23. MINERALOGICAL DATA FROM SITES 211, 212, 213, 214, AND 215 OF DEEP-SEA DRILLING PROJECT LEG 22 AND ORIGIN OF NONCARBONATE SEDIMENTS IN THE EQUATORIAL INDIAN OCEAN[1]

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ABSTRACT

During the pre-late or middle Miocene times, basalt volcanics were the main source of sediments in the eastern equatorial Indian Ocean. The alteration of these volcanics resulted in the formation of smectite, palygorskite, phillipsite, clinoptilolite, or metahalloysite-kaolinite. This rather predominantly single source is contrasted with the diverse origins for the sediments in the eastern Indian Ocean during later times. These different sources are: the Indonesian silicic volcanic source resulting in the supply of smectite and volcanic ash; the Ganges-Brahmaputra River source supplying the illite-chlorite-rich sediments; the aeolian transport of kaolinite from western Australia; and the pelagic siliceous skeletal remains that have settled to the sea floor from the overlying waters in the equatorial productivity zone. In addition, basalt volcanics continued to be the source of the sediments in certain areas even though their importance was reduced. The diverse origins of the sediments during the late Cenozoic time are primarily the result of the northward movement of the Indo-Australian plate and the evolution of the eastern Indian Ocean—uplift of the Himalayas and the formation of the prominent subduction zone along the Indonesian islands—and certain paleoclimatological changes in the region during the Miocene and later.

INTRODUCTION

The objectives of this paper are: (1) to describe the mineral composition of the sediments drilled by DSDP Leg 22 at Sites 211, 212, 213, 214, and 215 and (2) in the light of this information, to discuss the origin and dispersal of sediments deposited through Cretaceous to Quaternary times in the equatorial eastern Indian Ocean. Except for the preliminary data reported by Venkatarathnam and Biscaye (in press), no information is available on the mineralogy of the sediments deposited during the pre-Quaternary period in the eastern Indian Ocean.

METHODS OF STUDY

The DSDP Leg 22 sites from which sediment samples have been chosen and analyzed are shown in Figure 1. The pre-Quaternary cores analyzed by Venkatarathnam and Biscaye (in press) are also shown in this figure.

Sample preparation (as described in more detail by Biscaye, 1965), consisted of treating the sediments with sodium acetate (pH = 5.0) to dissolve calcium carbonate, with sodium dithionate-citrate to remove amorphous iron and manganese oxides, and with hot sodium carbonate to disaggregate particles cemented together by amorphous silica and alumina.

The last treatment takes away only small amounts of amorphous silica and will not affect much of the chert or siliceous skeletal remains. After all the treatments, sediments were size-fractioned by gravity settling and decanting of the $<2\mu$ size material; $2\text{-}20\mu$ and $>20\mu$ size fractions were separated by sieving. The $<2\mu$ size fractions were freeze-dried, and thick clay pastes were made with a few drops of water and smeared on glass slides. Two or three slides were thus prepared for each sample. All the clay slides were glycolated and some were heat-treated. The $<2\mu$ size fractions were analyzed on a Siemen's X-ray diffractometer. Where the presence of palygorskite and a few other minerals was suspected, the clays were also examined under the transmission and scanning electron microscopes for confirmation of mineral identification (Plate 1).

The major clay mineral groups identified are smectite, kaolinite, illite, and chlorite. The method of estimating these minerals is as described by Biscaye (1965). In some samples, palygorskite was found to be abundant. Nonclay minerals were also observed in small amounts in some of the $<2\mu$ fractions. These minerals were not taken into account in the estimations of smectite, kaolinite, illite, and chlorite. In the case of one sample, 214-42[2], with an

[1]Lamont-Doherty Geological Observatory contribution No. 1961.

[2]When a reference is made in text to a specific sample analyzed, it is done by mentioning only the core number of a particular hole and no other details about the section of the core, interval of the section, etc., since only one sample per core was analyzed. All the details of each sample are noted in the tables.

