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Some Aspects of Mineralogy and Geochemistry of Paleogene Sedimentation on the West African Shelf, Benin

Yu. O. Gavrilov*, C. Zevounou, V. N. Ben'yamovskii*, N. G. Muzylev*, and T. A. Sadchikova***

** Geological Institute (GIN), Russian Academy of Sciences, Pyzhevskii per. 7, Moscow, 109017 Russia*

*** Benin Republic*

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Abstract—Results of the stratigraphic, lithological-mineralogical, and geochemical studies of the Paleogene section of the Atlantic paleoshelf of Benin are considered. The structure of the Eocene sequence, as well as the mineral and geochemical composition of deposits, depended on the combined impact of some global, regional, and local factors, which determined the sedimentation regime in the Coastal Trough of Benin. The Ypresian and Lutetian deposition stages were marked by an accumulation of sequences substantially different in mineral composition and in spectrums of specific elements. It has been established that alternating periods of sedimentation and hiatuses were controlled by transgressive–regressive cycles, which were related to eustatic sea-level fluctuations.

Paleocene and Eocene deposits of the West African shelf are of interest in many respects. They were accumulated on the relatively stable margin of the African continent. The sedimentation regime was under the significant influence of sea-level fluctuations, which controlled, in particular, the alternation of deposition and nondeposition periods. They also changed the depth of shelf basins, which, in turn, influenced lithology, mineralogical composition, and geochemical properties of deposits. In addition to eustatic fluctuations, which represented, in fact, a global phenomenon, there were some other regional-scale factors. That were responsible for the formation of deposits enclosing substantial amounts of magnesian silicates (palygorskite and sepiolite) and phosphate horizons, which were accumulated in spacious areas, extending at least from Central Africa to Spain, in certain periods of the Paleocene and Eocene. In addition, some local factors typical of certain shelf areas contributed to the specifics of accumulated deposits. In this connection, the Eocene sequences of Benin are of significance because they were formed under the influence of eustatic, regional, and some local factors.

In different geodynamic, paleoclimatic, and lithofacial settings, synchronous sea level fluctuation could result in the formation of sedimentary rocks substantially different in texture and composition. The problem of influence of sea level changes on deposition in different sea basins was considered earlier based on the spacious epicontinental Paleocene sea in southern Russia and adjacent regions, as well as on the Early–Middle Jurassic basin of the Greater Caucasus (Gavrilov, 1992; Gavrilov *et al.*, 1997).

The purpose of this work is to analyze lithological-geochemical properties of deposits accumulated on the ancient oceanic shelf against the background of eustatic sea-level fluctuations. Cores of Paleocene–Eocene rocks sampled from two holes—BS-4 (Kpome) and SM-4 (Sokhum)—drilled by the BREDA Company (Italy) in the central part of the Coastal Trough, the West African Atlantic shelf (Benin), served as the object of investigation (Fig. 1). Samples were obtained by C. Zevounou during field work on the territory of Benin in 1989–1990.

The Coastal Trough of Benin is located on the continental margin in the northern part of the Guinea Gulf. The evolution of the craton's stable margin is closely related to the opening of the South Atlantic Ocean (Delteil *et al.*, 1978). The Coastal Trough of the Guinea Gulf represents an element of the system consisting of several pericontinental troughs, which developed in similar tectonic and sedimentation settings along the Atlantic margin of Africa (*Geologiya...*, 1990). The trough of the Guinea Gulf covers coastal land areas and adjacent oceanic areas from Cameroon to Côte d'Ivoire. The trough comprises three depressions separated by uplifts (from west to east): the Abidjan Depression, the Togo–Dahomey depression, and the Niger River delta depression. The first two depressions are separated by the Romanche Fault. The on-land part of the Togo–Dahomey depression covers the territory of southeastern Ghana, Togo, Benin, and southwestern Nigeria. The Coastal Trough of Benin represents a segment of this major structure, which is characterized here by its maximum width (about 150 km), and encompasses the territory of southern Benin and adjacent shelf areas. The trough is separated into western and eastern parts by transverse uplift expressed both in the topography of shelf zone bottom and continental slope and in the structure of Mesozoic–Cenozoic deposits. The western part of the trough is entirely

