41. CENOZOIC CLAY MINERALOGY OF SITES 604 AND 605, NEW JERSEY TRANSECT, DEEP SEA DRILLING PROJECT LEG 93[1]

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ABSTRACT

Examination of the clay mineralogy of Cenozoic sediment samples from Deep Sea Drilling Project Sites 604 and 605 on the upper continental rise off New Jersey indicates that sediment deposition of two different clay mineral facies has occurred. These sites are marked by Paleogene deposition of illite with subordinate kaolinite and smectite covarying in inverse proportion, and by Neogene deposition dominated by illite with subordinate kaolinite and chlorite. Leg 93 results agree with the clay mineral facies proposed by Hathaway (1972), which defined a "Northern facies" consisting of illite and chlorite, with feldspar and hornblende, from erosion of rocks north of Cape Hatteras, and a "Southern facies" composed of smectite, kaolinite, and mixed-layer illite–smectites. Neogene and Quaternary sediments at Sites 604 and 605 contain the "Northern facies," and Paleogene sediments contain the "Southern facies" minerals. Feldspar is exclusively found in Neogene–Quaternary sediments, as is the majority of the amphibole found in these samples. Widespread Paleogene volcanic source materials are suggested by the presence of smectite throughout the early Paleocene–middle Eocene sediments recovered at Site 605. The clay mineral stratigraphy at Leg 93 sites is comparable to the record at nearby DSDP sites on the lower continental rise and abyssal plain of the northwestern Atlantic (DSDP Sites 388, 105, and 106), and also with the sediments recovered by drilling on the Mazagan Plateau off northwestern Morocco (DSDP Sites 544–547) in the eastern North Atlantic.

INTRODUCTION

Leg 93 drilled three holes at two sites on the proposed New Jersey Transect, which was scheduled to be completed by drilling on DSDP Leg 95. The complete New Jersey Transect will provide a transect of drill holes across the continental margin off eastern North America. Two holes were drilled at Site 604 on the upper continental rise, in 2364 m (Hole 604) and 2340 m (Hole 604A) water depths, with both holes terminating in a Miocene slump deposit that was impenetrable by rotary drilling (See Sites 604/605 chapter, this volume). Site 605 was drilled at a 1.6-km offset to the northwest along USGS multichannel seismic line 25 (Fig. 1), at a water depth of 2197 m. The location of Site 605 was successfully chosen to avoid the impenetrable Miocene lithologic unit, and to recover Paleogene sediments of the upper continental rise. By combining the cored sediments from Holes 604, 604A, and 605, it was possible to obtain a sediment history of the hemipelagic deposits of the New Jersey continental margin.

This study is a preliminary investigation of the Cenozoic clay mineralogy of Sites 604 and 605. Samples of each lithologic unit defined by the shipboard sedimentologists were analyzed for their clay mineralogy in an attempt to determine if any temporal changes occurred in the clay content of Cenozoic hemipelagic sediments of the upper continental rise.

Deep-sea clay minerals are generally derived from continental sediments with little change in the crystalline structure of the mineral (Biscaye, 1965). Fine-grained sediment materials are transported to continental margins by rivers and by aeolian transport, and this sediment is transported to hemipelagic and abyssal-plain depocenters by submarine slumping and turbidity currents. Thus deep-sea clay minerals may provide information on continental erosion and weathering (Biscaye, 1965). Chlorite is unstable, easily altered by chemical weathering, and is dominant in high-latitude marine sediments. Kaolinite is usually the result of intense chemical weathering and tends to be the dominant clay mineral in tropical latitudes. Detrital illite is the result of mechanical weathering of continental materials and tends to be found in river drainage patterns and in belts below the Jet Stream. Deep-sea clay minerals may also be formed *in situ* by authigenic processes, through the alteration of volcanic glass, or through neoformation of previous minerals (Millot, 1970). Smectite is an alteration product of volcanic materials, and tends to be more common in tropical to warm subtropical areas.

SEDIMENTS EXAMINED IN THIS STUDY

Drilling at Site 604 recovered three lithologic units of Pleistocene to late Miocene age (Table 1, Fig. 2). Lithologic Unit I, consisting of gray to greenish gray Pleistocene interbedded hemipelagic clay and silt layers, is divided into two subunits based on the presence or absence of slump structures. Unit II is late Miocene to Pleistocene greenish gray clay with variable amounts of glauconite and biogenic silica. Subunit IIA contains biogenic silica-rich clay with glauconite sand intervals; Subunit IIB consists of silty clay with glauconite silt and sand particles. Subunit IIC is biogenic silica-bearing clay, and Subunit IID is biogenic silica-bearing glauconite-rich claystones and clayey siltstones. Lithologic Unit III at Site 604 was
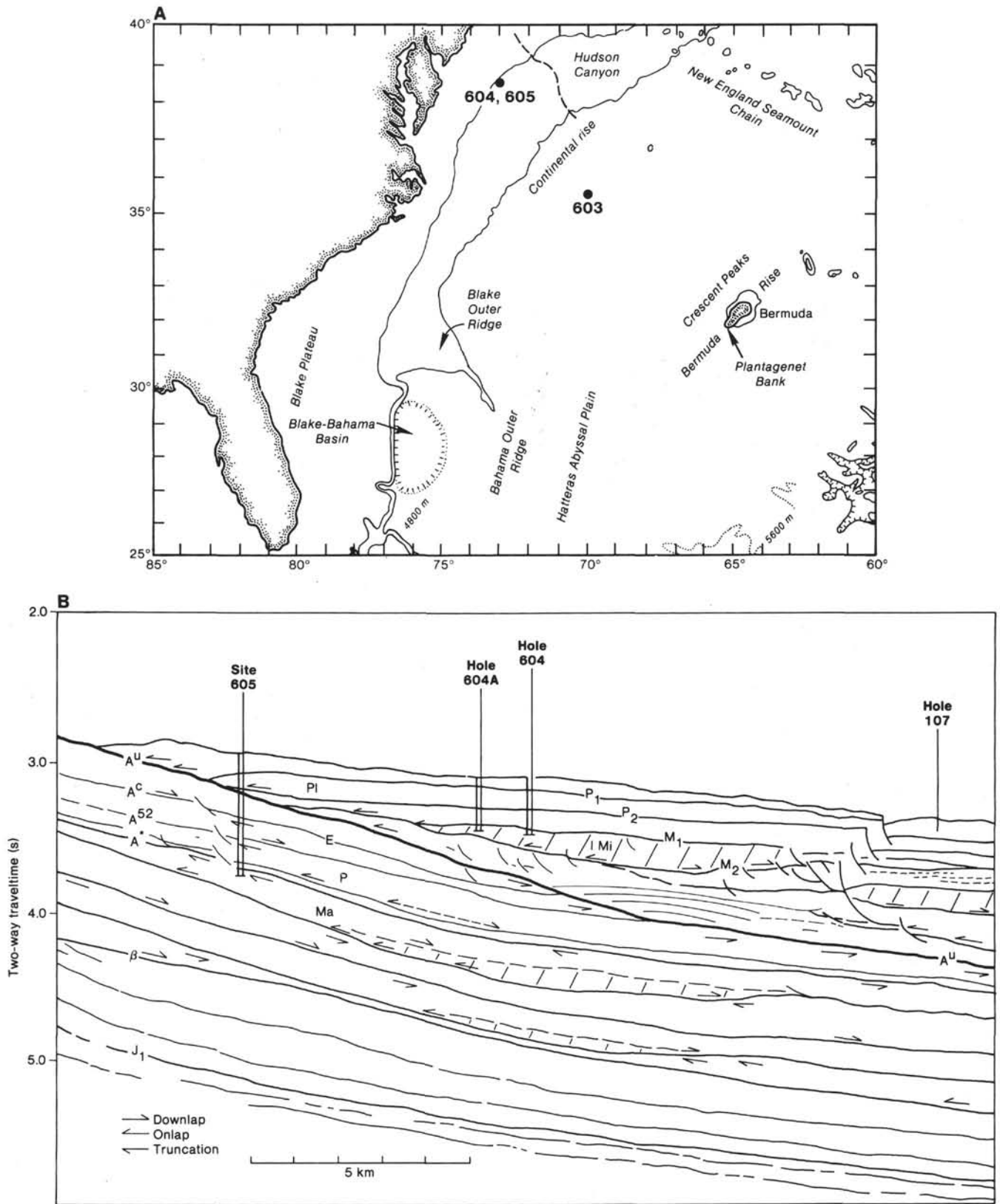
Figure 1. A. Location of sites drilled during Deep Sea Drilling Project Leg 93. B. Line drawing after USGS multichannel seismic reflection line 25, indicating the locations of DSDP Hole 604, Hole 604A, and Site 605, and the relationship between seismostratigraphic units (see Sites 604/605 chapter, this volume) drilled at these sites. Pl = Pliocene-Pleistocene, lMi = late Miocene, E = Eocene, P = Paleocene, and Ma = Maestrichtian.

Table 1. Site 604 lithostratigraphy.