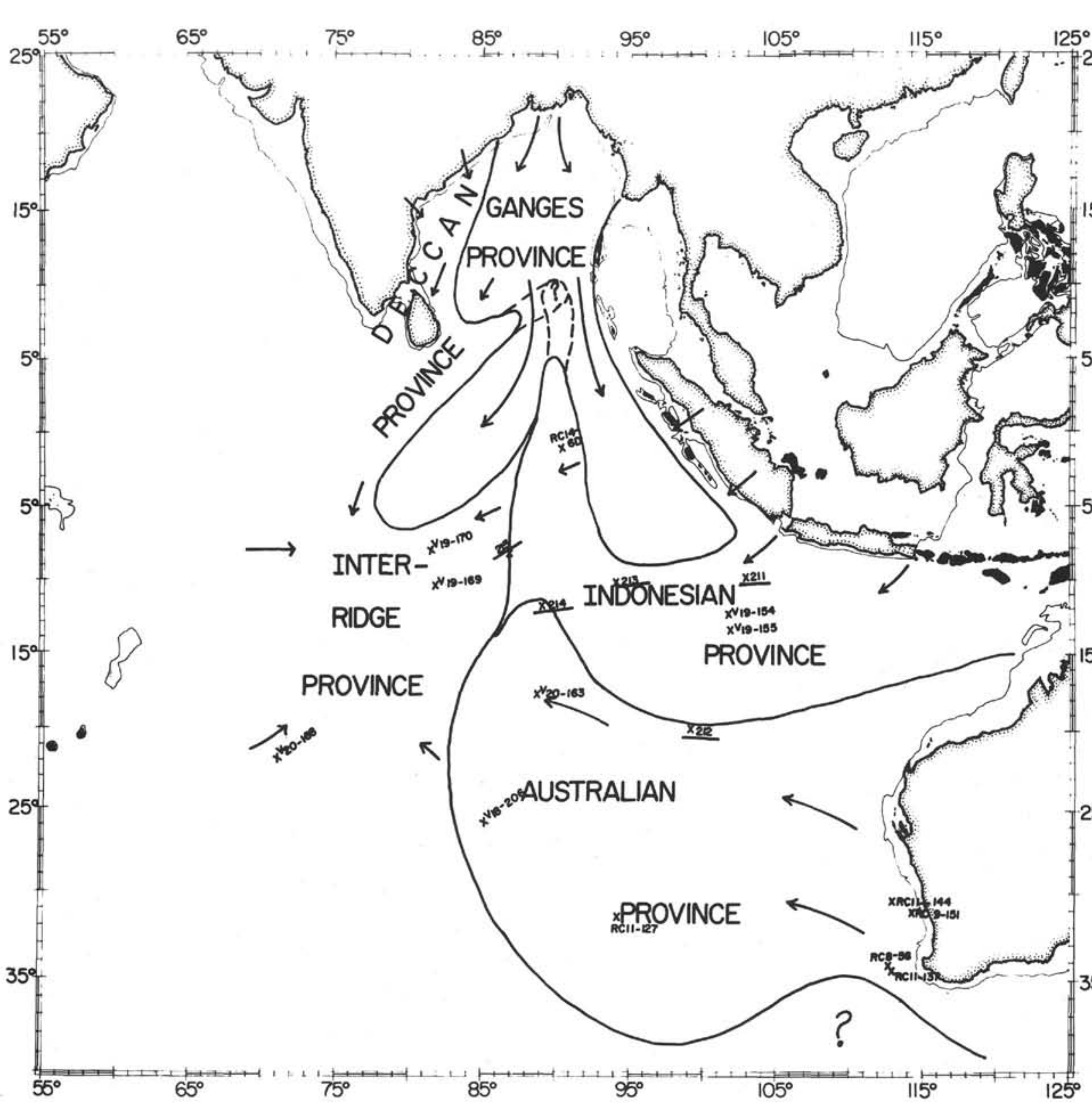

Figure 1. *Locations of DSDP Sites 211, 212, 213, 214 and 215 (underscored) and some pre-Quaternary piston cores. The mineral provinces shown in the map are from Venkatarathnam and Biscaye (in press).*

abundant kaolinite type of mineral, an attempt was made to distinguish the particular mineral species by X-ray diffraction and electron microscopy. The ratio of the 7Å and 4.47Å peak heights on the diffractograms is similar to that of metahalloysite rather than kaolinite (Brindley, 1961). The asymmetry and the rather wide distribution of each of these peaks indicate the presence also of some poorly crystallized kaolinite. Electron microscopic examination has revealed the presence of hexagonal as well as irregular shaped crystals (Plate 1, Figure 3). These observations taken together indicate the presence of metahalloysite and well to poorly crystallized kaolinite in the sample, 214-42.

In some samples rich in palygorskite, a peak at 10Å attributed to illite is present as a shoulder on the 10.6Å treatment at 400 to 600° C does destroy the 10Å peak. The identification of the illite mineral in such cases may be questionable and is so indicated in Figure 1 and Table 1.

The procedures adopted in this mineralogical study are similar to those of Goldberg and Griffin (1970) and Venkatarathnam and Biscaye (in press), thus enabling discussion of the significance of the present results in the context of these earlier investigations on the Quaternary and pre-Quaternary sediments of the eastern Indian Ocean.

The 2-20μ size fractions were X-rayed on a Norelco diffractometer. Besides the minerals quartz and feldspar, an attempt was made to look for the presence of minerals such as zeolites, cristobalite, barite, pyrite, magnetite, apatite, etc. The mineral peak heights in the X-ray tracings were compared and correlated with the results of the microscopic counts of the minerals on the smear slides. The minerals were then ranked according to an approximate

TABLE 1
Clay Mineral Composition of $<2\mu$ Size Fraction

Sample	Interval (cm)	Smectite (%)	v/p Ratio Smectite	Illite (%)	Kaolinite (%)	Chlorite (%)	Age	Remarks	Lithology
211-1-3	0-10	76	0.53	10	11	2	Quat.	–	Siliceous ooze with ash
211-2-3	0-10	83	0.71	8	8	2	Quat.	–	Siliceous ooze with ash
211-3-4	0-10	77	0.60	11	10	2	Lt. Plio.	–	Siliceous ooze with ash
211-4-3	0-10	66	0.72	22	4	7	Plio.	–	Micac. silty sand clay
211-6-5	0-10	51	0.69	35	5	7	Plio.	–	Siliceous ooze (micac.)
211-9-3	0-10	22	0.43	57	7	14	Plio.	–	Silty sand
211-12, CC	8-10	17	0.02	69 (?)	11	2	Camp.	Abundant palygorskite	Hard brown clay
211-14-1	12-19	14	0.00	83 (?)	3	3	–	Abundant palygorskite	Brown clay
212-2-3	0-10	47	0.40	12	40	–	E. Plio.	–	Brown clay
212-5, CC	–	74	0.83	6	20	–	Lt. Mio.	–	Nannofossil ooze
212-10-5	0-10	83	0.74	8	8	1	Lt. Mio.	–	Nannofossil ooze
212-11-3	0-10	82	0.79	6	11	–	E.-M. Mio.	–	Nannofossil ooze
212-14-5	0-10	79	0.66	8	12	–	E.-M. Mio.	–	Nannofossil foraminifera chalk
212-15-3	0-10	61	0.34	21	17	–	–	–	Brown clay
212-20, CC	–	96	0.66	1	2	–	M. Eoc.	–	Calc. dark gray clay
212-25-5	0-10	99	0.91	1	–	–	M. Eoc.	Clinoptilolite traces	Nannofossil chalk
212-29, CC	–	89	0.82	5	5	1	(?)	–	Brown clay
212-33-3	0-10	97	0.87	3	–	–	U. Cret.	Clinoptilolite traces	Nannofossil foraminifera chalk
212-35-2	0-10	96	0.83	4	–	–	(?)	–	Nannofossil foraminifera chalk
212-37, CC	–	76	0.61	23 (?)	–	–	(?)	Considerable clinoptilolite and poorly crystallized mixed layer mineral present	Brown clay
213-1-0	–	70	0.41	9	21	–	Quat.	–	Siliceous ooze
213-2-5	0-10	70	0.39	11	18	–	Lt. Plio.	–	Siliceous ooze
213-5-5	0-20	70	0.63	9	20	–	E. Plio.	–	Siliceous ooze
213-7-5	0-20	73	0.70	8	17	1	Lt. Mio.	–	Siliceous ooze
213-9-6	0-20	88	0.82	3	8	–	M. Mio.	–	Brown clay
213-11-5	0-20	75	0.74	7	16	1	(?)	–	Brown clay
213-13-6	0-20	80	0.66	13	5	2	(?)	–	Brown clay
213-15-6	0-20	79	0.53	15	5	–	Lt. Paleo.	Palygorskite	Nannofossil ooze
213-16-4	0-10	79	0.34	20	1	–	Lt. Paleo. (?)	Palygorskite	Nannofossil ooze
214-1-5	130-150	54	0.35	18	26	–	Pleist.	–	Foraminifera-Nannofossil ooze
214-7-5	0-20	63	0.31	7	30	–	Plio.	–	Foraminifera-Nannofossil ooze
214-11-5	0-20	70	0.00	3	22	4	Lt. Mio.	–	Foraminifera-Nannofossil ooze
214-15-3	0-20	78	0.39	5	11	5	Lt. Mio.	–	Foraminifera-Nannofossil ooze
214-19-5	0-20	91	0.60	2	5	1	M. Mio.	–	Foraminifera-Nannofossil ooze
214-23-5	0-20	80	0.56	9	7	2	E. Mio.	Clinoptilolite considerable	Foraminifera-Nannofossil ooze
214-27-5	0-20	71	0.24	22 (?)	4	2	Oligo.	Mixed layer mineral traces	Nannofossil ooze
214-31-5	0-20	58	0.22	37 (?)	2	2	Eoc.	Palygorskite and clinoptilolite	Nannofossil ooze
214-35-5	0-10	–	–	–	–	–	Paleo.	Mostly palygorskite	Glauconite calcarenite
214-37-2	0-10	>95%	0.73	–	–	–	Paleo.	–	Glauconite calcarenite
214-39-3	0-10	>95%	0.75	–	–	–	Paleo.	–	Glauconite calcarenite
214-41-3	0-10	>95%	0.92	–	–	–	Paleo.(?)	–	Calcarenite
214-42, CC	–	–	–	–	100	?	Paleo.(?)	–	Lignite clays
214-52, CC	–	>95%	0.37	–	–	–	Paleo.(?)	–	Brown clay
215-1-5	0-20	64	0.54	13	17	5	Lt. Plio.	–	Siliceous ooze
215-3-5	0-20	68	0.55	8	18	5	E. Plio.	–	Siliceous ooze
215-5-2	0-20	64	0.62	11	16	7	Lt. Mio.	–	Siliceous ooze
215-8-3	0-20	88	0.85	6	5	1	Lt. Mio.	–	Brown clay
215-9-2	0-20	51	0.39	43 (?)	–	5	E. Eoc.	Abundant palygorskite	Brown clay
215-10-2	0-20	35	0.00	63 (?)	1	1	E. Eoc.	Abundant palygorskite	Nannofossil ooze with some clay
215-11-5	0-20	>95	0.78	–	–	–	Paleo.	Clinoptilolite traces	Nannofossil ooze with some clay
215-15-4	0-20	>95	0.80	–	–	–	Paleo.	Clinoptilolite traces	Nannofossil ooze with some clay
215-17-1	73-80	>95	0.91	–	–	–	Paleo.	–	Brown clay

