. These consist of dark variegated calcareous claystones ranging in color from dark red (5R 3/4), to brown (5YR 3/4), to green (5GY 6/1, 5GY 4/1), and blackish red (5R 2/2). Samples 534A-117-1, 9–10 cm and 534A-119-1, 120–121 cm are mottled black and dark gray. In the Callovian of Cores 534A-124 to 534A-127, only the darkest (5G 2/1, 5Y 2/1) calcareous nannofossil claystones were sampled. None of the limestones was sampled in this formation.

Table 1 lists the samples that were studied, the organic facies assigned the recovered organic residue, and a quantitative estimate of the amount of residue recovered. Of the 145 samples analyzed, 19 proved to be barren of palynomorphs. Each sample was treated with acids (HCl, HF) to remove the mineral matter. The recovered organic residue was then placed in a 3-dram glass vial and compacted by centrifuging for 1 min. at 2000 rpm. The height of the residue (in millimeters) in the vial was then measured, and the height of residue per one gram of dried raw sample was calculated. This method does not give an absolute value of the total organic matter contained in a given sample, but does provide an internally consistent quantitative estimation of the distribution of the total organic matter in the investigated section (cf., Habib, 1982a).

The organic residue profile (Fig. 3) compares closely to the percentage distribution of organic carbon (Site 534 report, this volume). Values less than 0.5 mm/g represent very little to little organic matter in the sediment, values between 0.5 to 1.0 mm/g a moderate amount, and values greater than 1.0 mm/g a relatively large amount (Table 1, Fig. 3). It is interesting to note that all the samples, including the red clays, yielded at least some organic residue and that, according to this scale, samples barren of palynomorphs varied from very little to relatively large amounts of residue.

The organic facies was initially identified by mounting some of the residue on a microscope slide (temporary glycerine or water mount) and the residue was then macerated in a 50% solution of laboratory-grade nitric (HNO_3) acid to facilitate counting of the biologically structured (e.g., pollen, dinoflagellates, tracheids) components. The

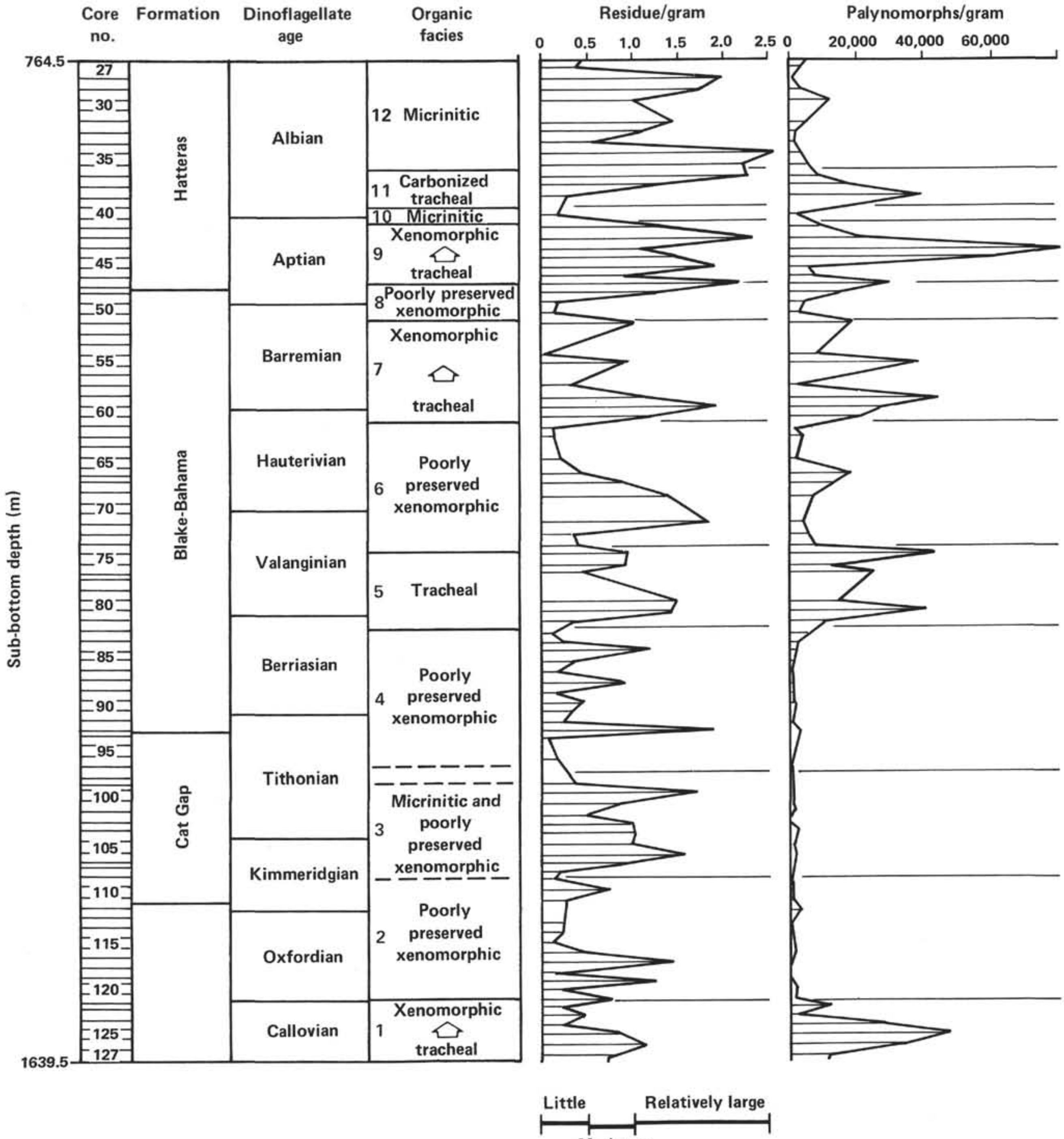

Figure 3. Palynomorph abundance curve compared with curves of the various terrigenous organic particles, proportion of marine dinoflagellates, and organic residue. (Terrigenous components are responsible for greatest palynomorph abundance; the highest percentages of dinoflagellates occur where the total numbers of palynomorphs are fewest. Abundance of xenomorphic or micrinitic debris is estimated by comparing the organic residue and palynomorph curves.)