Unit	Subunit	Lithology	Hole-Core-Section, cm level	Sub-bottom depth (m)	Age
I		Gray to dark greenish gray alternations	604-1 to 604-10-1, 7 cm	0.0–84.0	Late to middle Pleistocene
	IA	Interbedded clay and silt layers	604-1-1, 0 cm to 604-5-1, 0 cm	0.0–35.3	
	IB	Gray and dark greenish gray clay and silt with slump structures	604-5-1, 0 cm to 604-10-1, 7 cm	35.3–84.0	
II		Greenish gray clay with glauconite-rich intervals and variable amounts of biogenic silica	604-10-1, 7 cm to 604-26-2, 46 cm	84.0–238.9	early Pleistocene-latest Miocene
	IIA	Greenish gray clay with glauconite-rich sand and biogenic silica	604-10-1, 7 cm through 604-13,CC	84.0–121.7	
	IIB	Greenish gray clay with glauconite-rich sand	604-14 through 604-19,CC	121.7–179.3	
	IIC	Greenish gray clay with biogenic silica	604-20 through 604-24,CC	179.3–227.3	
	IID	Greenish gray clay with glauconite-rich sand and biogenic silica	604-25 through 604-26-2, 46 cm	227.3–238.9	
III		Glauconite- and biogenic silica-rich silty claystone and conglomerates	604-26-2, 46 cm to 604-31 and 604A-2 through 604A-4,CC	238.9–294.5	late Miocene

drilled for 55.6 m, with extremely poor recovery (a total of 8.20 m of recovered sediment). This unit consists of a late Miocene debris-flow deposit, composed of glauconite-rich and biogenic silica-rich silty claystone and conglomerate, with rounded quartz pebbles, pebble- to cobble-sized clasts of Eocene limestone, and clay-rich biogenic silica-rich nannofossil chalk.

It is necessary to specify both the lithologic unit and the site number when referring to Leg 93 Sites 604 and 605 New Jersey Transect sediments. For example, lithologic Unit II of Site 604 differs both in lithology and age from Lithologic Unit II of Site 605. In addition, Site 605 was positioned so that Lithologic Unit III of Site 604 (the Miocene debris-flow deposits) was not penetrated at Site 605.

At Site 605, five different lithologic units were recovered, ranging in age from Pleistocene to Maestrichtian (Table 2, Fig. 2). Lithologic Unit I consists primarily of Pleistocene gray silt-rich clay (which approximately correlates with Subunits IA and IB of Site 604), and 24 cm of upper Pliocene green homogeneous, structureless, biogenic silica-bearing, calcareous-rich clay. Because of the extreme thinness of Lithologic Subunit IB at Site 605 (24 cm total thickness), no sample was taken from this unit. Erosion of sediments of late Eocene to early Pliocene age from this site produced a major unconformity at Site 605 (Fig. 2). Lithologic Unit II consists of greenish gray middle Eocene biogenic silica-rich nannofossil chalk. Unit III is early Eocene greenish gray nannofossil limestone, differentiated from the overlying unit only by its greater induration and lack of biogenic silica. Lithologic Unit IV consists of early to late Paleocene dark greenish gray clay-rich to clayey nannofossil limestone ("marl"). Unit V of Site 605 contains early Paleocene to latest late Maestrichtian olive gray terrigenous silt-rich foraminifer–nannofossil limestone, and late Maestrichtian olive gray clay-rich foraminifer–nannofossil limestone. No samples were analyzed from Subunit VB, as this entire subunit is of Cretaceous (late Maestrichtian) age.

ANALYTICAL METHODS

Sediment samples used in this study (Table 3) were examined and described using the criteria and sediment classification scheme devised by the Leg 93 shipboard sedimentologists (Dunn, this volume). Color was determined for samples prior to processing, using either the GSA Rock-Color charts or Munsell Sediment Color charts. Table 4 lists the samples examined in this study, their sub-bottom depths, age, color, and sediment name, determined in the laboratory by criteria used during Leg 93. Textural classification was determined by visual estimation of the grain size of sedimentary particles on smear slides, regardless of the composition of the sedimentary particles. For example, whole foraminifers were considered as sand-sized grains. The sediment name assigned to each lithology generally follows DSDP principles, but with certain modifications made by the Leg 93 shipboard sedimentologists (Dunn, this volume).

Although grain-size distributions were not determined for this study, the XRD data suggest that the sediment classifications determined by visual examination of smear slides have systematically overestimated the amount of clay present in the samples. Therefore, clayey silt or clayey siltstone may be more appropriate sediment names for those samples classified as clays or claystone.

Bulk (whole-rock) and oriented (< 2-μm) samples were examined by X-ray diffraction (XRD). Bulk samples were powdered and sieved through a 3.5-ϕ (88 μm) screen; then the powdered and screened sample was sprinkled upon glass sample holders for XRD analysis. Sample disaggregation and dispersion to prepare oriented slides was accomplished by placing the sediment sample in a mechanical blender with distilled water for approximately two minutes, then samples were diluted and washed repeatedly with distilled water until dispersion occurred. No acids or dispersants were used. Two aliquots representing the < 2-μm size fraction (based on Stokes Law settling) were decanted by pipette from the dispersed sample and placed upon glass slides. One slide was allowed to dry at room temperature and, upon drying, was used for the oriented, nonsolvated XRD analysis; the second slide was dried in an ethylene glycol environment for approximately 24 hours and was used for oriented and solvated XRD analysis (Carver, 1971).

XRD samples were analyzed using a General Electric Model 1200 X-ray diffractometer. Samples were subjected to Cu Kα radiation at a scanning rate of 2° 2θ/min., and diffraction patterns were recorded on chart paper at a recording rate of 1 in./min.

Clay mineral identifications were made from diffractograms of the < 2-μm fraction as follows: smectite by the presence of a 17-Å peak
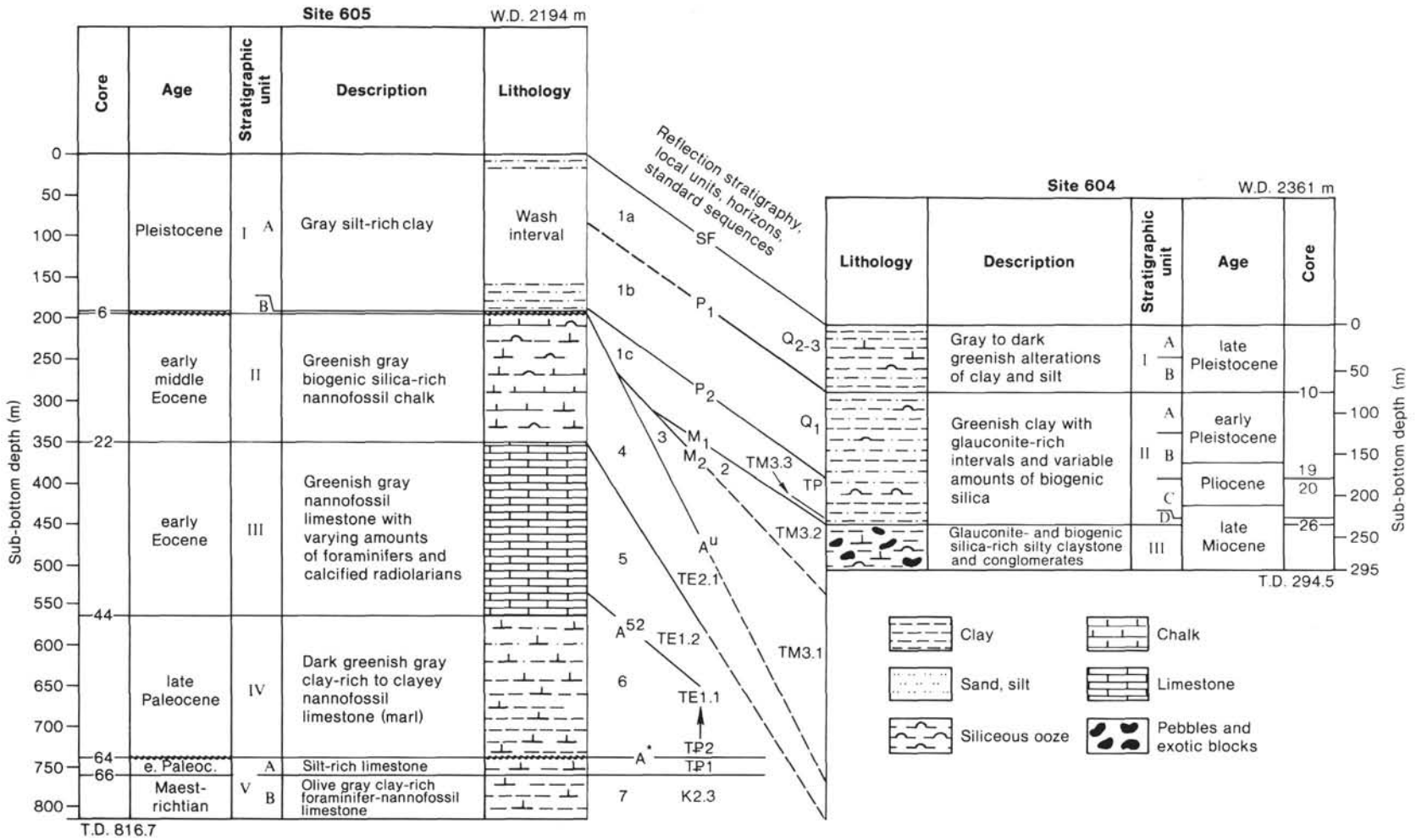
Figure 2. Stratigraphic summary of Sites 604 and 605 (from Sites 604/605 chapter, this volume). Units I to III (604) and I to V (605) are local lithostratigraphic units. Seismic reflection horizons drilled at Sites 604 and 605 are indicated (SF, P_1, P_2, M_1, M_2, A^u, A^c, A^{52}, and A^*. Standard seismic sequence notation after Vail et al. (1977).

