9. EOCENE TO PLEISTOCENE CLAY MINERAL SEDIMENTATION OFF NEW JERSEY, WESTERN NORTH ATLANTIC (SITES 903 AND 905)¹

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ABSTRACT

The clay fraction of sediments drilled at Sites 903 and 905 is composed of variable proportions of chlorite, illite, random mixed layers (including illite-smectite and illite-vermiculite), smectite, and kaolinite. The coincidence of major changes in clay mineralogy with increasing values of oxygen isotopes suggests a dominant climatic control of the clay sedimentation. At Site 903, we distinguish four intervals (Eocene, upper Oligocene-middle Miocene, middle Miocene, upper Miocene, and Pleistocene) characterized by distinct clay assemblages.

The Eocene clay sedimentation is dominated largely by land-derived smectites, except close to a microtektites layer, where smectites probably formed by submarine alteration of glass. Across the major unconformity separating the Eocene chalks from Oligocene-Miocene siliciclastic sediments, the sharp increase in illite and kaolinite reflects the active erosion of the Appalachians Highlands. Sea-level lowering associated with Cenozoic global cooling seems to be responsible for the reworking of these minerals. Kaolinite was probably reworked from ancient rocks and from alterations. The step-by-step increase of both clay minerals lasted until the middle Miocene. The highest percentages of kaolinite from that time also indicate increasing humidity on land.

During the late middle Miocene and late Miocene, illite still increased, but kaolinite decreased. This major change in clay mineralogy probably resulted from the combination of a glacioeustatic event previously documented by δ^{18} O data and the erosion of uplifted crystalline terrains in the Appalachians. The Pleistocene clay sedimentation is characterized by abundant chlorite and illite resulting from the mechanical erosion of crystalline rocks outcropping in northern areas (e.g., Canadian Shield).

A similar trend is recorded at Site 905, but in comparison with sediments from the upper slope (Site 903), sediments deposited on the upper rise are significantly enriched with illite-smectite mixed layers over either illite and kaolinite. This difference results from the combination of differential settling processes of clay minerals and from the north-south circulation of bottom water carrying suspended clays to the region from sources farther north.

INTRODUCTION: PREVIOUS CLAY MINERAL DATA IN THE WESTERN NORTH ATLANTIC

During Leg 150 of the Ocean Drilling Program (ODP), holes were drilled at five sites. Sites 902, 903, 904, and 906 are located on the slope off New Jersey and Site 905 is on the upper rise (Fig. 1). The upper Oligocene through Pleistocene sediments deposited on the passive continental margin off New Jersey are composed dominantly of clays, silty clays, and clayey silts lying above Eocene nannofossil clayey chalks (Shipboard Scientific Party, 1994a, 1994b, 1994c, 1994e). Most terrigenous particles were brought to the New Jersey Margin by rivers crossing the Appalachian Highlands (Poag and Sevon, 1989; Poag, 1992). After deposition, they were redistributed on the continental margin by oceanic currents, submarine slumping, and turbidity currents through canyons cutting the continental shelf and slope.

Numerous clay mineral data have been reported for Cenozoic sediments deposited in deep-sea basins and abyssal plains from the western North Atlantic (Rothe and Tucholke, 1981; Rothe, 1989), but limited clay mineral data are available for sediments deposited on the rise and slope. Some clay mineral analyses have been performed on Cenozoic sediments drilled during Deep Sea Drilling Project (DSDP) Leg 93 on the upper rise (Sites 604 and 605) (Dunn et al., 1987), but most clay mineral data are from sediments deposited in deeper environments, on the lower continental rise (DSDP Leg 44, Site 388; Flood, 1978), in the Cape Hatteras basin (DSDP Leg 11, Site 105), in the Labrador Sea (ODP Leg 105, Site 646; Cremer et al., 1989), and in the Baffin Bay (ODP Leg 105, Site 645; Thiébault et al., 1989; Thiébault and Cremer, 1990).

The aim of this study is (1) to document variations in the nature and composition of clay mineral assemblages brought from the North American continent to the New Jersey Margin, and (2) to identify environmental changes from the Eocene to the Pleistocene. In the proximal rise and slope areas, the composition of clay mineral assemblages should be more sensitive to climatic, tectonic, and sea-level fluctuations than in distal oceanic basins where they were studied previously.

Pleistocene

At Sites 604 and 605 drilled on the upper rise (Fig. 1), the clay fraction of the Pleistocene sediments is composed dominantly of illite (average quantity, 60%), with chlorite (23%) and kaolinite (17%). Smectite occurs sporadically (Dunn et al., 1987). On the lower rise, Pleistocene sediments are also rich in illite (mica) occurring together with chlorite and kaolinite (Flood, 1978). In deeper environments of the western North Atlantic, chlorite and illite are generally the dominant minerals of Pleistocene sediments at DSDP Sites 388 and 391 (Pastouret et al., 1978), 105 (Chamley et al., 1980), and 534 (Chamley et al., 1983). In recent sediments deposited on the continental margin of the East Coast of the United States, Hathaway (1972) distinguished a northern assemblage composed dominantly of chlorite, illite, amphibole, and feldspars and a southern assemblage composed dominantly of kaolinite and smectite.

¹Mountain, G.S., Miller, K.G., Blum, P., Poag, C.W., and Twichell, D.C. (Eds.), 1996. *Proc. ODP, Sci. Results*, 150: College Station, TX (Ocean Drilling Program).

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Figure 1. Location of Leg 150 sites and most of the DSDP sites drilled in the western North Atlantic.

Miocene and Eocene

The clay fraction of Miocene sediments is composed of illite and kaolinite at Site 604 on the upper rise (Dunn et al., 1987). On the lower rise, illite is the dominant clay mineral with smectite, kaolinite, and chlorite in late to middle Miocene age clays and silty clays (Flood, 1978). In the deep-sea basins and abyssal plains of the western North Atlantic, smectite is usually the dominant clay mineral occurring commonly with small amounts of illite, kaolinite, and fibrous clays, including palygorskite and sepiolite.

Middle Eocene sediments were drilled at Site 605 on the upper rise. Clay minerals comprise smectite, illite, and kaolinite (Dunn et al., 1987). In deeper environments, smectites are the dominant clay minerals in the western Atlantic Ocean (Rothe, 1989).

METHODS

The clay mineral associations were identified using X-ray diffraction (XRD) on oriented mounts. Defloculation of clays was done by successive washing with distilled water after decarbonation of the crushed rock with 0.2 N HCl. The clay fraction (particles < 2 μ m) was separated by sedimentation and centrifugation (Brown and Brindley, 1980; Holtzapffel, 1985). XRD diagrams were obtained using a Philips PW 1730 diffractometer with CuK α radiation and Ni filter. A tube voltage of 40 kV and a tube current of 25 mA were used. Three XRD analyses were performed, after samples were air-dried, ethylene-glycol-solvated, and heated at 490°C for 2 hr. The goniometer scanned from 2.5° to 28.5° 2 θ for air-dried, glycol-solvated conditions and from 2.5° to 14.5° 2 θ for heated conditions. The identification of clay minerals was made according to the position of the (001) series of basal reflections on the three XRD diagrams (Brown and Brindley, 1980; Reynolds, 1980; Moore and Reynolds, 1989). Semiquantitative estimates are based on the intensity and on the area of the main diffraction peak of each clay mineral (Holtzapffel, 1985). The percentages of smectite layers in illite/smectite mixed layers (I/S) are estimated by measuring the "saddle index" (Inoue et al., 1989).

In addition, clay minerals were observed by transmission electron microscopy (TEM) using a JEOL 100 CX to identify the possible occurrence of traces of palygorskite and to determine the shape and size of clay particles.

RESULTS

Site 903

Two-hundred ninety-five samples from Site 903 were X-rayed. The clay mineral assemblages identified are composed of dominant illite, kaolinite, and smectitic minerals, including smectite and randomly interstratified illite/smectite minerals. Chlorite abundance is very low (5%) throughout the section, but increases sharply in Pleistocene sediments (Fig. 2). Four distinct clay mineral zones (CMZ) were identified according to (1) the appearance or disappearance of clay species and (2) the behavior of relative percentages of clay minerals. They are considered in the stratigraphic order.

CMZ IV

Clay Mineral Zone IV coincides with lithological Unit VII, an Eocene, heavily bioturbated nannofossil clayey chalk that becomes



Figure 2. Clay mineralalogy and clay mineral zones (CMZ) of sediments drilled at Site 903. I/S = random illite-smectite mixed layers, I/V = random illite-vermiculite mixed layers.

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Table 1. X-ray diffractometry mineralogical results (CMZ IV), Site 903.

Core, section, interval (cm)	Depth (mbsf)	Illite (%)	1/S (%)	Kaolinite	Quartz (%)	Opal-CT	Saddle
	(11001)	(37)	(10)	()	(10)	opu er	
150-903C-							
51R-5, 47-48	1059.6	9	85	6	+	+	0.370
51R-6, 50-52	1061.1	7	91	2	+	+	0.301
51R-7, 49-51	1062.6	28	72	0	+	+	0.864
53R-1, 50-52	1074.3	5	92	3	+	+	0.205
53R-2, 50-52	1075.8	6	92	2	+	+	0.222
53R-3, 50-52	1077.3	4	95	1	+	+	0.165
53R-4, 50-52	1078.8	4	95	1	+	+	0.159
53R-5, 50-52	1080.3	4	95	1	+	+	0.167
54R-1, 50-52	1083.9	4	95	1	+	+	0.167
54R-3, 49-51	1086.9	5	93	2	+	+	0.301
54R-5, 49-51	1089.9	6	92	2	+	+	0.212
55R-1, 50-51	1093.3	5	93	2	+	+	0.220
55R-4, 50-52	1097.8	3	95	2	+	+	0.182
55R-5, 139-140	1100.2	5	94	1	+	+	0.204
56R-1, 49-51	1102.8	4	96	0	+	+	0.187
56R-3, 49-51	1105.2	4	96	0	+	+	0.189
56R-5, 49-51	1108.2	5	95	0	+	+	0.347
56R-7, 49-51	1111.2	8	88	4	+	+	0.300
57R-1, 50-52	1112.0	5	90	5	+	+	0.261
57R-3, 50-52	1115.0	4	93	3	+	+	0.232
58R-2, 54-56	1121.8	5	93	2	+	+	0.255
58R-3, 43-45	1123.2	4	94	2	+	+	0.238
58R-4, 52-54	1124.8	7	91	2	+	++	0.309
58R-5, 49-51	1126.3	5	93	2	+	++	0.285
58R-6, 48-50	1127.7	8	89	3	+	++	0.418
58R-7, 50-52	1129.3	6	93	1	+	++	0.318
58R-8, 47-50	1130.7	8	92	0	+	++	0.414
59R-2, 52-54	1131.5	10	90	0	+	++	0.458
60R-4, 47-49	1143.8	5	95	0	+	+	0.257

Note: Results for quartz and opal-CT are reported as rare (+) or common (++).