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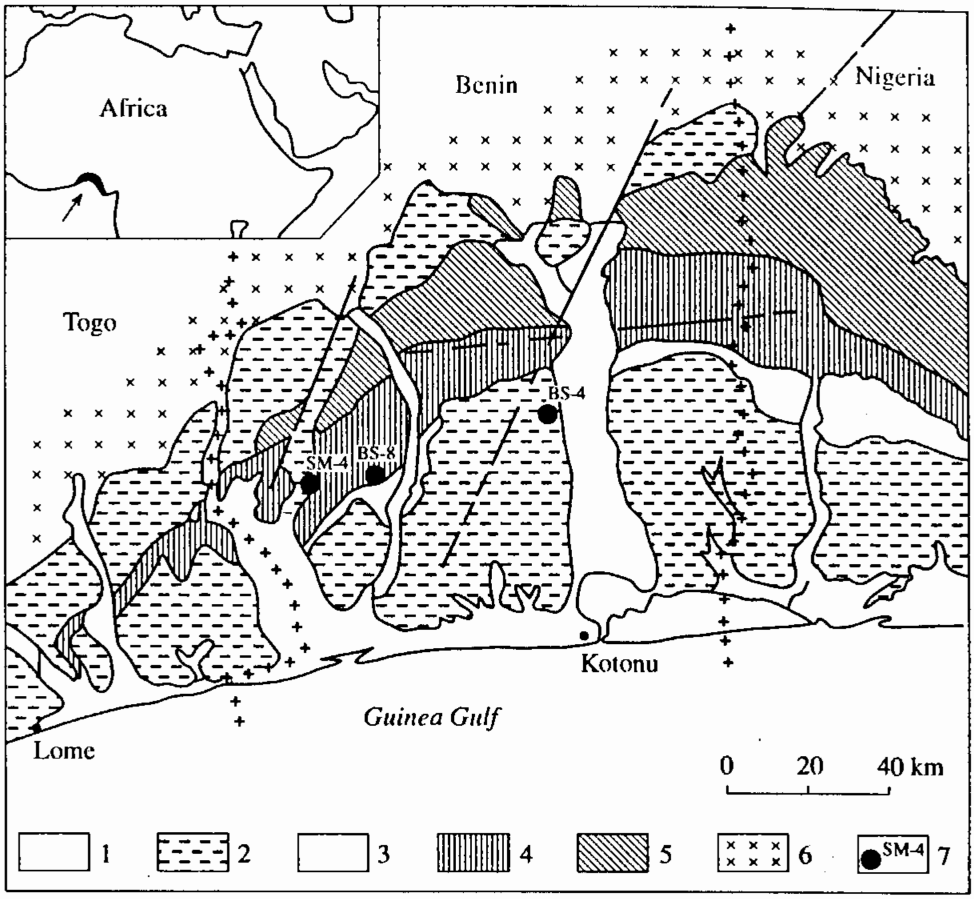

Fig. 1. Schematic geological map of the Coastal Trough of Benin (after Slansky, 1962) and its position on the African continent. Age of deposits: (1) Recent (alluvial, lacustrine, lagoonal, and others), (2) post-Eocene terrestrial, (3) Lower and Middle Eocene, (4) Paleocene, (5) Upper Cretaceous (Maastrichtian), (6) Precambrian rock complex; (7) borehole location.

located in the oceanic domain, whereas its eastern part includes both the oceanic shelf area (relatively narrow zone) and land areas. Our investigations were conducted in the eastern part of the trough. The tectonic structure of the Coastal Trough is dominated by the NNE-oriented and latitudinal faults. The NNE-oriented faults divide the trough into three parts of different widths (Fig. 1). The analysis of paleostructural maps indicates the synsedimentary nature of these faults.