Table 2. Site 605 lithostratigraphy.

Unit	Subunit	Lithology	Hole-Core-Section, cm level or interval	Sub-bottom depth (m)	Thickness (m)	Age
I	IA	Gray silt-rich clay	605-1 to 605-6-4, 125 cm	0–198.00	198.0	Pleistocene
	IB	Green biogenic silica-bearing calcareous-rich clay	605-6-4, 125–149 cm	198.00–198.14	0.14	Pleistocene
II		Greenish gray biogenic silica-rich nannofossil chalk	605-6-4, 149 cm to 605-22-3, 50 cm	198.14–350.00	ca. 152	lower middle Eocene
III		Greenish gray nannofossil limestone with varying amounts of foraminifers and calcified radiolarians	605-22-3, 50 cm to 605-44-5, 33 cm	350.00–564.00	214	early middle Eocene to earliest Eocene
IV		Dark greenish gray clay-rich to clayey nannofossil limestone (marl)	605-44-5, 33 cm to 605-64-1, 54 cm	564.00–740.00	184	late Paleocene to early Paleocene
V		Olive gray, silt-rich or foraminifer-rich, clayey nannofossil limestone	605-64-1, 54 cm through 605-71,CC	740.00–816.70	77	early Paleocene to middle Maestrichtian
	VA	Dark greenish gray, glauconite-bearing and silt-rich nannofossil clayey limestone	605-64-1, 54 cm to 605-66-1, 120 cm	740.40–760.20	19.8	Paleocene to latest Maestrichtian
	VB	Olive gray, clay-rich foraminifer-nannofossil limestone	605-66-1, 120 cm to 605-71,CC	760.20–816.70	56.5	Maestrichtian

Table 3. Lithologic units of Sites 604 and 605, and samples of each unit examined in this study.

Unit	Subunit	Age	Core-Section, cm level
Site 604			
I		Pleistocene	
	IA		1-1, 130
	IB		6-3, 130, 8-2, 57
II		early Pleistocene-late Miocene	
	IIA		10-4, 100, 13-1, 106
	IIB		16-4, 100, 18-4, 100
	IIC		22-2, 100
	IID		25-4, 100
III		late Miocene	27-1, 140
Site 605			
I		Pleistocene-late Pliocene	
	IA		1-1, 100, 4-3, 100
	IB		Not sampled
II		middle Eocene	7-6, 100, 15-2, 100, 21-3, 100
III		early Eocene	27-1, 100, 33-5, 100, 40-2, 100
IV		late-early Paleocene	48-4, 100, 54-1, 100, 59-4, 100
V		early Paleocene-late Maestrichtian	
	VA		64-3, 100
	VB		Not sampled

Semiquantitative estimates of the nonclay mineralogy of Sites 604 and 605 sediments, exclusive of cristobalite, glauconite, and amphibole, were made from diffractograms of bulk samples (Table 5), on the basis of unweighted peak areas and by assuming that the identified minerals composed 100% of the sample. Cristobalite and amphibole were identified from XRD data, but were not quantified, as the cristobalite peaks were broad and irregular and the abundance of amphibole was small. Glauconite was identified from smear slides made from Leg 93 samples, but was present in quantities less than or equal to 1%. The presence of these minerals in Sites 604 and 605 samples are shown in Table 5 by an X.

RESULTS

Bulk Mineralogy

Estimates of nonclay mineral abundances of all samples examined in this study are shown in Table 5. Quartz and/or calcite predominate in all samples, and a small amount of feldspar is present in some samples of late Pliocene and younger age. Generally, calcite occurs in higher concentrations than quartz through the middle Eocene, after which quartz is the predominant nonclay mineral present. Quartz and calcite also occur in minor amounts in the <2-μm size fractions. One sample from the early Eocene (605-27-1, 100 cm) contained a small amount of siderite.

The examination of smear slides did not reveal volcanic glass or other volcaniclastic components; however, silica polymorphs were identified by XRD in Site 605 samples from early Paleocene (Sample 605-59-4, 100 cm) to middle Eocene age (Sample 605-15-2, 100 cm), and in one middle Pleistocene sample (605-4-3, 100 cm). The identification was based upon rather broad XRD peaks representing d-spacings of approximately 4.00 to 4.07 Å (Fig. 3); no secondary peaks were detected. These d-spacings are similar to those of both opal-A and opal-C. There was no XRD evidence of the presence of opal-CT or zeolites in these samples. Smear slides of the late Miocene sample (604-27-1, 140 cm) and a middle Pleistocene sample (605-4-3, 100 cm) contained glauconite.

The presence of amphibole was indicated by peaks on the X-ray diffractograms of one upper Paleocene sample

after glycolation; illite by a 10-Å 001 peak on both oriented and glycolated diffractograms; chlorite by a 14-Å peak after glycolation. Because a 7-Å peak may be present on oriented diffractograms from either kaolinite (001 d-spacing) or chlorite (002 d-spacing), kaolinite-chlorite proportions were based upon the relative areas under the 3.57-Å and 3.54-Å peaks, respectively.

Clay mineral abundances were approximated from ratios between the peak areas of the different clay minerals, using the semiquantitative techniques of Biscaye (1965) and Carroll (1970). However, quantification of clay mineralogy from X-ray diffractograms is still only semiquantitative at best, because of variations between diffractometers, variance in the degree of orientation and crystallinity of clay minerals, and the possible presence of mixed-layer clay minerals. Our quantitative abundances have a precision of ±10%.

Table 4. Sub-bottom depth, age, lithology, and color of samples examined in this study.

Core-Section, cm level	Depth (m)	Age	Sediment name	Color
Site 604				
1-1, 130	1.32	late Pleistocene	Quartz-rich, nannofossil-bearing silty clay	Olive gray (5Y5/2)
6-3, 130	49.20	late Pleistocene	Foraminifer-bearing silty clay	Grayish green (5GY4/2)
8-2, 57	66.19	late Pleistocene	Carbonate-bearing, silt-rich clay	Dark greenish gray (5GY4/1)
10-4, 100	88.82	early Pleistocene	Glauconite-bearing, nannofossil-rich clay	Dark greenish gray (5Y4/1)
13-1, 106	113.16	early Pleistocene	Carbonate-bearing silty clay	Greenish gray (5GY4/1)
16-4, 100	146.40	early Pleistocene	Carbonate-rich silty clay	Greenish gray (5GY4/1)
18-4, 100	165.62	late Pliocene	Nannofossil-bearing silty clay	Dark greenish gray (5GY5/1)
22-2, 100	201.00	early Pliocene	Biogenic silica-bearing nannofossil-rich clay	Dark greenish-gray (5GY4/1)
25-4, 100	232.82	early Pliocene	Nannofossil-rich claystone	Dark grayish green (5GY3/2)
27-1, 140	247.92	late Miocene	Glauconite-rich clayey sandy siltstone	Dark greenish gray (5GY3/1)
Site 605				
1-1, 100	??	middle Pleistocene	Biogenic silica- and carbonate-bearing clay	Medium gray (N5)
4-3, 100	177.52	middle Pleistocene	Carbonate- and quartz silt-rich clay	Dark gray (N4)
7-6, 100	210.82	middle Eocene	Biogenic silica-rich nannofossil chalk	Light greenish-gray (5GY7/1)
15-2, 100	281.70	middle Eocene	Biogenic silica-rich nannofossil chalk	Light greenish gray (5GY7/1
21-3, 100	340.70	middle Eocene	Biogenic silica-rich nannofossil chalk	Light greenish gray (5GY7/1)
27-1, 100	395.30	early Eocene	Foraminifer-bearing nannofossil limestone	Greenish gray (5GY6/1)
33-5, 100	458.92	early Eocene	Foraminifer- and clay-bearing nannofossil limestone	Light greenish gray (5GY7/1)
40-2, 100	521.60	early Eocene	Foraminifer-bearing clay-rich nannofossil limestone	Pale green (10G6/2)
48-4, 100	601.42	late Paleocene	Clayey nannofossil limestone	Greenish gray (5GY4/1-5GY5/1)
54-1, 100	649.40	late Paleocene	Foraminifer-bearing clayey nannofossil limestone	Gray (N5)
59-4, 100	697.40	early Paleocene	Clayey nannofossil limestone	Dark greenish gray (5GY4/1)
64-3, 100	743.92	early Paleocene	Quartz-bearing, clay-rich nannofossil limestone	Greenish-gray (5GY6/1)

(605-48-4, 100 cm), one upper Pliocene sample (604-18-4, 100 cm), and samples of middle to late Pleistocene age at both sites.

The total abundance of clay minerals relative to non-clay minerals in bulk samples was not determined; however, clay mineral peaks on the diffractograms of bulk samples were extremely weak or absent, suggesting that these minerals do not compose an appreciable proportion of the total sample.