scale as: abundant (A, with >50%), common (C, with 50%-10%), and traces (Tr, with <10%). Microscopic examination has, in particular, helped to identify and estimate glauconite, rock fragments, and palagonite grains.

The >20μ size fractions were examined only microscopically. Aggregates of mineral grains (other than glauconite and pyrite aggregates) were identified as volcanic rock fragments or cristabolite, depending upon the optical properties. If the grains were present as individual minerals, they were separately identified and estimated. The arbitrary limits chosen for abundances of the different constituents, are the same as for the 2-20μ size fractions.

RESULTS AND DISCUSSION

Venkatarathnam and Biscaye (in press) distinguished a number of Quaternary clay mineral provinces in the eastern Indian Ocean (Figure 1). Briefly, these provinces are: (1) The Deccan Province in the northwestern part of the area characterized by abundant smectite clay derived from the Deccan trap soils; the sediment dispersal in the province is by surface water circulation and turbidity currents in the western Bay of Bengal. (2) The Ganges (illite-chlorite) Province extending to the south of the equator on both sides of the Ninetyeast Ridge; turbidity currents have chiefly been responsible in the transport of these sediments. (3) The Indonesian Province with high smectite adjacent to the Indonesian Islands, on the Cocos-Roo Rises, and on the Ninetyeast Ridge between 5°N and 14°S. This province is influenced by aeolian transport of silicic volcanic ash from the Indonesian Island arc. (4) The Australian Mineral Province in the southern Wharton Basin and on the Ninetyeast Ridge south of about 15°S, characterized by relatively high amounts of kaolinite transported by aeolian process from the western Australian continent. (5) The Inter-Ridge Province between the Ninetyeast Ridge and the mid-Indian Ridge south of about 5°S with a high amount of smectite derived in part from the mid-Indian Ridge volcanism and in part from local submarine volcanics.

The mineralogical composition and the sources of noncarbonate sediments characteristic of the Quaternary period have changed markedly during certain times in the pre-Quaternary period in the equatorial Indian Ocean.

Site 211

The Quaternary sediments (Cores 1 and 2) contain abundant smectite and volcanic ash beds (Figure 2, Table 1). This high smectite abundance persists into the late Pliocene (Core 3) as well. In the sediments of early (?) Pliocene age (Cores 4, 6, and 9), however, a marked mineralogical change has occurred. These sediments have high amounts of illite and chlorite minerals in the <2μ size fraction, and abundant quartz, colorless and brown micas with small amounts of green amphibole and epidote in the coarser fractions (Tables 2 and 3). Turbidites are frequently present in these Pliocene sediments. (Scientific Staff, DSDP Leg 22, 1972). Another change in mineral composition is in the Cretaceous sediments (Cores 12 and 14) which contain abundant palygorskite with small amounts of smectite (Table 1). The amounts of illite (?) among the nonpalygorskite clay minerals are high. In the coarser fractions of these cores, feldspar (with some sanidine) and amphibole (green and basaltic hornblendes) are common, and volcanic rock fragments and palagonite grains are definitely present, though in traces. It should be noted that the samples analyzed from Cores 12 and 14 are from near a basalt horizon.

Amorphous siliceous skeletons are present in abundance in Cores 1, 2, and 3 and in traces in Core 4. They are absent in the rest of the cores (Table 2).

It is inferred that the Upper Cretaceous sediments, rich in palygorskite, are derived from the alteration of in situ volcanics. If the identification and therefore the estimation of illite in the Cretaceous sediments is correct, this mineral, like palygorskite, may also be of authigenic origin. In the early Pliocene, the Ganges-Brahmaputra River sediments, rich in illite, chlorite, and the other minerals described, have been transported to the area of Site 211 by turbidity currents similar to the adjacent Quaternary Ganges Province (Figure 1). This source has been cut off due to the tectonics in the region of Site 211 (see Site Report) and was replaced in late Pliocene by smectite and silicic volcanic ash sediments derived from the Indonesian arc. This arc has since continued to supply material to the region. The study of the piston cores V19-155 and V19-154 (Venkatarathnam and Biscaye, in press) south of Site 211, but from the same Quaternary province as the site, corroborates the inference of the basalt volcanic source for the sediments in Late Cretaceous times as opposed to the silicic Indonesian volcanic source in Quaternary times. No illite- and chlorite-rich sediments were observed in these piston cores.

Site 212

This site is located in the Quaternary Australian Mineral Province (Figure 1).

Except in the Pliocene and to some extent in the upper Miocene sediments (Cores 2 and 5), where kaolinite is present in relatively higher amounts, abundant smectite is present in the <2μ size fractions in all the sediments of Site 212 irrespective of lithology (Figure 2). In the coarse fractions, volcanic rock fragments, palagonite, feldspar, and quartz are either common or present in traces throughout the hole. However, in the 2-20μ fractions of calcareous chalks of the early-middle Miocene and the brown clays of unknown age overlying the Eocene chalks (Cores 10, 11, and 15), the zeolite phillipsite is common (Table 2); in the Eocene and Upper Cretaceous chalks and in the brown clays directly overlying the basalt, clinoptilolite is common.