STRATIGRAPHY OF PALEOGENE DEPOSITS OF THE COASTAL TROUGH OF BENIN

Stratigraphy of Coastal Trough deposits of West Africa, including Benin (Slansky, 1958, 1962), was studied by many researchers. Most comprehensive materials on stratigraphy of the region considered, based on the distribution of foraminifers and ostracods, were given in (Kogbe and Me'hes, 1986). However, recent data on biostratigraphic zonation of Cenozoic deposits of the region are scarce. We conducted biostratigraphic subdivision of Paleocene–Eocene deposits of the Coastal Trough of Benin using nannofossils (C. Zevounou and N.G. Muzylev) and data on foraminifers. Nannofossils were studied in samples from boreholes SM-4 (Sokhum), BS-4 (Kpome), and BS-8 (Bapodzhi) and the nannofossil zones are shown in Fig. 2.

The study of nannofossils revealed the following.

Upper Paleocene nannofossil assemblage was discovered in the basal layers of the section penetrated by only one of the boreholes (BS-8). The assemblage is poorly preserved and characterized by the low abundance and species diversity. It includes *Discoaster multiradiatus, Heliolithus* sp., *Toweius* sp., *Coccolithus eopelagicus, Chiasmolithus californicus, Zygodiscus sigmoides*, and *Neochiastorygus distentus*. The presence of *Discoaster multiradiatus* in this assemblage and absence of any Eocene forms indicate that host sediments belong to the *Discoaster multiradiatus* Zone (CP8) of the standard nannofossil scale (Okada and Bukry, 1980), most likely to its lower (CP8a) Subzone, i.e., to the uppermost Thanetian. At the base of the sequence drilled by borehole BS-4, samples from which were studied, in particular, for mineralogical and geochemical features, upper Thanetian deposits are likely to be present but this assumption is not substantiated by fossils.

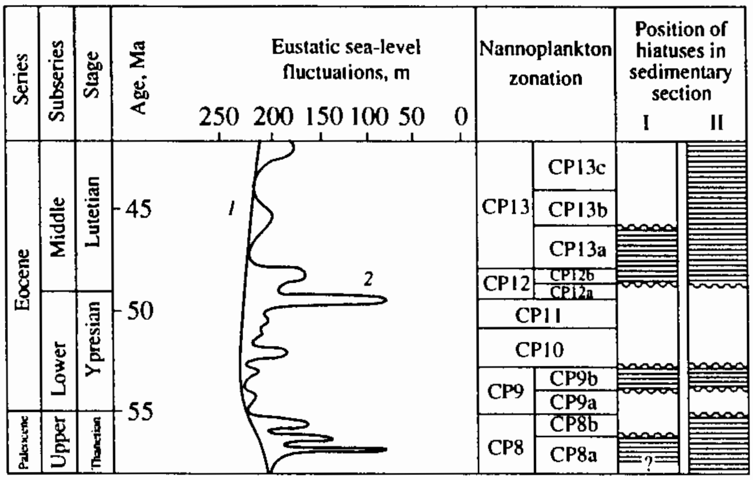

Fig. 2. Stratigraphic position of sedimentary units and unconformities in sections of the (I) Coastal Trough of Benin and (II) Eastern Peri-Tethys. Curve of eustatic sea-level fluctuation is adopted from (Haq *et al.*, 1987); fluctuations: (1) long-term, (2) short-term. Age in Ma (after Cande and Kent, 1992). Nannoplankton zonation is adopted from (Okada and Bukry, 1980). Position of unconformities in sedimentary sequences of the Eastern Peri-Tethys is given after (Muzylev, 1980, 1996).