Clay Mineralogy

The relative proportions of kaolinite, chlorite, illite, and smectite are given in Table 6, and are plotted in Figure 4. The occurrence of these minerals is discussed below. Kaolinite occurred in all samples except one from the lower Paleocene and one of early Eocene age. The proportion of kaolinite was high in Paleocene samples, decreased to a minimum value in the uppermost middle Eocene sample, then reached peak abundances (36–45%) during the late Miocene to early Pliocene. Following these peak values, kaolinite abundances remained relatively constant through the late Pliocene to late Pleistocene, ranging from 10 to 25% of the total clay mineral assemblages of these sediments. The 001 peaks were rather broad, indicating a low degree of crystallinity.

Minor amounts (<15%) of chlorite were found in one late Paleocene sample from lithologic Unit IV and two early Eocene samples from lithologic Unit III of Site 605 (Fig. 2). Chlorite was not present in the middle Eocene biogenic silica-rich chalks (lithologic Unit II) of Site 605, or in samples of early Pliocene sediments, whereas late Pliocene and younger sediments at both sites contained significant amounts of this clay mineral (Fig. 5). Maximum values (29–32%) were found in middle to late Pleistocene sediments at both sites. As with kaolinite,

peaks were broad and low; some mixed-layer chlorite–smectite was indicated by separation of 14-Å peaks and slight shift to lower 2-θ spacings upon glycolation.

Illite was present in the <2-μm fraction of all samples and predominated in most. An early Eocene limestone sample (605-33-5, 100 cm) was exclusively illitic (Fig. 4). Most 001 peaks were rather low and broad, and low 2-θ shoulders on the 001 peaks for most samples suggested some mixed-layer illite–smectite (Fig. 6). Some proportion of the illite may represent glauconite that was visually identified in two of the samples (604-27-1, 140 cm and 605-4-3, 100 cm).

Smectite was mainly limited to Paleogene samples, although one early Pliocene sample (604-25-4, 100 cm) and one late Pleistocene sample (604-1-1, 100 cm) contained this mineral. Much smectite was present in an early Paleocene sample (605-64-3, 100 cm), and predominated in late Paleocene (605-48-4, 100 cm) and middle Eocene (605-7-6, 100 cm) samples. For untreated slides the 001 peaks were low and broad; however, ethylene glycol solvation produced distinct 17-Å 001 peaks (Fig. 7).

DISCUSSION

New Jersey Transect Sedimentology

Olsson (1978) divides the eastern coastal plain Tertiary sediments into two sequences separated by a disconformity: a lower Paleogene (Paleocene–middle Eocene) unit composed of glauconite-rich sand, silt, and clay strata, and a Neogene unit of fine- to coarse-grained sands and gravels, with some clay interbeds. These two sedimentary units are separated by a disconformity that may be the result of a major Eocene transgression followed by regressive offlap at the middle/late Eocene boundary, caused by severe climatic cooling and lower-

Table 5. Proportions of nonclay minerals in samples arranged by geologic age.

Hole-Core-Section, cm level	Nonclay mineralogy[*a]						
	QTZ	CAL	FSP	SID	GLC	CRST	AMPH
late Pleistocene							
604-1-1, 130	81	7	12	—	—	—	X
604-6-3, 130	48	21	31	—	—	—	X
604-8-2, 57	73	12	15	—	—	—	—
middle Pleistocene							
605-1-1, 100	100	—	—	—	—	—	—
605-4-3, 100	57	16	26	—	X	X	X
early Pleistocene							
604-10-4, 100	100	—	—	—	—	—	—
604-13-1, 106	55	14	31	—	—	—	—
late Pliocene							
604-16-4, 100	80	6	14	—	—	—	—
604-18-4, 100	77	13	10	—	—	—	X
early Pliocene							
604-22-2, 100	70	30	—	—	—	—	—
604-25-4, 100	100	—	—	—	—	—	—
late Miocene							
604-27-1, 140	100	—	—	—	X	—	—
middle Eocene							
605-7-6, 100	—	100	—	—	—	—	—
605-15-2, 100	—	100	—	—	—	X	—
605-21-3, 100	—	100	—	—	—	X	—
early Eocene							
605-27-1, 100	—	90	—	10	—	X	—
605-33-5, 100	14	86	—	—	—	X	—
605-40-2, 100	32	68	—	—	—	X	—
late Paleocene							
605-48-4, 100	45	55	—	—	—	—	X
605-54-1, 100	39	61	—	—	—	X	—
early Paleocene							
605-59-4, 100	42	58	—	—	—	X	—
605-64-3, 100	57	43	—	—	—	—	—

Note: Dashed rule indicates no samples of late Eocene to middle Miocene age recovered. — indicates searched for but not found.
[*a] Key to mineral codes: QTZ: Quartz; CAL: calcite; FSP: feldspar; SID: siderite; GLC: glauconite; CRST: cristobalite; and AMPH: amphibole. X = present, but not quantified.

ing of sea levels (Ingle et al., 1976). Following this Eocene cooling, a late Oligocene to earliest Miocene warming (Haq and Lohmann, 1976) caused the deposition of transgressive sediments atop the disconformity.

The sediments drilled at Sites 604 and 605 generally show the stratigraphic division described by Olsson (1978), having two different lithologies separated by a middle to late Eocene disconformity. At Site 605, Maestrichtian to Paleocene marls, early Eocene nannofossil limestones, and middle Eocene biogenic silica-rich nannofossil chalks are separated by a disconformity from late Pliocene-Pleistocene silty clays and claystones. Lithologic Unit I of Site 605 was cored for only 34.24 m, and the hole was washed through for most of its thickness, as these Pliocene-Pleistocene silty clays and claystones were continu-

ously cored at Site 604. Underlying these silty clays and claystones at Site 604 was a middle to late Miocene slump deposit that was impenetrable by rotary drilling, so we were unable to determine the age and nature of the seismostratigraphic unit immediately below the slump deposits (Fig. 1). Thus we were unable to determine at Site 604 the age or nature of the disconformity that corresponds to the one drilled at Site 605.

The major change in sediment types across the disconformity at Site 605 may be either related to a change in the carbonate compensation depth (CCD) or the result of increased continental erosion that provided greater supplies of terrigenous material. There are insufficient numbers of drill holes this close to the North American continent in this area to permit definition of the CCD. The Cenozoic CCD record for this region of the deep Atlantic is well-known (Jansa et al., 1979), but the information is of little assistance in the analysis of near-continent CCD levels, as it is known that the CCD typically shoals near continents.

The change from calcareous lithologies to silty clays and claystones across the disconformity at Site 605 may be due to increased input of terrigenous debris to the upper continental rise in conjunction with changes in sedimentation created by the Western Boundary Undercurrent (WBUC). Heezen et al. (1966) and Lancelot et al. (1972) have documented the building of a depositional sedimentary ridge at the foot of the continental slope along the northeastern margin of the United States during the Miocene-Pliocene, caused by deposition of hemipelagic muds that had been reworked by the WBUC. The formation of these lower continental rise sediments during the Miocene must have been related to an increase in the supply of terrigenous silts from North America (Asquith, 1979), so it seems reasonable to assume that a change in the sediment supply to the lower continental rise could also have affected the upper continental rise sediments cored during Leg 93.

New Jersey Transect Clay Mineralogy

Generally, the clay mineral suite at Sites 604 and 605 is considered to represent both inherited (detrital) and neoformed (authigenic) origins (Millot, 1970). The kaolinite is believed to be exclusively inherited from continental sources to the west. These sources (soils and reworked sediments) had originated under relatively humid-warm climatic conditions that culminated in the late Miocene-early Pliocene. At nearby DSDP Hole 388A on the lower continental rise, tropical to subtropical radiolarians (Orosphaerids and Collosphaerids) were found only in middle Miocene sediments (Weaver and Dinkelman, 1978), indicating a warm middle Miocene climate on the eastern United States Continental margin.

