39. X-RAY MINERALOGY OF THE CLAY FRACTION FROM CENOZOIC STRATA, LEG 94: COMPARISON WITH PREVIOUS NORTH ATLANTIC DATA[1]

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ABSTRACT

Leg 94 Sites are located in a large geographic area of the northeastern Atlantic. Clay mineral analyses of the sediments recovered on Leg 94 (Eocene to the present), together with results obtained from previous DSDP legs (47B, 48, 80, 81, 82), provide greater insight into the paleoenvironmental evolution of the northeastern Atlantic.

The characteristics of Eocene clay sediments are regional, reflecting, in the absence of strong bottom currents, the influence of neighboring petrographic environments: basic volcanic rocks (Sites 403–406, 552, and 608) and acid volcanic rocks (Sites 508 to 510). During the Oligocene, atmospheric circulation patterns left their mineralogical signatures in the southern part of the area investigated (Sites 558 and 608), whereas during the Miocene the intrusion of northern water masses led to the gradual homogenization of the clay sedimentation throughout the North Atlantic. In the late Pliocene, input from glacial sources became widespread.

INTRODUCTION

Samples studies are from six sites located between 38°N and 53°N. Their ages range from Miocene to the present. A few Eocene and Oligocene samples, from Site 608 only, have been investigated (Fig. 1). X-ray diffraction was used in the mineralogical analysis of the samples (see Appendix).

The primary objective of this study was to confirm or question hypotheses previously put forward in mineralogical studies of North Atlantic sediments from DSDP Legs 47B, 48, 80, 81, and 82 (Chamley et al., 1979; Chennaux et al., 1985; Latouche and Maillet, 1979, 1984, and in press). The main conclusions drawn from these studies were as follows:

1. Strong regional mineralogical characteristics in each northeastern Atlantic domain from the Eocene to the early Miocene.
2. Mineralogical uniformity in the northeastern Atlantic from the middle Miocene to the present, attributed to intense circulation of bottom waters in various regions, after the intensification of oceanic circulation in the early Miocene (Roberts and Montadert, 1979).
3. Wide distribution of northern clay minerals toward the south as a result of climatic variations (glacial cycles) in the Pliocene and Quaternary.

Interpretation of the different mineralogical assemblages was based on work by several authors, in particular that of Millot (1964), Yeroschev-Shak (1964), Biscaye (1965), Bonatti (1967), Griffin et al. (1968), Rateev et al. (1969), Paquet (1969), Tardy (1969), and Chamley (1971, 1979).

Because bulk sample analyses showed very high carbonate contents, only fractions in which $CaCO_3$ had been dissolved were used in the mineralogical analysis of coarse detritus. These fractions represent only a small part of the total sediment, and are considered to be detrital sediments of continental origin.

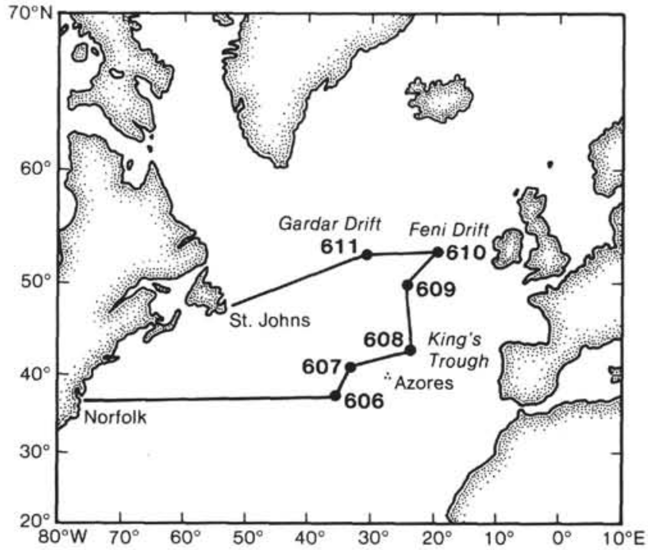

Figure 1. Locations of the sites drilled, Leg 94.

The carbonate-free fraction with a grain size of less than 2 μm consists mainly of abundant smectite in Eocene, Oligocene, and Miocene deposits. Smectites may either originate from badly drained soils under a warm climate with contrasting seasons (Millot, 1964; Paquet, 1969), as evidenced by their present latitudinal distribution (Biscaye, 1965; Rateev et al., 1969), or they may result from the submarine or subaerial alteration of basic volcanic material (Yeroschev-Shak, 1964; Bonatti, 1967).

Illites are well represented in the Pliocene and Quaternary, and are often associated with chlorites. They may result from the erosion of crystalline or metamorphic rocks, and are common at the present time in marine deposits (Biscaye, 1965; Rateev et al., 1969).

[1] Ruddiman, W. F., Kidd, R. B., Thomas, E., et al., *Init. Repts. DSDP*, 94: Washington (U.S. Govt. Printing Office).
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Kaolinites are best represented at Site 606, the southernmost site. These clay minerals occur in small quantities in the Pliocene and Quaternary sediments of all six sites; they are characteristic of alteration processes in humid tropical climates. Their origin is generally thought to be detrital and continental. They are present in most samples of the Miocene and Quaternary, but are so rare that they can not be regarded as climate markers.

Quartz and feldspars associated with the fine-grained fraction ($<2\ \mu m$) have been identified at Site 608 in Oligocene sediments and at all other sites in Pliocene and Quaternary sediments; they are detrital and continental. They occur throughout the Oligocene at Site 608, accompanied by illites, kaolinites, and chlorites. No coarse fraction of quartz and feldspars was found; they are so poorly represented in the bulk samples as to be barely identifiable. Since they occur only in the fine-grained fraction, their presence has been attributed to eolian flux (Grousset et al., 1983). Quartz detected both in fine and coarse fractions (as in the Pliocene and Quaternary sediments) is assumed to have been transported by marine currents or by ice. Such an assumption, however, does not necessarily exclude the possibility of eolian input masked by minerals carried in other ways.

RESULTS AND DISCUSSION

Site 606 (Fig. 2 and Table 1)

This site is on the western flank of the Mid-Atlantic Ridge, southeast of the Azores and close to Site 335 (DSDP Leg 37), and in the same region as DSDP Leg 82 sites.

The sediments sampled are Pliocene and Quaternary, and are composed mainly of foraminiferal nannofossil oozes.

Lower Pliocene. Smectites are dominant (48%); illites, kaolinites, and chlorites are present. Minerals are well crystallized.

Upper Pliocene. This sample has the same clay minerals as in the lower Pliocene, but there is a slight predominance of illites over smectites. The mineral crystallinity is good.

Quaternary. Illites predominate, whereas smectites diminish and kaolinites and chlorites increase with respect to the Pliocene samples. Mineral crystallinity is fair. Quartz and feldspars are always present in the Pliocene and Quaternary, and have been identified in both the bulk sample and the fine-grained fraction.

Site 606 Environment

Because the number of samples analyzed was limited, we found it useful to compare our results with previous results from samples collected at neighboring sites (Legs 37 and 82).

Samples from Site 606 are characterized by a clay mineral assemblage with dominant smectite. Smectites are less dominant, however, in the upper Pliocene and progressively surpassed by illites and chlorites in the Quaternary. Mineralogical analyses of Leg 82 samples (Latouche and Maillet, in press) from sites close to Site 606 showed similar assemblage variations: an increase of illites and chlorites from the upper Miocene throughout the Pliocene and Quaternary. We have attributed these mineralogical changes to an intensification in north-to-south oceanic circulation.

