

## 27. CLAY-SIZED MINERALS FROM CORES OF THE SOUTHEAST PACIFIC OCEAN, DEEP SEA DRILLING PROJECT, LEG 35<sup>1</sup>

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### ABSTRACT

Terrigenous illite, chlorite, kaolinite, and small amounts of vermiculite occur in sediments at the four sites drilled during DSDP Leg 35. Montmorillonite (mix-layered clay), which can result from alteration of volcanogenic material on land and under water, increased and the amount of chlorite plus kaolinite decreased in the older sediments from Sites 322, 323, and 325. The trend in illite content is not well defined.

In the Pliocene-lower Miocene age sediments, the crystallization of montmorillonite was more or less constant and increased noticeably only in horizons above the basalts (Sites 322 and 323) as a result of hydrothermal activity. The montmorillonite content increases with depth without a change of its crystallization, perhaps due to the greater influx of montmorillonite into the older sediments, or as the result of postdepositional changes of the clay minerals. This same tendency exists in most oceanic sediments. Other diagenetic but non-clay minerals, clinoptilolite, cristobalite, and goethite, occur in the cores.

### INTRODUCTION

The suites of clay minerals, the degree of mineral crystallization, and the content of amorphous material are related to their provenance, depositional mechanism and diagenetic alterations. These minerals are stable and can be transported great distances from their source without changes to their basic crystallochemical properties (Rateev et al., 1968; Griffin et al., 1968; Biscaye, 1965; Hayes, 1973). Illites, kaolinites, chlorites, and montmorillonites, the four principal groups of clay minerals, can be transported to the ocean from land, but only montmorillonite usually occurs in mix-layered sequences and can be formed in substantial amounts in marine sediments from the alteration of the volcanic rocks in contact with seawater (Skornyakova et al., 1971; Rex, 1967).

The composition of clay minerals in hydrothermally altered sediments is rather distinctive. For example, well-crystallized montmorillonites as well as trioctahedral vermiculites and illite occur in the sediments of the South Pacific Basin (Gorbunova, 1974). The metaliferous sediments, which were located near the East Pacific Rise, are characterized by montmorillonitic minerals in the very initial stages of crystallization.

The deep cores of Leg 35 provide samples to evaluate clay mineral transformations during low-temperature diagenesis. We previously studied the coring results from the northeastern Pacific Ocean (Hayes, 1973), where oceanic crust subduction provides deep burial of the sediment and an increase of illitic layers in the

mixed-layered montmorillonite-illite was expected as a result of diagenesis, but a reverse trend was noted at Sites 174, 175, and 176. Hayes (1973) explained this in that burial of the sediments occurred shallower than 3000 meters, which is not sufficient for low-temperature diagenesis. Perry and Hower (1970) noted that in the Gulf of Mexico alteration of montmorillonite into mica occurred only below 2000 meters depth of burial. In the eastern equatorial zone of the Pacific Ocean, Zemmels (1973) noted a high degree of diagenesis and related this to the presence of clinoptilolite, pyrite, cristobalite, and barite in the sediments. In his opinion, montmorillonite alters to mica in the deeper layers of the sediment. In the western part of the Pacific Ocean, Okada and Tamuda (1973) noted changes in the interlayered water content in montmorillonites: one layer occurred in shallow sediments and two layers occurred in the deeper ones.

### METHODS

The  $<1 \mu\text{m}$  minerals were studied after dispersal with tripolyphosphate and isolation by decantation. At Site 323 we also studied bulk samples. For mineral determinations we used the X-ray diffractometer Dron-I with a scintillation counter with Cu K $\alpha$  radiation and a nickel filter. Samples were transferred by pipette to 2 glass slides and dried at room temperature. Since the samples were mostly of light color, the contaminating  $\text{Fe}_2\text{O}_3$  were thought to be insignificant and not removed.

All samples were analyzed following magnesium saturation, glycerin saturation, heating to 520°C for one hour, and after 1N HCl treatment to determine the stability of the minerals and differentiate between chlorite and kaolinite. Some samples were treated with 1N KOH to determine the nature of mix-layered mont-

<sup>1</sup>Translated and edited from Russian.

morillonite and vermiculite and help to distinguish vermiculite from chlorite (Hayes, 1973).

In order to establish the nature of the octahedral layers, we surveyed randomly oriented samples in a special holder to obtain the 060 reflection. The dioctahedral montmorillonites were treated with lithium chloride in order to distinguish the nontronite-beidellite subgroup from the montmorillonite (Green-Kelly, 1953).

The illite polymorphs could not be distinguished because of the excessive feldspar content which produces similar reflections. Many samples were studied with an electron microscope in order to identify crystals with a specific morphology.

The quantitative ratios of the groups of clay minerals were evaluated according to Biscaye (1965) and, accordingly, chlorite and kaolinite were calculated simultaneously.

In the  $<1\ \mu\text{m}$  fraction we also discovered nonclay minerals: quartz, feldspar (common and abundant), amphiboles (determined by the  $8.5\text{\AA}$  peak), clinoptilolite (determined by a peak at approximately  $9.0\text{\AA}$ ), cristobalite (by the  $4.04\text{\AA}$  peak), and goethite (by the  $4.18\text{\AA}$  peak).

## RESULTS OF INVESTIGATIONS

Cores from four sites were studied. Sites 322 and 323 were located on the Bellingshausen Abyssal Plain and Sites 324 and 325 were on the Antarctic continental rise.

Site 323 was most thoroughly studied. The total sub-bottom penetration was 731 meters, and the cored interval was divided into six lithologic units, ending in basalt (see site summary report, this volume). The basalt is overlain with brown claystones, enriched with hydrous ferric oxide and manganese, as well as zeolites. This type of sediment was probably formed from subaqueous volcanic exhalations near spreading centers. Terrigenous material, for example, quartz and feldspar, occurs above 638 meters. Apparently, turbidity currents were significant, especially in the upper units to a subbottom depth of about 500 meters. The material, however, is well sorted, which is indicative of reworking by bottom currents.