number of specimens of the various categories (Fig. 3) per gram of dried raw sediment was then calculated, after the method originally described by Traverse and Ginsburg (1966). The amount of micrinitic and xenomorphic debris was not counted, because of its abundance in certain intervals, but an estimate of its distribution is evident by comparing the organic residue curve with the curve for palynomorph abundance (Fig. 3). In those intervals where the organic residue is relatively large and there are few or no palynomorphs, the residue is composed of xenomorphic and/or micrinitic debris (Table 1).

Stratigraphic Units

Twelve stratigraphic units are described, based on the dominant organic facies contained in the interval or the close stratigraphic association of organic facies in the investigated samples. Figure 3 illustrates the stratigraphy of the sedimentologically interpreted units and the parameters used. These include the amount of resi-

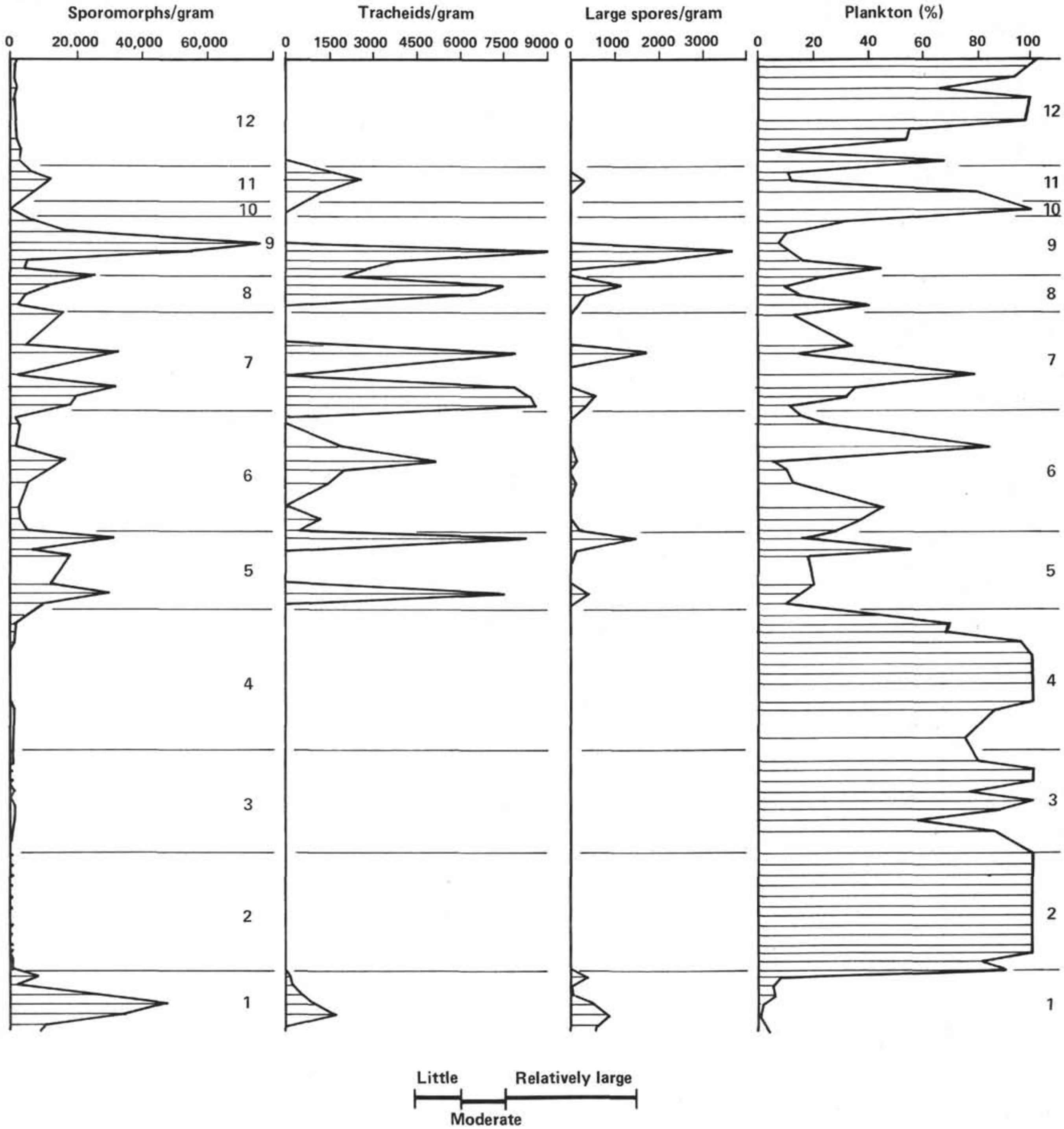

Figure 3. (Continued).

due per gram of sediment, number of palynomorphs, sporomorphs, tracheids, and larger spores per gram of sediment, and the relative proportion of the organic-walled marine microflora (dinoflagellate cysts and small acritarchs) to the biologically recognized land-plant flora. In the description of each stratigraphic unit, these parameters are compared with the lithology of the samples studied.