On the basis of a planktonic foraminiferal study of Site 335 (Leg 37), near Site 606, Miles and Howe (1977) suggested that cooling of water masses took place in a period between the middle Miocene and the Pliocene; this would confirm the arrival of water masses from the

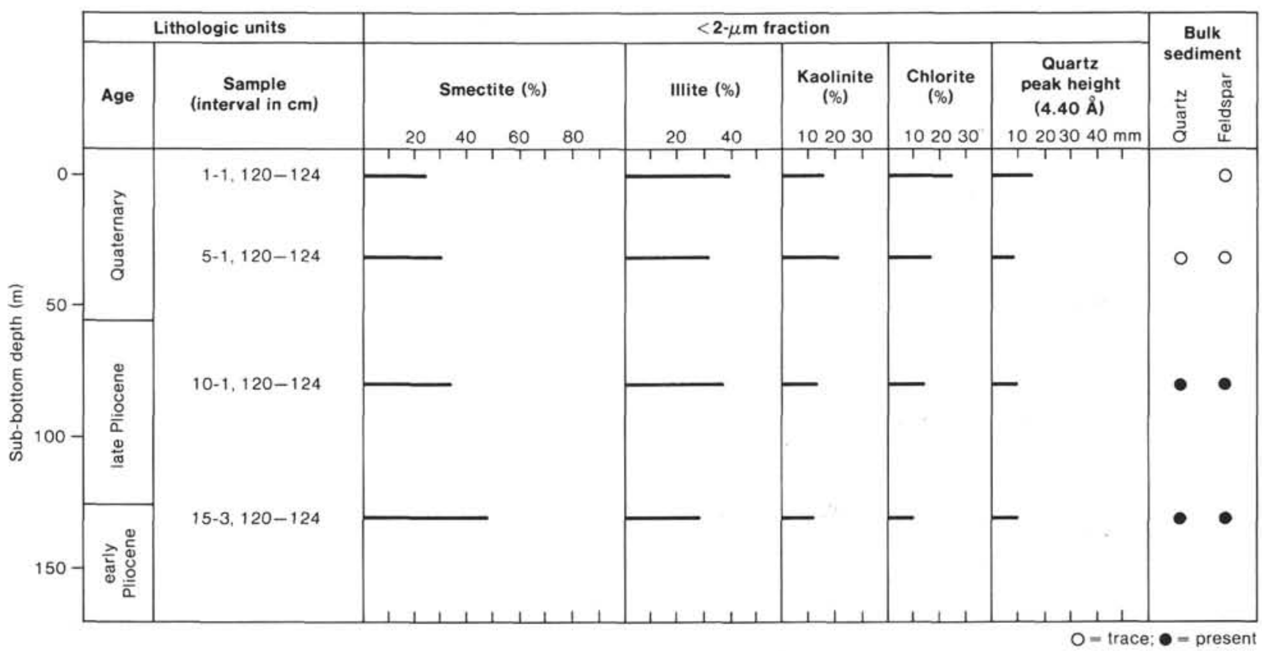

Figure 2. Mineralogical log of Site 606 (Hole 606).

Table 1. Mineralogical data, Site 606.

Sample (interval in cm)	Sub-bottom depth (m)	<2-μm fraction Smectite (%)	Illite (%)	Kaolinite (%)	Chlorite (%)	Quartz peak height (mm)	Bulk sediment Quartz	Feldspar
606-1-1, 120-124	1.24	21	40	15	24	15		Trace
606-5-1, 120-124	32.85	31	32	21	16	8	Trace	Trace
606-10-1, 120-124	80.85	35	38	13	14	10	Present	Present
606-15-3, 120-124	131.55	48	29	13	10	19	Present	Present

north into this region. Likewise, the mineralogical evolution of the Site 606 sediments (smectites, illites, kaolinites, chlorites) is a further indication of the arrival of this northern water mass and a northern origin of clays. The increase in illite and chlorite in the Quaternary could be associated with glacial phenomena: ice-rafting in this period reached to latitudes as low as the 40th parallel (Shor and Poore, 1979; Davies and Laughton, 1972), that is, the Azores region neighboring Site 606. Even if transport by ice had not gone as far as the Azores, clay minerals, once released from ice, could have been transported by currents to a more southern part of the basin.

Site 607 (Fig. 3 and Table 2)

Site 607 is on the upper middle western flank of the Mid-Atlantic Ridge. Sediments studied are upper Miocene, Pliocene, and Quaternary.

Upper Miocene: Foraminiferal nannofossil ooze. Smectites are abundant, illites well represented; kaolinites and chlorites are present. All clay minerals are highly crystalline.

Lower Pliocene: Nannofossil ooze. The clay mineral assemblage is dominated, as in the upper Miocene, by smectites.

Quaternary: Nannofossil ooze, foraminiferal nannofossil ooze, and marly foraminiferal nannofossil ooze Illite is dominant, chlorite more abundant than in the Pliocene, and smectite less abundant. The clay minerals are moderately crystallized and scarce.

All levels studied show evidence of quartz in the fine fraction. Quartz and feldspars in the bulk sediment are infrequent, but they are slightly better represented in the Quaternary.

Site 607 Environment

Variations are evident in the clay mineral assemblage of sediments at Site 607. In the upper Miocene and the lower Pliocene, smectites predominate. Conversely, throughout the Quaternary the mineral assemblages are characterized by the predominance of illite and chlorite. Previous DSDP sites in this region are few. Comparison with distant sites, such as those of Legs 48, 80, 81, and 82 (Chennaux et al., 1985; Latouche and Maillet, 1979, 1984, and in press), show clay-mineralogical similarities. Oceanic input from the north probably accounts for the arrival of these minerals (e.g., illites and chlorites), as in the Rockall region.

The distinct increase in illites and chlorites throughout the Quaternary, as well as the occurrence of quartz in both the fine fraction and the bulk sediment, may be linked to glacial cycles. Quaternary sedimentation north of the 40th parallel is marked by ice-rafting phenomena (Shor and Poore, 1979). It is probable, therefore, that quartz detected at Site 607 has been transported by floating ice.

Site 608 (Figs. 4 and 5 and Table 3)

Site 608 is on the southeastern flank of the King's Trough tectonic complex. Sediments are Quaternary to middle Eocene, which is in contact with basalt reached in Core 608-58.

Middle and upper Eocene: Marly nannofossil chalk and volcaniclastic nannofossil chalk. Clay minerals are represented chiefly by highly crystalline smectites. These show an 060 reflection at 1.50 Å, as is characteristic of aluminous smectites (Desprairies, 1983). In Sample 608-54-4, 100–104 cm, a 10-Å mineral of the illite type has been identified.

The grain-size fraction <2 μm in Samples 608-57-1, 135–137 cm and 608-54-4, 100–104 cm reveals traces of zeolite (clinoptilolite).

Upper Oligocene and lowermost Miocene: Marly nannofossil chalk. The clay mineral assemblage is dominated by smectites, but illites, kaolinites, and chlorites (minerals not present in the Eocene) are also present. Quartz is present in the <2-μm fine-grained fraction.

Lower and middle Miocene: Nannofossil chalk. Smectite is present exclusively, as in the middle and upper Eocene. Smectites are highly crystallized and aluminous in the lower Miocene (060 reflection at 1.50 Å), in contrast with the middle Miocene, where smectites are barely crystalline and are accompanied by amorphous matter (higher background at about 4.24 Å).

Upper Miocene, Pliocene, and Quaternary: Nannofossil ooze and foraminiferal nannofossil ooze. In the lowermost sample, as in the middle Miocene, smectites are the only clay minerals present, but here they are highly crystalline.

From Sample 608-25-1, 130–134 cm to the top of the hole, illites, kaolinites, and chlorites increase in relative abundance. This increase is marked from the upper Pliocene upsection (608-10-1, 130–134 cm). The uppermost Quaternary sample (608-1-1, 130–134 cm) is characterized by the predominance of illite. The <2-μm quartz occurs at the same level as illites, kaolinites, and chlo-