Lower Eocene clays contain few fossils. Geologists from the BREDA Company, who conducted investigations in Benin, discovered impoverished assemblages of planktonic and benthic foraminifers in certain intervals. Nannofossil assemblage is also not diverse and includes *Tribrachiatus orthostylus, Fiscoaster binodosus, Neococcolithes dubius, Sphenolithus radians, Transversopontis pulcheroides, Rhabdosphaera tenuis, Pontosphaera bicaveata, Discoaster cruciformis*, and some other forms. This assemblage is indicative of the *Discoaster binodosus* Zone (CP9b Subzone) of the lower part of the Lower Eocene, which is in agreement with data on foraminifers. Deposits of CP10 and CP11 zones are missing from the sections considered.

Middle Eocene deposits are characterized by more diverse nannoplankton assemblage. They are divided into two subzones: *Rhabdosphaera inflata* Subzone (CP12b) of the *Discoaster sublodoensis* Zone and *Discoaster strictus* Subzone (CP13a) of the *Nannotetrina quadrata* Zone. The assemblage of the zone includes *Coccolithus formosus, Coccolitus eopelagicus, Helicosphaera seminulum, Discoaster barbadiensis, D. lodoensis, D. distinctus, D. wemmelensis, D. deflandrei, D. martini, Pemma basquense, Pontosphaera gladus, Nannotetrina quadrata*, and others. Perch-Nielsen (1981), who studied several samples from the same age interval in the Zongbodonu area (the western part of the trough), discovered an almost identical assemblage there and arrived at a similar stratigraphic conclusion. Middle Eocene deposits of Benin are overlain with a large stratigraphic hiatus by an Upper Oligocene–Miocene (Upper Miocene in the boreholes considered) sequence.

Thus, data on nannofossil composition and distribution (Fig. 2) indicate the presence of Upper Paleocene (CP8a Subzone), Lower and Middle Eocene (CP9b, CP12b and CP13a subzones) in the Coastal Trough of Benin (Zevounou, 1992). Foraminifers (determinations by N.S. Os'kina and N.S. Blyum) and nannofossils substantiate the presence of Upper Oligocene deposits in the trough. Based on microfossils, the duration of the late Thanetian (CP8b Subzone)–early Ypresian (CP9a Subzone) and late Ypresian (CP10, CP11, and CP12a) hiatuses was estimated. These hiatuses are of a global nature and related to eustatic regressions. The absence of Upper Eocene–Middle Oligocene deposits in the Benin Trough is confirmed, which is well correlated with data on the hiatus of similar duration in other Cenozoic basins of West Africa (Ly and Carbonnel, 1987; and others).

LITHOLOGICAL–MINERALOGICAL AND GEOCHEMICAL CHARACTERISTICS OF DEPOSITS

The Paleogene section of the part of the Benin Trough considered can be divided into four intervals of different age (from bottom to top): Paleocene, Lower Eocene, Middle Eocene, and Miocene–Quaternary.

According to drilling data, the Upper Paleocene deposits developed in the Coastal Trough are represented by a sequence of dark gray low-carbonate shaly clays with rare limestone interlayers. The thickness of Paleocene deposits is 130 m. The basal layers of the sequence from the 67- to 70-m depth interval of borehole BS-4 (Fig. 3) probably also belong to the Upper Paleocene (upper Thanetian). These layers are composed of variegated cloddy greenish gray and light brown clays locally with distinct bedding (in greenish gray clays), spots of small carbonate inclusions (1–2 mm), microglobular pyrite aggregates (up to 4.0 mm), and rare fragments of mollusk shells. In particular abundance we find authigenic glauconite, which locally fills spaces between grains of other minerals and serves as a