Unit 1. Samples 534A-127-2, 33–35 cm to 534A-121-1, 46–48 cm (middle Callovian–early Oxfordian)

The lowermost sedimentologically defined stratigraphic unit is characterized by well-preserved, diversified, and numerous land-plant particles, including abundant *Classopollis* (65–81% of all palynomorphs) and both well-preserved and darker brown larger tracheids, as well as well-preserved and abundant xenomorphic debris, small acritarchs, and a diversified dinoflagellate flora. The lower part of unit 1, from Cores 534A-127 to 534A-125, contains a well-developed tracheal facies, including numerous tracheids, schizaeaceous ferns, and other larger pteridophyte spores. The presence of the schizaeaceous fern genus *Cicatricosisporites* is unusual in sediments as old as the Callovian, although it has been reported in the Callovian of North Africa (Reyre, 1973). Notwithstanding the age of this sediment, its occurrence in unit 1 is sedimentologically consistent with an episode of large and rapid supplies of terrigenous plant materials (Habib, 1979a). Palynomorphs occur as high as 48,000 specimens/gram, with the land-derived components composing at least 90% of the samples. The organic residue is relatively large. Well-preserved chitinous inner linings of trochoidally spired foraminifers are also numerous throughout unit 1.

In the upper part of unit 1, in Cores 534A-124 to 534A-121, the well-preserved xenomorphic debris and *Classopollis* remain abundant, but there is a decrease in the number of tracheids and larger spores, resulting in a well-preserved xenomorphic facies. The relative abundance of organic residue declines as well to small amounts, and the number of palynomorphs/gram of sediment falls below 10,000. Fecal pellets composed of xenomorphic debris occur.

The lithology of the lower part of unit 1 is primarily black calcareous nannofossil clays, some of which are phosphatic, whereas in the upper part it is a dark greenish calcareous clay containing radiolarian silt layers. Within the upper part, in Sample 534A-121-1, 46–48 cm, inflated dinoflagellate cysts occur in a highly calcareous sample, suggesting that this sediment is little compacted.

Unit 2. Samples 534A-121-1, 8–10 cm to 534A-109,CC (Oxfordian–Kimmeridgian)

Units 2, 3, and 4 (Fig. 3) also contain xenomorphic debris. However, in sharp contrast to that of unit 1, this debris is poorly preserved, and there are only relatively few palynomorphs composed almost entirely of dinoflagellate cysts and small acritarchs. The pollen grains abundant in unit 1 are now very rare in the entire interval, as they are represented only by scattered specimens of *Classopollis, Exesipollenites,* and bisaccate forms.

Most samples in unit 2 contain only small amounts of organic residue consisting of a fine granular admixture of xenomorphic and micrinitic debris in a poorly preserved xenomorphic facies. The marine microflora (dinoflagellates and acritarchs) range between 77 and 100%, with most samples composed completely of this flora. Samples 534A-110,CC, 534A-117-1, 9–10 cm, and 534A-119-1, 120–121 cm contain residues of black micrinitic debris, however, and are either barren of palynomorphs or contain only few, poorly preserved dinoflagellates. In these samples, the residue is relatively large (Table 1, Fig. 3) and black, by virtue of the abundant micrinitic debris. The occurrence of recognizable carbonized tracheids in Sample 534A-110,CC suggests that the residue is the oxidized remains of terrigenous organic matter.

Unit 3. Samples 534A-108-1, 23–25 cm to 534A-99-3, 79–80 cm (Kimmeridgian–Tithonian)

This unit is distinguished by a higher frequency of residues composed almost completely of micrinitic debris. Most of these samples contain larger amounts of debris (Fig. 3) and very few palynomorphs (less than 500/g) consisting of more poorly preserved dinoflagellates. These samples (and the three micrinitic samples from unit 2) are blackish red or mottled blackish green. Several are barren of palynomorphs, yet contain appreciable debris (e.g., Sample 534A-107-2, 90–100 cm). Other samples in unit 3 contain more dinoflagellates (approximately 2000/g) in relatively large amounts of poorly preserved, admixed fine-granular xenomorphic and micrinitic debris.

Unit 4. Samples 534A-96-2, 35–36 cm to 534A-83-4, 90–91 cm (Tithonian–late Berriasian)

Unit 4 occupies the upper, pale reddish, calcareous, clay facies of the Cat Gap Formation and the lowermost, uniform whitish limestone facies of the Blake-Bahama Formation. With only two exceptions, the organic residues are very small to small. Like unit 2, the organic facies is poorly preserved xenomorphic. Xenomorphic debris and micrinitic debris are admixed, and there are few palynomorphs (fewer than 1500/g) consisting almost entirely of dinoflagellates and acritarchs. Also, several samples contain very little residues of micrinitic debris. However, Sample 534A-93-2, 99–101 cm contains a well-preserved xenomorphic facies and a rich dinoflagellate flora in a large residue, and Sample 534A-85-5, 48–49 cm contains a poorly preserved xenomorphic facies and a diversified marine microflora.