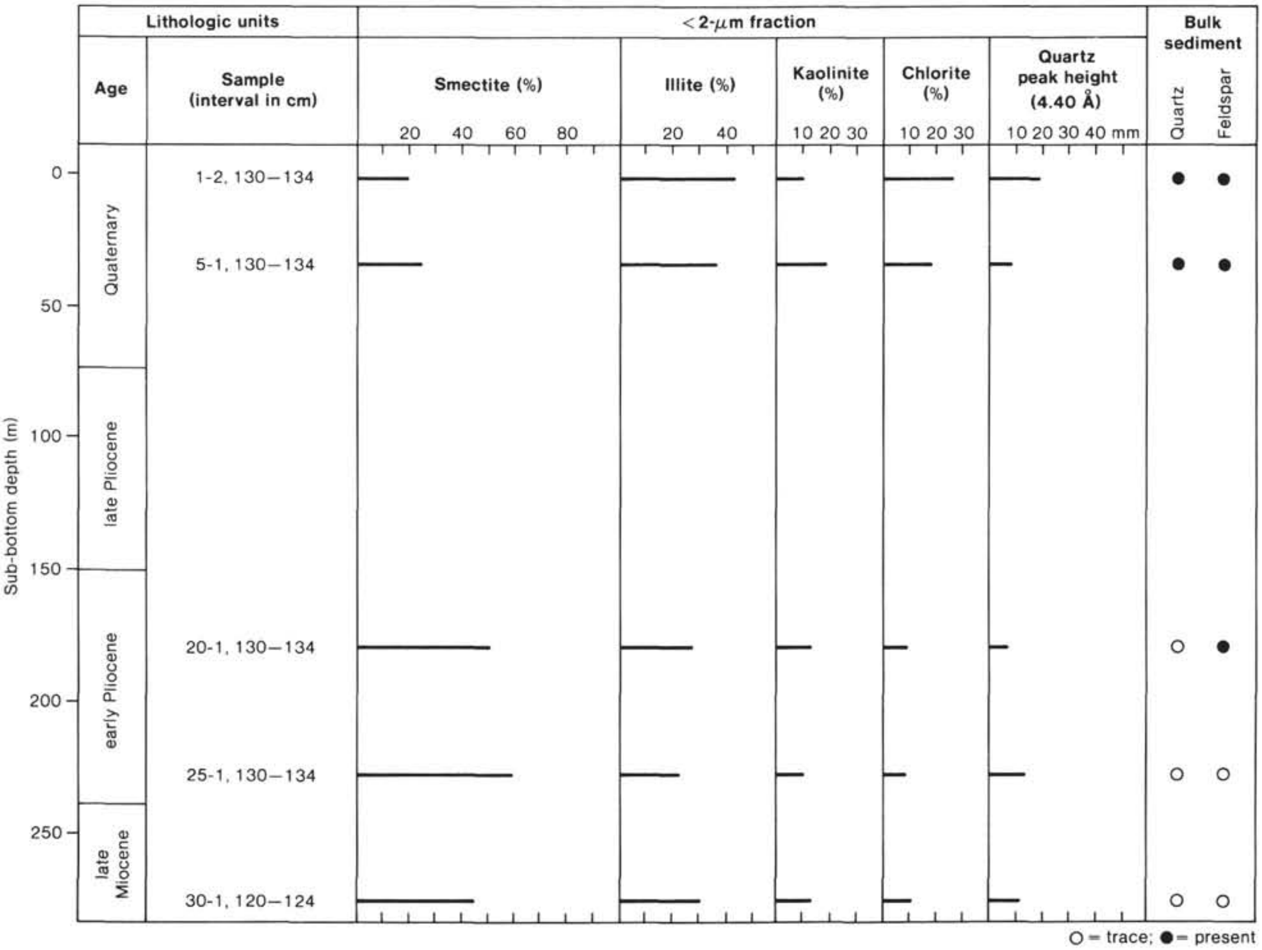

Figure 3. Mineralogical log of Site 607 (Hole 607).

Table 2. Mineralogical data, Site 607.

Sample (interval in cm)	Sub-bottom depth (m)	<2-μm fraction Smectite (%)	Illite (%)	Kaolinite (%)	Chlorite (%)	Quartz peak height (mm)	Bulk sediment Quartz	Feldspar
607-1-2, 130–134	2.80	18	44	11	27	20	Present	Present
607-5-1, 130–134	35.80	25	31	19	19	10	Present	Present
607-20-1, 130–134	180.10	50	28	13	9	7	Trace	Present
607-25-1, 130–134	228.10	59	23	10	8	15	Trace	Trace
607-30-1, 120–124	276.00	45	31	13	11	12	Trace	Trace

rites. In the bulk sediment, quartz is identifiable only in the Quaternary (608-9-1, 130–134 cm and 608-1-1, 130–134 cm).

Site 608 Environment

At this site, where Eocene was recovered, there are several variations in the clay mineral assemblage. In the middle Eocene and the middle Miocene, clays are exclusively smectite. In the upper Oligocene, they are associated with illite, kaolinite, and chlorite and with <2-μm quartz. In the upper Miocene, illites and chlorites reappear and increase in relative abundance up to the Quaternary.

After the Eocene sedimentation, which was strongly influenced by volcanic ash and glass, probably accounting for the smectite, the Oligocene deposition was marked by the arrival of "primary" clay minerals (illite and chlorite) and also by fine-grained quartz. This clay mineral assemblage fades out in the Miocene. Kidd et al. (1982) suggested in their study of King's Trough that local tectonism occurred between 21 and 33 Ma. Such an uplift could have prevented the arrival of "detrital" minerals by blocking the bottom currents. Oligocene sediments from farther southwest (Hole 558) show the same mineralogical (illite, chlorite, quartz) assemblage patterns. We have attributed these assemblages to eolian trans-

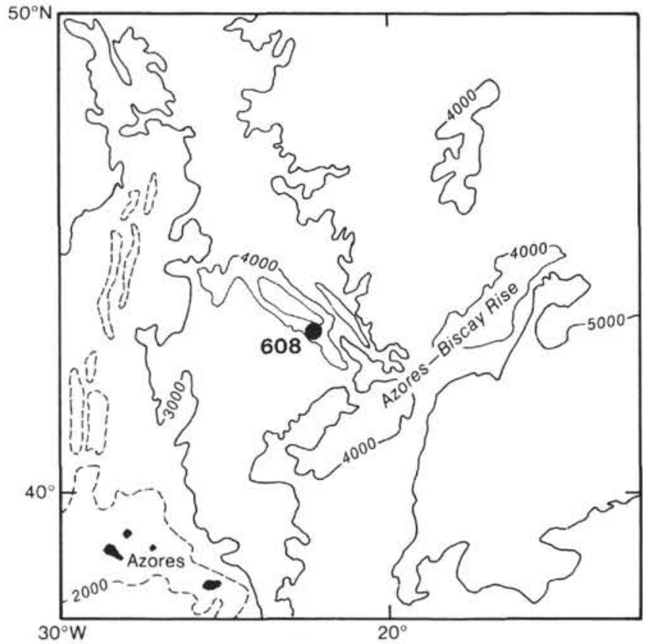

Figure 4. Location of Site 608, King's Trough complex.

port (Leg 82, Latouche and Maillet, in press), and the appearance of quartz, illite, chlorite, and kaolinite at Site 608 supports this attribution.

In the middle Miocene, the clay sediments become once more identical to the Eocene sediments, thereby suggesting the end of the eolian input.

The second interesting feature at Site 608 is the reappearance—after an episode rich in smectite—of illite, kaolinite, and chlorite, associated with fine-grained quartz, in the upper Miocene. This change in the mineralogical assemblage corresponds to a period of intense exchange between the high and low latitudes in the northeastern Atlantic, resulting from vigorous oceanic circulation. Thus, bottom currents could account for the arrival of minerals such as illites and chlorites. Eolian transport, to which we have attributed arrival of the minerals in the Oligocene, could also have contributed to this new influx, but the changes in oceanic circulation could account for the mineralogical changes without eolian input.

The sharp increase in illite, chlorite, and quartz in the upper Pliocene is as striking as at any other northeastern Atlantic sites (e.g., Sites 403, 404, 405, and 406, Leg 48; Latouche and Maillet, 1979). This phenomenon is closely related to the effect of ice-rafting.

Site 609 (Figs. 6 and 7 and Table 4)

Site 609 is on the upper middle eastern flank of the Mid-Atlantic Ridge, WSW of Ireland and south of the Charlie Gibbs Fracture Zone. The sediments studied are upper Miocene to Quaternary.

Lower Miocene and Pliocene: Nannofossil chalk and nannofossil ooze. Smectites are abundant (more than 60%), illites, kaolinites, and chlorites present. Smectites are aluminous (060 reflection at 1.50 Å).

Upper Pliocene and Quaternary: Nannofossil ooze and marly nannofossil ooze. Smectite is predominant near the base, but progressively illite becomes predominant upsection; chlorites and kaolinites also increase. Quartz associated with the <2-μm fraction occurs throughout the section and increases distinctly in the uppermost Quaternary. In the bulk samples, quartz is usually present in the Miocene as well as the Quaternary sediments. Feldspars are also well represented.

Site 609 Environment

The mineralogical assemblage of sediments at Site 609 is highly variable, from dominantly smectitic in the upper Miocene and lower Pliocene to dominantly illitic in the Quaternary.

This site is exceptional for the constant occurrence of quartz in the bulk sediment, giving the sedimentation pattern its detrital nature.

The site's location in the vicinity of the southern branches of the Maury Channel, which drained sands and silts (Ruddiman, 1972) in the late Pliocene and Pleistocene, could account for the occurrence of quartz in the bulk sediment. It is most likely that quartz input from the Maury Channel occurred in this region earlier than did input by glacial processes at other sites, but in small quantities. The occurrence of quartz at this site shows that an Icelandic origin of detritus, as proposed by Ruddiman (1972) for the Pleistocene, could also be valid for the Miocene. Icelandic detritus is, however, derived mainly from the weathering of basic volcanic rocks, which contain very little quartz.

The variability in the clay mineralogical assemblages could also be due to the very presence of the Maury Channel. The progressive increase in illite is similar to the increase at the other sites—where illite was carried by north-to-south oceanic circulation—and was certainly favored by the Channel's presence.