In sediments from this site we encountered clay minerals of the montmorillonite, illite, chlorite, and kaolinite groups. The montmorillonite occurs in mix-layer forms with illite. The magnesium-saturated complex is characterized by a broad and asymmetrical maximum diffraction peak at approximately  $15.2\text{\AA}$ , with a glycerine reflection at  $18\text{\AA}$  (001); the consecutive orders of reflection are usually expressed by broad asymmetrical peaks. Reflections 002 and 003 are usually diminished or completely lacking. The degree of the crystallization of montmorillonite is average or high as suggested by the  $v/p$  ratio (Biscaye, 1965) which ranges from 0.6 to 0.9.

The stability of montmorillonite treated with  $1N\ \text{HCl}$  changed at various horizons. From the sediment surface to a depth of nearly 600 meters, the montmorillonites disintegrated rather easily, and only in the lower parts of the section are they partially preserved. Consequently, we believe that the composition of the octahedral layers changes in the deeper layers. The chemical data revealed a high content of barium here.

The 060 reflection near  $1.501\text{\AA}$  is characteristic of dioctahedral clay minerals. A reflection at  $1.530\text{\AA}$ , possibly that of quartz, was encountered in samples throughout the cored section. Small amounts of trioctahedral minerals (if they do exist) could have been overlooked.

The dioctahedral illite is characterized by reflections at  $10\text{\AA}$ ,  $5\text{\AA}$ ,  $3.3\text{\AA}$ , which do not change upon heating or saturation with glycerin. Reflections 001 and 002 are asymmetrical, indicating the mix-layer character of the mineral. The illites are stable in  $1N\ \text{HCl}$  throughout the entire sediment sequence.

The chlorite is characterized by reflections at  $14.2\text{\AA}$  (001),  $7.1\text{\AA}$  (002),  $4.7\text{\AA}$  (003), and  $3.54\text{\AA}$  (004), which do not change when saturated with glycerin or various cations. On heating to  $520^\circ\text{C}$ , reflection 001 changes to  $13.8\text{\AA}$ , whereas the others disappear or weaken. Chlorite reflections overlap those of kaolinite and cannot always be resolved. However, treatment with hydrochloric acid allowed the recognition of a small amount of kaolinite on a background of chlorite. The reflection near  $7\text{\AA}$ , which is characteristic of both kaolinite and chlorite, frequently is broadened towards greater  $2\theta$  angles (approximately  $7.3\text{\AA}$ ) and is related to the presence of serpentine or halloysite. In samples which consist almost entirely of montmorillonite, there is a wide asymmetrical peak at approximately  $7\text{\AA}$ , which probably reflects a complicated mixture of serpentines, zeolites, and other minerals.

The clay minerals at Site 323 were determined in both the bulk and  $<1\ \mu\text{m}$  fractions. The relative abundances of the major groups of clay minerals are in both cases rather similar (Figure 1). Kaolinite abundance in this hole is minor, and because it is poorly resolved from chlorite, the two were calculated together. Montmorillonite content shows a downhole increase (Table 1). In the upper sediments of the hole (Pliocene), the montmorillonite content ranges from 30% to 40%, whereas below, in Units 2 and 3, horizons containing as much as 70% montmorillonite are common. In lithologic Units 4 and 5, almost pure montmorillonite with traces of other clay minerals was found in the bulk and  $<1\ \mu\text{m}$  fractions. Electron microscope examination (Figure 2a, b) revealed particles with cloudy contours and elongated rods with distinct edges (zeolites), which are characteristically associated with montmorillonite. Goethite was also found in these horizons.

The degree of crystallization of the montmorillonite increases in the lower horizons; this is expressed by a distinct increase in the intensity of the 001 reflection, which cannot be attributed solely to the increase in abundance (Figure 3). The monomineralic composition of these sediments can probably be attributed to hydrothermal exhalations at spreading ridge crests. Analogous sediments were found on the East Pacific Rise (Böstrom and Peterson, 1969); however, the nature of the clay minerals differs substantially in that on the rise, the montmorillonite is in its initial stage of crystallization. Montmorillonites of a similarly high degree of crystallization were also found in the hydrothermally altered surface sediment layers in the southern Pacific Ocean Basin (Gorbunova, 1974).

Units 1 to 3 contain, in addition to the minerals noted above, illite (up to 40%), chlorite, and, to a lesser degree,