From the late Pliocene through the Pleistocene, kaolinite was apparently no longer forming on the continents, due to lowered continental paleotemperatures during glacial episodes; kaolinite in late Pliocene and Pleistocene sediments is thought to have originated by reworking of older sediments. Generally, kaolinite abundances in these sediments are lower than those of Paleocene to Miocene age (Fig. 4). The inherited origin of the kaolin-
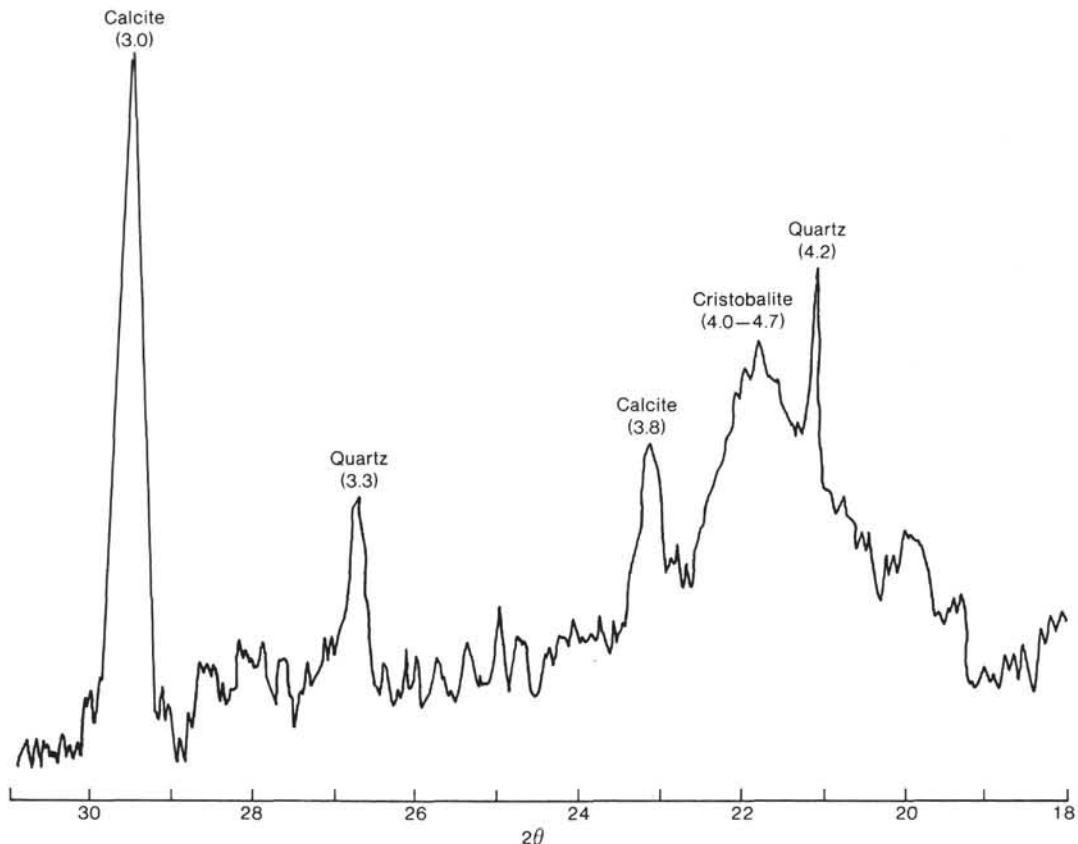
Figure 3. X-ray diffractogram of the bulk fraction of Sample 605-33-5, 100 cm, illustrating typical broad XRD peaks between 4.00 and 4.07 Å seen in Leg 93 samples and identified as cristobalite. Also seen are two calcite XRD peaks (3.0 and 3.8 Å) and two quartz peaks (3.3 and 4.2 Å).

ite is supported by the presence of accompanying detrital quartz and feldspar. There is no evidence to support neoformation of kaolinite in such an ion-rich marine environment. However, neoformation of kaolinite is best observed petrographically or by using scanning electron microscopy, so these avenues should be addressed in later studies.

The chlorite is presumed to be primarily inherited. The first consistent occurrence of this mineral in the early Pliocene must be related to changing climatic conditions and the beginning of Pleistocene glaciation. During these times kaolinization was decreasing due to lowered temperatures, and glaciers were transporting large quantities of chlorite and illite to the south from igneous and metamorphic sources on the Canadian Shield.

The origin of the illite may be primarily by inheritance. No doubt some of the illite originated in the same manner as the kaolinite and accompanied the latter from the same or a nearby source area. However, the presence of glauconite grains in smear slides of late Miocene and middle Pliocene samples suggests that clay minerals were being either neoformed or transformed by the processes of glauconitization. Probably a part of the material identified as illite at Sites 604 and 605 samples is really glauconite.

Smectite may also be contained in glauconite; however, those samples described as glauconitic from observations of smear slides did not contain smectite. There-fore, one is forced to the conclusion that appreciable smectite did not originate with glauconite but rather represents inheritance and/or neoformation from the devitrification of volcanic ash. The latter origin would be better substantiated if quantities of volcaniclastic materials such as volcanic ash were present.

Leg 93 Volcanogenic Minerals

The rather irregular stratigraphic distribution of smectite may support neoformation rather than inheritance and may reflect periodic ash falls in the region. A middle Eocene rhyodacite to rhyolite ash layer found in Sample 605-21-2, 145–147 cm and dated at 40 to 45 Ma by K/Ar methods (von Rad and Kreuzer, this volume) was the only megascopic evidence of volcanism found at Site 605. The presence of silica polymorphs in Site 605 samples suggests volcanic activity; however, the inability to distinguish inorganic, high temperature opal-C from biogenic opal-A precludes the establishment of a positive relationship between a silica polymorph and volcanism (Kastner, 1979).

A number of potential volcanic source areas in the North Atlantic may explain the presence of Paleogene volcanogenic minerals (smectite and possibly cristobalite), including the New England Seamount chain to the east, and Bermuda to the southeast of Site 605. The age of New England Seamount volcanism has been estimated at 110 to 85 Ma (Gradstein and Sheridan, 1983), with

Table 6. Proportions of clay minerals in <2-μm fraction in samples examined for this study.

Hole-Core-Section, cm level	Clay minerals (%)			
	Kaolinite	Chlorite	Illite	Smectite
late Pleistocene				
604-1-1, 130	12	15	66	7
604-6-3, 130	25	32	43	—
604-8-2, 57	23	23	54	—
middle Pleistocene				
605-1-1, 100	10	32	58	—
605-4-3, 100	6	29	65	—
early Pleistocene				
604-10-4, 100	24	13	63	—
605-13-1, 106	17	19	64	—
late Pliocene				
604-16-4, 100	16	17	67	—
604-18-4, 100	5	22	73	—
early Pliocene				
604-22-2, 100	9	24	67	—
604-25-4, 100	45	—	41	14
late Miocene				
604-27-1, 140	36	—	64	—
middle Eocene				
605-7-6, 100	5	—	32	63
605-15-2, 100	48	—	45	7
605-21-3, 100	35	—	65	—
early Eocene				
605-27-1, 100	24	9	67	—
605-33-5, 100	—	—	100	—
605-40-2, 100	19	14	67	—
late Paleocene				
605-48-4, 100	16	—	33	51
605-54-1, 100	40	7	53	—
early Paleocene				
605-59-4, 100	43	—	57	—
605-64-3, 100	—	—	58	42

Note: Dashed rule indicates no samples of late Eocene to middle Miocene age recovered. — indicates searched for but not found.

the "latest significant volcanism" occurring in the early Campanian (78–74 Ma) (Vogt and Tucholke, 1979). The seamounts of the New England Seamount chain were drilled by DSDP Leg 43 (Tucholke, Vogt, et al., 1979), and the easternmost peak of this chain (Nashville Seamount) contained basaltic clasts from volcaniclastic breccias that were dated at 79 ± 4 to 88.3 ± 5.7 Ma by ^{40}Ar/^{39}Ar and by K/Ar dating (Houghton et al., 1979). Reworking of Late Cretaceous volcanic ash produced by eruptions of the New England Seamounts may have produced the Paleogene volcanic alteration minerals found at Site 605. More-weathered volcaniclastic breccias at Site 385 (Vogel Seamount of the New England Seamount

chain) were dated by Houghton et al. (1979) at 38.3 ± 15 to 91.2 ± 3 Ma, an age range in agreement with the Paleocene to middle Eocene cristobalites at Site 605.

Another potential source for Site 605 volcaniclastics is volcanic products from Bermuda volcanoes. Vogt and Tucholke (1979) indicate that the main Bermuda tholeiitic shield volcanoes had been built above sea level by the Late Paleocene (45 Ma). Abundant evidence is found for the deposition of middle Eocene volcaniclastic material at Site 605, including the rhyodacitic-rhyolitic ash layer in Sample 605-21-2, 145–147 cm, and the increased smectite abundances in the middle Eocene samples (605-15-2, 100 cm and 605-7-6, 100 cm) examined in this study. Gradstein and Sheridan (1983) indicate that Bermuda volcanism occurred between the late Eocene and middle Oligocene (50–30 Ma).

Periodic occurrences of possible volcanogenic materials are found in the Neogene to Quaternary sediments of the New Jersey Transect, including early Pliocene smectite and zeolites (604-25-4, 100 cm and 605-22-2, 100 cm), middle Pleistocene zeolites and cristobalite (605-4-3, 100 cm), and late Pleistocene smectite and zeolites (604-6-3, 130 cm and 604-1-1, 130 cm). A number of potential volcanic sources for these materials exists, including Miocene (25–5 Ma) volcanism related to the uplift of the Moroccan Atlas Mountains (Gradstein and Sheridan, 1983) and Miocene volcanism in the Canary Islands, Biscay Seamount, the Cape Verde Islands, and Iceland (Houghton et al., 1979). The Azores Islands are still actively volcanic (Vogt and Tucholke, 1979), but were intermittently active from the early or middle Miocene (19–15 Ma; Anguita and Hernan, 1975). A Miocene basaltic sill recovered at Site 382 on the Sohm Abyssal Plain to the southeast of the Leg 93 sites was dated at 21.0 ± 3 Ma by whole-rock potassium-argon methods (Houghton et al., 1979). This sill was geochemically similar to another Miocene sill recovered at DSDP Site 10 to the southeast, which was dated at 15.9 ± 1.6 Ma by fission-track dating (MacDougall, 1971).