The sudden increase of illites and chlorites in the upper Pliocene, related to the presence of the Maury Channel (Ruddiman, 1972), also corresponds in time to the first effects of ice-rafting.

Site 610 (Figs. 6 and 8 and Table 5)

Site 610 is on the western side of Rockall Trough, at the crest of Feni Drift. Holes drilled yielded lower Miocene to Quaternary sediments.

Lower Miocene: Nannofossil chalk and marly nannofossil chalk. The dominant characteristic is the abundance of aluminous smectites (77–92%); illites are present, but kaolinites and chlorites are only barely represented. There is also evidence of the presence of quartz in both the fine-grained fraction and the bulk sample.

Middle and upper Miocene: Nannofossil chalk. Smectite is the dominant mineral, but illite, chlorite, and kaolinite are more abundant than in the lower Miocene. Quartz occurs in fine-grained fraction, and can be identified in the bulk sediment.

Pliocene and Quaternary: Nannofossil ooze, calcareous mud, and siliceous nannofossil ooze. This mineralogical assemblage is characterized by the decrease of

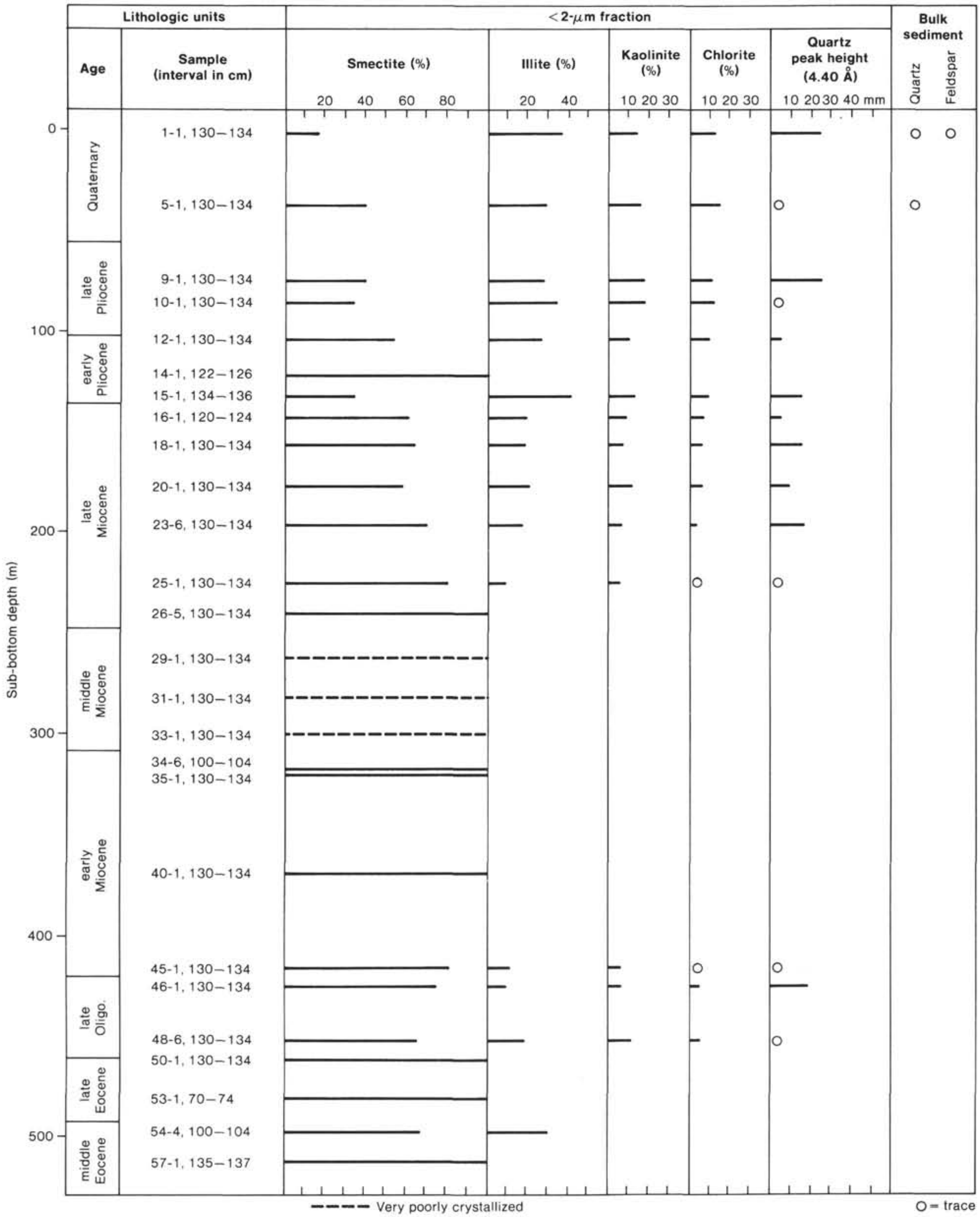

Figure 5. Mineralogical log of Site 608 (Hole 608).

Table 3. Mineralogical data, Site 608.

		<2-μm fraction						Bulk sediment	
Sample (interval in cm)	Sub-bottom depth (m)	Smectite (%)	Illite (%)	Kaolinite (%)	Chlorite (%)	Quartz peak height (mm)	Zeolite	Quartz	Feldspar
608-1-1, 130-134	1.30	17	37	23	23	25		Trace	Trace
608-5-1, 130-134	37.10	40	30	15	15	Trace		Trace	
608-9-1, 130-134	75.50	41	29	18	12	25			
608-10-1, 130-134	85.10	35	35	18	12	Trace			
608-12-1, 130-134	104.30	56	24	10	10	5			
608-14-1, 122-126	123.42	100							
608-15-1, 134-136	133.30	36	42	13	9	15			
608-16-1, 120-124	142.60	62	20	9	9	5			
608-18-1, 130-134	157.80	66	20	8	6	16			
608-20-1, 130-134	177.00	59	22	12	7	10			
608-23-6, 130-134	196.20	71	18	7	4	15			
608-25-1, 130-134	225.00	81	11	8	Trace	Trace	Clinopt.		
608-26-5, 130-134	240.60	100							
608-29-1, 130-134	263.40	100							
608-31-1, 130-134	282.60	100							
608-33-1, 130-134	301.80	100							
608-34-1, 100-104	318.60	100							
608-35-1, 130-134	321.00	100							
608-40-1, 130-134	369.00	100					Clinopt.		
608-45-1, 130-134	417.00	82	12	6	Trace	Trace			
608-46-1, 130-134	426.60	77	11	7	5	20			
608-48-6, 130-134	453.30	65	19	11	5	Trace			
608-50-1, 130-134	463.00	100							
608-53-1, 70-74	483.60	100							
608-54-4, 100-104	498.00	68	32				Clinopt.		
608-57-1, 135-137	513.00	100					Clinopt.		

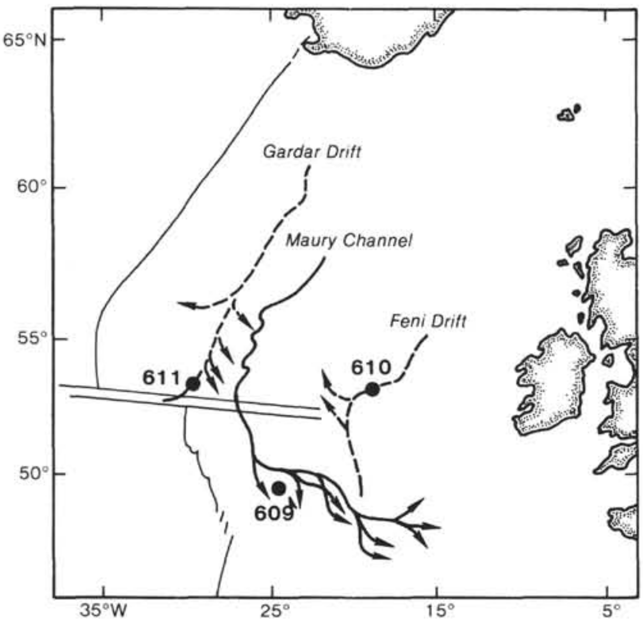

Figure 6. Map showing Maury Channel, Gardar Drift and Feni Drift, and general deep-water flow (after Ruddiman et al., 1972).

smectites and the increasing relative abundance of illites in the Quaternary; the relative abundance of kaolinites and chlorites also increases. The <2-μm quartz is present mainly in the Quaternary. Quartz in the bulk sediment is continuously present and more abundant than in the Miocene.