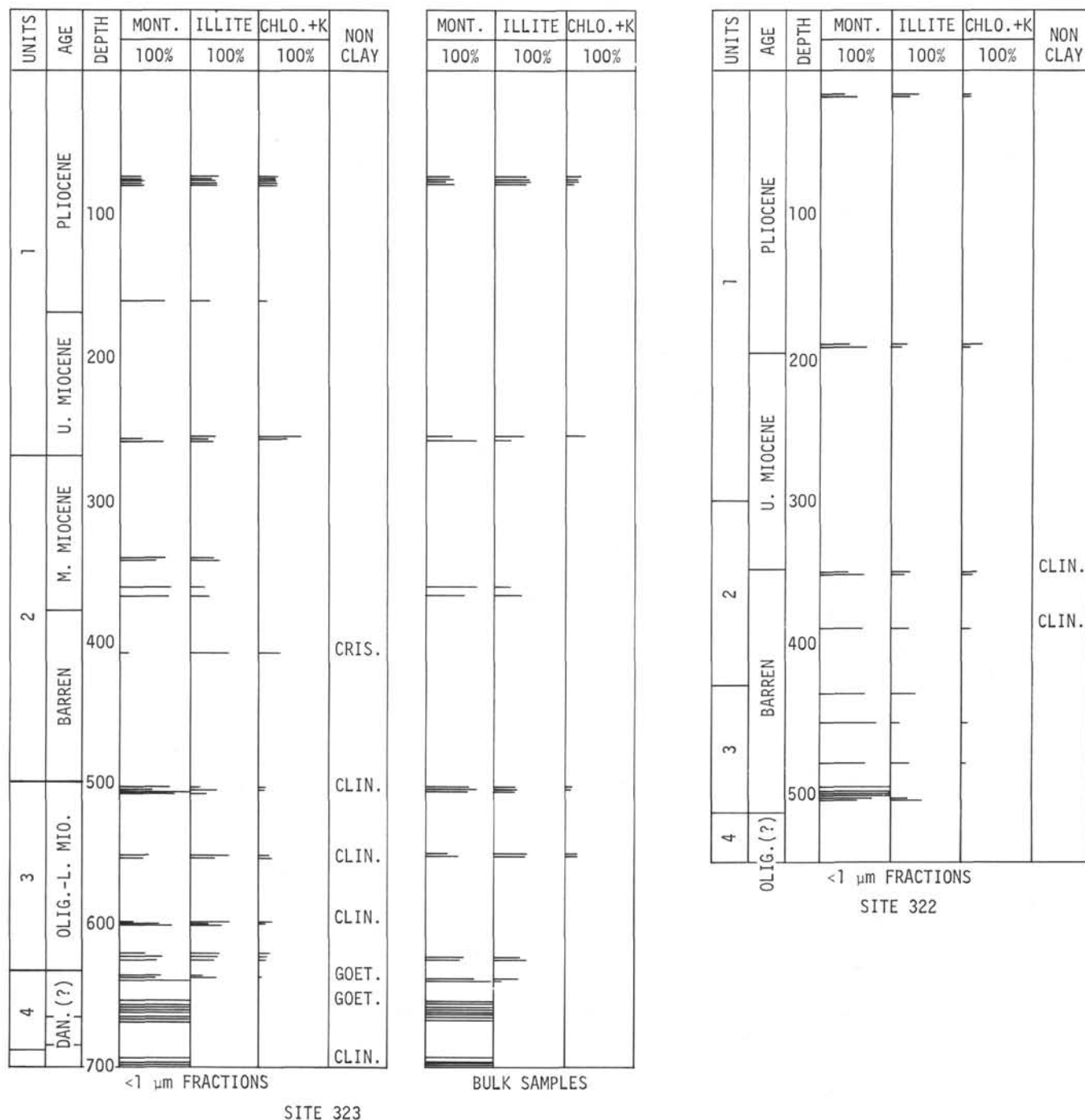


Figure 1. Distribution of clay minerals at Sites 322 and 323.

kaolinites (i.e., typical minerals of terrigenous provenance) along with quartz and feldspar. In electron microscope micrographs, these minerals occur as particles with distinct outlines (Figure 2c, d). The following diagenetic minerals were also encountered at various levels of Site 323 in the  $<1 \mu\text{m}$  fraction: clinoptilolite in the third and fourth lithologic units, cristobalite in the second unit, and goethite in the fourth unit. The relative abundances of these minerals vary. The content of chlorite and kaolinite has a tendency to decrease down the hole. The trend in illite content is unclear; in the lithologic Units 4 and 5 it disappears almost completely. In general, there does not seem to be any correlation

between the distribution of clay minerals and lithologic units at this site. The only major trend seems to be the one noted above of an increase in montmorillonite and a decrease in the chlorite plus kaolinite content with depth and thus with age. Superimposed on this trend are a few sharp breaks. For example, a sharp decrease in montmorillonite abundance and the appearance of cristobalite occurs at a depth of approximately 400 meters. However, only lithologic Units 4 and 5 are characterized by a distinct mineral assemblage.

According to Bogdanov (this volume) the mineralogy of silt-sized fractions and the chemical data indicate upward migration of hydrothermal solutions to a depth of

TABLE 1  
Composition <1  $\mu$ m Fractions of Leg 35 Siltstones

Sample (Interval in cm)	Approximate Depth (m)	Age	Montmor- illonite (%)	Illite (%)	Chlorite and Kaolinite (%)	Nonclay Minerals
<b>Site 322</b>						
1-2, 26-30	18.2	Pliocene	37	39	24	
1-3, 70-76	20.2	Pliocene	53	31	16	
2-2, 113-116	193.1	Pliocene	45	26	29	
3-1, 18-20	195.2	Late Miocene	68	18	14	
4-1, 65-67	352.6	Late Miocene	46	26	27	
4-2, 57-60	354.0	Late Miocene	64	20	16	
5-1, 81-85	391.8	Barren	63	24	13	Clin.
6-1, 30-33	438.8	Barren	65	35	tr	Clin.
9-2, 143-146	469.9	Early to mid. Miocene	82	11	7	
10-1, 101-105	487.0	Early to mid. Miocene	64	25	11	
11-1, 42-46	505.4	Early to mid. Miocene	100	tr	tr	
11-2, 45-49	506.9	Early to mid. Miocene	100	tr	tr	
11-3, 24-32	508.2	Early to mid. Miocene	100	tr	tr	
11-4, 17-24	509.7	Oligocene to early Miocene	100	tr	tr	
11-5, 36-40	511.4	Oligocene to early Miocene	73	27	tr	
<b>Site 323</b>						
1-1, 50-60	76.0	Pliocene	27	42	31	
1-1, 140-150	76.9	Pliocene	27	47	26	
1-2, 24-43	77.3	Pliocene	38	43	19	
1-3, 78-88	79.3	Pliocene	33	37	30	
1-4, 118-127	81.2	Pliocene	43	38	19	
2-1, 128-130	162.3	Pliocene	64	30	6	
3-1, 88-94	256.9	Late Miocene	tr	40	60	
3-2, 14-20	257.6	Late Miocene	35	28	37	
3-2, 61-70	258.1	Late Miocene	64	36	tr	
6-1, 100-110	342.5	Early Miocene	65	85	tr	
6-1, 140-142	343.9	Early Miocene	54	46	tr	
7-2, 105-110	363.0	Early Miocene	77	23	tr	
7-3, 18-24	368.7	Early Miocene	70	30	tr	
8-1, 133-143	409.3	Barren	15	58	27	Crist.
10-1, 133-122	504.1	Barren	74	18	8	
10-2, 75-85	505.2	Barren	51	42	7	Clin.
10-3, 99-102	507.0	Oligocene to early Miocene	100	tr	tr	Clin.
10-3, 106-114	508.0	Oligocene to early Miocene	66	34	tr	
11-1, 22-32	550.7	Oligocene to early Miocene	38	47	15	
11-2, 137-148	553.4	Oligocene to early Miocene	41	39	20	Clin.
12-1, 110-114	559.1	Oligocene to early Miocene	25	58	17	Clin.
12-2, 9-18	599.6	Oligocene to early Miocene	65	27	8	
12-2, 73-77	600.2	Oligocene to early Miocene	72	28	tr	
13-5, 63-70	623.6	Oligocene to early Miocene	40	43	17	
13-5, 106-115	624.1	Oligocene to early Miocene	64	23	13	
13-6, 145-150	625.9	Oligocene to early Miocene	49	37	14	
14-2, 1-8	637.5	?	69	25	6	
14-2, 65-72	638.1	?	57	38	5	