Siliceous skeletal remains are abundant in the middle Eocene chalk.

Though local submarine volcanics is the main source of much of the sediments at Site 212, it appears that in late Miocene and Pliocene times, detrital kaolinite has been supplied to the area in greater abundances similar to the Quaternary. This observation is corroborated by the data reported by Venkatarathnam and Biscaye (in press) on piston cores V20-163, RC 11-127, RC 11-137, RC 11-144, and RC 9-151 from the Australian Province. According to Gill (1961), the present aridity and desert conditions in western Australia have developed during the last one million years. However, the temperature and humidity of

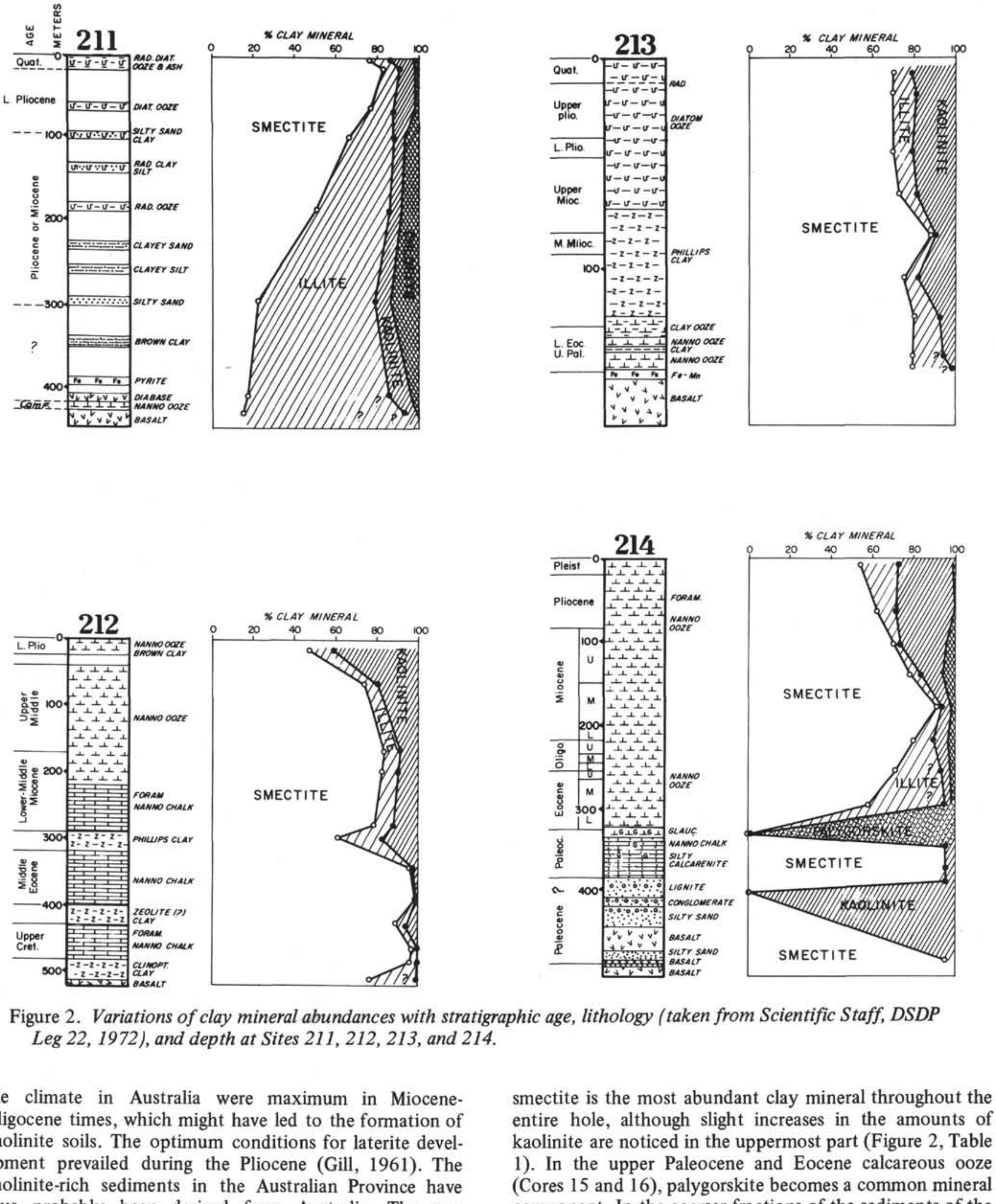

Figure 2. *Variations of clay mineral abundances with stratigraphic age, lithology (taken from Scientific Staff, DSDP Leg 22, 1972), and depth at Sites 211, 212, 213, and 214.*

the climate in Australia were maximum in Miocene-Oligocene times, which might have led to the formation of kaolinite soils. The optimum conditions for laterite development prevailed during the Pliocene (Gill, 1961). The kaolinite-rich sediments in the Australian Province have thus probably been derived from Australia. The pre-Quaternary kaolinite, however, may not have reached in this province by aeolian transport.

Site 213

This site is located in the Quaternary Indonesian Mineral Province similar to Site 211. In the $<2\mu$ size fractions, smectite is the most abundant clay mineral throughout the entire hole, although slight increases in the amounts of kaolinite are noticed in the uppermost part (Figure 2, Table 1). In the upper Paleocene and Eocene calcareous ooze (Cores 15 and 16), palygorskite becomes a common mineral component. In the coarser fractions of the sediments of the middle Miocene and brown clays of unknown age overlying the lower Eocene calcareous ooze (Cores 9 and 11), phillipsite is a common mineral component. Both the palygorskite and phillipsite minerals have associated with them volcanic rock fragments and palagonite in considerable amounts. In addition, in Cores 15 and 16 (with