Site 610 Environment

As at Site 609, sediments at Site 610 appear to be detrital because of the continuous presence of quartz in the total bulk sediment. The clay mineralogical assemblage (smectite, illite, chlorite) varies in the lower Miocene. The relative abundance of illites, kaolinites, and chlorites increases gradually toward the upper part of the stratigraphic series.

The site's location on a sediment drift, believed to have been built since Oligocene–Miocene time by the action of the intermittent southward flow of Norwegian Sea Water (Jones et al., 1970; Ellett and Roberts, 1973), could account for the detrital character of the carbonate-free sediment, and for the presence of illites and chlorites, which we consider to be markers of northern input. But, as at Site 609, the input of clay and of quartz fluctuated. The fluctuations were associated with increasingly intense north-to-south circulation (progressive increase of illite and chlorite of northern origin) and with glacial cycles of the late Pliocene (striking increase of "northern" minerals, i.e., illite, chlorite, and quartz in the bulk sample, which may have been brought by ice-rafting).

Site 611 (Figs. 6 and 9 and Table 6)

This site is on the lower southeastern flank of Gardar Drift. Several holes yielded upper Miocene to Quaternary sediments. Hole 611C is in the trough and Hole 611 is on the crest of a sediment wave.

Upper Miocene: Nannofossil chalk to marly nannofossil chalk. The clay mineralogical assemblage is made up chiefly of highly crystalline aluminous smectite (83%–89%) and some illites. There is evidence of quartz and feldspars in all bulk samples, but in the fine-grained fraction evidence of these minerals is very scarce.

Upper Miocene and Lower Pliocene: Nannofossil chalk. The dominant characteristic of the mineralogical

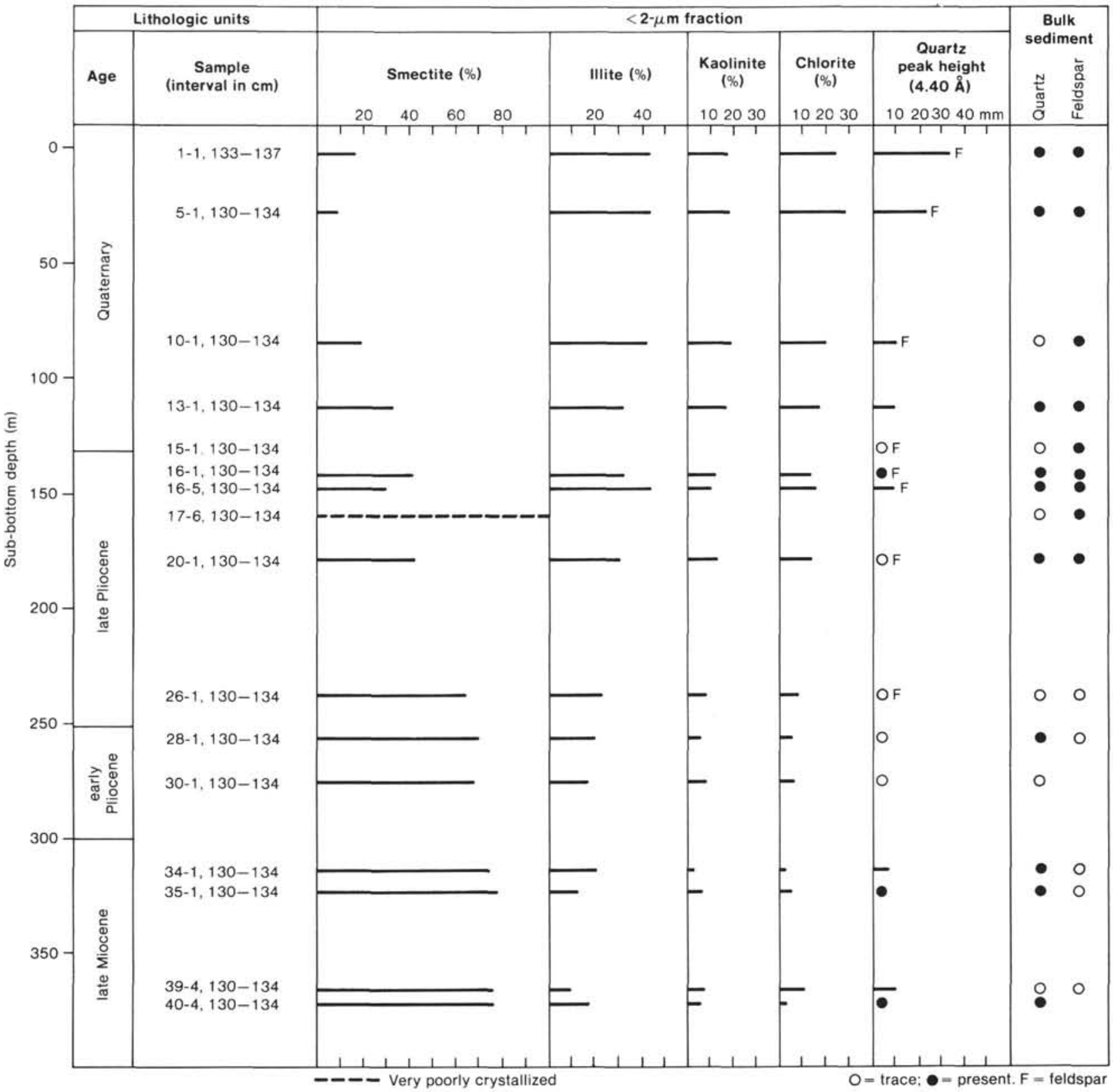

Figure 7. Mineralogical log of Site 609 (Hole 609).

assemblage is still the abundance of smectite (more than 65%), but it is associated here with illite, kaolinite, and chlorite. In the fine-grained fraction, only traces of quartz and feldspars are present.

Two samples, 611C-35-1, 130–134 cm and 611C-33-4, 130–134 cm, are characterized by a very low content of clay minerals, with traces of smectite.

Throughout the upper Miocene and lower Pliocene, quartz and feldspars are present in the bulk sample.

Lower and upper Pliocene: Nannofossil ooze and siliceous nannofossil ooze. These sections are characterized by the absence or very poor representation of clays; the only clays identified are smectites. Quartz is also rare. When quartz is barely identifiable in the bulk sample, plagioclase feldspars are present, and these are more abundant in the upper Pliocene sections (611C-20-1, 135–139 cm to 611C-15-1, 130–134 cm and 611-14-1, 130–134 cm).

Uppermost Pliocene and Quaternary: Calcareous mud and marly foraminiferal nannofossil ooze. The dominant clay minerals are alternatively smectite and illite; kaolinite and chlorite are well represented. Quartz and feldspars are abundant in both the fine-grained fraction and the bulk sample.

Site 611 Environment

In the upper Miocene, there is the beginning of a considerable change in the clay sedimentation at Site 611. In the Miocene, abundant smectites and illites dominate the clay mineral assemblage, but there is a sudden influx of kaolinites and chlorites. Throughout a large part of

Table 4. Mineralogical data, Site 609.

		<2-μm fraction						Bulk sediment	
Sample (interval in cm)	Sub-bottom depth (m)	Smectite (%)	Illite (%)	Kaolinite (%)	Chlorite (%)	Quartz peak height (mm)	Feldspar	Quartz	Feldspar
609-1-1, 133–137	1.33	16	44	16	24	33	Present	Present	Present
609-5-1, 130–134	37.10	9	44	19	28	25	Present	Present	Present
609-10-1, 130–134	84.60	19	43	19	19	10	Present	Trace	Present
609-13-1, 130–134	113.90	33	33	17	17	10		Present	Present
609-15-1, 130–134	131.90					Trace	Present	Trace	Present
609-16-1, 130–134	141.50	42	32	13	13	Present	Present	Present	Present
609-16-5, 130–134	147.50	30	45	10	15	10	Present	Present	Present
609-17-6, 130–134	158.60	100						Trace	Present
609-20-1, 130–134	179.90	43	31	13	13	Trace	Present	Present	Present
609-26-1, 130–134	237.50	63	23	7	7	Trace	Present	Trace	Trace
609-28-1, 130–134	256.70	70	20	5	5	Trace		Present	Trace
609-30-1, 130–134	275.90	68	17	9	6	Trace		Trace	
609-34-1, 130–134	314.30	75	21	2	2	7		Present	Trace
609-35-1, 130–134	323.90	78	13	5	4	Present		Present	Trace
609-39-4, 130–134	366.8	75	9	7	9	10		Trace	Trace
609-40-1, 130–134	371.9	77	17	4	2	Present		Present	

the Pliocene, clay minerals are absent; they reappear in the uppermost Pliocene sections, and through the Quaternary there are mixed assemblages (smectites, illites, kaolinites, chlorites). Quartz and feldspars are always present in the bulk sample. Their distribution is somewhat different in the fine-grained fraction, where these minerals occur in traces in the Miocene, disappear in the Pliocene, and reappear in abundance in the Quaternary.