Leg 93 Clay Mineral Facies

Hathaway (1972) described two major clay mineral facies on the continental margin of the eastern United States: a "Northern facies," consisting of illite, chlorite, and traces of feldspar and hornblende, and a "Southern facies," composed of montmorillonite and kaolinite (including mixed-layer montmorillonite–illite and dioctahedral vermiculite). The presence of the "Northern facies" was interpreted as being the result of clay minerals, derived from glacial sources to the north, which moved southward out of estuary mouths along the continental shelf and passed to the continental rise by submarine canyon transport. Of the clay minerals composing the "Southern facies," illite was found only in rivers to the north of Chesapeake Bay, and montmorillonite was found mainly in rivers to the south of the Pamlico Sound estuary in North Carolina. Vermiculite was found to be common to both the northern and southern mineral assemblages, with a maximum in the Pamlico Sound estuary, which approximately divides the sources of the "North-
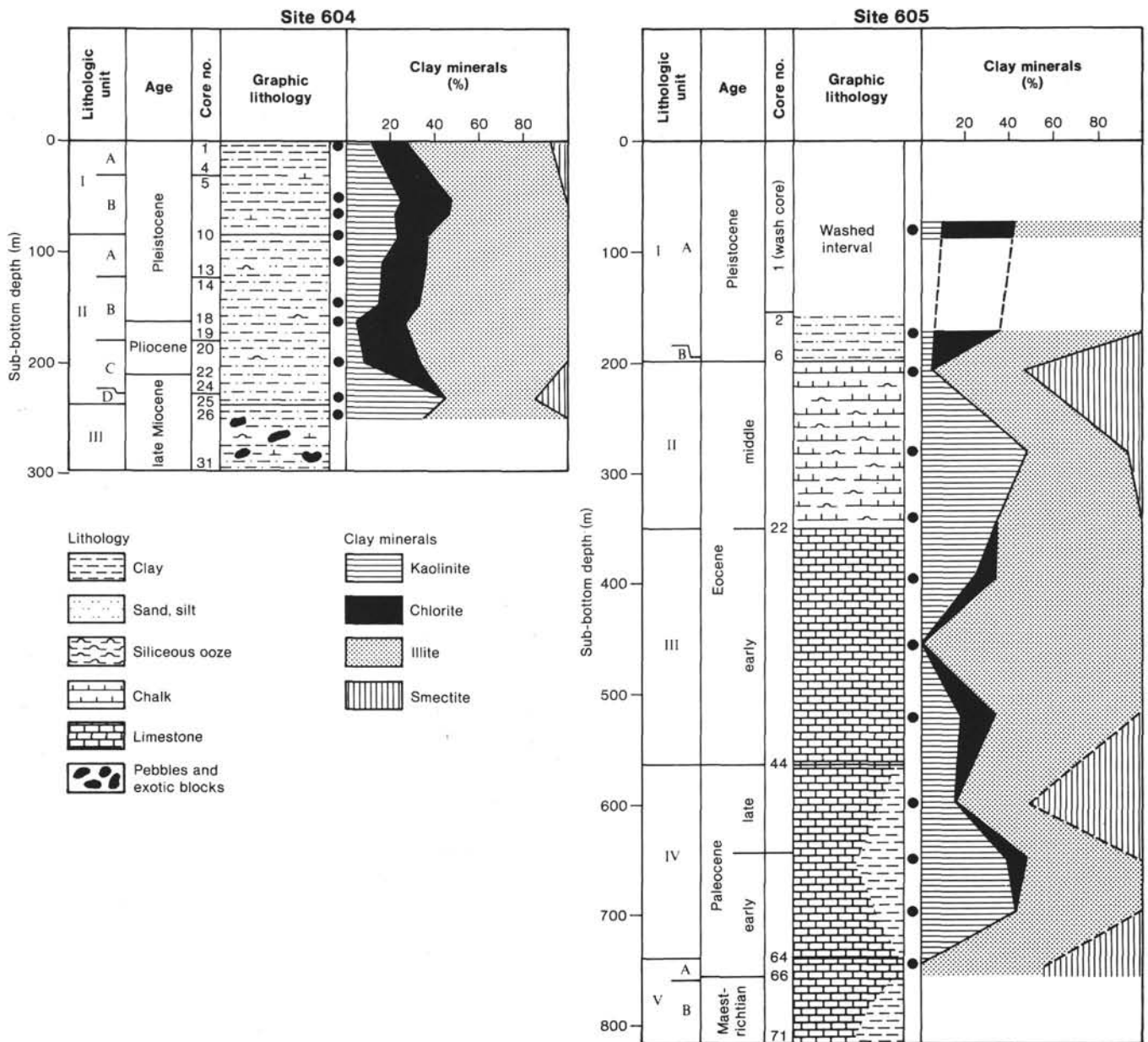
Figure 4. Cenozoic clay mineralogy, graphic lithology, and lithostratigraphy of DSDP Sites 604 and 605. Sample locations are indicated by large dots next to the graphic lithology columns.

ern" and "Southern clay mineral facies." No dioctahedral vermiculite was found to the north of the Chesapeake Bay estuary.

The distribution of clay minerals in the Leg 93 New Jersey Transect sites parallels that discussed in Hathaway (1972), as clay minerals of the post-middle Miocene sediments are similar to the "Northern facies," with dominant illite, plus chlorite, feldspar, and amphibole. No feldspar was found in sediments older than Miocene age, and only one occurrence of amphibole was found in Paleogene sediments (late Paleocene Sample 605-48-4, 100 cm). Because chlorite and feldspar are readily susceptible to chemical weathering (Biscaye, 1965), their presence in post-middle Miocene sediments at Sites 604 and 605 may reflect glacial erosion of the Appalachian

Mountains, with relatively unweathered minerals being carried to the edge of the North American continent by the ancestral Hudson, Delaware, and other rivers emptying into the northwestern Atlantic Ocean.

Although the Paleogene clay mineralogy of Site 605 is generally similar to the "Southern facies" of smectite, kaolinite, and mixed-layer illite–smectite (Hathaway, 1972), there are differences between Site 605 Paleogene mineralogy and Hathaway's model. At Site 605, Paleogene sediments are dominated by illite, with kaolinite and smectite covarying in inverse proportions to each other (Fig. 4), a pattern in overall agreement with that of the "Southern clay mineral facies." However, significant quantities (7–15%) of chlorite were present in late Paleocene and early Eocene samples at Site 605, in contrast to the Ha-
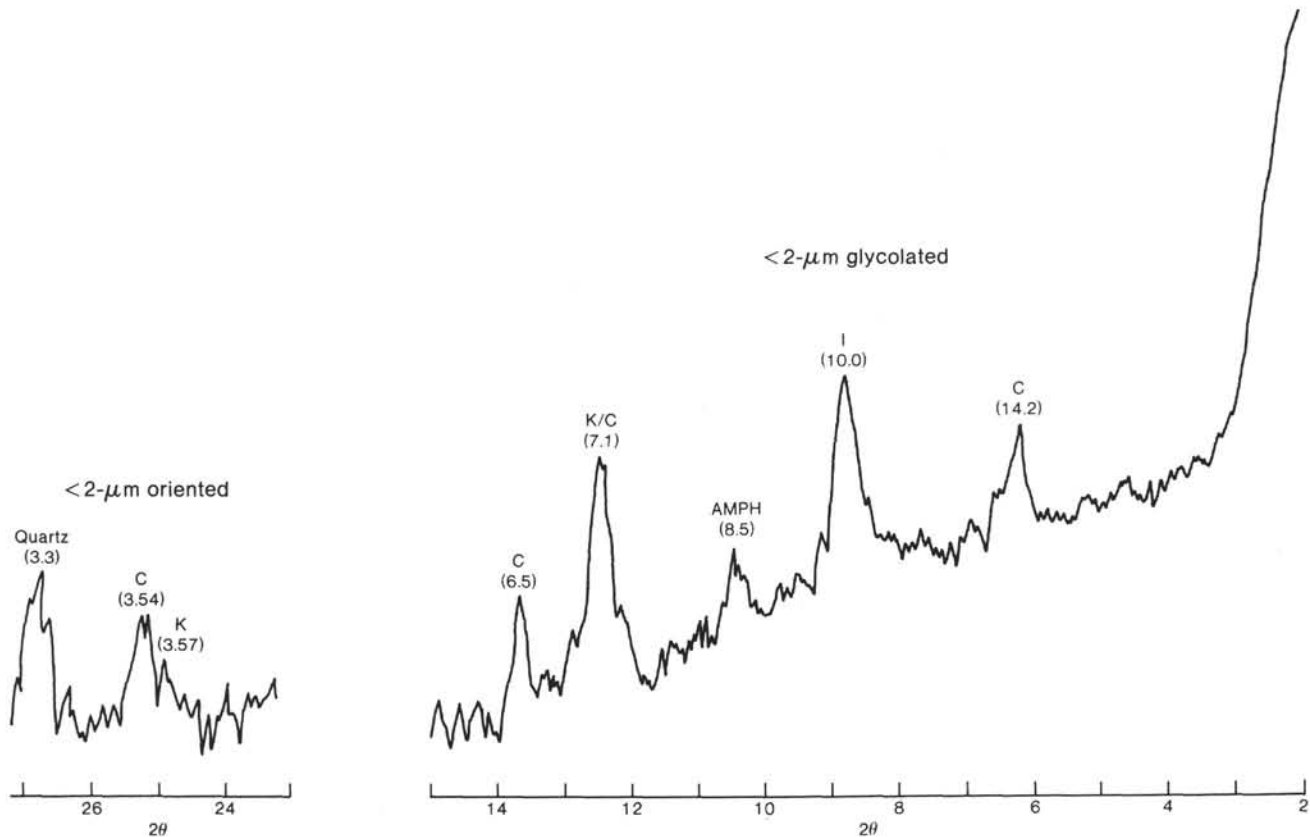
Figure 5. X-ray diffractogram of the <2-μm fraction of Sample 604-18-4, 100 cm, indicating typical 14-Å chlorite (C), illite (I), and kaolinite (K) peaks seen in samples saturated with ethylene glycol. A small 8.5-Å amphibole peak (AMPH) is also seen in this diffractogram. Kaolinite-chlorite proportions were estimated based on relative areas under the 3.57- and 3.54- Å peaks seen on diffractograms of oriented <2-μm samples, as shown on the left.

thaway model, which puts chlorite exclusively in the "Northern clay mineral facies." Thus it would appear that chlorite was being transported at least sporadically to the edge of the North American continent during the Paleogene, and being incorporated into marine sediments of the upper continental rise. Another difference between Site 605 mineralogy and the "Southern clay mineral facies" is the dominance of illite at Site 605, in contrast to the predicted dominance of smectite in the "Southern facies."