Figure 3. A–D. Typical X-ray diffractograms (glycolated) from the four clay mineral zones identified at Site 903. I/S = random illite-smectite mixed-layers, I/V = random illite-vermiculite mixed layers, Amph. = amphibole

Core, section, interval (cm)	Depth (mbsf)	Chlorite (%)	Illite (%)	I/S (%)	Kaolinite (%)	Quartz	Opal-CT	Saddle index
150-903C-								
17R-2, 50-52	738.80	2	37	15	46	++		0.857
17R-3, 50-52	740.30	2	41	10	47	++		0.897
17R-4, 50-52	741.80	2	42	14	44	++		0.955
18R-1, 40-42	746.90	2	41	12	45	++		0.905
18R-2, 50-52	747.63	ō	43	12	45	++		0.902
18R-3, 50-52	749.13	2	37	13	48	++		0.891
18R-4, 50-52	750.63	2	43	12	43	++		0.915
19R-1, 50-52 19R-2, 50-52	758.20	2	35	22	40	++		0.850
19R-3, 51-53	759.71	2	32	31	35	++		0.800
19R-4, 51-53	761.21	2	31	31	36	++		0.812
19R-5, 51-53	762.21	2	30	23	45	++		0.828
20R-2, 50-52 20R-3, 50-52	766.61	5	29	29	37	++		0.875
20R-4, 50-52	769.61	ő	34	22	44	++		0.857
20R-5, 48-50	771.09	2	30	31	37	++		0.823
20R-6, 50-52	772.61	2	28	-28	42	++		0.845
20R-7, 50-52	774.11	0	26	35	39	++		0.835
21R-1, 50-52 21R-2, 50-52	777.08	2	29	38	32	++		0.830
21R-3, 50-52	778.58	õ	29	34	37	++		0.810
21R-4, 50-52	780.08	2	28	37	33	++		0.826
21R-5, 50-52	781.58	2	27	40	31	++		0.842
21R-6, 50-52 21P 7 50-52	783.08	2	24	40	34	++		0.819
22R-1, 50-52	785.70	2	32	28	38	++		0.810
22R-2, 50-52	787.20	2	30	29	39	++		0.884
22R-3, 50-52	788.70	2	30	28	40	++		0.847
22R-4, 50-52	790.20	2	29	32	37	++		0.794
22R-5, 50-52 22R-6, 50-52	791.70	2	28	32	38	++		0.829
23R-1, 50-52	795.40	2	32	33	33	++		0.865
23R-2, 50-52	796.90	2	30	29	39	++		0.856
23R-3, 50-52	798.40	2	31	36	31	++		0.809
23R-4, 26-28	799.66	2	29	31	38	++		0.881
23R-5, 50-52 23R-6, 50-52	802.90	2	32	31	35	++		0.866
25R-1, 19-21	813.99	5	32	35	28	++		0.843
25R-2, 59-61	815.89	2	30	36	32	++		0.784
27R-1, 112-114	834.22	0	17	44	39	++		0.707
28R-1, 99-101 28R-2 100-102	845.09	2	32	35	31	++		0.825
29R-1, 49-51	852.89	2	21	52	25	++		0.833
29R-2, 50-52	854.40	2	27	44	27	++		0.805
29R-3, 130-132	856.70	2	25	47	26	++		0.846
29R-5, 80-88 31R-1 40-51	859.26	2	22	40	30	++		0.728
31R-2, 97-99	874.17	õ	23	48	29	++		0.853
32R-1, 50-52	881.90	2	23	42	33	++		0.871
32R-2, 50-52	883.40	2	21	44	33	++		0.823
32R-3, 83-85	885.23	2	25	41	32	++		0.882
33R-2, 49-51	893.09	2	23	45	30	++		0.794
33R-3, 49-51	894.59	2	24	37	37	++		0.857
33R-4, 49-51	896.09	2	23	38	37	++		0.871
33R-5, 49-51	897.59	0	22	47	31	++		0.887
34R-1, 48-49	901.18	2	21	45	26	++		0.775
34R-2, 48-49	902.68	õ	22	53	25	++		0.702
35R-2, 50-52	911.31	0	25	53	22	++		0.895
35R-3, 50-52	912.81	0	24	51	25	++		0.800
35R-5 47-49	915.78	2	25	50	29	++		0.840
35R-6, 50-52	917.31	2	24	44	30	++		0.819
35R-7, 50-52	918.81	2	26	44	28	++		0.842
36R-1, 48-50	920.48	2	22	45	31	++		0.810
150-903C-	000000000		23		2101			0.000
36R-2, 48-50	921.98	0	29	43	28	++		0.865
37R-1 49-51	925.48	2	29	38	32	++		0.795
37R-2, 49-51	931.69	2	32	29	37	++		0.836
37R-3, 27-28	932.97	2	30	37	31	++		0.869
37R-4, 49-51	934.69	2	30	38	30	++		0.825
37R-5, 49-51	936.19	2	30	38	30	++		0.823
39R-3, 40-42	952.00	2	18	59	21	++		0.628
40R-3, 50-52	961.70	2	25	49	24	++		0.764
41R-3, 52-54	971.02	2	21	48	29	++		0.761
44R-1, 104-106	997.54	0	18	63	19	++		0.619
45R-1, 44-46	1006.6	0	24	55	21	++		0.659
47R-1, 51-52	1026.0	2	15	73	10	+	+	0.497
47R-2, 91-92	1027.9	0	9	84	7	+	+	0.266
48R-1, 49-51	1029.6	0	8	88	4	+	+	0.254
48R-2, 118-120	1031.8	0	9	86	5	+	+	0.321
401-3, 49-31	1032.0	0	12	15	13	- T	+	0.440

Table 2. X-ray diffractometry mineralogical	l results (CMZ III), Site 903	3.
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Table 2 (continued).

Core, section, interval (cm)	Depth (mbsf)	Chlorite (%)	Illite (%)	I/S (%)	Kaolinite (%)	Quartz	Opal-CT	Saddle index
49R-2, 50-52	1035.8	2	13	79	6	+	+	0.489
49R-3, 50-52	1037.3	0	6	90	4	+	+	0.270
49R-4, 49-51	1038.8	0	14	73	13	+	+	0.559
49R-5, 50-52	1040.3	0	4	92	4	+	+	0.198
49R-6, 50-52	1041.8	0	8	87	5	+	+	0.357
49R-7, 50-52	1043.3	2	18	61	19	+	+	0.791
51R-2, 49-51	1055.1	0	15	67	18	+	+	0.677
51R-3, 51-53	1056.6	2	10	85	3	+	+	0.386
51R-4, 48-50	1058.1	0	14	73	13	+	+	0.518

Note: Results for quartz and opal-CT are reported as rare (+) or common (++).



Figure 4. Illite/kaolinite diagram showing the correlation between these minerals in CMZ III.

porcellanitic downhole (Shipboard Scientific Party, 1994b). The clay fraction, representing a few percent, is composed typically almost entirely of smectitic minerals (up to 96%, Table 1) with traces of illite and kaolinite. Opal-CT (cristobalite/tridymite) is common toward the base (Fig. 3A). The percentage of smectitic sheets in the smectitic minerals is between 70% and 90% according to the saddle index values (Table 1). The (060) reflection has a position of 1.499 Å, which indicates a dioctahedral type of crystal lattice. Observations by transmission electron microscopy show that the smectites display a fleecy shape (Pl. 1) without any crystalline overgrowths that would indicate an authigenic origin.

At Sites 903 and 904, a microtektite layer interbedded within the chalk was recovered (Shipboard Scientific Party, 1994b, 1994c). The clay mineral associations were closely studied across the microtektite layer at Site 904 because this layer is better preserved than at Site 903. Fourteen samples selected in Section 150-904A-45X-2, 50–130 cm, are characterized by a clay fraction composed dominantly of smectite with minor illite and kaolinite. The microtektite layer and the clay fraction of the overlying chalk are significantly enriched with smectite probably derived from the submarine alteration of glassy material (McHugh et al., this volume). At Site 903, a similar trend was observed, with the maximum smectite occurrence in Core 150-903C-56R above the microtektite layer (Table 1).

CMZ III

Illite and kaolinite increase significantly from CMZ IV to III, across the major sequence boundary (reflector O1) separating the



Figure 5. Evolution of the saddle index of I/S within CMZ III.

Eocene chalk from the Oligocene-Miocene siliciclastic sediments. Clay Mineral Zone III includes lithological Units V and VI. The clay mineralogy of this dominantly argillaceous zone is characterized from the base to the top by decreasing proportions of smectitic minerals, and concurrently increasing illite and kaolinite (Fig. 2; Table 2). The percentages of these latter minerals are positively correlated (Fig. 4). In lithological Unit VI, the dominant smectitic minerals (55%-95%) occur with 5% to 30% of well-crystallized illite (the illite crystallinity index is between 0.3° and 0.4° 20) and kaolinite (0%-20%) (Fig. 3B). Unit V consists of diatomaceous silty clays, with the clay fraction composed of smectitic minerals (10%-60%), illite (15%-40%), and kaolinite (20%-40%). There is no significant mineralogical change between lithological Units VI and V, but the evolution of the saddle index (Fig. 5) shows that the percentage of smectite layers in I/S from Unit VI ranges between 60% and 90%, whereas I/S from Unit V is composed of less than 60% smectite layers. Therefore, percentages of I/S and percentages of smectite layers in these interstratified minerals decrease simultaneously upsection. Transmission electron microscopy reveals the occurrence of short and broken fibers of palygorskite (Pl. 1), which were not detected by XRD because the amounts are too small.

Core, section, interval (cm)	Depth (mbsf)	Chlorite (%)	Illite (%)	I/V (%)	1/S (%)	Kaolinite	Quartz	Saddle index
150-903A-								
39X-3, 82-84	340.22	9	35	0	14	42	++	0.750
39X-4, 109-111	341.99	17	41	0	20	22	++	0.800
40X-1, 55-56	340.53	16	41	0	32	18	++	0.750
41X-3, 82-84	359.52	2	46	ŏ	22	30	++	0.894
42X-4, 81-83	370.71	5	38	0	24	33	++	0.845
43X-4, 82-84	380.22	5	34	0	24	37	++	0.817
44X-5, 17-19 45X-4, 12-14	387.77	5	44	0	19	32	++	0.872
46X-4, 27-29	408.27	5	32	ő	23	40	++	0.800
47X-3, 21-23	416.91	2	36	0	20	42	++	0.821
48X-3, 99-101	427.29	2	37	0	30	31	++	0.826
48X-0, 123-125 49X-4 49-51	432.03	2	45	0	20	33	++	0.815
50X-3, 105-107	446.75	õ	33	ő	40	27	++	0.648
51X-3, 86-88	456.06	2	42	0	24	32	++	0.819
52X-3, 110-120	466.00	2	50	0	21	27	++	0.815
54X-0, 39-41 54X-3 100-102	479.49	2	44	0	20	34	++	0.852
55X-4, 29-31	495.69	2	39	ŏ	23	36	++	0.842
56X-2, 59-61	502.69	2	42	0	21	35	++	0.886
903C-5R-2, 39-41	507.49	2	38	0	25	35	++	0.825
903A-57X-3, 129-131	514.49	2	37	0	26	35	++	0.862
903C- 7R-1, 52-54	515.82	2	36	0	24	38	++	0.882
7R-2, 43-45	517.23	2	39	Ő	21	38	++	0.868
7R-3, 45-47	518.75	2	35	0	24	39	++	0.839
7R-4, 50-52	520.30	5	37	0	19	39	++	0.868
903A-38A-1, 82-84	520.72	2	38	0	27	33	++	0.870
7R-5, 29-31	521.59	2	41	0	19	38	++	0.905
7R-6, 27-29	523.07	2	42	0	15	41	++	0.895
903A- 59X-3 127-129	533 77	5	44	0	17	34	++	0.877
60X-1, 49-51	539.69	5	45	õ	15	35	++	0.833
60X-2, 48-50	541.18	5	47	0	12	36	++	0.898
60X-3, 50-52	542.70	5	45	0	11	39	++	0.921
60X-5, 50-52	545 70	2	53	0	10	35	++	0.933
60X-6, 50-52	547.20	2	46	ŏ	15	37	++	0.895
61X-1, 50-52	549.40	2	45	0	12	41	++	0.893
61X-2, 50-52	550.90	2	46	0	10	42	++	0.918
61X-3, 50-52	552.40	2 5	48	0	15	30	++	0.803
61X-5, 50-52	555.40	2	43	ő	14	41	++	0.821
61X-6, 50-52	556.90	2	48	0	10	40	++	0.880
62X-1, 50-53	559.00	2	44	0	15	39	++	0.900
62X-2, 50-53	562.00	2	40	0	15	39	++	0.891
62X-4, 50-52	563.50	2	48	ŏ	14	36	++	0.909
62X-5, 50-52	565.00	5	46	0	13	36	++	0.852
62X-6, 50-52	566.50	2	37	0	20	40	++	0.896
63X-1, 50-52 63X-2, 50-52	569.80	0	37	0	21	42	++	0.870
63X-3, 50-52	571.30	2	37	ŏ	11	50	++	0.930
63X-4, 50-52	572.80	5	38	0	10	47	++	0.929
63X-5, 50-52	574.30	0	40	0	10	50	++	0.923
63X-6, 50-52 63X-7, 35-37	575.80	0	37	0	13	50	++	0.868
64X-1, 50-52	578.00	2	44	0	11	43	++	0.926
64X-2, 50-52	579.50	õ	43	0	20	37	++	0.855
64X-3, 50-52	581.00	0	40	0	21	39	++	0.900
64X-4, 03-05 64X-5, 49-51	582.03	2	35	0	25	38	++	0.876
64X-6, 47-49	585.47	2	48	ő	9	41	++	0.935
64X-7, 10-12	586.60	2	44	ŏ	11	43	++	0.930
903C-9R-1, 50-52	587.00	2	44	0	11	43	++	0.877
903A-65X-1, 50-52	587.60	2	52	0	10	36	++	0.909
903C-9R-2, 50-52	588.50	5	45	0	10	40	++	0.907
903A-65X-2, 51-54	589.11	2	46	0	10	42	++	0.900
903C-9K-3, 50-52	590.00	2	42	0	14	42	++	0.843
65X-3, 50-52	590.60	2	55	0	8	35	++	0.917
65X-4, 50-52	592.10	2	45	0	12	41	++	0.880
903C-10R-1, 49-51	592.59	2	44	0	14	40	++	0.865
903A-65X-5, 50-52	593.60	2	48	0	12	38	++	0.929
903C-10R-2, 49-51	594.09	2	42	0	15	41	++	0.868

Table 3. X-ray diffractometry mineralogical results (CMZ II), Site 903.