The striking feature at Site 611 is the ubiquitous occurrence of plagioclase feldspars, even if in low percentages. Ruddiman and Bowles (1976), in a study of neighboring area, have attributed this feldspar occurrence to the arrival of minerals resulting from erosion of Icelandic basalts. This could also apply at Site 611. Consequently, it may be assumed that associated clays have the same origin. The relatively high smectite content in the Miocene could further support the hypothesis of Icelandic input. Further, the occurrence of "immature" smectite in the Pliocene as the only clay mineral identified could indicate alteration of volcanic material (as at Sites 403 and 404 of Leg 48, already cited). In spite of sedimentation of Icelandic origin, the same succession of events recognized at the other Leg 94 sites could be identified.

An increased variability in the clay mineralogical assemblage in the Miocene suggests a mixing of smectites with northern minerals (illite, chlorite). A further increase of these minerals at the end of the Pliocene and in the Quaternary can be attributed to glacial effects. This interpretation is confirmed by the presence of glacial erratics, detected in the uppermost 100 m of the hole.

CONCLUSIONS

The mineralogical study of sediments at Leg 94 sites has provided greater insight into the evolution of the Tertiary and Quaternary sediment input in the northeastern Atlantic (Fig. 10).

Throughout the Eocene, Oligocene, and lower Miocene, the so-called regional characteristics are predominant: major influence of local geology, not obliterated by ocean currents. Although in this chapter the only Paleogene sediments studied are from Site 608, a comparative study of the overall data with data from Legs 47, 48, 80, 81, and 82 (Chamley et al., 1979; Chennaux et al., 1985; Latouche and Maillet, 1979, 1984, and in press) unraveled the impact of the immediate geologic environment and of climate upon sediments. For instance, the Rockall region (Legs 48, 81), in which there are essentially only basic rocks, is a preferential source of smectites, because of both the composition of the parent rock and the climatic conditions under which weathering occurred. At Goban Spur (Leg 80), the erosion of the acid rocks leads to the formation of illites, kaolinites, chlorites, and coarser detrital elements such as quartz; furthermore, weathering of these rocks under a warm climate also can lead to the formation of smectite. Off west Portugal (Leg 47B), the influence of the continent is also very important; in a warm climate smectites and palygorskites are abundant, and evidence of erosion (illite, chlorite, kaolinite) and of pedogenic alteration is very clear (vermiculites and chlorite/vermiculites). At the King's Trough site (608), the clay mineral assemblage is the result of erosion and alteration of basic volcanic rocks (smectite). South of the Azores, the clay mineral assemblage is mostly oceanic, as a result of volcanism and tropical climatic effects (mixing of clay species with preponderant smectites and, occasionally, kaolinites).

In addition to these regional particularities, more geographically extensive phenomena began to appear in the Oligocene. Oligocene regional deposits south of the 40th parallel show evidence of eolian input (Sites 558 and 608), indicated by the arrival of illite, kaolinite, and chlorite, associated with fine-grained quartz.

In the Miocene, clay sedimentation is similar (smectite, illite, kaolinite, chlorite) at all sites studied and at sites of other North Atlantic DSDP legs (e.g., 48, 80, 81, 82). This is mainly a consequence of regular north–south exchanges between Norwegian Sea Water and North Atlantic Water in the early Miocene (Roberts and Montadert, 1979). Northern currents carried illites and chlorites. This current impact upon the clay sedimentation was not simultaneous in the different parts of the north-

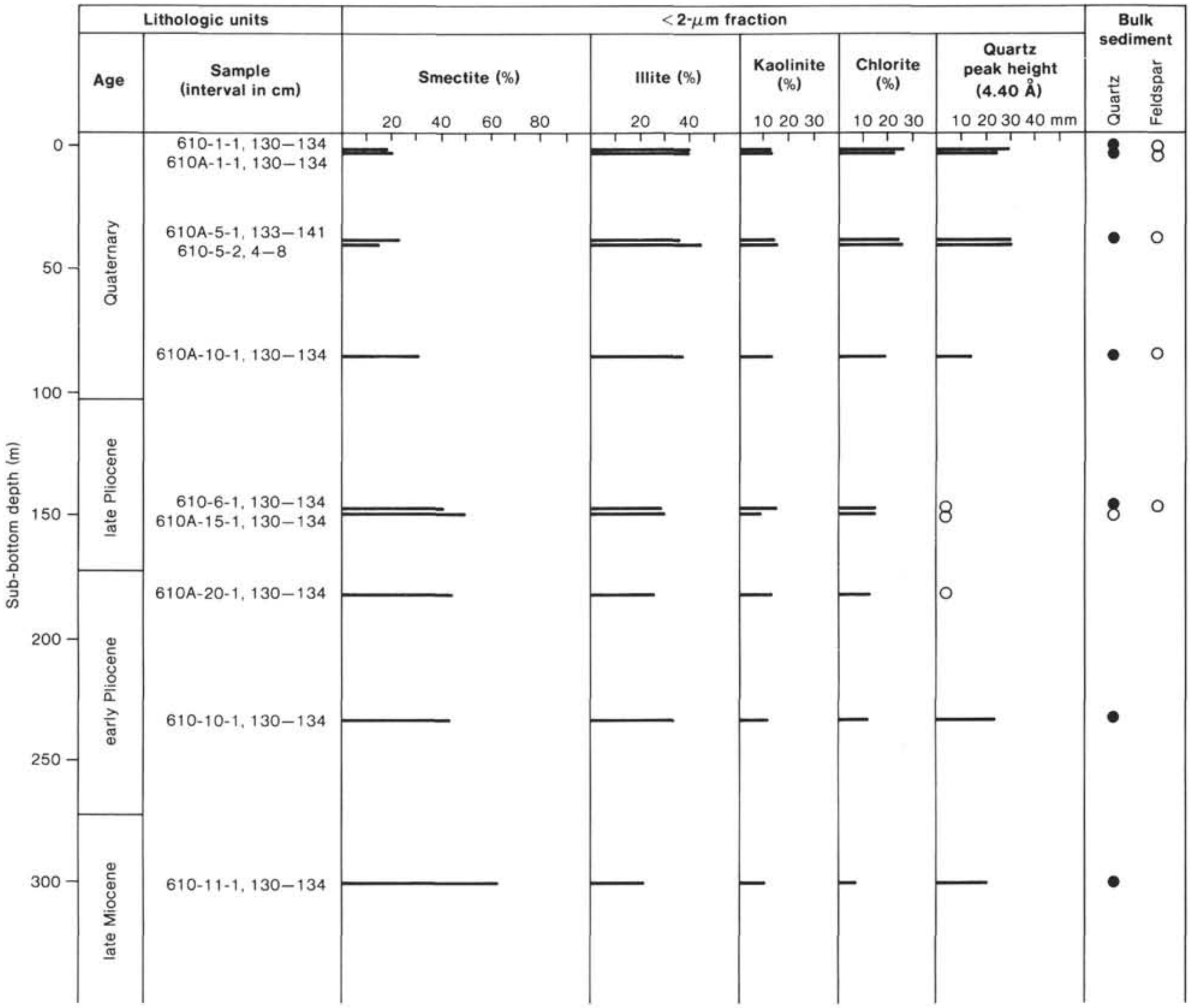

Figure 8. Mineralogical log of Site 610 (Holes 610, 610A).

eastern Atlantic. It differed according to the water depth; in Rockall region for example, the mineralogical change occurs in the lower Miocene (Site 403) and in the upper Miocene (Site 405).

In the late Pliocene, massive arrivals of minerals such as illites and chlorites, which we have considered to be typical for high latitudes, as well as coarse-grained quartz, reached the entire northeastern Atlantic. This phenomenon, independent of the topography and geology of the ocean bottom, was probably caused by sedimentary processes linked to ice-rafting.

In sum, this comparative site study (Leg 94, with Legs 47, 48, 80–82) has shown that the sediment pattern became homogeneous over the northeastern Atlantic in two periods, as a result of different phenomena: (1) during the Miocene by intensification of the influence of oceanic circulation; and (2) at the beginning of the late Pliocene by the effect of ice transport.