Unit 5. Samples 534A-82-1, 53–55 cm to 534A-75-1, 43–44 cm (late Berriasian–Valanginian)

Unit 5 marks the beginning of an increased supply of abundant terrigenous organic matter, which characterizes much of the North Atlantic Lower Cretaceous. It contains large numbers of pollen grains and larger pteridophyte spores, schizaeaceous fern spores, and both well-preserved and carbonized larger tracheids in a well-developed tracheal facies. Dinoflagellates, small acritarchs, and foraminiferal linings are numerous throughout. Palynomorphs are abundant, to the extent of 44,000/g, and are dominated by the terrigenous fraction. Within unit 5, other samples contain a well-preserved xenomorphic facies in which the terrigenous matter is dominated by *Classopollis*. The sampled lithologies of unit 5 include both terrigenous carbonaceous clays and gray calcareous clays.

Unit 6. Samples 534A-74-6, 54–56 cm to 534A-62-1, 41–42 cm (late Valanginian–Hautervian)

Unit 6 includes the laminated calcareous sediments interbedded with minor carbonaceous clays. In both general lithologies, the organic facies is a poorly developed xenomorphic one characterized by fine granular, admixed, xenomorphic and micrinitic debris. The organic residue is very little to moderate, except for those carbonaceous clay samples (Table 1) with large amounts of residue. Palynomorphs range mostly between 3000 and 18,000/g. The uppermost sample in this interval, (534A-62-1, 41–42 cm) yielded very little residue of micrinitic debris and very few poorly preserved palynomorphs in pale gray calcareous clay. Sample 534A-67-1, 131–133 cm contains little residue of a facies that can best be interpreted as carbonized tracheal. Larger tracheids are numerous but, along with abundant micrinitic debris, are completely carbonized. The palynomorphs are dominated by *Classopollis*, which are also poorly preserved.

Unit 7. Samples 534A-61-2, 73–75 cm to 534A-52-3, 2–4 cm (late Hauterivian–Barremian)

This unit is characterized by moderate to large amounts of organic residues containing abundant and well-preserved organic matter in both dark carbonaceous and dark calcareous clays sampled in the terrigenous turbidite intervals. Two subunits are distinguished. The lower ranges from Cores 534A-61 through 534A-56, and contains a well-developed and well-preserved tracheal facies with numerous palynomorphs (mostly between 25,000 and 45,000/g) including *Classopollis*, well-preserved schizaeaceous ferns, and other larger pteridophyte spores, numerous well-preserved and carbonized larger tracheids, fungal spores, and a higher frequency of tetrads (*Classopollis, Leptolepidites*), as well as diversified dinoflagellate and small acritarch flora. Xenomorphic and micrinitic debris occur, but are relatively little. Sporomorphs are most abundant. The larger number of palynomorph specimens is accompanied by a large number of species, between 25 and 36. An exception to this facies occurs in Sample 534A-58-4, 59–61 cm, which contains very little residue of micrinitic debris, carbonized tracheids, and few palynomorphs, most of which are dinoflagellates. The stratigraphically higher subunit also contains appreciable residue, but this consists mainly of xenomorphic debris and only few tracheids in the xenomorphic facies. Palynomorphs are fewer (10,000–18,000/g) and are dominated by *Classopollis* and dinoflagellates. Foraminiferal linings are abundant throughout unit 7.

Unit 8. Samples 534A-51-1, 30–32 cm to 534A-48-2, 19–21 cm (late Barremian–earliest Aptian)

This unit is a somewhat heterogeneous mixture of facies that has in common the poor preservation of organic debris and palynomorphs. The facies is either micrinitic or poorly preserved xenomorphic. Palynomorphs are fewer, ranging between fewer than 500 to 12,000/g, and consist mainly of *Classopollis* and dinoflagellates. The organic residue is very little in the lower part, but becomes larger in the upper part (Cores 534A-48 and 534A-49). In these cores, the abundant residue is composed chiefly of black micrinitic debris and carbonized larger tracheids, to such an extent that the two samples in the uppermost cores can be considered "carbonized tracheal" facies.

Unit 9. Samples 534A-47-4, 2–4 cm to 534A-42-3, 15–17 cm (Aptian)

The lower part of unit 9 can be considered transitional to the upper part of unit 8. Although palynomorphs remain relatively few, it is distinguished by numerous carbonized and well-preserved tracheids. The sequence of facies in this transitional lithologic unit is similar to that of the tracheal-to-xenomorphic unit 7 within the Barremian. The amount of organic residue is large throughout the unit, with a well-developed tracheal facies in the lower part (Cores 534A-44, 534A-45) and a well-developed xenomorphic facies in the upper part. Sample 534A-44-3, 94–96 cm contains the largest number of palynomorphs in the investigated section, as many as 78,000 specimens/g in 34 species. Sporomorphs comprise approximately 90% of all palynomorphs in this sample.

Unit 10. Samples 534A-42-2, 15–17 cm to 534A-41-1, 42–44 cm (late Aptian, in part)

This palynologic unit lies within the red clay facies of Cores 534A-40 to 534A-42. The age of part of the unit is based entirely on an assemblage of a few dinoflagellates recovered in Sample 534A-41-6, 42–44 cm. All other samples are barren of palynomorphs. Very little organic residue was recovered. All of the investigated samples are classified in a well-developed micrinitic facies, which consists entirely of very small, black, carbonized particles.

Unit 11. Samples 534A-39-6, 0–2 cm to 534A-37-3, 25–27 cm (early Albian)

This unit is characterized by large amounts of organic residue consisting to a large extent of black micrinitic debris and larger carbonized particles. The facies is mostly tracheal, but most of the woody tissue is black in color. Palynomorphs may be abundant (up to 38,000/g) but are dominated by *Classopollis* or dinoflagellates and are poorly preserved. One sample (534A-39-1, 26–28 cm) contains little micrinitic residue. It is considered to be barren, because only two corroded palynomorphs were discovered.