Table 3 (continued).

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Core, section, interval (cm)	Depth (mbsf)	Chlorite (%)	Illite (%)	I/V (%)	I/S (%)	Kaolinite	Quartz	Saddle index
903A-65X-6, 50-52	595.10	0	44	0	14	42	++	0.860
10R-3, 49–51 10R-4, 18–20	595.59 596.78	5 2	43 43	0 0	19 15	33 40	++ ++	0.852 0.825
903A-66X-CC	597.03	0	42	0	12	46	++	0.922
903C- 10R-5 19-21	598 29	2	44	0	14	40	++	0.868
10R-7, 10-12	600.00	ĩ	34	ö	28	36	++	0.854
11R-1, 49-51	602.29	2	32	0	34	32	++	0.835
11R-2, 131–133	603.88 604.60	2	33	0	30	32 35	++ ++	0.837
903A-	101.00	2	22		20	24		0.000
67X-1, 50-52 67X-2, 51-53	606.80	2	33	0	29	36	++	0.800
67X-3, 50-52	609.80	5	36	ŏ	25	34	++	0.860
67X-4, 49-51	611.29	2	34	0	25	39	++	0.878
67X-5, 49-51 67X-6, 49-51	612.79	2	34	0	29	35	++	0.819
68X-1, 50-52	616.50	2	36	õ	23	39	++	0.907
68X-2, 50-52	618.00	2	33	0	26	39	++	0.871
68X-3, 50-52	619.50	0	36	0	20	42	++	0.901
68X-5, 50-52	622.50	2	36	ŏ	20	42	++	0.882
68X-6, 32-34	623.82	2	33	0	18	47	++	0.851
68X-7, 33-34	625.33	0	36	0	11	53	++	0.909
69X-2, 50-52	627.60	0	42	ő	12	46	++	0.880
69X-3, 50-52	629.10	2	41	0	13	44	++	0.896
69X-4, 50-52	630.60	0	39	0	14	47	++	0.885
69X-5, 52-54	633.62	0	40	0	13	40	++	0.882
70X-1, 50-52	635.70	ö	41	Ö	13	46	++	0.900
70X-2, 50-52	637.20	2	38	0	13	47	++	0.898
70X-3, 50-52 70X-4, 50-52	638.70	2	32	0	26	39	++	0.885
70X-5, 50-52	641.70	$\tilde{2}$	32	ŏ	26	40	++	0.890
70X-6, 50-52	643.20	2	36	0	21	41	++	0.894
70X-7, 50-52 71X-1 49-51	644.20	0	35	0	24	41	++	0.915
71X-2, 50-52	646.70	õ	33	ö	23	44	++	0.864
71X-3, 44-46	648.14	2	32	0	16	50	++	0.922
71X-4, 50-52	649.70	2	35	0	15	48	++	0.949
71X-6, 49-51	652.69	ő	32	0	29	39	++	0.835
72X-1, 50-52	654.90	2	31	0	26	41	++	0.848
72X-2, 48-50	656.38	2	39	0	20	39	++	0.911
72X-4, 39-41	659.29	0	30	0	31	39	++	0.833
72X-5, 49-51	660.89	2	34	0	25	39	++	0.874
72X-6, 43-45	662.33	2	35	0	20	43	++	0.880
73X-2 51-53	004.38 666.11	20	37	0	21	39	++	0.889
73X-3, 50-52	667.60	ŏ	36	ŏ	23	41	++	0.900
73X-4, 50-52	669.10	2	32	0	23	43	++	0.901
73X-5, 50-52 73X-6, 48-50	672.08	ő	37	0	21	42	++	0.925
74X-1, 48-50	674.28	2	34	ŏ	19	45	++	0.897
74X-2, 47-49	675.77	2	34	0	17	47	++	0.905
74X-3, 44-40 74X-4 45-47	678 75	2	33	0	17	43	++	0.833
74X-5, 48-50	680.28	ŏ	34	ŏ	21	45	++	0.892
74X-6, 47-49	681.77	0	30	0	22	48	++	0.859
75X-1, 48-50 75X-2, 48-50	683.98	2	35 29	0	22 21	41 48	++ ++	0.878
903A-	200000		2.2	~	2/25/	0,220		
75X-3, 48-50 75X-4, 48-50	686.98 688.48	22	29 27	0	19 15	50 56	++ ++	0.848 0.900
903C-12R-1, 47-49	689.07	2	35	0	18	45	++	0.905
903A-75X-5, 48-50	689.98	0	35	0	18	47	++	0.831
903C-12R-2, 69-71	690.79	0	33	0	19	48	++	0.857
903A-75X-6, 48-50	691.48	0	36	0	15	49	++	0.891
12R-3, 34-36	691.94	0	34	0	18	48	++	0.926
12R-4, 39-41	693.49	2	40	0	17	41	++	0.869
903A-76X-1, 50-52	693.60	0	38	0	16	46	++	0.937
903C-12K-5, 21-23 903A-	094.81	2	30	0	22	40	++	0.928
76X-2, 43-45	695.03	0	33	0	21	46	++	0.893
76X-3, 45-47	696.55	0	34	0	21	45	++	0.815
003C 12D 1 50 52	609 70	2	20	0	10	40	**	0.870
505C-15K-1, 50-52	098.70	2	29	0	18	21	++	0.879

Table 3 (continued).

Depth (mbsf)	Chlorite (%)	Illite (%)	I/V	I/S			Saddle
100 11			(70)	(%)	Kaolinite	Quartz	index
699.61	0	40	0	18	42	++	0.893
700.21	5	36	0	13	46	++	0.873
701.13	0	30	0	17	53	++	0.891
701.69	2	35	0	18	45	++	0.841
702.05	0	36	0	18	46	++	0.877
708.30 709.80 711.31 712.80 714.28 715.29	0 0 2 2 0	30 31 30 31 31 24	0 0 0 0 0	20 21 15 18 10 15	50 48 55 49 57 61	++ ++ ++ ++ ++ ++	0.830 0.864 0.867 0.863 0.895 0.895
717.72 719.21 720.70 722.20 727.50 729.00 730.50 732.00	2 2 2 0 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2	32 36 40 37 38 37 43 40	000000000000000000000000000000000000000	15 14 16 17 10 12 8 8	51 48 42 44 52 49 47 50	+ + + + + + + + + + + + + + + + + + +	0.902 0.854 0.898 0.850 0.902 0.891 0.933 0.857
	 699.61 700.21 701.13 701.69 702.05 708.30 709.80 711.31 712.80 714.28 715.29 717.21 719.21 720.70 722.20 727.50 729.00 730.50 732.00 732.20 732.20 732.20 732.20 732.20 	699.61 0 700.21 5 701.13 0 701.69 2 702.05 0 708.30 0 709.80 0 711.31 0 712.82 2 714.28 2 719.21 2 720.70 2 727.50 0 727.50 0 729.00 2 730.50 2 732.00 2 732.00 2 732.90 2	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$

Note: Results for quartz are reported as common (++).



Figure 6. Illite/kaolinite diagram showing the absence of correlation in CMZ II.

CMZ II

CMZ II comprises lithological Units IV and III and the lowermost part of Subunit IIB. This interval is also dominantly argillaceous with the common occurrence of silty and sandy, 1- to 10-m-thick glauconitic beds (Shipboard Scientific Party, 1994b). Well-crystallized illite increases from the base (30%) to the top (45%-50%), whereas kaolinite decreases (45% at base, 30% to the top) (Fig. 2; Table 3). In contrast with CMZ III the amounts of illite and kaolinite show no covariance (Fig. 6). The transition from CMZ III to CMZ II is therefore characterized by a major change in the behavior of illite and kaolinite relative to each other. The transition between these CMZs is also lithologically characterized by the occurrence, at 730 m below seafloor in Core 150-903C-16R, of a 4-m-thick section of redeposited strata showing micro-normal faulting (Shipboard Scientific Party, 1994b). The mineralogical change does not coincide with a seismic reflector but occur at the time of the formation of a canyon at Site 906 (Shipboard Scientific Party, 1994e). The quantities of I/S, with less than 55% of smectite layers (Fig. 3C), are relatively constant, with an average value of about 20% (Fig. 2). Transmission electron microscopy reveals a mixture of large, irregular-shaped and well-outlined particles of illite with tiny subhexagonal particles of kaolinite (Pl. 1).

CMZ I

The clay fraction of sediments from CMZ I differs significantly from those of the underlying sediments. It is composed mainly of well-crystallized illite and chlorite (Pl. 1), associated with random illite/vermiculite mixed layers and small amounts of kaolinite (Figs. 2, 3D; Table 4). Therefore, a mineralogical change characterized by the decrease of kaolinite and by increasing chlorite occurs between upper Miocene and lower Pleistocene. Because most of the Pliocene is missing, this sharp change is readily apparently. Pleistocene sediments are also characterized by the occurrence of random illite/vermiculite mixed-layers, the abundance of detrital feldspars and the common occurrence of amphibole (Fig. 3D). This mineralogical assemblage corresponds to the Northern assemblage defined by Hathaway (1972).

Site 905

Three-hundred ninety-one samples were studied from Site 905. The clay mineral assemblages have a similar composition as Site 903, but their relative proportions are quite different. The clay fraction is also more homogeneous throughout the stratigraphic column (Fig. 7). Three clay mineral zones were distinguished.

CMZ III

Clay Mineral Zone III, which coincides with lithological Unit IV, is characterized by homogeneous clay assemblages composed of dominant illite/smectite mixed layers (50%–70%) occurring with well-crystallized illite (10%–20%), kaolinite (10%–30%), and traces of chlorite (Fig. 8A; Table 5). The amounts of kaolinite increase weakly upsection (Fig. 7). A similar trend is observed in CMZ III of Site 903 (Fig. 2). The percentage of smectite layers within I/S ranges between 50% and 75%. Transmission electron microscopy reveals the lath shape of smectite particles and the occurrence of rare, short fibers of palygorskite (Pl. 2).

Table 4. X-ray diffractometry mineralogical results (CMZ I), Site 903.

Core, section, interval (cm)	Depth (mbsf)	Chlorite (%)	Illite (%)	I/V (%)	I/S (%)	Kaolinite (%)	Quartz	Feldspar	Amphibole	Saddle index
150-903A-										
37X-3, 69-71	319.98	25	52	5	7	11	++	+	+	0.903
38X-3, 102-104	330.72	37	30	15	16	2	++	++	++	0.845
39X-1, 92-94	337.32	22	42	15	13	8	++	++	++	0.964

Note: Results for quartz, feldspar, and amphibole are reported as rare (+) or common (++).

CMZ II

Clay Mineral Zone II comprises lithological Units III and II (Fig. 7; Table 6). The clay assemblages are composed of small quantities of chlorite, well-crystallized illite (15%-45%), kaolinite (5%-40%), and I/S (30%-75%) in which the percentage of smectite layers ranges between 45% and 85% (Fig. 8B). Unit III, a succession of mass-transport deposits, shows slightly more kaolinite and fewer illite-smectite mixed layers than Unit II (Fig. 7). As at Site 903, CMZ II is characterized by decreasing proportions of kaolinite upsection balanced by an increase of illite and chlorite. Kaolinite occurs as tiny (less than 0.5 µm), subhexagonal particles (Pl. 2).

CMZ I

The clay fraction of CMZ I at Site 905 is composed dominantly of chlorite and illite associated with small quantities of random mixed layers (including illite-smectite and illite-vermiculite) and kaolinite (Fig. 8C; Table 7). In contrast with CMZ II, the clay fractions are very heterogeneous from one sample to another. The I/S layers are generally less smectitic than in the underlying sediments, with the percentage of smectite layers composing between 40% and 70%. Illite occurs as large well-outlined particles, whereas kaolinite still occurs as small subhexagonal crystals (Pl. 2).

DISCUSSION

Most Cenozoic sediments recovered from the Eocene to the Pleistocene of the North Atlantic show an irregular increase of illite and chlorite associated with mixed layers, quartz, feldspars, and amphibole (Chamley, 1979). This evolution was also observed at Site 903 and is interpreted as a consequence of worldwide cooling that developed since the Eocene/Oligocene boundary (Barron, 1985; Frakes et al., 1992). The comparison between clay mineralogy and the composite oxygen isotope records for the Atlantic published by Miller et al. (1987) indicates a rather good correspondence between boundaries separating clay mineral zones and sharp increase of isotope values (Fig. 9). Therefore, climatic fluctuations appear to be the main factor controlling the clay mineral sedimentation on the continental slope and rise off New Jersey.