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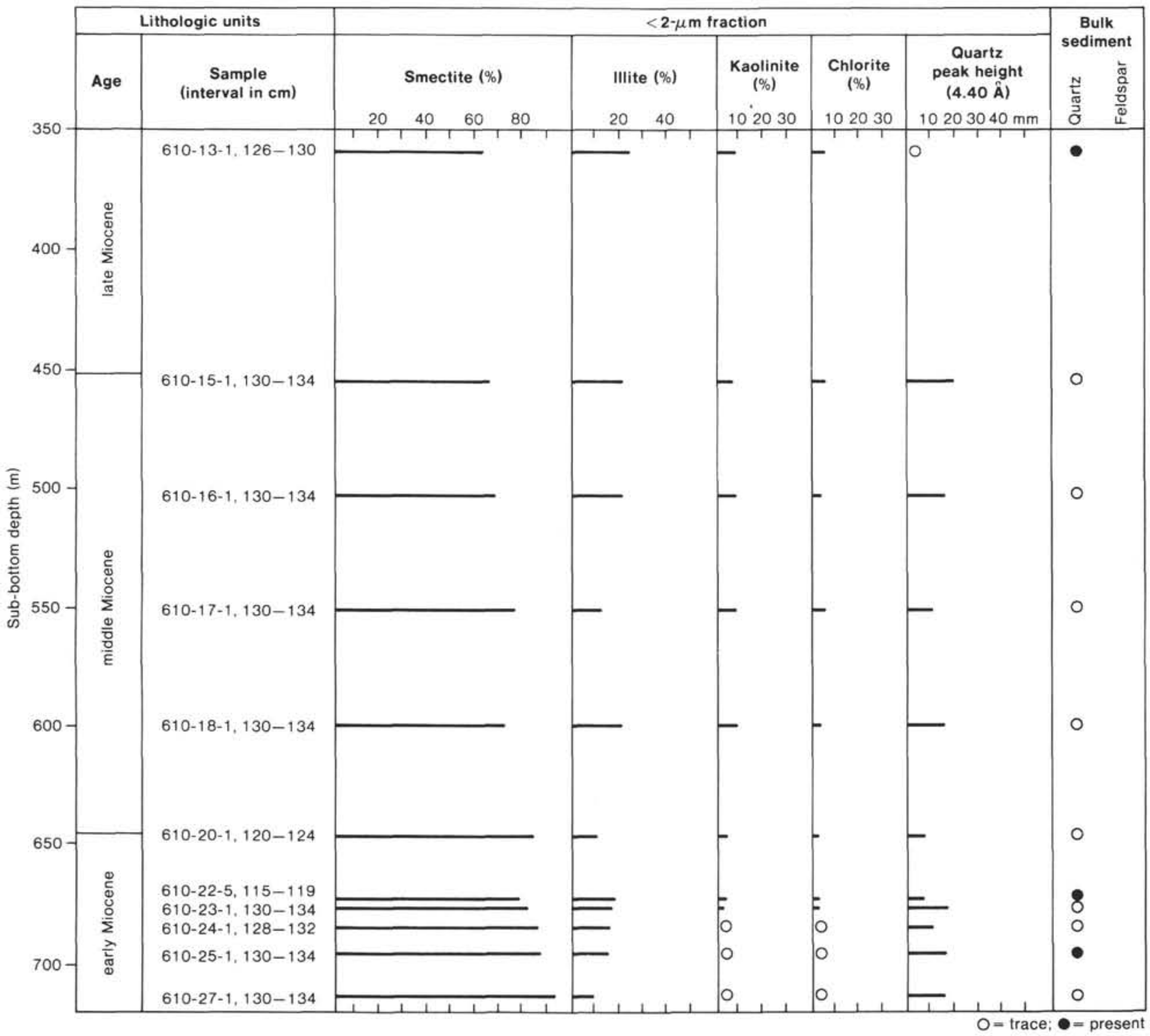

Figure 8 (continued).

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APPENDIX
Methods

X-ray diffraction was employed in the analysis of 97 samples. A Philips diffractometer was used, and operating conditions were as follows: nickel-filtered copper $K\alpha$ radiation at 40 kV, 20 mA. The samples were mainly from carbonate-rich sediments.

Total Sediment

Because bulk sediments were too rich in $CaCO_3$, our analyses concerned only the carbonate-free fractions. Dried and pulverized sediment of the carbonate-free fractions were analyzed according to the powder method (Brown, 1961). The abundance of quartz (3.35 Å) and feldspars (plagioclases, 3.20 Å) was estimated in the X-ray diagrams as follows: trace = peak just visible, or weak; present = peak distinctly visible or medium.

Clay Fraction (<2 μm)

Total sediments were dispersed in deionized water, using mechanical agitation. Samples with high carbonate contents were first treated with $N/10$ HCl. After several (2–3) times washing in deionized water. <2-μm subfraction was separated by gravity settling. After <2-μm portion of the suspension was centrifuged, the resulting thick paste was spread across 3 slides, as follows: slide 1 was scanned untreated; slide 2 was saturated with ethylene glycol; slide 3 was heated at 550° for an hour.

Minerals were identified on the basis of their typical reactions to this classical treatment (Brown, 1961; Thorez, 1975). Percentages of the different minerals were estimated from the glycolated samples. The heights of the 001 peaks were used to determine smectite (17 Å), illite (10 Å), kaolinite, and chlorite (7.1 Å). Chlorite was distinguished from kaolinite on the basis of the difference between their reflections: 002 for kaolinite (3.37 Å) and 004 for chlorite (3.55 Å). Results are given in percentage values; these percentages are evaluated only with regard to the crystallized clay minerals in the <2-μm fraction. In this fraction several minerals such as zeolites and quartz were observed. The heulandite group in zeolites was identified (7.90 and 8.90 Å). After heating, a distribution was drawn between heulandite and clinoptilolite. Quartz, within the fine-grained fraction, was identified at 4.24 Å. The 3.35-Å peak, usually used to determine quartz, was superimposed on the illite 003 peak. The 4.24-Å peak—measured in millimeters—was used not to quantify quartz accurately, but to give it a relative value. All mineralogic analyses were carried out under the same operating conditions.

Table 5. Mineralogical data, Site 610.

Sample (interval in cm)	Sub-bottom depth (m)	<2-μm fraction: Smectite (%)	Illite (%)	Kaolinite (%)	Chlorite (%)	Quartz peak height (mm)	Bulk sediment: Quartz	Feldspar
610A-1-1, 130–134	1.30	21	42	14	23	25	Present	Trace
610A-5-1, 133–141	39.13	23	31	15	25	30	Present	Trace
610A-10-1, 130–134	87.10	31	37	13	19	15	Present	Trace
610A-15-1, 130–134	135.10	50	30	7	13	Trace	Trace	
610A-20-1, 130–134	183.10	45	27	14	14	Trace		
610-1-1, 130–134	1.30	18	42	13	27	30	Present	Trace
610-5-2, 4–8	40.10	15	44	15	26	30		
610-6-1, 130–134	148.30	40	30	15	15	Trace	Present	Trace
610-10-1, 130–134	234.70	44	34	11	11	23	Present	
610-11-1, 130–134	301.90	62	21	10	7	20	Present	
610-13-1, 126–130	359.46	63	24	8	5	Trace	Present	
610-15-1, 130–134	455.50	65	22	8	5	20	Trace	
610-16-1, 130–134	503.50	68	21	7	4	15	Trace	
610-17-1, 130–134	551.50	76	12	8	4	10	Trace	
610-18-1, 130–134	599.50	70	20	8	2	15	Trace	
610-20-1, 120–124	647.40	84	10	4	2	6	Trace	
610-22-5, 115–119	672.55	77	18	3	2	7	Present	
610-23-1, 130–134	676.30	80	16	2	2	15	Trace	
610-24-1, 128–132	685.88	85	15	Trace	Trace	10	Trace	
610-25-1, 130–134	695.50	86	14	Trace	Trace	15	Present	
610-27-1, 130–134	714.70	92	8	Trace	Trace	15	Trace	