Unit 12. Samples 534A-37-1, 25–27 cm to 534A-27-1, 66–68 cm (middle Albian–Vraconian Albian)

Unit 12 represents the uppermost interval defined palynologically. All the samples contain the micrinitic facies. Most of the samples contain relatively large amounts of organic matter, of which the vast majority consists of black micrinitic debris. Xenomorphic debris is sparse and there are few palynomorphs. Except for two samples (534A-30-1, 15–17 cm and 534A-32-1, 21–24 cm), which contain between 5000 and 10,000 specimens per gram, fewer than 500 specimens per gram were recorded in each of the other samples. Dinoflagellate cysts are the predominant component, ranging in most samples between 92 and 100% of all palynomorphs. Despite their small numbers in the samples, the dinoflagellates are represented by as many as 25 species. Sporomorphs are very few in most samples, mainly occurring in the morphologically sorted pollen genera *Classopollis* and *Pinuspollenites*; sporomorph specimens are also scattered in the ubiquitously distributed genera *Exesipollenites, Vitreisporites, Eucommiidites, Cycadopites*, and *Taxodiaceaepollenites*.

Most of the investigated samples of unit 12 are carbonaceous clays. However, in Section 1 of Core 534A-36, greenish clays were also sampled, in order to compare the organic matter with that of the black clay samples. Sample 534A-36-1, 20–22 cm contains a sharp contact between black and green clay. Both colors in this sample were studied and showed that although the residue is relatively large in both splits (Table 1), the amount in the black clay is about twice that in the green clay. Another green clay sample (534A-36-1, 59–61 cm) also contains appreciable micrinitic residue but in a lesser amount than the immediately subjacent black clay sample (534A-36-1, 62–64 cm).

A review of the description of units 1 to 12 indicates that all 145 samples yielded at least some organic residue (Table 1), regardless of lithology. The smallest amounts of residue (0.10–0.25 mm/g) are characterized by the micrinitic facies or the poorly preserved xenomorphic facies, and are either barren of palynomorphs or contain dinoflagellates fewer than 1500 specimens per gram. The amount of residue is smallest in the pale reddish lithologies, in the little micrinitic debris of the Aptian hematitic clays of unit 10, and in the little xenomorphic–micrinitic debris of late Jurassic–Berriasian calcareous clays and calcilutites of units 2 and 4.

The micrinitic facies is also represented where the amount of residue is relatively large, in black and green noncalcareous clays, blackish red calcareous clays, and burrow-mottled greenish black calcareous clays. In these Kimmeridgian–Tithonian (unit 3) and Albian (unit 12) samples, palynomorphs are generally absent, or are relatively few in a relatively large number of dinoflagellate species. Black micrinitic debris and larger carbonized tracheids compose the bulk of these residues, which is considered to be responsible for the dark color in the blackish red, blackish green, and black clay samples. There appears to be no correspondence between the color of the Albian green clays in Core 534A-36 and their appreciable black residues, however, unless the total amount of carbonized debris in these samples was insufficient to blacken the clay (Table 1) relative to the effect of reduced iron. The alternation of black and green colors in unit 12 may thus be due to the corresponding changes in amounts of highly micrinitic residues.

Xenomorphic debris is distributed through most of the investigated section. It is represented principally in two states of preservation in Hole 534A relative to sedimentation rate. It is well-preserved and especially abundant in the xenomorphic facies containing well-preserved specimens of *Classopollis* as well as well-preserved dinoflagellate cysts. Its co-occurrence with large numbers of pollen grains per gram, and its close stratigraphic relation to the tracheal facies within units 1, 5, 7, and 9 suggest a relatively rapid supply of organic matter to the seafloor. The abundant chitinous remains of foraminifers in both the tracheal and xenomorphic facies is unusual; it may represent the shallower-water benthic foraminifers that were displaced into deeper water. The second xenomorphic facies consists of poorly preserved xenomorphic debris and micrinitic debris in units 2 (Oxfordian), 4 (Tithonian–Berriasian), 6 (late Valanginian–Hauterivian), and 8 (late Barremian–earliest Aptian). In this example, dinoflagellate cysts are the principal palynomorph group. An exception lies in Sample 534A-93-2, 99–101 cm, where the debris is well-preserved and where dinoflagellates are well-preserved and numerous.

In Hole 534A, the tracheal facies is well-developed in units 1 (middle Callovian), 5 (late Berriasian–Valanginian), 7 (late Hauterivian–Barremian), and 9 (early Aptian) and is associated with terrigenous turbidites or with graded carbonaceous clays. Xenomorphic and micrinitic debris always occur as well, but are sparse in the tracheal portions of these units. Unit 11 (early Albian) may be considered a carbonized tracheal interval. It contains numerous tracheids and pollen grains, but these are very poorly preserved and carbonized.

The sequence of facies-defined stratigraphic units at Site 534 indicates an initial (Callovian) episode of terrigenous organic sedimentation, a longer Late Jurassic episode in which terrigenous organic matter was largely not deposited at this site, and a long Early Cretaceous episode punctuated by pronounced events of large and rapid supplies of terrigenous organic matter (Fig. 2).