Origins of Clay Minerals

In the Atlantic Ocean, most deep-sea clay minerals are derived from continental areas with little change in the crystalline structure (Biscaye, 1965; Chamley, 1989). This is particularly the case for chlorite, illite, and kaolinite. Chlorite is readily altered by chemical weathering. Together with illite, chlorite is typical of high-latitude sediments deposited during glacial periods (Chamley, 1979). Both illite and chlorite are the result of mechanical weathering of crystalline rocks cropping out on continental areas (Weaver, 1989). By contrast, kaolinite occurs mainly in soils of hot and humid climates by weathering in well-drained environments in low-latitude areas (Chamley, 1989). The origin of smectite is more controversial, as it can be detrital, authigenic, or an alteration product of volcanic material.

Eocene Smectitic Sedimentation (CMZ IV, Site 903)

The clay fraction of Eocene chalks drilled in the Atlantic Ocean is commonly composed almost entirely of smectitic minerals (Rothe, 1989). Three main origins for smectite and smectitic minerals are currently envisaged for marine deposits of the Atlantic Ocean: reworking of exposed soils and sediments, early diagenetic authigenesis, and submarine alteration of volcanic material.

A detrital origin of smectitic minerals was presented for various locations of the Atlantic Ocean. Numerous mineralogical, micromorphological, and chemical studies including rare earth elements (REE) and Sr isotopes of smectitic minerals suggested that smectites from most Mesozoic and Cenozoic sediments were little controlled by postsedimentary processes and were mainly soil-derived minerals (in Chamley, 1979, 1989). The abundance of these minerals in the clay fraction of marine sediments was attributed to the dominantly equable warm and seasonally humid climate of the late Mesozoic and early Cenozoic times that favored the pedogenic formation of Al-Fe smectites in the soils extensively developed in continental areas. Notice that an eolian origin of smectitic minerals has been suggested for Cretaceous North Atlantic sediments (Lever and McCave, 1983) and for the Coniacian chalk of England, in which calculation of mass accumulation rates suggested that smectitic minerals were deposited almost entirely from the background concentration of tropospheric dust (Kimblin, 1992). The atmospheric circulation of the middle Eocene suggests the occurrence of west to east winds (Parrish and Curtis, 1982), which would have been able to transport smectite from the North American continent to the North Atlantic (Fig. 10).

Authigenic formation of smectites in the host sediment was supported mainly by Jeans (1968, 1978; Jeans et al., 1982), who noticed that smectite-dominated clay assemblages were associated with silicifications (opal-CT and α-quartz). Jeans (1978) proposed that silica and smectite were precipitated from the pore waters of the sediments a few meters below the seawater/sediment interface. More recent studies have shown that overgrowth laths occur commonly in Atlantic deposits characterized by low sedimentation rates, without significant changes in the total percentage of smectitic minerals relative to other clay species (Holtzapffel et al., 1985; Holtzapffel and Chamley, 1986; Steinberg et al., 1987). Recently Thiry and Jacquin (1993) suggested that the abundance of smectite in oceanic sediments could be the result of in situ transformation of detrital particles. According to them, transformation of the terrigenous clay components into smectite is the mechanism that best explains the abundance of smectites in oceanic sediments. They argued that smectite cannot be detrital, because weathering profiles contain mainly illite and kaolinite. An authigenic formation of Al-Fe smectite was also rejected by these authors, using the argument that Al is highly insoluble in the seawater.

The alteration of volcanic material is common close to the basalt/ sediment transition in the ocean especially in hydrothermal environments (in Chamley, 1989). Volcanic glass is converted to smectite showing a magnesian or a highly ferriferous composition different from those of Al/Fe beidellite, which characterizes most open-sea sediments. The alteration of volcanic glass shards scattered in the sediments has also been called up to explain the abundance of smectites. The main question that arises about this hypothesis is that volcanic debris are rarely recognized in common Atlantic sediments and



Figure 7. Clay mineralogy of sediments drilled at Site 905. Abbreviations as in Figure 2.

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Figure 8. A–C. Typical X-ray diffractograms (glycolated) from each clay mineral zone identified at Site 905. Abbreviations as in Figure 3.

should have been supplied in huge quantities to justify the large amounts of smectite identified. Dunn et al. (1987) suggested that the irregular stratigraphic distribution of smectite at Site 605 (upper continental rise) supports neoformation rather than inheritance, but the only direct evidence of volcanism is the occurrence of an ash layer in the middle Eocene. In addition, the number of analyzed samples is too small to give a good representation of the stratigraphic distribution. Our data show by contrast that the composition of the clay fraction is rather homogeneous throughout the Eocene chalk drilled in an area close to the North American continent. In addition, smectite particles observed by TEM display the usual fleecy aspect of detrital particles. These observations indicate that smectites are principally landderived minerals, except in the microtektite layer and in a few meters above, where the smectite enrichment results from the submarine alteration of glass (Shipboard Scientific Party, 1994c; McHugh et al., this volume).

Paleoclimatic reconstructions of the Late Cretaceous and Early Cenozoic indicate high rainfall on the eastern North American margin (including the Appalachians), which may have favored the widespread formation of kaolinite (Parrish and Curtis, 1982; Barron, 1989). A temperature maximum in the Eocene is indicated by continental and marine records (Frederiksen, 1984; Miller et al., 1987). During the Eocene, the tropical rainforest probably prevented soils from the erosion as ever-wet tropical climates would minimize the availability and dispersal of siliciclastic particles (Cecil, 1990). Therefore, despite the favorability of the climatic conditions to the formation of kaolinite in soils, this mineral is rare in the Eocene marine deposits of the continental slope. This supports that as in Late Cretaceous chalks, smectites from the Eocene chalks may have been transported by winds.

Upper Oligocene to Lower Middle Miocene Clay Sedimentation (CMZ III, Site 903)

The most striking feature of this interval is the increasing proportions of illite and kaolinite relative to smectitic minerals. The increase of typical detrital minerals indicates the active erosion of continental areas and is consistent with the passage from a carbonate to a siliciclastic sedimentation. The Appalachian Highlands were the main terrigenous source terrain, and the ancient Susquehanna, Delaware, and Hudson Rivers were the main sediment dispersal routes (Fig. 10; Poag, 1992). Surprisingly, the amounts of chlorite are always very low by comparison with illite, suggesting that hydrolyzing conditions were too strong to allow the preservation of this mineral. The increasing proportions of illite are consistent with global cooling starting in the Oligocene (Chamley, 1986), but the parallel increase of kaolinite that is typical of soils from tropical to equatorial areas is more unusual. The direct correlation between illite and kaolinite (Fig. 4) suggests a common origin of these minerals. They were probably brought by rivers from the Appalachians; but, according to the climatic context characterized by global cooling, it is difficult to consider kaolinite to be reworked only from Oligocene to lower Miocene soils. It is more likely that kaolinite was also reworked from sedimentary rocks eroded together with crystalline rocks of the Appalachians, or from kaolinite-bearing soils developed during Eocene, Paleocene, and even Late Cretaceous times. Late Cretaceous to early Cenozoic hydrolyzing climates have favored the widespread formation of kaolinite on the eastern North American continent (Barron, 1989). For example, Paleocene to middle Miocene formations from Virginia contain abundant kaolinite (McCartan, 1988). Therefore, it is very likely that kaolinite was eroded from pre-Oligocene weathering profiles by rivers crossing the Appalachians. The increasing erosion probably results from the glacioeustatic lowering of the sea level. As in many sites from the North and South Atlantic and the Pacific Oceans, the maximum amount of kaolinite occurs in the middle Miocene. This is attributed to an increase of global humidity by Robert and Chamley (1987), which may have favored the formation of kaolinite in soils. An additional factor may be the increasingly proximal pro-deltaic depositional environment for clays from the Oligocene to the middle Miocene (Hesselbo, this volume).

In summary, the progressive increase of illite and kaolinite from the upper Oligocene to middle Miocene of offshore New Jersey results from the global cooling and sea-level lowering that have favored the active erosion of the Appalachian Highlands. Kaolinite seems to be mainly reworked from paleoalterations but also expresses increasing humidity during the middle Miocene and increasingly proximal depositional environments through Oligocene to middle Miocene.

Table 5. X-ray	diffractometr	v mineralogical	results	(CMZ III).	Site 905.
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Core, section, interval (cm)	Depth (mbsf)	Chlorite (%)	Illite (%)	I/S (%)	Kaolinite (%)	Quartz	Opal-CT	Saddle index
150-905A-	(01.24	2	20					0.64
76X-1, 46-48	684.26	2	20	58	20	++		0.641
76X-2, 49-31	686.47	2	14	61	18	++		0.620
76X-4 47-49	687.92	2	14	63	21	++		0.631
76X-5, 46-48	689.41	2	18	60	20	++		0.611
76X-6, 46-48	690.91	2	16	62	20	++		0.684
76X-7, 49-51	692.44	2	15	63	20	++		0.584
77X-1, 45-48	693.85	2	17	62	19	++		0.587
77X-2, 45-50	694.45	2	18	60	20	++		0.578
77X-3, 45-47	695.95	2	15	63	20	++		0.619
77X-4, 46-48	697.46	2	18	58	22	++		0.599
778 6 49 52	700.49	2	15	59	22	++		0.014
778-7 47-50	701.07	2	15	51	20	++		0.565
78X-1. 46-48	703.36	2	16	63	19	++		0.595
78X-2, 47-49	704.87	ĩ	15	62	21	++		0.591
78X-3, 47-49	706.37	2	14	67	17	++		0.594
78X-4, 47-49	707.87	2	17	62	19	++		0.552
78X-5, 47-49	709.37	2	16	63	19	++		0.684
78X-6, 48-50	710.88	2	16	64	18	++		0.599
79X-1, 47-49	713.07	2	15	64	19	++		0.597
79X-2, 47-49	714.57	2	19	59	20	++		0.589
79X-3, 47-49	717.56	2	18	57	21	++		0.552
79X-5 46-48	719.06	2	10	50	20	++		0.508
79X-6, 47-49	720 57	2	19	55	24	++		0.598
80X-1, 48-50	722.68	$\tilde{2}$	16	64	18	++		0.578
80X-2, 48-50	724.18	2	17	61	20	++		0.574
80X-3, 48-50	725.68	2	18	62	18	++		0.571
80X-4, 48-50	727.18	2	17	63	18	++		0.590
80X-5, 48-50	728.68	2	16	61	21	++		0.559
80X-6, 48-50	730.18	2	15	61	22	++		0.582
80X-7, 48-50	731.68	2	20	55	23	++		0.610
81X-1, 47-49	732.27	2	19	56	23	++		0.587
81X-2, 47-49 81X 4 47 40	732.85	2	1/	50	25	++		0.560
81X-4, 47-49 81X-5 47-40	737 33	2	18	52	24	++		0.502
81X-6 46-48	738.82	2	17	58	23	++		0.582
81X-7, 47-49	740.33	2	16	61	21	++		0.540
81X-8, 47-49	741.83	2	17	63	18	++		0.631
82X-1, 48-50	741.98	2	19	58	21	++		0.592
82X-2, 48-50	743.08	2	16	64	18	++		0.607
82X-3, 48-50	744.23	2	16	64	18	++		0.621
82X-4, 48-50	745.73	2	17	59	22	++		0.613
82X-5, 47-49	747.22	2	18	56	24	++		0.616
828-0, 40-48	748.71	2	17	62	19	++		0.590
83X-1, 47-49	751.50	2	18	59	22	++		0.580
83X-2, 47-49	753.07	2	17	63	18	++		0.578
83X-3, 46-48	754.56	2	15	66	17	++		0.521
83X-4, 38-40	755.98	2	15	66	17	++		0.578
83X-5, 47-49	757.57	2	14	67	17	++		0.530
83X-6, 45-47	759.05	2	16	62	20	++		0.540
83X-7, 47-49	760.57	2	19	55	24	++		0.590
84X-1, 49-51	761.19	2	18	63	17	++		0.622
84X-2, 47-49	/62.6/	2	15	65	18	++		0.645
84X-3, 48-50 84X 4 47-40	765.67	2	17	61	20	++		0.620
84X-5 47-49	767.17	2	15	65	17	++		0.620
84X-6 46-48	768 66	2	16	64	18	11		0.596
84X-7, 48-50	770.18	2	17	66	15	++		0.603
85X-2, 50-52	772.40	2	15	67	16	++		0.618
85X-3, 48-50	773.88	2	14	68	16	++		0.603
85X-4, 48-50	775.38	2	18	61	19	++		0.648
85X-5, 47-49	776.87	2	15	62	21	++		0.670
85X-6, 47-49	778.37	2	14	67	17	++		0.614
85X-7, 47-49	779.87	2	19	58	21	++		0.664
86X-1, 42-44	780.52	2	16	63	19	++		0.651
86X 3 47-40	782.05	2	14	67	19	++	20 E	0.599
86X-4 47-49	785.07	2	13	68	17	++		0.523
86X-5, 44-46	786.54	2	14	66	18	++		0.566
86X-6, 48-50	788.08	ĩ	17	60	21	++		0.589
87X-1, 47-49	790.17	2	17	64	17	++		0.571
87X-2, 47-49	791.67	2	12	68	18	++		0.568
87X-3, 47-49	793.17	2	16	64	18	++		0.594
87X-4, 46-48	794.66	2	20	62	16	++		0.583
87X-5, 46-48	796.16	2	16	67	15	++		0.611
8/X-6, 47-49	797.67	2	13	66	19	++		0.488
0/A-1, 4/-49	700.07	2	15	67	18	++		0.531
88X.2 47-49	800.04	2	15	64	18	++		0.595
88X-3 49-51	802.46	2	14	69	15	++		0.566
88X-4, 46-48	803.93	2	17	65	16	++		0.578
88X-5, 46-48	805.43	2	17	67	14	++		0.562
88X-6, 47-49	806.94	2	14	69	15	++		0.514
88X-7, 47-49	808.44	2	15	66	17	++		0.595
89X-1, 49-51	809.59	2	15	68	15	++		0.639