TABLE 1 – *Continued*

Sample (Interval in cm)	Approximate Depth (m)	Age	Montmor- illonite (%)	Illite (%)	Chlorite and Kaolinite (%)	Nonclay Minerals
14-2, 128-135	638.8	?	100	tr	tr	Goethite
15-1, 52-60	655.5	?	100	tr	tr	Goethite
15-2, 91-100	657.4	?	100	tr	tr	
15-3, 29-35	658.3	?	100	tr	tr	Goethite
15-4, 54-63	660.0	?	100	tr	tr	
15-5, 89-98	661.9	Late Danian	100	tr	tr	Goethite
15-6, 19-26	662.7	Late Danian	100	tr	tr	Goethite
16-1, 57-62	665.0	Late Danian	100	tr	tr	
16-3, 32-37	667.8	Mid. Danian	100	tr	tr	
16-4, 83-92	669.8	Mid. Danian	100	tr	tr	Clin.
18-2, 80-86	695.3	Maestrichtian	100	tr	tr	
18-3, 130-139	697.3	Maestrichtian	100	tr	tr	Clin.
18-4, 115-124	698.6	Maestrichtian	100	tr	tr	Clin.
18-5, 14-20	699.1	Maestrichtian	100	tr	tr	Clin.
18-5, 65-73	699.6	Maestrichtian	100	tr	tr	Clin.

Note: Feldspars and quartz were found throughout.