SEDIMENTATION-RATE ORIGIN OF BLACK SHALES

At Hole 534A, the nature and rate of supply of organic matter controlled the occurrence and distribution of blackish-color organic sediment in the section ranging in age from middle Callovian to latest Albian. The supply of organic matter in this interval was controlled by sedimentation rates. Lower rates of sedimentation are estimated from the reddish or brownish color of authigenic hematite in the hemipelagic clays, co-occurrence in these red clays of clay minerals of the illite and mixed-layer association, bioturbation and reddish color in calcareous clays and nannofossil oozes, and lack of sedimentary structures indicative of rapid sedimentation (Site 534 report, this volume). Higher rates are estimated from sedimentary structures indicating turbiditic input of terrestrial origin, graded silty clays, general lack of red coloration and bioturbation, and clay mineral associations of smectite and kaolinite in sediments where quartz is dominant (Site 534 report, this volume). Based on these estimates, higher rates of sedimentation are evident in the Callovian, late Berriasian–Valanginian, Hauterivian–Barremian, early Aptian, and early Albian, and to a lesser degree in the middle to latest Albian. Lower rates of sedimentation prevailed during the Oxfordian–Berriasian, late Valanginian–Hauterivian, and late Aptian (in part). Biostratigraphically estimated rates of sedimentation derived mainly from the stratigraphy of calcareous nannofossils (Site 534 report, this volume) show general agreement with the sedimentological evidence, as they do elsewhere in the western North Atlantic (e.g., Site 105, Hollister, Ewing, et al., 1972); lowest sedimentation rates were calculated for the Cat Gap Formation (Late Jurassic), highest rates for the Blake-Bahama Formation (Early Cretaceous), and lower rates for the Hatteras Formation (Aptian–Albian).

The palynological data show a close correspondence with the sedimentological evidence and thus were also used to estimate relative sedimentation rates for Hole 534A. Rapid sedimentation was accompanied by large influxes of terrigenous organic matter in the tracheal facies and directly followed in each unit by abundant, well-preserved, xenomorphic debris of fecal-pellet origin and numerous *Classopollis* pollen in the xenomorphic facies (Fig. 2). The morphologically poorly sorted tracheal facies is especially well-developed in the Blake-Bahama Formation (unit 7), where distal turbidites are best expressed, and in the transitional lithology of the lower part of the Hatteras Formation (unit 9) in graded carbonaceous clays. In these units abundant xenomorphic debris and morphologically sorted pollen (*Classopollis*) represent a rapid supply of mixed terrigenous and marine zooplanktonic organic matter. On the other hand, slower sedimentation produced little or no land-plant materials and fewer fossils represented by a diversified organic-walled marine microflora, as is best expressed in the Tithonian hematitic calcareous clays (lower part of unit 4) and in Berriasian bioturbated pelagic oozes and limestones (upper part of unit 4).

The colors of the lithologies studied are related to the inherent color of the mineral species (e.g., whitish calcite, reddish or brownish hematite) composing the sediment, and also to the organic matter supplied to the seafloor and its contribution to diagenetic processes. The colors black, green, and red in Hole 534A were influenced by factors such as the amount of organic matter contained in the sediment (compare the amount of residues in Table 1) and to anoxic processes related to the presence of buried organic matter. For example, very little residue (0.1–0.4 mm/g) composed entirely of black micrinitic debris had no effect on the coloration of the barren red clays of unit 10. Whether this debris represents the well-sorted diminutive remains of woody tissue oxidized on the land surface and deposited slowly or was oxidized to its black color in the buried sediment is not known. However, its very presence in this sediment indicates that it survived red clay oxic diagenesis. Micrinitic debris and carbonized larger tracheids are concentrated also in the blackish red calcareous clays of Jurassic units 2 and 3. These samples are also either barren of palynomorphs or contain few poorly preserved dinoflagellates. Their occurrence is attributed to oxic diagenesis survival as well, although in this example, opposite to that of unit 10, the larger residues (1.0–1.5 mm/g) turned the sediments blackish.

In other stratigraphic intervals, the black color of the carbonized debris contributed mostly, if not entirely, to the blackish color of the sediment. In the stratigraphically alternating black and green Albian noncalcareous clays and in several black Jurassic calcareous clays, residues are also appreciable in most of the samples. In the blackish samples, again, palynomorphs are absent or are represented mainly by a sparse assemblage of marine microflora, despite a carbonized residue of between 1.0 and 2.7 mm/g in most samples (Table 1). In the absence of red coloration, the nature of this organic matter cannot in itself prove that it was oxidized in the buried sediment; however, its concentration in the residues does show that it would have survived oxic diagenesis. Carbonized debris in the micrinitic facies is also appreciable (ca. 1.0 mm/g) in the Albian green clays. The black color of the organic matter in these samples did not directly produce the color of these sediments, but its oxidation may have completely depleted the dissolved oxygen in the interstitial water and provided the environment to reduce iron. According to Rozanov et al., (1974), iron is reduced within sediments below oxic shallow waters of the Black Sea shelf.

The origin of xenomorphic debris is different from that of micrinitic debris. In contrast to the tracheid origin of the carbonized debris, xenomorphic debris may have been produced from the relatively hydrogen-rich cells of marine algae or from the exines of pollen grains. This amorphous debris is abundant and well-preserved at North Atlantic sites (e.g., 105, 398D), which recovered marine carbon-rich Cenomanian black clays (Habib, 1979b). If xenomorphic debris of various origins formed from zooplanktonic feeding and settled relatively rapidly as fecal pellets, then its supply also would have affected the Eh environment of the buried sediment. Increased zooplanktonic feeding during episodes of high productivity of land or marine plants would rapidly deposit xenomorphic-rich fecal pellets and turn the buried sediment anoxic. A lesser supply would result in little, poorly preserved debris or, in the case of unit 10, no xenomorphic debris as the result of sediment oxidation. The marine carbon-rich Cenomanian event found at other sites in the North Atlantic has been correlated with increased organic productivity in the open ocean and marginal seas (Habib, 1982a).