			Table 5	(contin	uea).			
Core, section,	Depth	Chlorite	Illite	1/S	Kaolinite			Saddle
interval (cm)	(mbsf)	(%)	(%)	(%)	(%)	Quartz	Opal-CT	index
89X-3, 44-46	812.54	2	14	63	21	++		0.593
89X-5, 48-50	815.58	2	15	69	14	++		0.583
90X-1, 45-47	819.15	2	12	72	14	++		0.509
90X-3, 44-46	822.14	2	14	69	15	++		0.583
90X-5, 44-46	824.94	2	15	68	15	++		0.572
91X-1.52-54	828.92	2	13	71	14	++		0.545
91X-2, 46-48	829.52	2	16	64	18	++		0.545
91X-3, 49-51	831.05	2	13	68	17	++		0.537
91X-4, 48-50	832.54	2	16	64	18	++		0.538
91X-5, 48-50	834.04	2	15	67	16	++		0.509
91X-6, 50-52	835.56	2	14	67	17	++		0.559
91X-7, 49-51	837.05	2	13	68	17	++		0.524
92X-1.47-50	838.47	2	15	65	18	++		0.478
92X-2, 49-51	839.99	2	13	61	24	++		0.550
92X-3, 46-49	841.46	2	18	63	17	++		0.554
92X-4, 49-53	842.99	2	16	65	17	++		0.544
92X-5, 47-49	844.47	2	15	66	17	++		0.602
92X-6, 48-50	845.98	2	15	65	18	++		0.590
92X-8, 45-47	847.88	2	14	65	19	++		0.595
93X-1, 37-39	848.07	2	13	67	18	++		0.535
93X-2, 40-42	849.27	2	15	64	19	++		0.573
93X-3 40-42	850.77	2	15	67	16	++		0.535
93X-4 46-48	852 33	2	16	66	16	++		0.550
93X-5 46-48	853.83	2	15	68	15	++		0.550
93X-6 47-49	855 34	2	14	67	17	++		0.563
93X-7 47-49	856.84	2	16	66	16	++		0.487
94X-1 46-48	857.86	2	14	65	19	++		0.564
94X-2 48-50	858.46	2	15	67	16	++		0.584
94X-3 48-50	850.96	5	16	67	15			0.491
94X-4 48-50	861.46	2	18	64	16	++		0.567
04X-5 48-50	862.06	5	14	67	17			0.575
94X-6 48-50	864.46	2	16	65	17	++		0.600
04X 7 48-50	865.06	2	17	62	10	1.1		0.503
94X-1, 40-30	867.47	2	15	64	10	++		0.576
95X-2 47-49	868 97	2	14	67	17			0.562
05X-3 47-49	870.47	2	14	60	15	4.4		0.502
05X / 17-49	871.07	2	14	68	16	11		0.555
05X 5 47-40	873 47	2	14	66	19	11		0.552
95X-5, 47-49	874.07	2	19	65	15	11		0.550
05V 7 47 40	074.97	2	16	59	24	11		0.550
95A-1, 41-49	877.06	2	15	67	16	++		0.561
06X 2 47-40	979 57	2	16	65	17	11		0.507
90A-2, 47-49	0/0.37	2	16	64	10	++		0.597
96X-5, 47-49	884 55	2	13	72	19	++		0.640
06V 7 47 40	004.33	2	16	64	13	++		0.574
100P 1 48 50	805.00	2	10	67	10	<u>++</u>	are o	0.010
100R-1, 48-50	093.98	4	15	07	10	++	+	0.510
100K-2, 51-53	000.10	2	14	70	14	++	+	0.500
102R-1, 50-52	900.10	2	15	/1	12	++	÷.	0.566

Note: Results for quartz and opal-CT are reported as rare (+) or common (++).

Upper Middle Miocene and Upper Miocene Clay Sedimentation (CMZ II)

At Site 903, the abundance of illite and kaolinite relative to smectite indicates the active erosion of the Appalachians, which is also suggested by the occurrence of terrestrial rather than marine organic matter (Shipboard Scientific Party, 1994b). The increasing proportions of illite associated with the decrease of kaolinite and the absence of any correlation between these minerals (Fig. 6) suggests the occurrence of a major paleoenvironmental change within the middle Miocene.

The long-term cooling trend is obviously partly responsible for the decrease of kaolinite recorded at Sites 903 and 905, but the change in clay sedimentation within the middle Miocene suggests a step-like event, a more rapid cooling that is also indicated by $\delta^{18}O$ data (Savin, 1977). Oxygen isotopic studies suggest that a glacioeustatic event occurred in the middle Miocene (Miller et al., 1987). Less hydrolyzing conditions are reflected by the sporadic occurrence of higher proportions of chlorite than in CMZ III. Climatic models predicted a general decline in precipitation rates through the Cenozoic for the Appalachians (Barron, 1989). Together with a lower average temperature, these climatic conditions would have favored the preservation of chlorite and illite and disfavored the formation of kaolinite.

Alternatively, increasing proportions of illite can be taken as a signal of renewed source-terrain uplift especially evident in the northern part of the Central Appalachians and suggested by the increase in terrigenous sediments accumulating in the middle Atlantic basins (Poag and Sevon, 1989; Poag, 1992). A large outer shelf depocenter developed off Maryland, Delaware, and southern New Jersey (Fig. 10). All the major ancient rivers systems joined to build a huge confluent delta at the shelf edge (Poag, 1992). The tectonic uplift of the Central Appalachians has favored the erosion of crystalline rocks to yield large quantities of micas (illite), whereas the formation of kaolinite was disfavored by deteriorating climatic conditions. Therefore, the evolution of clay mineral assemblages in CMZ II results mainly from the combination of tectonic and climatic factors.

Pleistocene Clay Sedimentation (CMZ I)

At both sites, the clay fraction of Pleistocene sediments is characterized by the abundance of chlorite and illite and by a relative depletion in smectite and kaolinite. From the Baffin Bay to the north to low latitudes, a similar increase of chlorite and illite is recorded in Pleistocene sediments of the North Atlantic (Hathaway, 1972; Chamley, 1989; Thiébault et al., 1989). Obviously, these clay assemblages reflect a significant change of detrital sources that is confirmed by the common occurrence of amphibole and by a change of quartz grain shape (Mazzullo, 1987). Illite and chlorite are inherited primarily from the North American crystalline basement (e.g., the Canadian Shield) and transported by continental ice sheets and marine currents (Hathaway, 1980; Dunn et al., 1987; Cremer et al., 1989; Thiébault

Table 6. X-ray diffractometry mineralogica	results (CMZ II),	Site 905.
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Core, section, interval (cm)	Depth (mbsf)	Chlorite (%)	Illite (%)	I/V (%)	I/S (%)	Kaolinite (%)	Quartz	Feldspar	Saddle index
150-905A-		ASSA		1.001	790				
27X-1, 46-48	219.46	9	46	0	33	12	++	+	0.758
27X-2, 50-52	221.00	10	35	10	35	10	++	+	0.770
27X-3, 50-52	222.50	12	24	0	54	10	++	+	0.541
27X-4, 50-52	224.00	.5	26	0	52	17	++		0.632
28X-2, 47-49	225.97	13	31	0	44	12	++		0.555
29A-1, 49-51 30X-1, 49-51	232.89	10	20	0	62	16	++		0.544
31X-1, 49-51	252 19	5	18	ő	64	13	++		0.537
32X-1, 50-52	261.80	5	20	ŏ	63	12	++		0.529
33X-1, 48-50	271.48	9	17	0	65	9	++		0.483
34X-1, 53-55	281.13	2	17	0	70	11	++		0.409
35X-1, 49-51	290.69	2	23	0	50	25	++		0.537
35X-2, 50-52	292.20	2	19	0	67	12	++		0.447
35X-3, 50-52 35X 4 50-52	293.70	2	19	0	0/	12	++		0.510
35X-5 50-52	295.20	2	10	0	64	15	++		0.433
35X-6, 50-52	298.20	10	22	ŏ	59	9	++		0.446
36X-1, 50-52	300.10	5	19	0	60	16	++		0.536
36X-2, 50-52	301.60	2	20	0	66	12	++		0.484
36X-3, 50-52	303.10	2	17	0	72	9	++		0.429
36X-4, 51-53	304.61	2	18	0	69	11	++		0.461
36X-5, 50-52	305.24	2	18	0	68	12	++		0.443
37X-1, 50-52	310.90	2	10	0	68	12	++		0.500
37X-3 50-52	312.40	5	20	0	58	17	++		0.491
37X-4, 50-52	313.90	2	21	ŏ	65	12	++		0.488
38X-1, 49-51	318.79	8	18	ŏ	66	8	++		0.446
38X-2, 49-51	320.29	2	19	0	68	11	++		0.486
38X-3, 49-51	321.79	2	20	0	65	13	++		0.449
38X-4, 49-51	323.29	2	21	0	64	13	++		0.481
38X-5, 49-51	324.79	2	19	0	66	13	++		0.449
38A-0, 49-51 20X 1 50 52	320.29	10	25	0	33	10	++		0.402
39X-2 50-52	320.20	10	24	2	52	12	++		0.482
39X-3, 50-52	331.20	5	20	õ	59	16	++		0.494
39X-4, 50-52	332.70	2	21	ŏ	64	13	++		0.506
39X-5, 50-52	334.20	2	21	0	64	13	++		0.479
39X-6, 50-52	335.70	2	17	0	70	11	++		0.431
40X-1, 50-52	337.80	9	21	0	63	7	++		0.460
40X-2, 50-52	339.30	2	18	0	69	11	++		0.427
40X-3, 50-52	340.80	10	16	0	71	11	++		0.470
40X-4, 50-52 40X-5, 50-52	342.50	10	25	8	59	12	++		0.491
40X-6, 50-52	345.30	5	22	ő	51	22	++		0.531
41X-1, 48-50	347.48	2	22	0	60	16	++		0.449
41X-2, 50-52	349.00	2	19	0	65	14	++		0.436
41X-3, 50-52	350.53	11	30	0	46	13	++		0.536
41X-4, 55-57	352.08	2	20	0	60	18	++		0.485
41X-5, 50-52	353.56	2	20	0	63	15	++		0.449
41X-0, 50-52 42X 1 40-51	355.00	5	25	0	56	15	++		0.497
42X-1, 49-51	358 50	2	15	ő	72	11	++		0.494
42X-3, 49-51	360.09	2	17	ŏ	69	12	++		0.446
42X-4, 49-51	361.59	2	17	Ő	70	11	++		0.452
42X-5, 49-51	363.09	2	19	0	67	12	++		0.387
42X-6, 49-51	364.59	2	18	0	68	12	++		0.427
42X-7, 19-21	365.79	2	19	0	66	13	++		0.400
43X-1, 50-52	366.70	2	21	0	5/	20	++		0.488
43X-2, 50-52 43X-3, 50-52	369.20	ő	23	0	50	12	++		0.424
43X-4, 50-52	371.20	2	18	ŏ	67	13	++		0.476
43X-5, 50-52	372.70	10	25	2	52	11	++		0.461
43X-6, 50-52	374.20	9	19	0	63	9	++		0.433
44X-1, 50-52	376.40	2	17	0	70	11	++		0.460
44X-2, 50-52	377.90	2	19	0	67	12	++		0.452
44X-3, 50-52	379.40	2	17	0	70	п	++		0.429
44X-4, 50-52	380.90	2	20	0	64	14	++		0.461
44X-5, 50-52 44X-6, 50-52	383.00	2	20	0	50	17	++		0.500
44X-7 50-52	384.90	2	17	ő	68	13	++		0.313
45X-1, 50-52	386.00	2	17	ŏ	67	14	++		0.400
45X-2, 50-52	387.50	2	18	ŏ	62	18	++		0.536
45X-3, 50-52	389.00	2	18	0	67	13	++		0.455
45X-4, 50-52	390.50	2	17	0	68	13	++		0.433
45X-5, 50-52	392.00	2	19	0	63	16	++		0.453
45X-0, 50-52	393.50	2	19	0	66	13	++		0.485
40A-1, 50-52 46X-2, 50-52	395.70	2	10	0	10	12	++		0.414
46X-3 49-51	398.60	2	18	0	65	15	++		0.495
46X-4, 48-50	400.18	2	18	ő	66	14	++		0.459
46X-5, 49-51	401.69	2	18	0	64	16	++		0.444
46X-6, 50-52	403.20	2	17	0	71	10	++		0.490
47X-1, 48-50	405.28	5	21	0	58	16	++		0.469
48X-1, 49-51	414.99	2	18	0	63	17	++		0.463
48X-2, 49-51	416.49	2	16	0	70	12	++		0.464
48X-3, 50-52	418.00	2	17	0	71	10	++		0.429
48X-4, 37-39	419.37	2	19	0	62	17	++		0.452
401-3, 49-31	420.99	2	17	0	08	15	++		0.425