TABLE 2
Mineral Composition of the 2-20μ Size Fraction

Sample	Interval (cm)	Diffracting Material	Amorphous Material	Diffracting Material			Quartz	Feldspar	Volc. Rock Volc. Clay Palagonite	Age	Remarks	Lithology
				Mica	Clinoptilolite	Phillipsite						
211-1-3	0-10	Tr	A	–	–	–	C	Tr	–	Quat.	Shards: C	
211-2-3	0-10	Tr	A	Tr	–	–	C	Tr	–	Quat.	–	
211-3-4	0-10	Tr-C	A	Tr	–	–	C	–	–	Lt. Plio.	Shards: Tr	
211-4-3	0-10	A	Tr	Tr-C	–	Tr-C	A	Tr	–	Plio.	Shards & amphibole: Tr Chlorite: Tr	
211-6-5	0-10	A	–	C	–	Tr	A	Tr	–	Plio.	Amphibole: Tr Chlorite: Tr	
211-9-3	0-10	A	–	C	–	Tr	A	Tr	–	Plio.	Amphibole: Tr Chlorite: Tr	
211-12, CC	8-10	A	–	Tr	–	–	A	Tr-C (some sanidine)	Tr	Camp.	Green & basalt hornblende: Tr-C Palygorskite: Tr	
211-14-1	12-19	A	–	–	–	–	.A	Tr-C	–	–	–	
212-2-3	0-10	A	–	Tr-C	–	Tr-C	C-A	Tr	Tr-C	E. Plio.	–	
212-5,CC	–	A	–	Tr	Tr	A	C	Tr	Tr	Lt. Mio.	–	
212-10-5	0-10	A	–	–	Tr	C	C	C	Tr-C	Lt. Mio.	–	
212-11-3	0-10	A	–	–	–	C	C	C	Tr-C	E.-M. Mio.	–	
212-14-5	0-10	A	–	Tr	–	Tr	A	Tr	C	E.-M. Mio.	–	
212-15-3	0-10	A	–	Tr	–	Tr-C	A	C	C	(?)	–	
212-20,CC	–	Tr	A	–	–	Tr	Tr	Tr	Tr	M. Eoc.	Cristobalite: Tr	
212-25-5	0-10	A	–	–	A	–	Tr	Tr	Tr	M Eoc.	Cristobalite: Tr	
212-29,CC	–	A	Tr	Tr	Tr?	Tr(?)	C-A	C (sanidine?)	Tr	(?)	Cristobalite: Tr	
212-33-3	0-10	A	–	Tr	A	–	Tr-C	Tr	Tr	U. Cret.	–	
212-35-2	0-10	A	–	Tr	Tr	–	C-A	C	Tr	(?)	–	
212-37,CC	–	A	–	–	A	–	C	Tr	Tr	(?)	–	
213-1-0	–	Tr	A	–	–	–	Tr-C	Tr	–	Quat.	–	
213-2-5	0-10	C	C	Tr	–	Tr	C	Tr-C	–	Lt. Plio.	–	
213-5-5	0-20	C	C-A	Tr	–	Tr	C	Tr-C	–	E. Plio.	Cristobalite (?): Tr	
213-7-5	0-20	Tr-C	A	–	–	Tr	C	Tr	–	Lt. Mio.	Cristobalite (?): Tr	
213-9-6	0-20	C	C	–	–	C	Tr-C	Tr	Tr	M. Mio.	Cristobalite (?)	
213-11-5	0-20	A	–	–	–	A	Tr	Tr	Tr	(?)	–	
213-13-6	0-20	A	–	–	–	Tr(?)	C	Tr-C	C	(?)	–	
213-15-6	0-20	A	–	–	–	Tr	Tr	A (sanidine)	Tr	Lt. Paleo.	–	
	0-10	A	Tr	–	–	Tr	Tr	A (sanidine)	Tr	Lt. Paleo.	–	
214-1-5	130-150	Tr	A	–	–	–	Tr	Tr	–	Pleisto.	–	
214-7-5	0-20	Tr	A	–	–	–	Tr	Tr	–	Plio.	–	
214-11-5	0-20	Tr	A	–	–	–	Tr	Tr	–	Lt. Mio.	–	
214-15-3	0-20	Tr	A	–	–	–	Tr	Tr	Tr	Lt. Mio.	–	
214-19-5	0-20	Tr	A	–	–	–	Tr	–	–	M. Mio.	–	
214-23-5	0-20	A	–	–	C	A	Tr	Tr	Tr	E. Mio.	–	
214-27-5	0-20	A	Tr	–	Tr	A	Tr	Tr	Tr	Oligo.	–	
214-31-5	0-20	A	–	–	A	Tr	C	Tr	A	Eocene	Palygorskite: Tr	
214-35-5	0-10	–	–	C (glauc)	–	–	–	–	A	Paleo.	–	

214-37-2	0-10	–	Tr	C (glauc)	–	–	–	–	A	Paleo.	–	
214-39-3	0-10	Tr	Tr	Tr (mixed layer)	–	–	–	C	A	Paleo.		
214-41-3	0-10	Tr	–	–	–	–	–	Tr	C	Paleo.	Pyrite: C	
214-42,CC	–	A			A	–	Tr	–	Tr	Paleo.	Pyrite: Tr	
214-52,CC	–	–	–	–	–	–	–	–	A	Paleo.	–	
215-1-5	0-20	Tr	A	–	–	Tr	Tr	Tr	Tr	Lt. Plio.	–	
215-3-5	0-20	Tr	A	–	–	Tr	Tr	Tr	–	E. Plio.	–	
215-5-2	0-20	Tr	A	Tr	–	Tr	Tr	Tr	–	L. Mio.	–	
215-8-3	0-20	C	C	–	–	Tr	Tr-C	Tr	C	Lt. Mio.	–	
215-9-2	0-20	A	Tr	–	–	C	C	Tr-C	C	E. Eoc.	Palygorskite: C	
215-10-2	0-20	A	Tr	–	–	–	C	Tr	Tr	E. Eoc.	Glauconite: Tr Palygorskite: C	
215-11-5	0-20	A	Tr	–	A	–	Tr	–		Paleo.	Clinoptilolite traces	Nanno ooze with some clay
215-15-4	0-20	A	Tr	–	A	–	–	–		Paleo.	Clinoptilolite traces	Nanno ooze with some clay
215-17-1	0-20	A	–	–	Tr	–	–	–		Paleo.	–	Brown clay

palygorskite), abundant sanidine has been observed. On the other hand, in the sediments of late Miocene and younger ages, palagonite is either absent or present only in traces. Amorphous siliceous skeletal remains are abundant in these younger sediments.

The fine and coarse fraction mineralogy described indicates that during the pre-middle Miocene, basalt volcanics was the main source of the sediments. In the sediments of late Miocene and younger ages, even though smectite is abundant, basaltic palagonite and rock fragments are present either in traces or absent in contrast to the higher abundances of these components in earlier times. This suggests that the silicic Indonesian volcanics characteristic of the Quaternary may have been a source since the late Miocene.

Site 214

This site is located in the Australian Province on the Ninetyeast Ridge, but near the border with the Indonesian Province (Figure 1). The Pliocene and upper Miocene sediments (Cores 1, 7, and 11) have relatively higher amounts of kaolinite (Figure 2, Table 1). Smectite is present in high amounts in these sediments, but its abundance is relatively higher in middle and lower Miocene, and Oligocene sediments (Cores 19, 23, and 27). Palygorskite begins to show up in the late Eocene (Core 31) and becomes abundant in the lower Eocene-Paleocene sediments (Core 35). In Cores 37, 39, and 41 of Paleocene age, smectite is again abundant. In Core 42 of Paleocene (?) age, in a lignite sample, metahalloysite-kaolinite mineral layers become abundant; further down in the hole in Core 52, smectite is abundant.