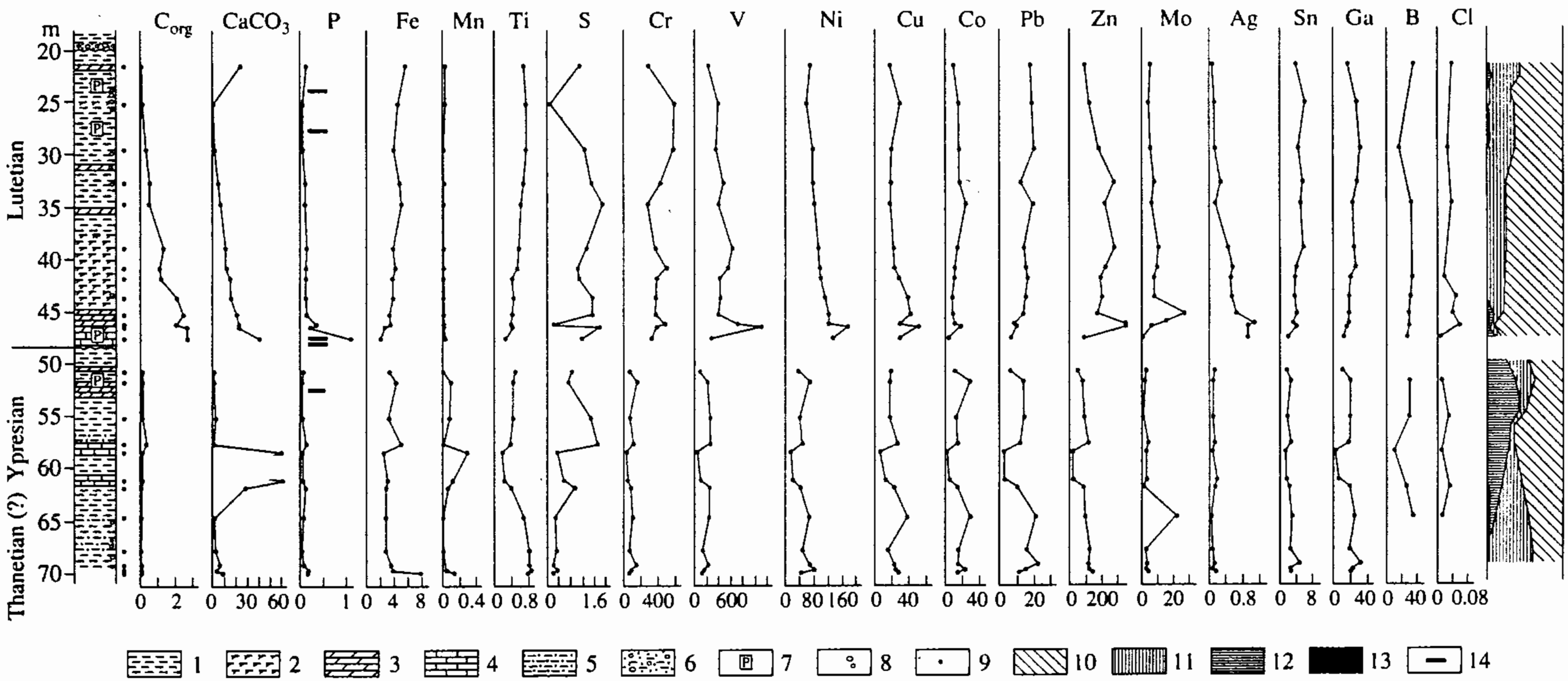

Fig. 3. Distribution of chemical elements and clay minerals in the borehole BS-4 section of the Coastal Trough of Benin. C_{org}, $CaCO_3$, Fe, Mn, Ti, P, S, Cl are given in %; other elements, in ppm. (1) Clay; (2) calcareous clay; (3) marl; (4) limestone; (5) silt; (6) silty sand with pebbles; (7) phosphorite; (8) authigenic glauconite; (9) sampling sites; (10) smectite; (11) kaolinite; (12) palygorskite; (13) hydromica; (14) phosphate-enriched horizons.

cement. Large accumulations of intricate glauconite segregations are confined to the interval of 69.25–69.50 m.

Upward from the section, Ypresian greenish gray clays occur up to a depth of approximately 48.75–49.0 m. The section is dominated by thin-bedded clays with rare laminae of quartz silt and rare fragments of plant remains, which are replaced by microglobular pyrite. The section contains rare foraminifers, siliceous fossils, fragments of molluscan shells (probably, *Cardium*), and imprints of bottom microorganisms *Crustacea*. Glauconite is observed as a rare dispersion of small grains amongst the clayey mass.