	Table 6 (continued).								
Core, section, interval (cm)	Depth (mbsf)	Chlorite (%)	Illite (%)	I/V (%)	1/S (%)	Kaolinite (%)	Quartz	Feldspar	Sadd inde:
48X-6, 49-51	422.49	2	15	0	70	13	++		0.45
48X-7, 49-51	423.50	2	18	0	67	13	++		0.43
49X-1, 49-51 49X-2, 47-40	424.29	2	17	0	6/	14	++		0.43
49X-3, 45-47	427.25	2	17	ő	67	14	++		0.45
49X-4, 47-49	428.77	2	16	0	69	13	++		0.432
49X-5, 48-50	430.28	2	16	0	69	13	++		0.45
49X-7, 32-34	433.12	2	18	0	67	13	++		0.45
50X-1, 50-52	433.80	2	17	0	69	12	++		0.42
50X-2, 54-56	435.34	5	23	0	54	18	++		0.47
50X-4, 49-51	438.29	2	20	0	63	15	++		0.37
50X-7, 50-52	441.30	2	17	0	70	11	++		0.40
51X-1, 50-52	443.50	$\overline{2}$	17	Õ	67	14	++		0.45
51X-2, 50-52	445.00	2	17	0	70	11	++		0.39
51X-3, 48-50	446.48	2	17	0	64	17	++		0.39
51X-5, 48-50	449.48	$\frac{2}{2}$	21	0	54	23	++		0.40
51X-6, 48-50	450.98	2	19	0	66	13	++		0.47
52X-1, 48-50	453.18	2	19	0	65	14	++		0.38
52X-2, 48-50	454.68	2	16	0	68	14	++		0.49
52X-3, 48-50	457.68	2	20	0	63	15	++		0.45
52X-5, 18-20	458.88	$\tilde{2}$	17	õ	68	13	++		0.46
52X-6, 48-50	460.68	2	17	0	67	14	++		0.43
52X-7, 48-50	462.18	2	18	0	62	18	++		0.46
52X-8, 48-50	463.68	2	15	0	63	20	++		0.40
53X-2, 50-52	464.30	$\overline{2}$	19	õ	63	16	++		0.45
53X-3, 50-52	465.80	2	17	0	67	14	++		0.43
53X-4, 50-52	467.30	2	18	0	64	16	++		0.41
53X-5, 49-51	408.79	2	17	ő	68	13	++		0.45
54X-1, 20-22	472.20	2	17	õ	67	14	++		0.42
54X-2, 20-22	472.65	2	18	0	65	15	++		0.40
54X-3, 20-22	474.15	2	17	0	67	14	++		0.42
54X-4, 20-22 54X-5, 20-22	477.15	2	17	0	68	14	++		0.40
54X-6, 20-22	478.65	2	17	ő	64	17	++		0.45
54X-7, 20-22	480.15	2	13	0	72	13	++		0.49
54X-8, 20-22	481.65	2	15	0	70	13	++		0.50
55X-1, 55-37	481.95	2	19	ő	65	14	++		0.42
55X-3, 35-37	484.95	2	15	õ	71	12	++		0.41
55X-4, 35-37	486.45	2	18	0	63	17	++		0.50
55X-5, 35-37	487.95	2	17	0	66	15	++		0.51
56X-0, 55-57	489.45	2	17	ő	66	15	++		0.40
56X-2, 47-49	493.27	2	18	ŏ	66	14	++		0.50
56X-3, 47-49	494.77	2	15	0	69	14	++		0.47
56X-4, 50-52	496.30	2	15	0	69	14	++		0.49
56X-5, 50-52	497.80	2	18	ő	68	13	++		0.47
57X-1, 49-51	501.09	2	18	ŏ	65	15	++		0.45
57X-2, 47-49	502.57	2	20	0	63	15	++		0.52
57X-3, 47-49	504.07	2	18	0	64	16	++		0.51
57X-5, 47-49	507.07	2	19	ő	62	17	++		0.52
7X-6, 47-49	508.57	2	20	Õ	59	19	++		0.59
57X-7, 47-49	510.07	2	21	0	60	17	++		0.57
8X-1, 48-50	510.68	2	18	0	62	18	++		0.52
58X-3, 48-50	513.68	2	21	ő	62	15	++		0.54
58X-4, 48-50	515.18	2	17	Ő	68	13	++		0.52
58X-5, 48-50	516.68	2	20	0	63	15	++		0.56
8X-6, 48-50	518.18	2	17	0	67	14	++		0.52
9X-2, 48-50	521.88	5	18	2	59	16	++		0.57
9X-3, 48-50	523.38	2	16	ō	68	14	++		0.52
59X-4, 48-50	524.88	2	20	0	61	17	++		0.54
9X-5, 48-50	526.38	2	17	0	65	16	++		0.58
50X-1, 48-50	529.98	2	20	ő	61	17	++		0.55
60X-2, 48-50	531.48	5	19	ŏ	61	15	++		0.47
60X-3, 48-50	532.98	2	18	0	65	15	++		0.47
0X-4, 48-50	534.48	2	18	0	63	17	++		0.49
0X-5, 48-50	537.48	2	18	0	68	15	++		0.50
51X-1, 47-49	539.57	2	18	ŏ	63	17	++		0.55
		2	20	ō	62	16	++		0.51
51X-2, 48-50	541.08	4			10	10			1.
51X-2, 48-50 51X-3, 46-48	541.08 542.56	2	20	0	60	18	++		0.52
51X-2, 48-50 51X-3, 46-48 51X-4, 46-48	541.08 542.56 544.06	222	20 19	0	60	17	++		0.52
51X-2, 48-50 51X-3, 46-48 51X-4, 46-48 51X-5, 46-48 51X-5, 46-48	541.08 542.56 544.06 545.56 547.07	2 2 2 2 2 2	20 19 20	0	60 62 63	18 17 16	++ ++ ++ ++		0.52 0.50 0.49 0.45
51X-2, 48-50 51X-3, 46-48 51X-4, 46-48 51X-5, 46-48 51X-6, 47-49 52X-2, 46-48	541.08 542.56 544.06 545.56 547.07 550.76	2222222	20 19 20 19 16	0 0 0 0	60 62 63 64	17 16 16 18	++ ++ ++ ++ ++		0.52 0.50 0.49 0.45 0.47
51X-2, 48-50 51X-3, 46-48 51X-4, 46-48 51X-5, 46-48 51X-6, 47-49 52X-2, 46-48 52X-2, 46-48 52X-3, 47-49	541.08 542.56 544.06 545.56 547.07 550.76 552.27	2 2 2 2 2 2 2 2 2 2 2 2 2 2	20 19 20 19 16 18	0 0 0 0	60 62 63 64 60	17 16 16 18 20	++ ++ ++ ++ ++ ++		0.52 0.50 0.49 0.45 0.47 0.47

$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	Core, section,	Depth	Chlorite	Illite	I/V	I/S	Kaolinite			Saddle
$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	interval (cm)	(mbsf)	(%)	(%)	(%)	(%)	(%)	Quartz	Feldspar	index
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	63X-4, 47-49	563.47	2	21	0	59	18	++		0.590
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	63X-5, 47-49	564.97	2	18	0	63	17	++		0.521
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	63X-6, 47-49	566.47	2	22	õ	53	23	++		0.605
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	64X-1.46-48	568 66	2	20	Ő	59	19	++		0.640
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	64X-2 48-50	570.18	2	17	õ	63	18	++		0.509
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	64X-3 47-49	571 67	2	18	õ	62	18	++		0.514
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	64X-4 48-50	573.18	2	10	õ	60	10	++		0 497
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	64X-5 58-60	574 78	2	25	0	54	10	11		0.775
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	64X-6 41-43	576.11	2	17	0	61	20	11		0.561
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	65X-1 48-50	578 28	2	21	ő	53	24	11		0.698
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	65X-2 48-50	570.28	2	17	0	62	10	11		0.592
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	65X-3 40-51	591.70	2	20	0	59	20	++		0.592
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	65X 4 40-51	592.70	ź	17	0	50	17	11		0.611
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	65V 5 49 50	504.79	2	20	0	60	10	++		0.540
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	65X 6 46 49	595 76	2	20	0	39	22			0.549
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	66V 1 46 49	507.06	2	20	0	49	25	++		0.055
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	00A-1, 40-48	587.80	4	21	0	59	10	++		0.038
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	00X-2, 40-48	589.50	2	19	0	62	17	++		0.627
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	00X-3, 4/-49	590.87	2	23	0	51	18	++		0.628
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	00X-4, 40-48	592.36	2	20	0	56	22	++		0.587
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	66X-5, 47-49	593.77	2	17	0	60	21	++		0.601
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	66X-6, 48-50	595.28	2	20	0	54	24	++		0.656
$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	66X-7, 48-50	596.78	2	18	0	61	19	++		0.632
$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	68X-1, 44-46	607.14	2	23	0	54	21	++		0.592
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	68X-2, 44-46	607.99	2	17	0	65	16	++		0.591
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	68X-3, 43-45	609.48	2	18	0	60	20	++		0.596
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	68X-4, 48-50	611.03	2	17	0	64	17	++		0.603
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	68X-5, 51–53	612.56	2	18	0	62	18	++		0.622
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	68X-6, 48-50	614.03	2	17	0	61	20	++		0.594
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	68X-7, 48-50	615.53	2	17	0	62	19	++		0.619
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	69X-1, 48-50	616.78	2	23	0	55	20	++		0.621
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	68X-8, 46-48	617.01	2	19	0	62	17	++		0.635
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	69X-2, 48-50	618.28	2	18	0	57	23	++		0.652
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	69X-4, 46-48	621.26	2	22	0	56	20	++		0.603
$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	69X-5, 48-50	622.78	2	17	0	63	18	++		0.614
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	69X-6, 47-49	624.27	2	20	0	57	21	++		0.643
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	69X-7, 46-48	625.76	2	20	0	56	22	++		0.615
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	70X-1, 48-50	626.48	2	23	0	56	19	++		0.611
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	70X-2, 48-50	627.98	2	20	0	60	18	++		0.638
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	70X-3, 48-50	629.48	2	18	0	63	17	++		0.606
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	70X-4, 48-50	630.98	2	17	0	61	20	++		0.606
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	70X-5, 45-47	632.45	2	18	0	61	19	++		0.610
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	70X-6, 50-52	633.50	2	16	0	62	20	++		0.570
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	71X-1, 46-48	636.06	2	17	0	55	26	++		0.611
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	71X-2, 46-48	637.56	2	20	0	53	25	++		0.639
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	71X-3, 46-48	639.06	2	18	0	60	20	++		0.555
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	71X-4, 46-48	640.56	2	17	0	61	20	++		0.599
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	71X-5, 46-48	642.06	2	17	0	59	22	++		0.593
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	71X-6, 46-48	643.56	2	16	0	61	21	++		0.573
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	72X-1, 47-49	645.67	2	18	0	59	21	++		0.600
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	72X-2, 48-50	647.18	2	16	0	63	19	++		0.571
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	72X-3, 47-49	648,67	2	16	0	58	24	++		0.559
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	72X-4, 46-48	650.16	2	18	0	57	23	++		0.591
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	72X-5, 50-52	651.70	2	18	0	53	27	++		0.627
73X-2,119-121 656.65 2 29 0 31 38 ++ 0.822 73X-3,82-84 657.78 2 22 0 44 32 ++ 0.778	72X-6, 50-52	653.20	ĩ	18	ŏ	52	28	++		0.554
73X-3, 82-84 657.78 2 22 0 44 32 ++ 0.778	73X-2, 119-121	656.65	2	29	ŏ	31	38	++		0.822
01110	73X-3, 82-84	657.78	2	22	0	44	32	++		0.778

Table 6 (continued).