In the coarse fractions in the sediments of middle Miocene and younger ages (Cores 19, 15, 11, 7, and 1), siliceous skeletal remains are abundant, but are absent in the older sediments. Phillipsite is abundant in the lower Miocene and Oligocene sediments (Cores 23 and 27). Though clinoptilolite is common in Core 23 (early Miocene), this zeolite is more abundant in Core 31 of middle Eocene and Core 42 (rich in lignite) of Paleocene (?) ages (Table 2). Pyrite is a common component in Cores 41 and 42. Starting from Core 23, volcanic rock fragments and palagonite become more and more abundant towards the bottom of the hole. Basaltic hornblende is abundant in Core 52 (Paleocene ?) immediately above the basalt. Smectite is the abundant clay mineral in the materials of dredge RC 14-6D from the Ninetyeast Ridge. This dredge consists of mudstones, limestones, and altered volcanic rocks of Cretaceous-Eocene age.

The source of kaolinite in sediments of late Miocene and Pliocene age is probably similar to that of Site 212. The metahalloysite-kaolinite of Paleocene (?) age was, however, of a different origin. It appears that basalt volcanics and their alteration products were the main source of the minerals during the pre-middle Miocene. Yet the different minerals–smectite, palygorskite, phillipsite, clinoptilolite, and kaolinite–have been formed at different stratigraphic horizons. These minerals are probably the result of different environmental conditions prevailing at different times. The metahalloysite-kaolinite minerals in the Paleocene (?) sediments have developed from volcanics and smectite.

TABLE 3
Mineral Composition of $>2\mu$ Size Fractions

Sample	Interval (cm)	Mineral Abundances	Age
211-1-3	0-10	Siliceous skeletons (Radiolaria and diatoms): A; terr. minerals: Tr; glass shards: Tr	Quat.
211-2-3	0-10	Siliceous skeletons: A	Quat.
211-3-4	0-10	Siliceous skeletons: A; terr. minerals: Tr; glass shards: Tr	Lt. Plio.
211-4-3	0-10	Siliceous skeletons: Tr to common; terr. minerals–mainly quartz and mica with hornblende and epidote: Tr; phillipsite: Tr	Plio.
211-6-5	0-10	Terr. minerals (mainly quartz and mica with hornblende in traces): A; phillipsite: Tr	Plio.
211-9-3	0-10	As in Core 6	Plio.
211-12-, CC	8-10	Feldspar (mainly plagioclase with some K-feldspar): A; volcanic rock fragments and palagonite: Tr	Camp.
211-14-1	12-19	Feldspar and quartz: A	–
212-2-3	0-10	Volcanic rock fragments and palagonite: A; quartz and feldspar: C; phillipsite: Tr	E. Plio.
212-5, CC	–	Palagonite (and magnetite): A; phillipsite: C; feldspar and quartz: Tr	Lt. Mio.
212-10-5	0-10	Palagonite and volcanic rock fragments: A; phillipsite: Tr	Lt. Mio.
212-11-3	0-10	Palagonite and volcanic clay: A; phillipsite: Tr; feldspar: Tr	E.-M. Mio.
212-14-5	0-10	Palagonite and volcanic clay: A; phillipsite: Tr; feldspar: Tr	E.-M. Mio.
212-15-3	0-10	Palagonite, volcanic rock fragments (and magnetite): A; feldspar: Tr	(?)
212-20, CC	–	Siliceous skeletons: A; palagonite: C; feldspar and phillipsite: Tr	M. Eoc.
212-25-5	0-10	Feldspar: C; clinoptilolite: Tr-C; palagonite and magnetite: Tr	M. Eoc.
212-29, CC	–	Rock fragments and palagonite: A; feldspar: C	(?)
212-33-3	0-10	Rock fragments and palagonite: C; feldspar: Tr-C; clinoptilolite: C	U. Cret.
212-35-2	0-10	Rock fragments and palagonite: A; feldspar: C; quartz: Tr	(?)
212-37, CC	–	Clinoptilolite: A; feldspar and palagonite: Tr	(?)
213-1-0	0-10	Siliceous skeletons: A; feldspar and palagonite: Tr	Quat.
213-2-5	0-20	Siliceous skeletons: A; feldspar, quartz, and palagonite: Tr	Lt. Plio.
213-5-5	0-20	Siliceous skeletons: A	E. Plio.
213-7-5	0-20	Siliceous skeletons: A	Lt. Mio.
213-9-6	0-20	Siliceous skeletons: C; phillipsite: C; palagonite and volcanic rock fragments: C; feldspar: Tr	M. Mio.
213-11-5	0-20	Phillipsite: A; palagonite: Tr-C	(?)
213-13-6	0-20	Palagonite, volcanic rock fragments, and clay; A; feldspar and phillipsite: Tr	(?)
213-15-6	0-20	Palagonite and volcanic rock fragments: A; feldspar (sanidine): C; phillipsite: Tr	Lt.Paleo.
213-16-4	0-10	Palagonite and volcanic fragments (palygorskite): A; feldspar (sanidine): C	Lt. Paleo.

TABLE 3 – *Continued*

Sample	Interval (cm)	Mineral Abundances	Age
214-1-5	130-150	Siliceous skeletons: A	Pleist.
214-7-5	0-20	Siliceous skeletons: A	Plioc.
214-11-5	0-20	Siliceous skeletons: A	Lt. Mio.
214-15-3	0-20	Siliceous skeletons: A; palagonite: Tr	Lt. Mio.
214-19-5	0-20	Siliceous skeletons: A; palagonite: Tr	M. Mio.
214-23-5	0-20	Rock fragments and palagonite: C; phillipsite and feldspar: Tr	E. Mio.
214-27-5	0-20	Rock fragments and palagonite: A; feldspar: C; phillipsite: Tr-C	Olig.
214-31-5	0-20	Volcanic rock fragments and palagonite: A; feldspar: Tr	Eoc.
214-35-5	0-10	Volcanic rock fragments and palagonite: A; glauconite: C	Paleo.
214-37-2	0-10	Volcanic rock and palagonite: C; siliceous skeletons: Tr; magnetite: Tr	Paleo.
214-39-3	0-10	Volcanic rock and palagonite: C; siliceous skeletons: Tr; magnetite: Tr	Paleo.
214-41-3	0-10	Volcanic clay fragments and palagonite: A; pyrite: Tr; feldspar: Tr	Paleo.(?)
214-42, CC	–	Volcanic clay and palagonite: A; feldspar: Tr	Paleo.(?)
214-52, CC	–	Volcanic fragments and palagonite: C; basalt hornblende: A; magnetite: Tr	Paleo.(?)
215-1-5	0-20	Siliceous skeletons: A	Lt. Plio.
215-3-5	0-20	Siliceous skeletons: A	E. Plio.
215-5-2	0-20	Siliceous skeletons: A; palagonite; Tr	Lt. Mio.
215-8-3	0-20	Siliceous skeletons: A; palagonite and volcanic fragments: C	Lt. Mio.
215-9-2	0-20	Volcanic rock fragments and palagonite: C; palygorskite and chert: A; phillipsite: Tr	E. Eoc.
215-10-2	0-20	No sample	E. Eoc.
215-11-5	0-20	Volcanic fragments and palagonite: C; clinoptilolite and chert: C; feldspar: Tr	Paleo.
215-15-4	0-20	Volcanic fragments and palagonite: C; clinoptilolite and chert: C; feldspar: Tr	Paleo.
215-17-1	73-80	Volcanic fragments and palagonite: A	Paleo.