Comparison of Site 604 and 605 Clay Mineralogy with Other North Atlantic DSDP Sites

The "Northern clay mineral facies" at Sites 604 and 605 is similar to the clay mineral distributions seen in Neogene–Quaternary sediments of nearby DSDP holes drilled on the lower continental rise and abyssal plains of the northwestern Atlantic Ocean. The Neogene–Quaternary clay mineralogy of Leg 93 sites is very similar to nearby DSDP Sites 388, 105, 106.

Flood (1978) found that at Site 388 in the lower continental rise hills to the southeast of the Leg 93 sites, lower Pleistocene to Recent sediments (lithologic Unit 1) contained kaolinite, illite, calcite, and quartz. Middle to late Miocene silty clays of Unit 2 contained dominant illite and smectite, with kaolinite, chlorite, quartz, and siderite also present. Flood used the presence of the "Northern clay mineral assemblage" (illite, chlorite, fine-

grained quartz particles, feldspar, and hornblende; Hathaway, 1972) at Site 388 as an indicator of post-Miocene erosion of Paleozoic and older sedimentary and metamorphic rocks of the northern Appalachian region due to Northern Hemisphere glaciation.

At nearby Site 105, also at the foot of the lower continental rise, to the southeast of the Leg 93 New Jersey Transect sites, Pliocene–Holocene hemipelagic muds were found to have dominant illite, with quartz, kaolinite, and smectite (Zemmels et al., 1972). Chlorite was found in the middle Miocene–Pleistocene, and the zeolite clinoptilolite was present in altered upper Oligocene to middle Miocene volcanic ash beds. Chlorite and illite were the dominant clay minerals in Pliocene to Recent sediments at Site 105, in agreement with Hathaway's (1972) "Northern clay mineral facies." Site 106, also located at the foot of the lower continental rise to the north of Site 105, only recovered a few cores containing early to late Pleistocene sediments, but they contained illite, quartz, calcite, amphibole, chlorite, and kaolinite (Zemmels et al., 1972), with an early Pleistocene palygorskite peak. Thus Pleistocene sediments of cores recovered from Site 106 also contain Hathaway's "Northern clay mineral assemblage."

So, DSDP cores in the western North Atlantic from both the upper continental rise (Sites 604 and 605) and the lower rise (Sites 388, 105, 106) contain evidence of post-middle Miocene glacial erosion of the North Ameri-
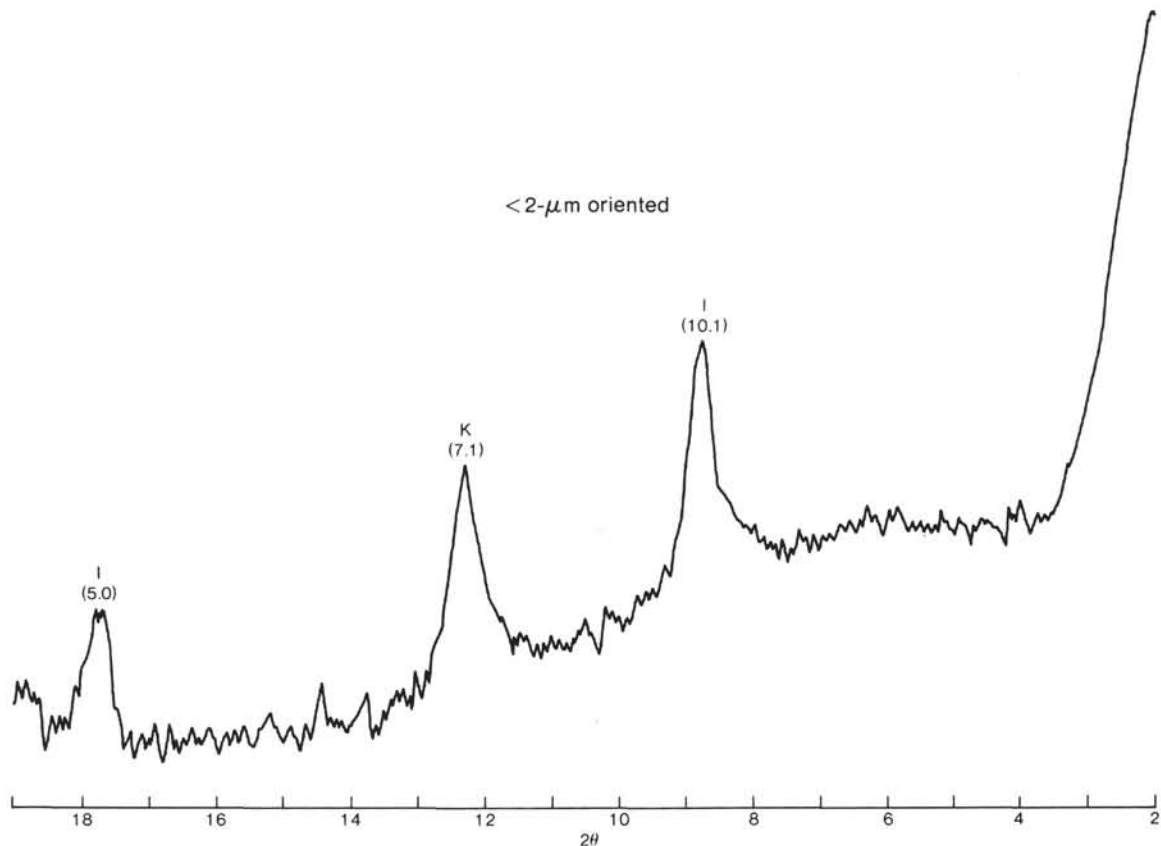
<2-μm oriented

Figure 6. X-ray diffractogram of the <2-μm fraction of Sample 604-27-1, 140 cm, indicating typical peaks for illite (I) and kaolinite (K) seen in samples of this study.

can continent, as evidenced by deposition of the "Northern clay mineral assemblage" (Hathaway, 1972) in these sediments. The dominant illite and chlorite at these sites is mixed with minor amounts of kaolinite and smectite from the "Southern clay mineral assemblage," which may have been transported northward by strong surface currents prior to deposition on the continental rise. Additional evidence of deposition of sediments derived from continental erosion at DSDP sites on the continental rise is provided by the presence of easily altered feldspar and hornblende, found both on the lower continental rise in middle to late Miocene sediments at Site 388, in early to late Pleistocene sediments at Site 106, and also on the upper continental rise in late Pliocene to Recent sediments at Sites 604 and 605.

A comparison between the Leg 93 New Jersey Transect Cenozoic clay mineralogy and equivalent sediments on the eastern margin of the North Atlantic Basin is possible by referring to the clay mineralogy sampled by drilling on the Moroccan continental margin by DSDP Leg 79 (Hinz, Winterer, et al., 1984). Although Leg 79 sediments contain greater amounts of calcium carbonate, because of greater upwelling off northwestern Africa (Hinz, Winterer, et al., 1984), the clay mineralogy of Leg 79 sediments is quite similar to the Sites 604 and 605 record.

Leg 79 drilled Sites 544 to 547 on the Mazagan Escarpment off northwestern Africa, and a preliminary study of the clay mineralogy of these sites was made by Schu-

mann (1984). At Site 544, Holes 544A and 544B (3607 m water depth) recovered early middle Miocene to Pleistocene clayey foraminiferal nannofossil ooze. Clay minerals of this lithologic unit were dominated (>50%) by illite, with minor (10-15%) amounts of kaolinite, chlorite, and smectite. Palygorskite and sepiolite were found in rare (2-8%) quantities in these sediments. The presence of these fibrous silicates was interpreted as resulting from downslope transport by turbidity currents from the Moroccan margin alkaline basins where they were formed. Site 545, drilled at the foot of the Mazagan Escarpment at a water depth of 3142 m, recovered early Miocene to Pleistocene clayey foraminiferal nannofossil oozes, which were also dominated by illite, with minor (10-15%) chlorite and kaolinite, and trace to minor (<5%) amounts of smectite. Some mixed-layer clays (illite and chlorite/smectite) and fibrous clays (palygorskite and sepiolite) were also present at this site. The Sites 544 and 545 sedimentary records primarily contain clay minerals from the "Northern clay mineral facies" of Hathaway (1972), with dominant illite and chlorite, and trace quantities of feldspar. However, they also contain minor amounts of smectite and kaolinite, which are part of the "Southern clay mineral assemblage" of Hathaway (1972), so these sediments may represent a mixture of tropical and temperate clay mineral sources.