Note: Results for quartz and feldspar are reported as rare (+) or common (++).

Table 7. X-ray diffractometry mineralogical results (CMZ I), Site 905.

Core, section, interval (cm)	Depth (mbsf)	Chlorite (%)	Illite (%)	I/V (%)	I/S (%)	Kaolinite (%)	Quartz	Feldspar	Amphibole	Saddle index
150-905A-										
2H-1, 50-52	30.00	26	43	15	12	4	++	++	++	0.881
3H-1, 50-52	36.50	41	32	10	15	2	++	++	++	0.778
4H-1, 50-52	46.00	15	29	0	42	14	++	+		0.543
6H-1, 50-52	61.50	16	46	5	18	15	++	+	+	0.793
7H-1, 50-52	63.50	14	29	2	44	11	++	+		0.590
9H-1, 48-50	80.48	24	45	15	12	4	++	++	++	0.865
10H-1, 49-51	89.49	34	31	20	12	3	++	++	++	0.833
11H-1, 49-51	98.99	38	33	15	10	4	++	++	++	0.864
12H-1, 50-52	107.00	25	36	15	15	9	++	++	++	0.785
13H-2, 93-95	113.93	24	35	15	16	10	++	++	++	0.810
15H-1, 50-52	126.50	15	48	10	11	16	++	+		0.805
16X-1, 49-51	134.99	30	35	15	15	5	++	++	++	0.826
17X-2, 50-52	146.10	23	44	10	14	9	++	+	+	0.886
19X-1, 49-51	163.89	32	31	20	14	3	++	++	++	0.881
22H-1, 50-52	192.70	21	35	15	20	9	++	++	++	0.800
23H-1, 50-52	196.20	24	37	15	16	8	++	++	++	0.817
24H-1, 50-52	202.00	28	32	15	22	3	++	++	++	0.829
24H-2, 50-52	203.50	26	31	25	12	6	++	++	++	0.881
25H-1, 50-52	211.50	19	31	10	31	9	++	++	++	0.724
25H-2, 50-52	213.00	13	27	0	48	12	++	+		0.574
25H-3, 50-52	214.50	14	31	0	43	12	++	+		0.553
26H-1, 50-52	215.50	11	28	2	49	10	++	+		0.595

Note: Results for quartz, feldspar, and amphibole are reported as rare (+) or common (++).



Figure 9. Correspondence between clay mineral zones and the composite oxygen isotope curve of the Atlantic Ocean published by Miller et al. (1987).

et al., 1989) (Fig. 10). Therefore, these clay assemblages are a consequence of the development of the Arctic polar ice sheet.

At Site 905, where 22 samples were studied, the proportions of clay minerals—especially chlorite, I/S, and kaolinite—show important variations. Pleistocene sediments were deposited by mass-transported processes. They consist of silty clay showing common color variations, and contorted and discordant beds with abundant clay clasts of various size and age (Shipboard Scientific Party, 1994d). The important fluctuations in the clay mineralogy may result from the mixture of reworked sediments from various origins. Alternatively, the changing mineralogy may be the result of alternating glacial (chlorite-rich) and interglacial episodes (I/S and/or kaolinite-rich). Further study on the clay mineralogy of Pleistocene sediments from Site 902 will allow us to establish the distinct influence of these factors.

Comparison Between Sites 903 and 905

The same clay mineral species and similar trends in the vertical evolution of percentages are observed at both sites. However, at Site 905, the clay assemblages are more homogeneous and the long-term trends are less obvious than at Site 903. In comparing both sites, the most striking feature is the difference between the amounts of I/S. In CMZ II of Site 903, the average percentage of I/S is 18% whereas in the coeval sediments of Site 905 this percentage reaches 62% (Fig. 11).

Several factors are probably responsible for such a difference. Numerous examples show that differential settling processes of clay minerals favor the deposition of smectite in distal oceanic basins and the preferential settling of kaolinite and illite in nearshore environments (Chamley, 1989). In recent sediments deposited off the Niger delta, smectite increases from about 30% in coastal environments to 60% at distances from the shore, reaching 120 km (Porrenga, 1966). Gibbs (1977) showed that from the mouth of the Amazon River along the continental shelf to the northwest for about 1400 km, smectite increases from 27% to 40%. The distance between Sites 903 and 905 is about 30 km and the difference in I/S percentages reaches 40%. According to modern examples, the increase of smectite from the slope

to the upper rise seems too high to be attributable only to differential settling processes. Therefore, other factors have also played a role in the smectite enrichment at Site 905.

Smectite may have been transported at Site 905 by bottom currents. The tertiary North Atlantic Ocean basin was affected by the action of abyssal currents causing seafloor erosion along the continental margins (Tucholke and Mountain, 1986). The pattern of bottom currents indicates that the studied region was probably submitted to the action of the Western Boundary Undercurrent (WBUC) flowing from the north through the Labrador Sea (Tucholke and Laine, 1982; Carter and Schafer, 1983; McCave and Tucholke, 1986; Locker and Laine, 1992). In near-surface sediments, chlorite is transported southward by the WBUC, along the margin of the basin as far as the Greater Antilles Outer Ridge (Tucholke, 1975). According to Tucholke (1986), the current extends at depth less than 1000 m and reaches depth greater than 5000 m. The upper rise of Newfoundland located between 2600 and 2800 m of water depth, as at Site 905, is swept by a rapid south-flowing core of the WBUC. Therefore, during the middle and late Miocene this current may have transported smectites at Site 905, because sources of smectites existed to the north. In upper Miocene sediments drilled in the Labrador Sea (ODP Site 646), the proportion of smectite resulting from the erosion of ancient formations reaches 60% (Cremer et al., 1989). Smectite may also have entered the Labrador Sea through the Baffin Bay, as Miocene sediments drilled at Site 645 contain an average proportion of 78% of smectites reworked mainly from old sedimentary rocks (Thiébault et al., 1989). Since the early middle Miocene, the Baffin Bay was probably a main conduit between the Arctic and Atlantic Oceans and the focus of southward directed flow to the Labrador Sea (Srivastava, Arthur, Clement, et al., 1987). Consequently smectite identified in sediments from Site 905 may have been partly brought by bottom currents flowing in a southward direction.

In summary, during the middle and late Miocene, the relative I/S enrichment of sediments deposited on the upper rise results at least from the combination of differential settling processes of clay minerals and from the influence of oceanic circulations (Fig. 10)

CONCLUSIONS

On the passive continental margin off New Jersey, the Cenozoic clay sedimentation is controlled mainly by the decrease of hydrolyzing conditions in relation with worldwide cooling. Major mineralogical changes coincide with increasing δ^{18} O values. The influence of climate is modulated by the influence of tectonic uplift occurring in the Appalachians and at Site 905 by the influence of marine currents flowing southward along the continental slope.

Four distinct intervals are described below (Fig. 12):

 The Eocene carbonate-rich/clay-poor sedimentation reflects restricted erosion of continental areas. A tropical rain forest covering continental areas probably prevented the erosion of the kaolinite-rich pedologic complex. Smectites from the Eocene chalks were probably transported by easterly winds from the North American continent to the Atlantic.

2. The progressive increase of illite and kaolinite at the expense of smectite occurring during late Oligocene to middle Miocene results from the influence of at least the three following processes, in order of importance:

- a. intensification of erosion in the Appalachians caused mainly by glacioeustatic lowering, with kaolinite partly reworked from pre-Oligocene weathering profiles;
- b. increasingly humid climatic conditions culminating in the middle Miocene; and
- c. decreasing distance between sites and the shoreline.

3. The glacioeustatic lowering that occurred in the middle Miocene is recorded by increasing proportions of illite reworked from crystalline rocks at the expense of kaolinite.



Figure 10. Inferred origins of clay minerals deposited on the continental slope and rise off New Jersey from the late Eocene to Pleistocene (modified after Poag and Sevon, 1989; Poag, 1992). J = ancient James River, P = ancient Potomac River, S = ancient Susquehanna River, D = ancient Delaware River, H = ancient Hudson River, C = ancient Connecticut River, EM = ancient river(s) of eastern Massachusetts. C = chlorite, I = illite, I/S = illite/smectite mixed layers, I/V = illite/vermiculite mixed layers, Sm = smectite, K = kaolinite, WBUC = Western Boundary Undercurrent.

4. The increasing proportion of chlorite in Pleistocene sediments reflects the development of the Northern Hemisphere ice caps and the mechanical erosion of crystalline basement.

To conclude, at each significant climatic cooling recorded from Eocene to Pleistocene, we noticed a renewal of clays from smectite to kaolinite at the Eocene/Oligocene transition, from kaolinite to illite in the middle Miocene, and from illite to chlorite from Miocene to Pleistocene. This succession clearly illustrates that the lessening hydrolyzing climates favored increased physical weathering.

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REFERENCES

- Barron, E.J., 1985. Explanations of the Tertiary global cooling trend. Palaeogeogr., Palaeoclimatol., Palaeoecol., 50:45–61.
- , 1989. Climate variations and the Appalachians from the Late Paleozoic to the present: results from model simulations. *Geomorphology*, 2:99–118.
- Biscaye, P.E., 1965. Mineralogy and sedimentation of recent deep-sea clays in the Atlantic Ocean and adjacent seas and oceans. *Geol. Soc. Am. Bull.*, 76:803–832.
- Brown, G., and Brindley, G.W., 1980. X-ray diffraction procedures for clay mineral identification. In Brindley, G.W., and Brown, G. (Eds.), Crystal

Structures of Clay Minerals and Their X-ray Identification. Mineral. Soc. Monogr. London, 5:305–359.

- Carter, L., and Schafer, C.T., 1983. Interaction of the Western Boundary Undercurrent with the continental margin off Newfoundland. Sedimentology, 30:751–768.
- Cecil, C.B., 1990. Paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks. *Geology*, 18:533–536.
- Chamley, H., 1979. North-Atlantic clay sedimentation and palaeoenvironment since the Late Jurassic. In Talwani, M., Hay, W., and Ryan, W.B.F. (Eds), Deep Drilling Results in the Atlantic Ocean: Continental Margins and Paleoenvironment. Am. Geophys. Union, Maurice Ewing Ser., 3:342–361.
 - —, 1986. Clay mineralogy at the Eocene/Oligocene boundary. In Pomerol, C., and Premoli Silva, I. (Eds.), Developments in Palaeontology and Stratigraphy, 9:381–386.

, 1989. Clay Sedimentology: Berlin (Springer-Verlag).