In conclusion, the kind and rate of supply of organic matter to Site 534 during the Middle Jurassic–Early Cretaceous governed the occurrence of carbonaceous sediments. The North Atlantic Ocean could have been oxic throughout this history. Episodes of black-shale formation resulted from a sufficient and rapid supply of organic matter that turned the bottom sediment anoxic. The black-shale episodes at Site 534 were formed primarily by rapid sedimentation of terrigenous organic matter associated with terrigenous mineral matter. They also formed during periods of rapid supply of xenomorphic debris within fecal pellets and during slower sedimentation of black carbonized debris. The presence, albeit in small amounts, of micrinitic debris in red clays indicates that this organic matter withstood oxic diagenesis. Its concentration in blackish red clays and black clays suggests that it formed the same way, with its greater amounts turning the sediment blackish. The nature of organic matter in Jurassic pale red calcareous clays, Cretaceous pale gray calcareous sediments, and Aptian red noncalcareous clays indicates a lower rate of supply. When palynomorphs occur they are represented almost entirely by the sparse marine microflora.

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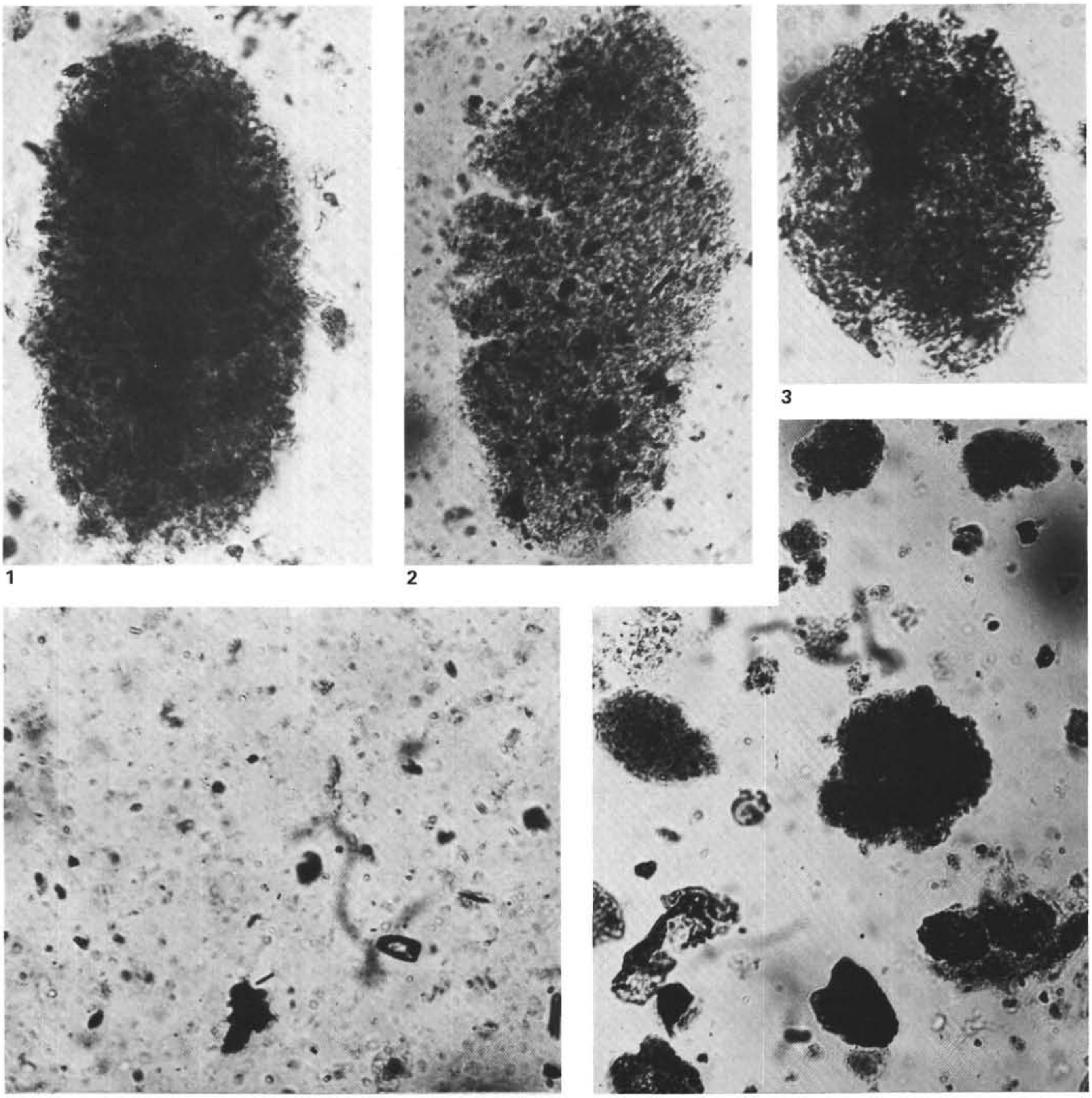

Plate 1. Black clay xenomorphic facies (magnifications not to scale; dimensions of each specimen specified in micrometers). **1–3.** Fecal pellets, (1) well-preserved pellet densely packed with yellow xenomorphic debris micrinitic particles largely absent; 97 × 51 μm. Sample 534A-123-1, 90–92 cm. Late Callovian, (2) poorly preserved pellet; note small black micrinitic particles in matrix of pale brown xenomorphic debris; 102 × 45 μm. Sample 534A-106-1, 3–4 cm. Kimmeridgian, (3) pellet of well-preserved yellow xenomorphic debris in marine carbon-rich xenomorphic facies at DSDP Site 105 (Habib, 1982a); 70 × 52 μm. Sample 105-9-6, 80–82 cm. Middle or late Cenomanian. **4.** Poorly preserved xenomorphic facies, consisting of admixed, fine, granular, brown xenomorphic debris and small, black micrinitic particles (compare with pellet in Fig. 2). Magnification approximately ×450. Sample 534A-106-1, 3–4 cm. Kimmeridgian. **5.** Well-preserved xenomorphic facies containing aggregates of pelletal debris. Magnification approximately ×400. Sample 534A-121-1, 46–48 cm. Early Oxfordian.