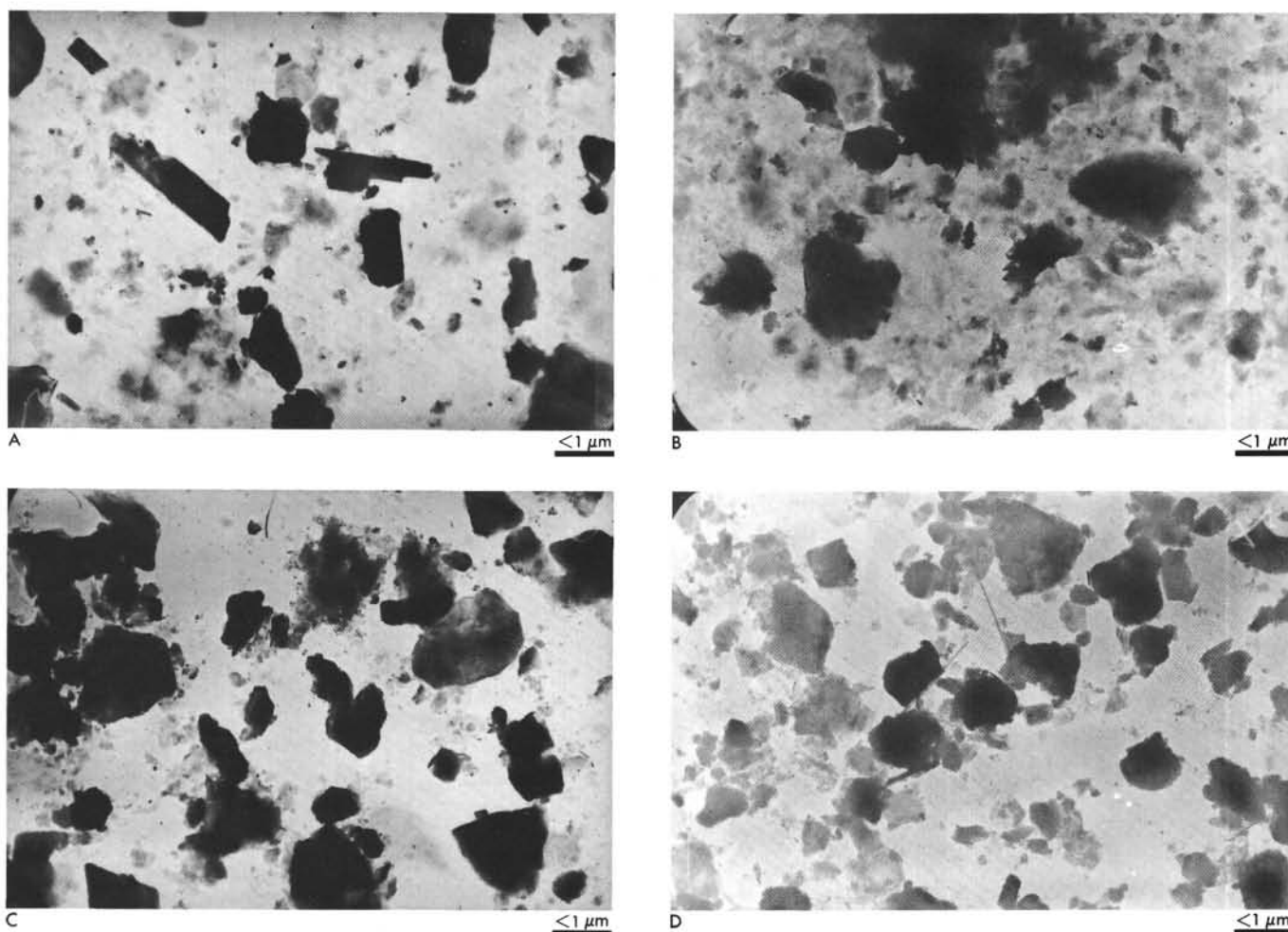


Figure 2. Electron microscope photos of the sediments of Site 323 (A, B) authigenic montmorillonite and clinoptilolite; (C, D) terrigenous illite and chlorite,  $\times 12,000$ .

553 meters in the sedimentary column (Unit 3). However, the composition of clay minerals does not change appreciably between Units 2 and 3.

Site 322 in the Bellingshausen Abyssal Plain was drilled to a depth of 544 meters. The lithologic sequence is divided into five lithologic units terminating in basalt.

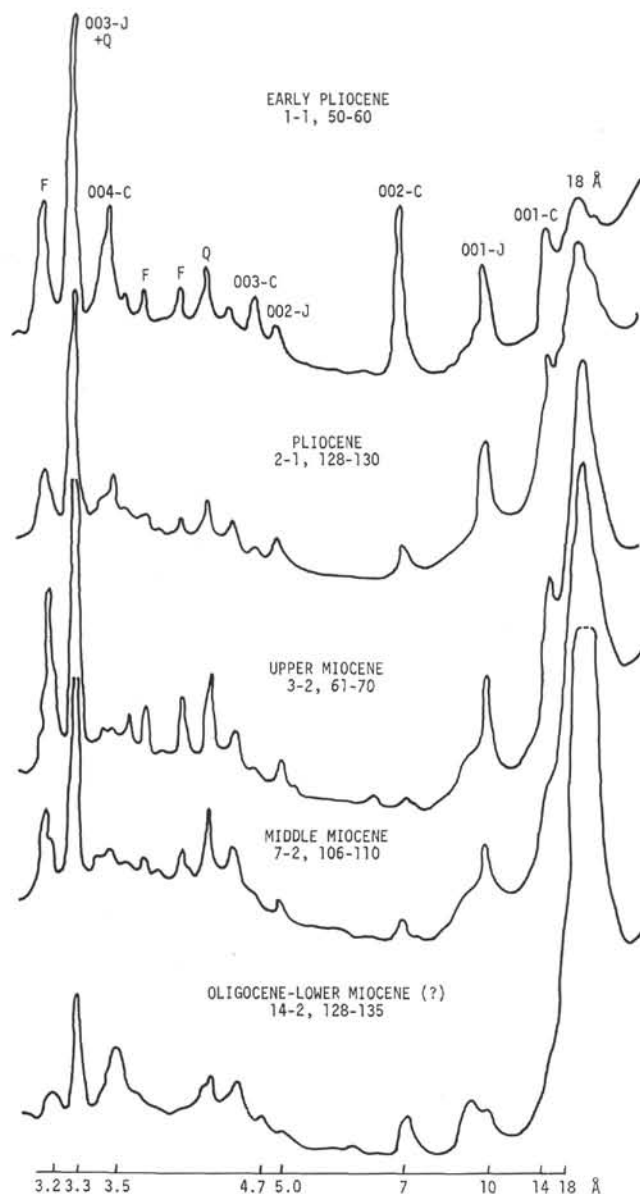


Figure 3. Diffraction pictures of clay minerals, showing the differences in depth of the sediments at Site 323.

The clay mineral composition is similar to that at Site 323 (Figure 1, Table 1). The montmorillonite is basically a mix-layered structure with illite, in which the 002 reflection is diffused and the 001 reflection is broad. The high reflection intensity and the  $v/p$  ratio (Biscaye, 1965) are indicative of average to good crystallization. Montmorillonite is abundant (over 50%) throughout the hole and increases in abundance with depth in the Neogene sequence. At a depth of 500 meters, montmorillonite is the only significant mineral at several horizons, with only trace amounts of other minerals present. Treatment with hydrochloric acid showed that this mineral is unstable except in lower horizons. In contrast to Site 323, goethite was not detected. Chlorite plus kaolinite decrease in abundance with depth. The 7Å peak is complicated and indicates the presence of several minerals: chlorite, kaolinite, serpentinite, and others. The occurrence of kaolinite is indicated by the presence of the 7Å peak after treatment with 1N HCl.

Illite content averages 30% and ranges from 11% to 62% except for several horizons near 500 meters where it occurs in trace amounts. Small amounts of feldspar and quartz were found in the same horizons. This suggests that the terrigenous influence is minimal at these levels. By analogy with cores from Site 323, hydrothermal formation for the montmorillonite at a depth of approximately 500 meters can be assumed.

The diagenetic mineral clinoptilolite was observed at many levels, and its maximum content was at 381 and 438 meters. There is at this site, as at Site 322, no distinct correlation between clay mineral composition and lithologic units. However, the same tendency of an increase of montmorillonite and a decrease of chlorite and kaolinite with depth was found. The variations noted by Bogdanov (this volume) for the mineralogy of the coarse fraction that reflect various sources areas do not occur in the clay mineral composition at Sites 322 and 323.