During the Paleocene, part of the Ninetyeast Ridge in the area of Site 214 existed as an island or was very shallow with lagoonal conditions which favored the production of abundant organic matter. This organic matter subsequently became lignite (Scientific Staff, 1972). Low pH and Eh conditions existed at Site 214 as a consequence of the presence of abundant organic matter. These conditions would transform the volcanogenic smectite into kaolinite-metahalloysite by a process similar to that described by Carroll and Hathaway (1963). These same conditions would also have produced the observed pyrite.

The origin of zeolites and palygorskite will be discussed later.

Site 215

This site is located on the border between the Indonesian and the Inter-Ridge provinces (Figure 1).

Smectite is the abundant clay mineral throughout this hole except in Cores 9 and 10 (early Eocene) where palygorskite is present in high amounts (Figure 3). In the coarser fractions, phillipsite is present in traces in the sediments of late Miocene and younger ages, but absent in the older sediments. In the older sediments (Cores 8, 9, 10, 11, 15, and 17), palagonite and volcanic rock fragments are common or abundant. Chert fragments and abundant clinoptilotite are present in Cores 11 and 15 of Paleocene age.

The mineralogy of Site 215 thus reflects a volcanic influence from the Paleocene to Quaternary, but basalt volcanics were more important as a source in pre-late Miocene times. In the younger sediments Indonesian volcanics may have provided a source of material.

Palygorskite

This mineral occurs in certain Upper Cretaceous, Paleocene, and Eocene calcareous sediments and brown clays in Sites 211, 213, 214, and 215. The X-ray tracings show relatively poorly to well crystallized palygorskite. In the palygorskite-rich sediments smectite is present in low amounts and is poorly crystallized (crystallinity was measured by Biscaye's, 1965, *v/p* ratio method). Smectite is abundant in the sediments just above or below palygorskite horizons. In the coarse fractions, usually volcanic rock fragments and palagonite, sometimes chert and sanidine are associated with palygorskite; zeolites are occasionally common.

The genesis of palygorskite in the deep sea is no doubt related to the alteration of volcanics (von Rad and Röch, 1972; Bonatti and Joensuu, 1968) possibly with smectite acting as an intermediary. In places, the palygorskite clays occur near basalts and basal iron-oxide-rich sediments of probable hydrothermal origin (see von der Borch and Rex, 1970). Elsewhere, the stratigraphic position of palygorskite is far above the basalt basement and separated from it by sediments without palygorskite. In the latter cases, volcanic rock fragments and palagonite grains occur both in sediments with or without palygorskite. With the available data, it is not known whether the magnesium ions required to combine with silica released from the alteration of volcanics and palagonite have been supplied from hydrothermal sources (Bonatti and Joensuu, 1968) or from seawater (Hathaway and Sachs, 1965). In either case, the genesis of palygorskite as opposed to zeolites in certain sediments and at particular stratigraphic horizons is not clear.

Zeolites

This study shows that phillipsite occurs both in calcareous sediments and brown clays and is restricted mostly to Miocene and younger sediments, but sometimes to Oligocene sediments. Clinoptilolite, on the other hand, is more abundant in Eocene and older sediments–calcareous ooze and in one case lignitic clay. The temporal distribution of the two zeolites is similar to that reported by Venkatarathnam and Biscaye (in preparation) from a study of about 70 piston cores in the Indian Ocean.

Abundant smectite, volcanic fragments, and palagonite are associated with both types of zeolites. From this preliminary examination, it appears there is no difference in the type of associated volcanics. If the chemical composition of the volcanics associated with both these zeolites is the same, it may be that the formation of clinoptilolite (richer in silica than phillipsite) is due to the mobilization of excess silica during Eocene-Cretaceous times. The alteration of volcanics appears, however, a prerequisite for the formation of both phillipsite and clinoptilolite.

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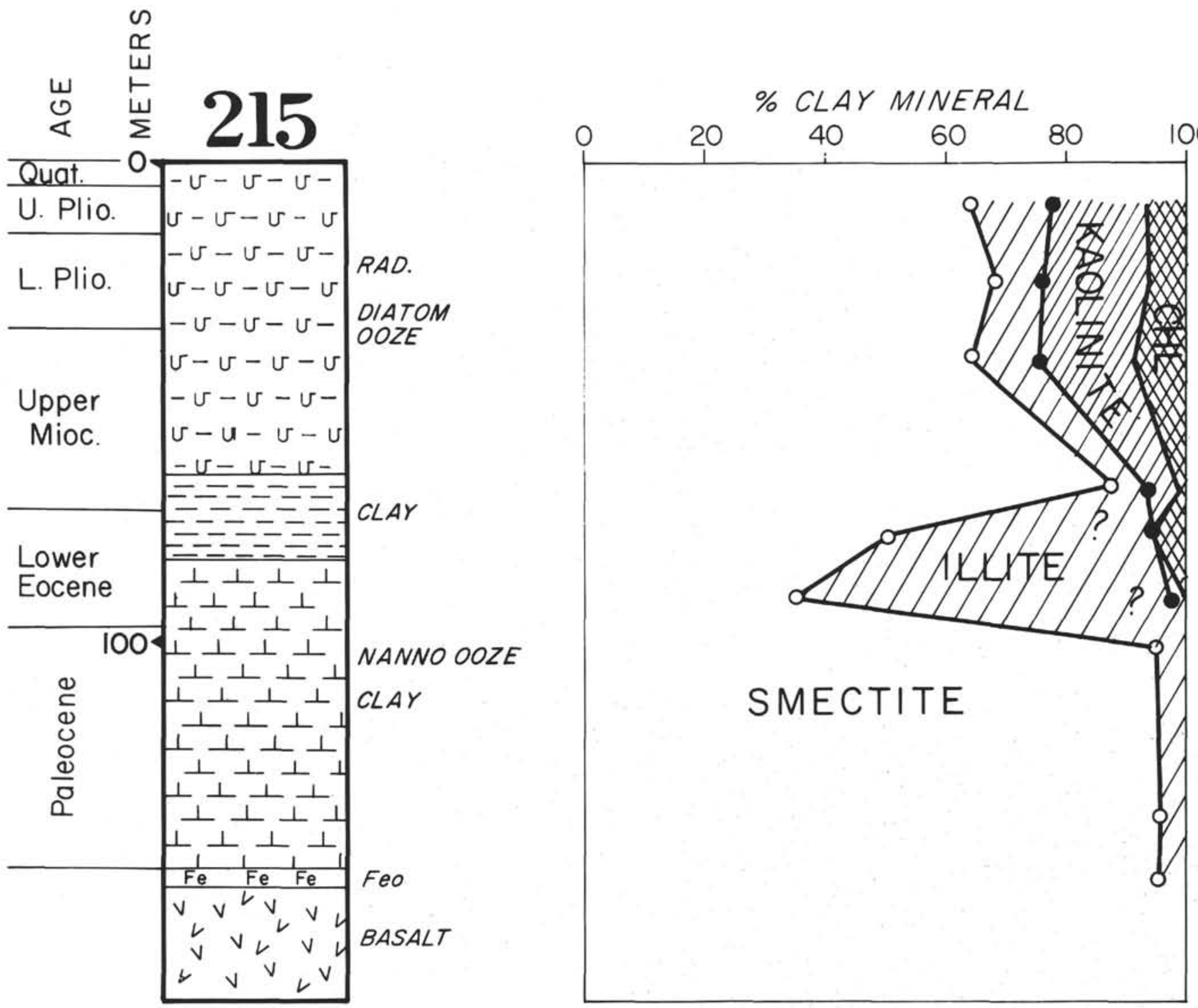