- Chamley, H., Debrabant, P., Candillier, A.M., and Foulon, J., 1983. Clay mineralogical and inorganic geochemical stratigraphy of Blake-Bahama Basin since the Callovian, Site 534, Deep Sea Drilling Project Leg 76. *In* Sheridan, R.E., Gradstein, F.M., et al., *Init. Repts. DSDP*, 76: Washington (U.S. Govt. Printing Office), 437–451.
- Chamley, H., Debrabant, P., Foulon, J., and Leroy, P., 1980. Contribution de la minéralogie et de la géochimie à l'histoire des marges nord-atlantiques depuis le Jurassique supérieur (sites 105 et 367 DSDP). *Bull. Soc. Geol. Fr.*, 7:745–755.
- Cremer, M., Maillet, N., and Latouche, C., 1989. Analysis of sedimentary facies and clay mineralogy of the Neogene-Quaternary sediments in ODP Site 646, Labrador Sea. *In Srivastava*, S.P., Arthur, M.A., Clement, B., et al., *Proc. ODP, Sci. Results*, 105: College Station, TX (Ocean Drilling Program), 71–81.
- Dunn, D.A., Patrick, D.M., and Cooley, U., Jr., 1987. Cenozoic clay mineralogy of Sites 604 and 605, New Jersey Transect, Deep Sea Drilling Project Leg 93. In van Hinte, J.E., Wise, S.W., Jr., et al., Init. Repts. DSDP, 93: Washington (U.S. Govt. Printing Office), 1023–1037.
- Flood, R.D., 1978. X-ray mineralogy of DSDP Legs 44 and 44A, Western North Atlantic: lower continental rise hills, Blake Nose, and Blake-Bahama Basin. *In* Benson W.E., Sheridan, R.E., et al., *Init. Repts. DSDP*, 44: Washington (U.S. Govt. Printing Office), 515–521.
- Frakes, L.A., Francis J.E., and Syktus, J.I., 1992. Climate Modes of the Phanerozoic: Cambridge (Cambridge Univ. Press).
- Frederiksen, N.O., 1984. Stratigraphic, paleoclimatic and paleobiogeographic significance of Tertiary sporomorphs from Massachusetts. *Geol. Surv. Prof. Pap. U.S.*, 1308.
- Gibbs, R.J., 1977. Clay mineral segregation in the marine environment. J. Sediment. Petrol., 47:237–243.
- Hathaway, J.C., 1972. Regional clay mineral facies in estuaries and continental margin of the United States East Coast. Mem.—Geol. Soc. Am., 133:293–316.
- Hathaway, J.C., 1980. Mineralogic evidence of Quaternary current regimes on the Atlantic continental margin. Conference on Continental Margin Mass Wasting and Pleistocene Sea-level Changes. *Geol. Surv. Circ.* (U.S.), 961:58–61.
- Holtzapffel, T., 1985. Les minéraux argileux: préparation, analyse diffractométrique et détermination. Publ. Soc. Geol. Nord., 12.
- Holtzapffel, T., Bonnot-Courtois, C., Chamley, H., and Clauer, N., 1985. Héritage et diagenèse de smectites du domaine sédimentaire nord-atlantique (Crétacé-Paléogène). Bull. Soc. Geol. Fr., 8:23–32.
- Holtzapffel, T., and Chamley, H., 1986. Les smectites lattées du domaine atlantique depuis le Jurassique supérieur: gisement et signification. Clay Miner., 21:133–148.
- Inoue, A., Bouchet, A., Velde, B., and Meunier, A., 1989. Convenient technique for estimating smectite layer percentage in randomly interstratified illite/smectite minerals. *Clays Clay Miner.*, 37:227–234.
- Jeans, C.V., 1968. The origin of the montmorillonite of the European chalk with special reference to the Lower Chalk of England. *Clay Miner.*, 7:311–329.

—, 1978. Silicifications and associated clay assemblages in the Cretaceous marine sediments of southern England. *Clay Miner.*, 13:101– 126.

- Jeans, C.V., Merriman, R.J., Mitchell, J.G., and Bland, D.J., 1982. Volcanic clays in the Cretaceous of Southern England and Northern Ireland. *Clay Miner.*, 17:105–156.
- Kimblin, R.T., 1992. The origin of clay minerals in the Coniacian Chalk of London. Clay Miner., 27:389–392.

- Lever, A., and McCave, I.N., 1983. Eolian components in Cretaceous and Tertiary North Atlantic sediments. J. Sediment. Petrol., 53:811–832.
- Locker, S.D., and Laine, E.P., 1992. Paleogene-Neogene depositional history of the middle U.S. Atlantic continental rise: mixed turbidite and contourite depositional systems. *Mar. Geol.*, 103:137–164.
- Mazzullo, J., 1987. Sources of Miocene, Pliocene, and Pleistocene siliciclastic sediments in Unit I, Sites 612 and 613. In Poag, C.W., Watts, A.B., et al., Init. Repts. DSDP, 95: Washington (U.S. Govt. Printing Office), 581–585.
- McCartan, L., 1988. Mineralogy of the Haynesville, Virginia, cores. Geol. Surv. Prof. Pap. (U.S.), 1489.
- McCave, I.N., and Tucholke, B.E., 1986. Deep current-controlled sedimentation in the western North Atlantic. *In Vogt*, P.R., and Tucholke, B.E. (Eds.), *The Western North Atlantic Region*. Geol. Soc. Am., Geol. of North Am. Ser., M:451–468.
- Miller, K.G., Fairbanks, R.G., and Mountain, G.S., 1987. Tertiary oxygen isotope synthesis, sea-level history, and continental margin erosion. *Paleoceanography*, 2:1–19.
- Moore, D.M., and Reynolds, R.C., Jr., 1989. X-ray Diffraction and the Identification and Analysis of Clay Minerals: Oxford (Oxford Univ. Press).
- Parrish, J.T., and Curtis, R.L., 1982. Atmospheric circulation, upwelling, and organic-rich rocks in the Mesozoic and Cenozoic eras. *Palaeogeogr.*, *Palaeoclimatol.*, *Palaeoecol.*, 40:31–66.
- Pastouret, L., Auffret, G.A., and Chamley, H., 1978. Microfacies of some sediments from the Western North Atlantic: paleoceanographic implications (Leg 44 DSDP). *In* Benson, W.E., Sheridan, R.E., et al., *Init. Repts. DSDP*, 44: Washington (U.S. Govt. Printing Office), 477–501.
- Poag, C.W., 1992. U.S. middle Atlantic continental rise: provenance, dispersal, and deposition of Jurassic to Quaternary sediments. *In Poag*, C.W., and de Graciansky, P.C. (Eds.), *Geologic Evolution of Atlantic Continental Rises*: New York (Van Nostrand), 100–156.
- Poag, C.W., and Sevon, W.D., 1989. A record of Appalachian denudation in postrift Mesozoic and Cenozoic sedimentary deposits of the U.S. middle Atlantic continental margin. *Geomorphology*, 2:119–157.
- Porrenga, D.H., 1966. Clay minerals in recent sediments of the Niger delta. Clays Clay Min. 14th Nat. Conf., 221–233.
- Reynolds, R.C., 1980. Interstratified clay minerals. In Brindley, G.W., and Brown, G. (Eds.), Crystal Structures of Clay Minerals and their X-Ray Identification. Mineral. Soc. London Monogr., 5:249–303.
- Robert, C., and Chamley, H., 1987. Cenozoic evolution of continental humidity and paleoenvironment, deduced from the kaolinite content of oceanic sediments. *Palaeogeogr., Palaeoecol., Palaeoclimatol.*, 60:171– 187.
- Rothe, P., 1989. Mineral composition of sedimentary formations in the North Atlantic Ocean. Geol. Rundsch., 78:903–942.
- Rothe, P., and Tucholke, B.E., 1981. Mineralogy of sedimentary formations in the western North Atlantic Ocean: preliminary results. *Geol. Rundsch.*, 70:327–343.
- Savin, S.M., 1977. The history of the Earth's surface temperature during the past 100 million years. Annu. Rev. Earth. Planet Sci., 5:319–355.
- Shipboard Scientific Party, 1994a. Site 902. In Mountain, G.S., Miller, K.G., Blum, P., et al., Proc. ODP, Init. Repts., 150: College Station, TX (Ocean Drilling Program), 63–127.
- ______, 1994b. Site 903. In Mountain, G.S., Miller, K.G., Blum, P., et al., Proc. ODP, Init. Repts., 150: College Station, TX (Ocean Drilling Program), 129–205.
- —, 1994c. Site 904. In Mountain, G.S., Miller, K.G., Blum, P., et al., Proc. ODP, Init. Repts., 150: College Station, TX (Ocean Drilling Program), 207–253.
- _____, 1994d. Site 905. In Mountain, G.S., Miller, K.G., Blum, P., et al., Proc. ODP, Init. Repts., 150: College Station, TX (Ocean Drilling Program), 255–308.
- ______, 1994e. Site 906. In Mountain, G.S., Miller, K.G., Blum, P., et al., Proc. ODP, Init. Repts., 150: College Station, TX (Ocean Drilling Program), 309–357.
- Srivastava, S.P., Arthur, M., Clement, B., et al., 1987. Proc. ODP, Init. Repts., 105: College Station, TX (Ocean Drilling Program).
- Steinberg, M., Holtzapffel, T., and Rautureau, M., 1987. Characterization of overgrowth structures formed around individual clay particles during early diagenesis. *Clays Clay Miner.*, 35:189–195.
- Thiébault, F., and Cremer, M., 1990. Sédimentologie, minéralogie des argiles et chimie des sédiments miocènes à quaternaires du Site 645 (Leg ODP-105—baie de Baffin). Origines et implications climatiques et courantologiques. *Bull. Soc. Geol. Fr.*, 8:457–468.

- Thiébault, F., Cremer, M., Debrabant, P., Foulon, J., Nielsen, O.B., and Zimmerman, H., 1989. Analysis of sedimentary facies, clay mineralogy, and geochemistry of the Neogene-Quaternary sediments in Site 645, Baffin Bay. In Srivastava, S.P., Arthur, M.A., Clement, B., et al., Proc. ODP, Sci. Results, 105: College Station, TX (Ocean Drilling Program), 83–100.
- Thiry, M., and Jacquin, T., 1993. Clay mineral distribution related to rift activity, sea-level changes and paleoceanography in the Cretaceous of the Atlantic Ocean. *Clay Miner.*, 28:61–84.
- Tucholke, B.E., 1975. Sediment distribution and deposition by the western boundary undercurrent: the Greater Antilles Outer Ridge. J. Geol., 83:177–207.
 - —, 1986. Submarine geology. In Milliman, J.D., and Wright, W.R. (Eds.), The Marine Environment of the U.S. Atlantic Continental Slope and Rise: Boston (Jones and Barlett Publ.), 56–113.
- Tucholke, B.E., and Laine, E.P., 1982. Neogene and Quaternary development of the lower continental rise off the central U.S. East Coast. In Watkins, J.S., and Drake, C.L. (Eds.), Studies in Continental Margin Geology. AAPG Mem., 34:295–305.
- Tucholke, B.E., and Mountain, G.S., 1986. Tertiary paleoceanography of the western North Atlantic Ocean. In Vogt, P.R., and Tucholke, B.E. (Eds.), The Western North Atlantic Region. Geol. Soc. Am., Geol. of North Am. Ser., 631–650.
- Weaver, C.E., 1989. Clays, Muds, and Shales: New York (Elsevier), Dev. in Sedimentol. Ser., 44.

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Figure 11. Average proportions of clay minerals in CMZ II of Sites 903 and 905.

Age	Clay sedimentation	Origins of clay minerals	Environmental events
Pleistocene CMZ I	Illite and chlorite-rich clay assemblages	Erosion of the crystalline North American basement	Growth of ice sheets
middle Miocene late Miocene CMZ II	Increasing illite Decreasing kaolinite No correlation	Deep erosion of crystalline rocks from the Appalachian Highlands	Tectonic uplift in the Appalachians
late Oligocene early Miocene early middle Miocene CMZ III	Step by step increase of illite and kaolinite Direct correlation between both minerals	Illite reworked from crystalline rocks of the Appalachians Kaolinite reworked mainly from Late Cretaceous to Eocene weathering profiles	Maximum humidity Glacio-eustatic lowering Eustatic
middle and late Eocene CMZ IV	Smectite-rich clay sedimentation	Air-born smectites?	lowering

Figure 12. Summary chart correlating clay sedimentation and related events of the study area.

CLAY MINERAL SEDIMENTATION OFF NEW JERSEY



Plate 1. TEM photographs of clay fractions of samples from Site 903. Scale bar = 1 μ m. **1.** Sample 150-903C-57R-3, 50–52 cm (CMZ IV), showing abundant fleecy particles of smectite (Sm). **2.** Sample 150-903C-39R-3, 40–42 cm (CMZ III). Lath-shaped particles of smectite are abundant. Notice the occurrence of short fibers of palygorskite (P). **3.** Sample 150-903A-63X-3, 50–52 cm (CMZ II) showing large particles of illite (I) occurring together with very small subhexagonal crystals of kaolinite (K). **4.** Sample 150-903A-75X-6, 48–50 cm (CMZ II) showing the abundance of kaolinite particles and the occurrence of palygorskite? **5. 6.** Sample 150-903A-38X-3, 102–104 cm (CMZ I). Well-outlined detrital illite and chlorite.



Plate 2. TEM photographs of clay fractions of samples from Site 905. Scale bar = 1 μ m, except for Fig. 4, in which scale bar = 0.25 μ m. **1**, **2**. Sample 150-905A-92X-8, 45–47 cm (CMZ III), has an abundance of smectite displaying a lath shape. Note the occurrence of palygorskite. **3**. Sample 150-905A-58X-5, 48–50 cm (CMZ II), has a mixture of large particles of illite (I), with subhexagonal kaolinite (K), and fleecy particles of smectites (Sm). **4**. Detail from Sample 150-905A-58X-5, 48–50 cm, of subhexagonal, small particles of kaolinite. **5**, **6**. Sample 150-905A-6H-1, 50–52 cm (CMZ I), has a mixture of well-outlined clay minerals comprising abundant illite, chlorite (large particles), and kaolinite (small particles).