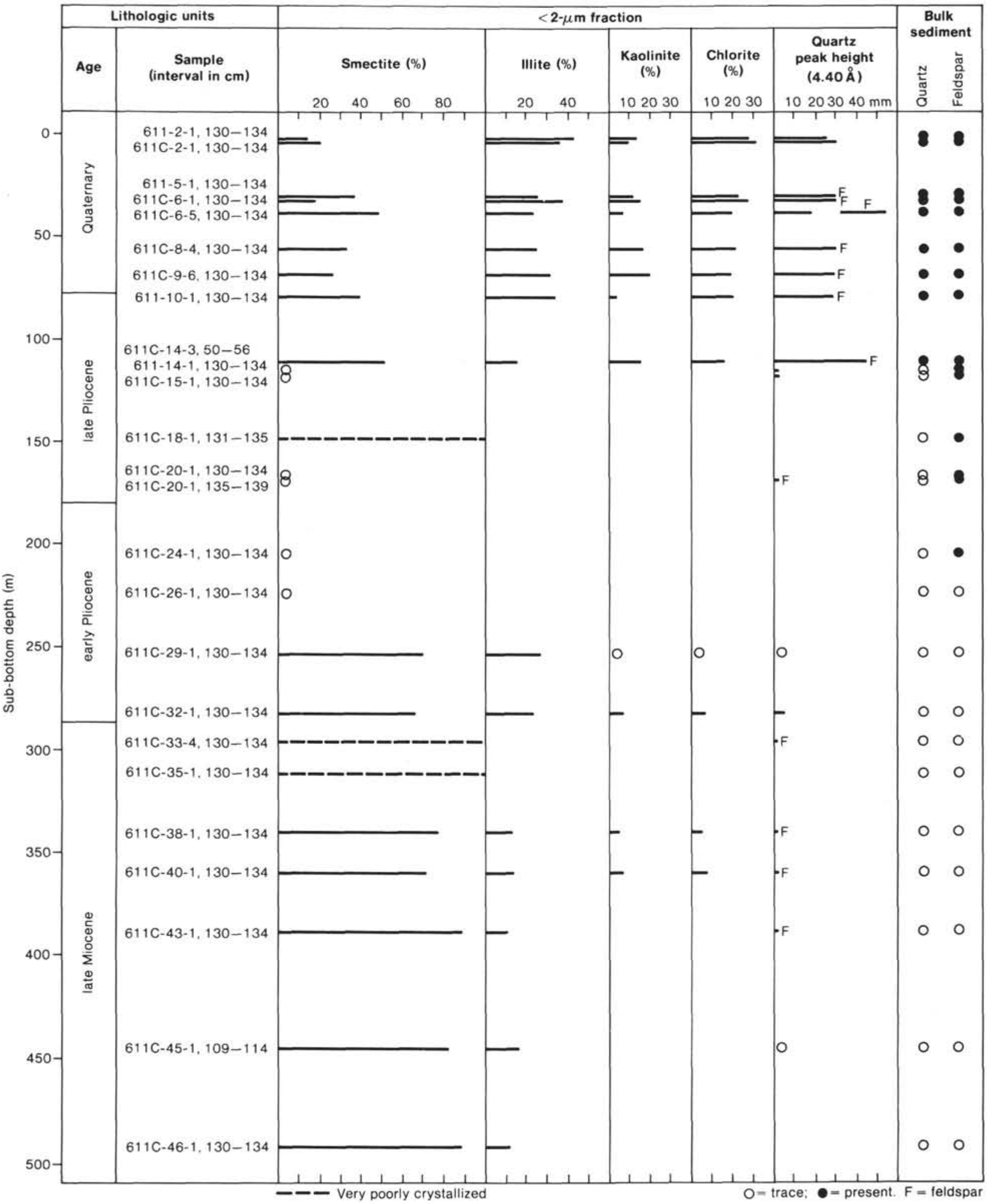

Figure 9. Mineralogical log of Site 611 (Holes 611, 611C).

Table 6. Mineralogical data, Site 611.

Sample (interval in cm)	Sub-bottom depth (m)	<2-μm fraction Smectite (%)	Illite (%)	Kaolinite (%)	Chlorite (%)	Quartz peak height (mm)	Feldspar	Bulk sediment Quartz	Feldspar
611-2-1, 130–134	2.30	14	44	14	28	25		Present	Present
611-5-1, 130–134	31.10	38	25	12	25	30	Present	Present	Present
611-10-1, 130–134	79.10	40	35	5	20	30	Present	Present	Present
611-14-1, 130–134	117.50	Trace						Trace	Trace
611C-2-1, 130–134	3.70	21	37	10	32	25	Present	Present	Present
611C-6-1, 130–134	32.90	18	38	16	28	30	Present	Present	Present
611C-6-5, 130–134	38.90	50	25	6	19	80	Present	Present	Present
611C-8-4, 130–134	56.60	35	26	17	22	30	Present	Present	Present
611C-9-6, 130–134	69.20	27	33	20	20	30	Present	Present	Present
611C-14-3, 50–56	111.90	52	16	16	16	45	Present	Present	Present
611C-15-1, 130–134	119.30	Trace						Trace	Trace
611C-18-1, 131–135	148.11	100						Trace	Present
611C-20-1, 130–134	167.30	Trace						Trace	Present
611C-20-1, 135–139	167.35	Trace					Present	Trace	Present
611C-24-1, 130–134	205.70	Trace						Trace	Present
611C-26-1, 130–134	224.90	Trace						Trace	Trace
611C-29-1, 130–134	253.30	71	29	Trace	Trace	Trace		Trace	Trace
611C-32-1, 130–134	282.50	65	23	6	6	6		Trace	Trace
611C-33-4, 130–134	296.60	100					Present	Trace	Trace
611C-35-1, 130–134	311.30	100						Trace	Trace
611C-38-1, 130–134	340.10	79	13	4	4		Present	Trace	Trace
611C-40-1, 130–134	359.30	72	14	7	7		Present	Trace	Trace
611C-43-1, 130–134	388.10	89	11				Present	Trace	Trace
611C-45-1, 109–114	445.49	83	17			Trace		Trace	Trace
611C-46-1, 130–134	493.70	88	12					Trace	Trace

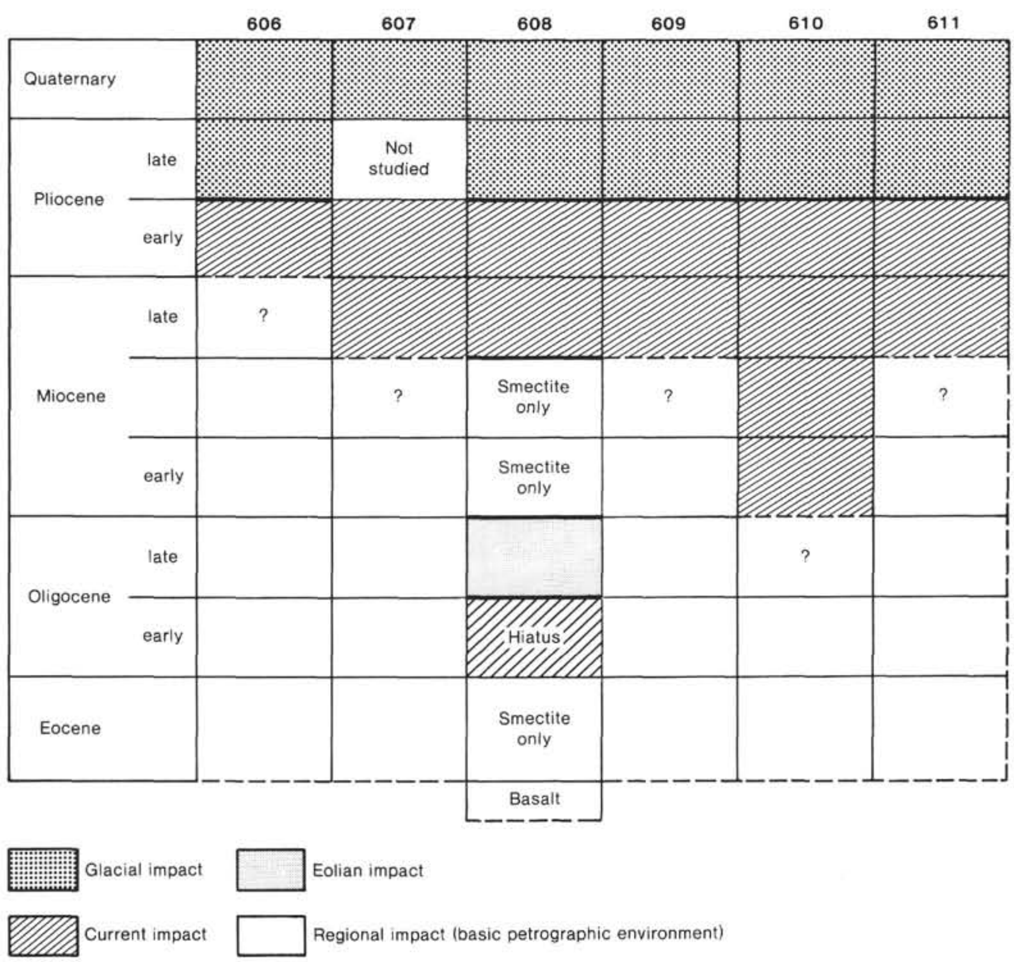

Figure 10. Schematic outline of major Cenozoic and Quaternary sedimentary processes.