Site 324 was drilled to a depth of 218 meters on the lower part of the Antarctic continental rise. The sediments consist almost completely of terrigenous clays. The clay content ranges from 30% to 40% for montmorillonite, 40% to 50% for illite, and about 25% for chlorite plus kaolinite. Treatment with 1N HCl indicates that the montmorillonite is not too stable as shown by the decrease in intensity or disappearance of the 001 reflection. As at Sites 322 and 323, the degree of its crystallization is high. Illite and chlorite plus kaolinite also have sharp, intense reflections indicative of good crystallization. However, because of the high feldspar content, the polymorphs of illite could not be determined. The illite content at Site 324 is considerably higher than at all the other Leg 35 sites (the sediments are of Pliocene age). Kaolinite plus chlorite are about equally abundant. This is clearly expressed by treatment with 1N HCl as the 7Å reflection remains intense. However, the complexity of this peak suggests that halloysite and serpentinite may also be present. Quartz occurs throughout the section, as does clinoptilolite, but the latter occurs only in trace amounts.

Site 325 was drilled to a depth of over 700 meters on the continental rise of the northwestern part of the Antarctic Peninsula. The deepest layers are represented by detrital sediments which are overlain by terrigenous sediment. The material here is more poorly sorted than at Site 324.

The clay minerals at this site show characteristically weaker X-ray reflections than those at Site 324. As at previous sites, montmorillonite is represented by an unstable mix-layered clay with illite. There is a general downhole increase in montmorillonite content with a minimum at a depth of 140 meters (Table 2, Figures 4, 5). In the lowermost layer, at a depth of 710 meters, the degree of crystallization is very high as shown by diffractograms with a narrow intense peak at 17.6Å after glycerin treatment. In the upper horizons the 001 peak of montmorillonite is wide and the  $v/p$  ratio (Biscaye, 1965) fluctuates from 0.5 to 0.6, whereas in the lower horizons it is approximately 0.9. The lithologic data indicate that the lower horizons were redeposited (Bogdanov et al., this volume). The illite content is lower than at Site 324 and ranges from 25% to 30%. Maximum chlorite plus kaolinite (about 50%) were found at a depth of approximately 170 meters. Feldspar and quartz

TABLE 2  
Composition <1  $\mu$ m Fractions of Leg 35 Mudstones

Sample (Interval in cm)	Approximate Depth (m)	Age	Montmor- illonite (%)	Illite (%)	Chlorite and Kaolinite	Nonclay Minerals
<b>Site 324</b>						
1-2, 126-131	11.8	Pleistocene	36	40	24	Clin.
1-3, 124-132	13.2	Pleistocene	25	52	23	Clin.
1-4, 125-131	14.7	Pleistocene	trace	65	35	Clin.
1-6, 31-38	16.8	Pleistocene	46	46	8	Clin.
2-1, 83-92	47.8	Pleistocene	16	47	37	Clin.
2-2, 61-70	49.1	Pleistocene	17	45	37	Clin.
2-3, 55-57	50.5	Pleistocene	37	41	22	Clin.
2-4, 27-36	51.8	Pleistocene	36	37	37	Clin.
2-5, 35-45	53.3	Pleistocene	20	50	30	Clin.
2-6, 95-104	55.4	Pleistocene	40	37	23	Clin.
3-1, 137-146	76.9	Pleistocene	35	39	26	Clin.
3-2, 136-145	78.4	Pleistocene	33	43	24	Clin.
3-3, 67-77	79.2	Pleistocene	35	40	25	Clin.
3-4, 47-57	80.5	Pleistocene	31	41	28	Clin.
3-5, 99-100	82.5	Pleistocene	25	46	29	Clin.
3-6, 138-148	84.4	Pleistocene	42	36	22	Clin.
4-2, 113-123	106.6	Pleistocene	37	38	25	Clin.
4-3, 30-40	107.3	Pliocene	27	45	28	Clin.
4-4, 56-64	109.0	Pliocene	35	42	23	Clin.
5-2, 66-83	134.7	Pliocene	33	42	25	
5-3, 25-35	135.7	Pliocene	26	47	27	
6-2, 19-30	143.7	Pliocene	37	40	23	
7-1, 69-78	149.2	Pliocene	29	46	25	
7-3, 110-120	155.6	Pliocene	25	46	29	
7-6, 119-129	160.2	Pliocene	22	47	31	
8-3, 61-71	174.1	Pliocene	27	49	24	
<b>Site 325</b>						
1-1, 133-144	35.3	Pliocene	47	32	21	Am.
1-2, 26-36	35.8	Pliocene	35	36	29	Am.
1-4, 81-92	39.3	Pliocene	42	31	27	Am. Clin.
2-2, 39-49	168.9	Pliocene	20	26	54	Am. Clin.
3-2, 11-24	177.1	Pliocene	25	20	55	Am.
3-3, 76-87	180.3	Pliocene	29	18	53	Am.
3-4, 26-36	181.3	Pliocene	26	26	48	Am.
5-1, 55-57	405.0	Miocene	38	36	26	Am. Clin.
5, CC	414.0	Miocene	49	33	18	Am. Clin.
6-1, 145-150	481.9	Miocene	45	30	25	Crist. Clin.
7-1, 131-135	519.8	Barren	60	25	15	Am.
7-2, 138-141	520.4	Early Oligocene to early Miocene	50	34	16	Clin.
8-1, 45-49	612.9	Early Oligocene to early Miocene	40	42	18	Clin.
8-2, 119-128	615.2	Early Oligocene to early Miocene	65	20	15	Clin.
8-3, 23-25	615.8	Early Oligocene to early Miocene	30	46	24	Crist. Clin.
9-3, 90-98	644.9	Early Oligocene to early Miocene	50	24	26	Clin. Am.
10-1, 35-39	708.8	Early Oligocene to early Miocene	53	27	20	Clin.
10-2, 26-30	710.3	Early Oligocene to early Miocene	71	17	12	Clin.