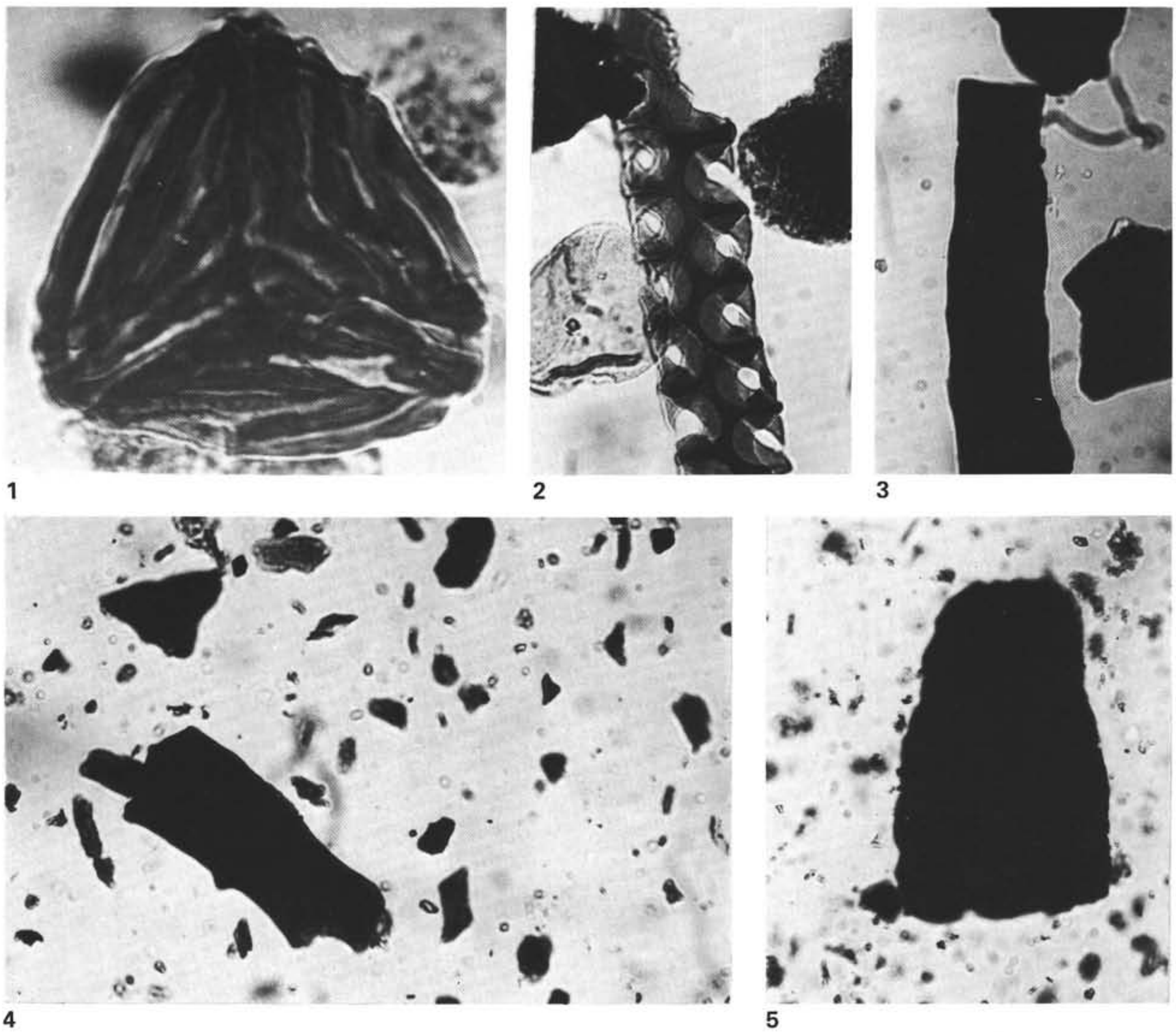

Plate 2. Tracheal and micrinitic facies (magnifications not to scale; dimensions specified in micrometers). **1-2.** Diagnostic constituents of tracheal facies, (1) larger pteridophyte spore attributed to schizaeaceous ferns (*Cicatricosisporites* sp.); 75 × 72 μm. Sample 534A-126-3, 13-17 cm. Middle Callovian, (2) relatively well-preserved, cross-pitted tracheid, 80 μm long. Sample 534A-126-3, 13-17 cm. Middle Callovian. **3-5.** Carbonized tracheids amidst fine micrinitic particles in the micrinitic facies (note the concentration of black particles and paucity of xenomorphic debris), (3) black clay; largest particle 85 mm long. Sample 534A-110,CC. Kimmeridgian, (4) blackish red clay (magnification approximately ×450). Sample 534A-100-2, 127-128 cm. Tithonian, (5) red clay (particle 85 mm long). Sample 534A-41-1, 42-44 cm. Late Aptian or early Albian.