Site 546 was drilled atop a structural high in 3992 m water depth, and recovered middle Miocene to Pleistocene clayey foraminiferal-nannofossil ooze above Juras-
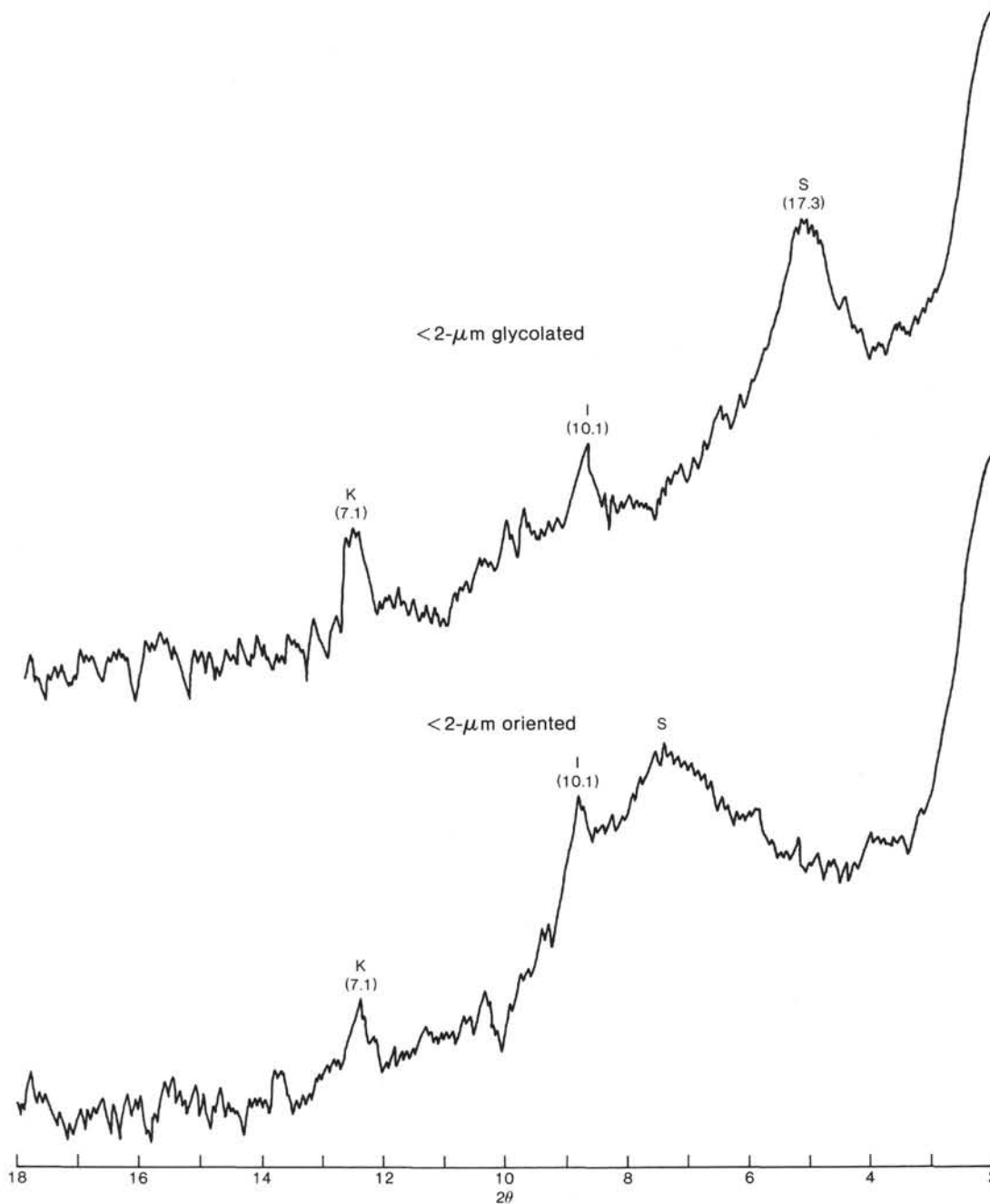
Figure 7. X-ray diffractogram of the <2-μm fraction of Sample 604-48-4, 100 cm, and the <2-μm fraction after saturation with ethylene glycol. The presence of smectite (S) is seen by a 17Å peak in the glycolated sample, whereas peaks of illite (I) and kaolinite (K) are not affected by glycolation.

sic halite and claystones. Neogene clay minerals at this site were again dominated by illite, with minor chlorite and kaolinite, and trace amounts of smectite and feldspar. No fibrous clays were found at this site. Neogene sediments at Site 546 contain clay minerals attributable to the "Northern clay mineral assemblage," and also contain trace amounts of smectite and kaolinite from the "Southern clay mineral assemblage," as did the sediments of Sites 544 and 545.

Site 547 was drilled on the same structural block as Site 544, but to the east–northeast, in 3940.5 m water depth. Site 547 recovered a relatively complete Cenozoic

sedimentary section, with Late Cretaceous to early Oligocene clayey nannofossil chalk and nannofossil claystone dominated by smectite and illite, and trace amounts of kaolinite, chlorite, and feldspar. Above an early Oligocene/early Miocene unconformity, early to late Miocene clayey nannofossil ooze and Pliocene–Pleistocene foraminiferal–nannofossil ooze contained dominant illite, with minor (10–15%) but approximately equal amounts of chlorite and kaolinite. Neogene samples at Site 547 contained minor (10–30%) smectite in late Miocene sediments, and trace (<5%) amounts of smectite in Pliocene–Pleistocene sediments. As at Site 546, no sepiolite

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or palygorskite was found in Cenozoic sediments from this site.

There is a strong similarity between the clay mineralogies of DSDP Site 547, on the Moroccan continental margin, and Sites 604 and 605, on the New Jersey continental margin. Sediments from both the western margin and the eastern margin of the North Atlantic Ocean demonstrate dominance of the "Southern clay mineral assemblage" (Hathaway, 1972) in Paleogene strata, with smectite and kaolinite being the dominant clay minerals. These sediments are unconformably overlain by Miocene to Recent strata whose clay mineralogy is dominated by illite and chlorite, the "Northern clay mineral assemblage." Neogene sediments in both locations also contain easily altered nonclay minerals, feldspar and amphibole, which are assumed to represent erosion of Northern Hemisphere continents by continental glaciation.

The similarity of the clay mineralogy of Leg 93 sediments and Leg 79 sediments is perhaps greater than expected, even considering that paleoreconstructions (closure of the North Atlantic Basin) would place these two sets of drill sites very close to each other. The only major difference between the clay mineralogy of the Leg 93 sites examined in this study and the Leg 79 sites (Schumann, 1984) is the lack of fibrous silicates (sepiolite and palygorskite) at Sites 604 and 605. The fibrous silicates are neoformed clay minerals, which form in humid subtropical environments, commonly in alkaline basins. Because of the greater latitude of potential source basins for Leg 93 clay minerals, it is not likely that the conditions necessary for neoformation of these fibrous clays were present in the northeastern part of North America.

CONCLUSIONS

The sediment record recovered at Sites 604 and 605 on the New Jersey Transect agrees in general with the stratigraphic division proposed by Olsson (1978) for the eastern costal plain of the United States. At these sites, Paleocene marls and nannofossil limestones, early Eocene nannofossil chalks to limestones, and middle Eocene biogenic silica-rich nannofossil chalks are separated by a disconformity from Pliocene–Pleistocene silty clays and claystones. At Site 604 a middle to late Miocene debris-flow unit composed of glauconitic silty claystone and conglomerate, reworked Eocene chalk and limestone, and exotic pebbles to cobbles is found below the early Pliocene claystones, but this unit was deliberately avoided in the offset to drill Site 605.

The clay mineralogy of these Leg 93 sites agrees in general with the model proposed by Hathaway (1972), which designates a "Northern clay mineral assemblage" composed of illite and chlorite, with associated feldspar and hornblende, and a "Southern clay mineral assemblage" composed of smectite and kaolinite, with mixed-layer illite–smectite clay minerals. The "Northern assemblage" is found in Leg 93 sediments atop the uppermost middle Eocene to middle Miocene disconformity, and the "Southern assemblage" typifies the Paleogene sediments at both sites. The clay mineral distribution and stratigraphy of Sites 604 and 605 agrees with the stratigraphies of nearly DSDP sites drilled on the lower continental rise and abyssal plains of the western North Atlantic (DSDP Sites 388, 105, and 106). The clay mineral stratigraphy of this study is also similar to the clay mineral stratigraphy of DSDP Leg 79 sites (544–547) drilled on the Mazagan Escarpment off northwestern Morocco, with the exception that fibrous clay minerals (sepiolite and palygorskite) seen at Leg 79 sites are not found at Sites 604 and 605. The absence of the fibrous clays is probably due to the lack of humid alkaline nearshore basins necessary for the neoformation of these fibrous silicates. Thus an apparent similarity may be noted between the clay mineralogy of the western and the eastern margins of the Cenozoic North Atlantic Ocean by comparing the records of Legs 93 and 79.

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