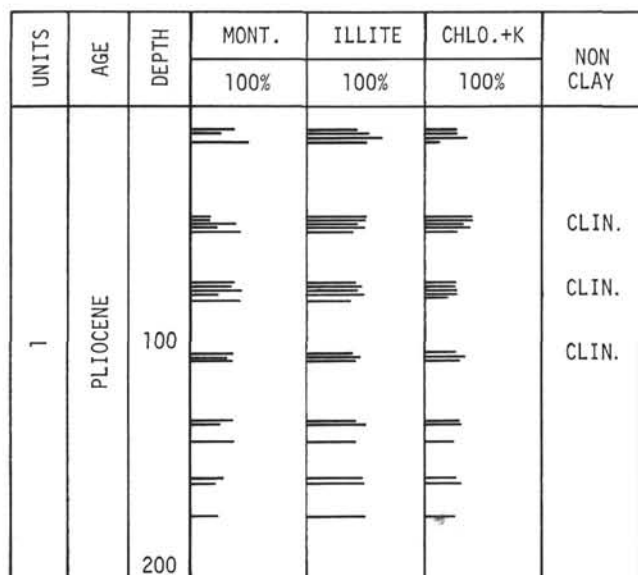
Note: Feldspars and quartz were found throughout.

occur throughout the section, and actinolite was noted down to 400 meters. At this depth a change in provenance of the sedimentary material occurs (see Bogdanov et al., this volume). Below 400 meters, the diagenetic minerals cristobalite and clinoptilolite occur.

As at Sites 322, 323, there seems to be no relation of clay mineral composition to lithologic changes.

## DISCUSSION OF RESULTS

Sites 322 and 323, are mineralogically similar. With the exception of the upper horizons, montmorillonite increases with depth and is the predominant mineral throughout. It is moderately to well crystallized and is

<1  $\mu$ m FRACTIONS

SITE 324

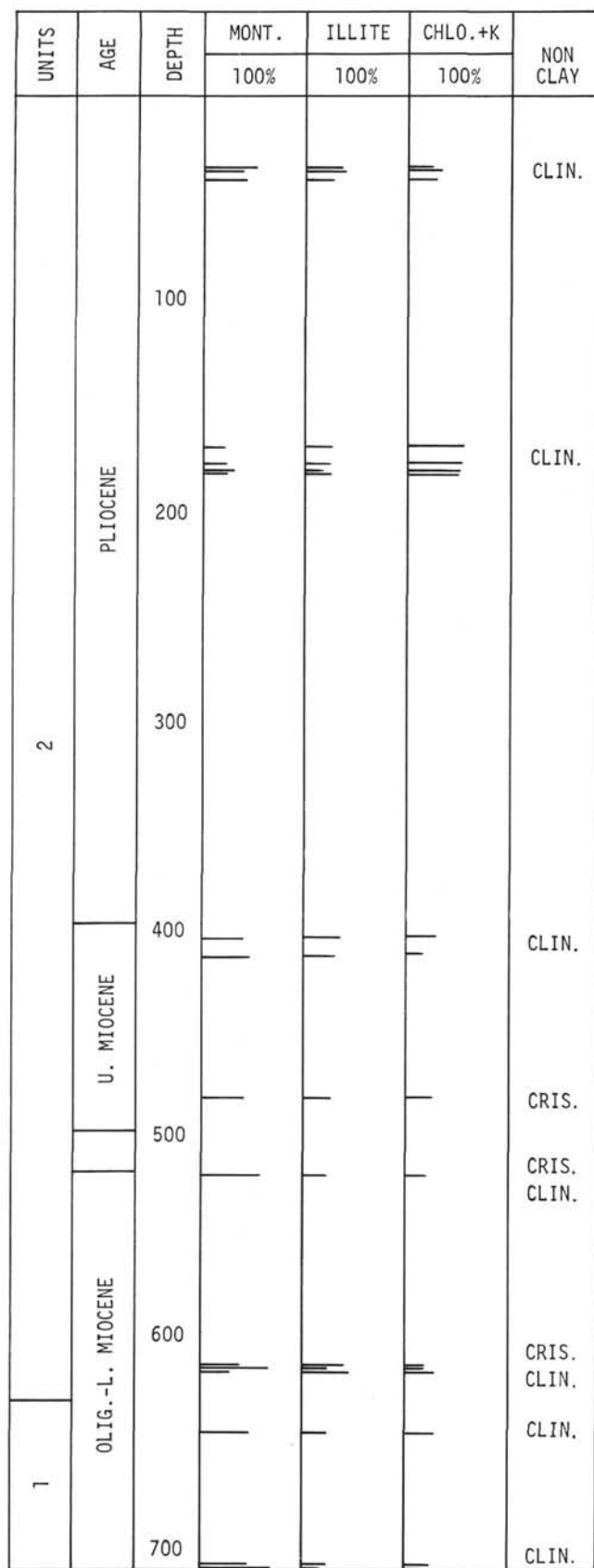
Figure 4a. Distribution of clay minerals at Site 324.

often mix-layered with illite. At both sites the basal sediments above basalt are nearly pure montmorillonite.

At Site 323 montmorillonite occurs together with goethite and clinoptilolite, whereas at Site 322 only clinoptilolite co-occurs. The nearly monomineralic composition and high degree of crystallization of these sediments (even in bulk samples from Site 323) are indicative of a hydrothermal origin and submarine diagenesis. Such mineral assemblages have been previously recognized in the surface layers of hydrothermally altered sediments of the southern basin of the Pacific Ocean (Gorbunova, 1974). The dark interlayers, enriched with ferromanganese hydroxides, have also been noted in many areas of the Pacific Ocean (Cook et al., 1970; Cook and Zemmels, 1971).