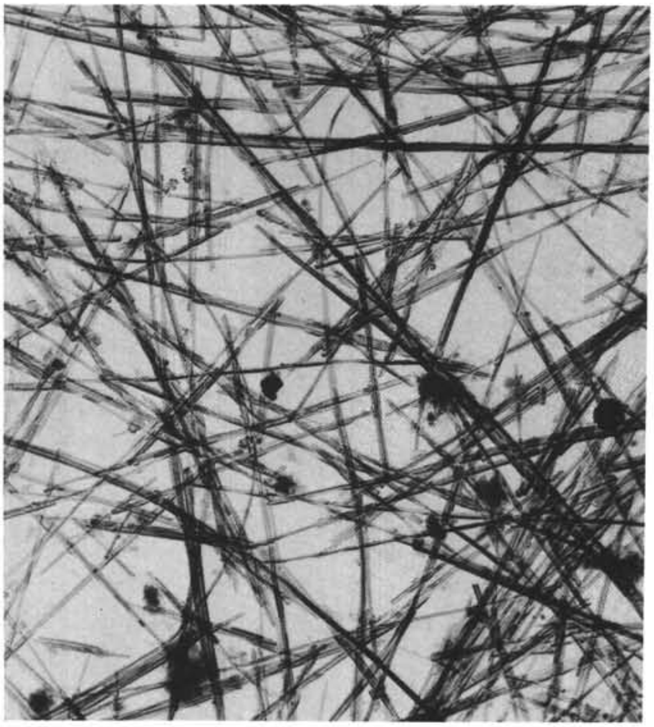
Figure 3. *Variations of clay mineral abundances with stratigraphic age, lithology, and depth at Site 215.*

PLATE 1

(Magnification ×16,000)

Figure 1	Palygorskite from Sample 214-35-5, 0-10 cm.
Figure 2	Palygorskite from Sample 215-10-2, 0-20 cm.
Figure 3	Kaolinite minerals from Sample 214-42, CC.

PLATE 1



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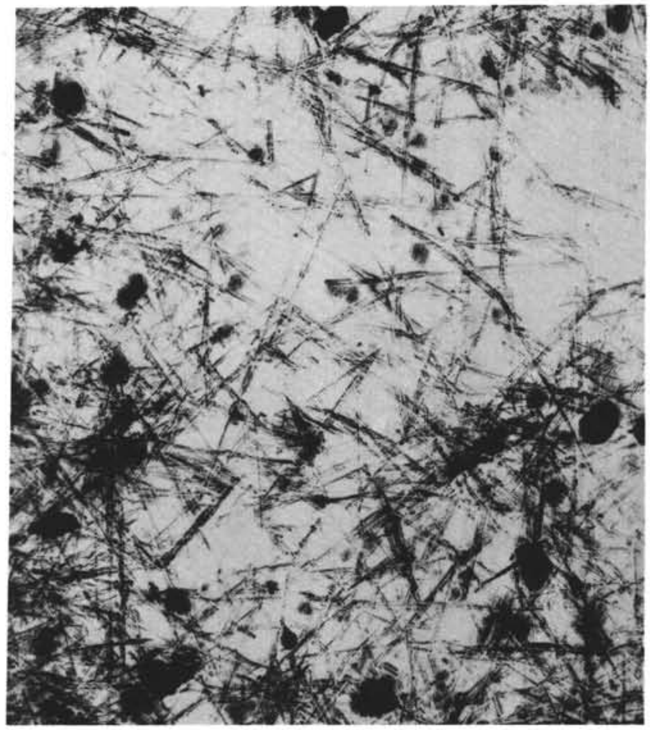

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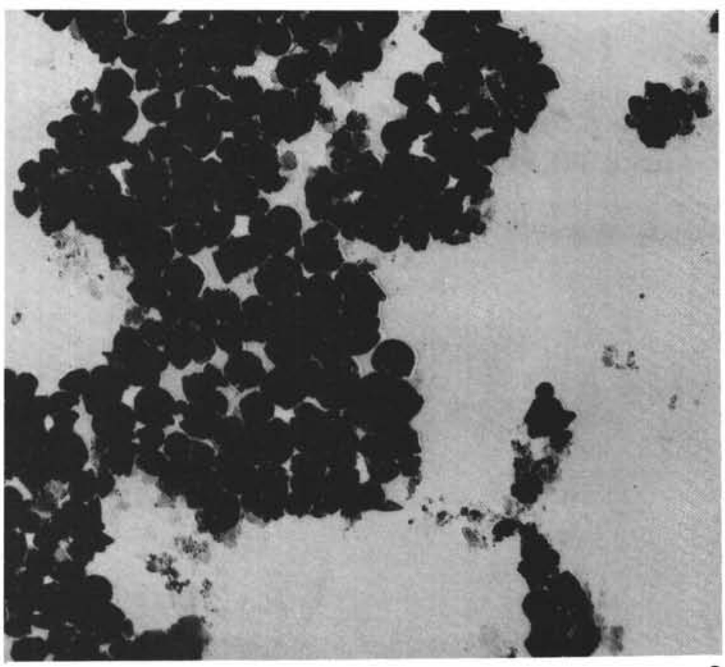

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