Illite content does not seem to show any changes with depth, whereas kaolinite plus chlorite decrease markedly. Montmorillonite is less common in the continental rise sites (324 and 325) than at the Bellingshausen Abyssal Plain sites. Well-crystallized illite and kaolinite plus chlorite, as well as montmorillonite, occur in normal abundance at Site 324. Illite is less abundant at Site 325 than at Site 324, suggesting different origins for the sediments at these sites. At Site 325, there is a tendency for montmorillonite content to increase with depth, but unlike Sites 322 and 323, monomineralic horizons were not encountered, although the lower horizons are characterized by well-crystallized montmorillonite. Apparently, these horizons represent redeposited material.

The distributions of chlorite plus kaolinite, as well as of illite (although less clearly) decrease. Similar trends of increasing montmorillonite and decreasing chlorite and illite contents with depth have been noted previously in DSDP sites in various areas of the Pacific Ocean—in the northeastern marginal zone (Hayes, 1973), in the Tasman Sea (Matti et al., 1973), and in the northwestern part of the Pacific Ocean (Okada and Tamuda, 1973). Hayes suggested that these trends are the result of the in-

<1  $\mu$ m FRACTIONS

SITE 325

Figure 4b. Distribution of clay minerals at Site 325.



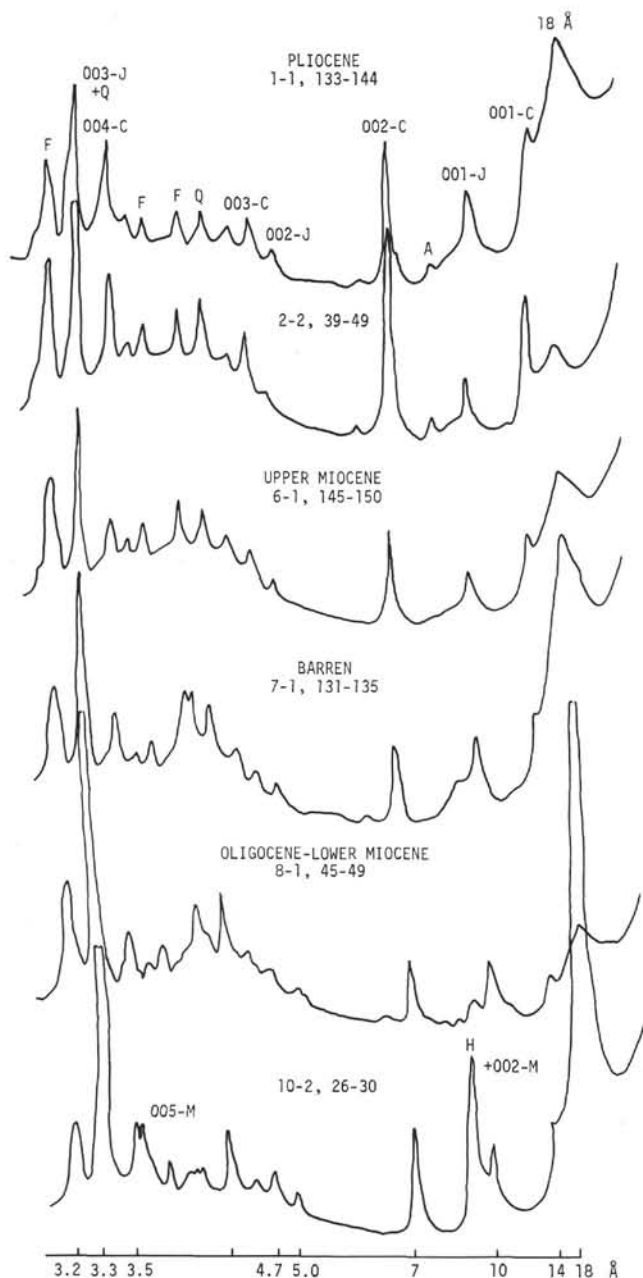


Figure 5. Diffraction pictures of clay minerals, showing the differences of depth in the sediments at Site 325.

fluence of many factors on the formation of clay such as, currents, turbidites, fluctuation of volcanic activity, glaciation, lowering of sea level, degree of erosion and weathering, mechanism of transport, etc. He proposed tectonic explanations for the differences between Pliocene and Pleistocene clays.

The increasing intensity of the 001 peak of the mixed-layered montmorillonite with site depth does not necessarily have the same origin. This may be attributed to the increase of unstable interlayers in the montmorillonite (Reynolds and Hower, 1970). This could also be the result of the increasing degree of crystallization of the montmorillonite in the basal sediments, or of the increasing abundance with depth. Between Pliocene

and lower Miocene sediments, the first two factors are not significant. The change in the degree of crystallization (if it occurs at all) is rather uncertain. The width of the 001 peak seldom varies and the 002 peak is more or less clearly expressed and shows no trend with depth. Only in hydrothermal sediments above the basalt is there any increase in the concentration and crystallization of the mineral. Thus, there is most probably an increase of the amount of the mineral with age. This could be attributed to a greater amount of volcanic activity in the Miocene in comparison to Pliocene, although the mineralogical data of the coarse fractions do not confirm it. A direct connection between the abundance of the volcanogenic material and montmorillonite can be hardly expected. The montmorillonite can be transported to the sediment from distant sources and not be formed locally. The basic source of the terrigenous materials in the cores was the weathering of the ancient crusts of Antarctica, which are rather homogeneous in composition. It is possible, that postdepositional alteration of the montmorillonite occurred because of other minerals or on account of an increase of its crystallization. This is hard to establish. Presently diagenesis and epigenesis are thought to be accompanied by an increase in illite abundance, however, this process has not been observed in the DSDP cores. In any case, an alternative explanation of this question has not been found as yet.

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