Clays enclose limestone interlayers of two types: (1) light gray compact fine-grained (up to pelitomorphic) interlayers with inclusions of rare fossils and sulfide microconcretions and with secondary recrystallization patches (intervals 61.25–61.5 and 58.25–58.5 m); (2) organogenic–clayey interbed with foraminifers, ostracods, and other microorganisms, cemented by macrocrystalline calcite (interval 52.0–52.25 m). There are also interlayers of light gray, compact, thin-bedded marl, with inclusions of silt-sized quartz grains, sulfide microconcretions, mollusk imprints, and rare foraminifers (intervals 52.25–52.75 and 51.0–51.5 m). The horizon with phosphate inclusions is present in the 52.0–52.5 m interval (Fig. 4, *1*, 2).

Hiatus occurs in the interval of 48.75–49.0 m.

The Middle Eocene sequence (interval ~20–49 m) drilled by borehole BS-4 is subdivided into two parts: the lower member composed of calcareous–marly and calcareous clays and the upper clayey member with marl interlayers. The transitions between the members are gradual (depth ~30 m), which is clearly evident from $CaCO_3$ distribution (Fig. 3).

The depth of about 48.0 m is marked by the horizon of compact, brownish, clayey, organogenic limestone, with foraminiferal fossils, phosphorite concretions (from fractions of millimeters to 2.0 mm across), plant detritus, and sulfide microconcretions (Fig. 4, *3*). Thin interlayers with abundant phosphate grains are also encountered (Fig. 4, *4*).

Gray to brownish gray, compact, thin-bedded, marls include segregations of sulfide microconcretions, foraminifers, siliceous microorganisms relics, and authigenic glauconite grains. Marls prevail in the lower part of the member (to a depth of approximately 44 m). Brownish gray calcareous clays compose mainly its upper part, where marl interlayers become rare and thin. Similarly to marl, clays contain abundant sulfide concretions, less common glauconite, foraminifers, and other microfossils.

The upper member (above 30.0 m) is mainly clayey with subordinate marl and limestone interlayers. Clays are mainly gray, greenish gray, locally brownish gray (at the expense of slight ferrugination), compact and bedded. They include microconcretions of sulfides (often developed after carbonate shells), mollusk shells, and foraminifers as well as authigenic glauconite grains (Fig. 4, *5*), which are most abundant at the depth of 24.0 m. Rocks in the interval of 29.25–29.50 m contain prismatic crystals of authigenic gypsum. The interval of 25.0–25.5 m is marked by the marl interlayer. Two horizons of phosphorite microconcretions are confined to intervals of 27.0–27.5 and 23.5–23.75 m; similar horizons occur at the same level in borehole SM-4 (Fig. 4, *6*).

Middle Eocene deposits are overlain with sharp unconformity by the Miocene sequence represented by conglomerate, gritstone, and sand with subordinate clayey interlayers. The unconformity occurs at the depth of approximately 20 m in borehole BS-4 and at the depth of 6.5 m in borehole SM-4. Miocene deposits are of continental origin and bear signs of hypergenic and other secondary processes, probably, because of their permeability and shallow occurrence. These deposits are not considered in this paper.

Mineral composition of Eocene deposits. As was noted, Eocene deposits are mainly composed of the clayey and carbonate material with a subordinate amount of glauconite, phosphate minerals, and sulfide concretions. Carbonate minerals are mostly represented by calcite and, less commonly, dolomite.

According to X-ray diffraction data, preponderant minerals in the fraction < 0.001 mm are dioctahedral smectite, kaolinite, palygorskite, and micaceous mineral registered as an insignificant admixture in some samples.

Dioctahedral smectite ($d_{(060)}$ = 1.497 Å) is identified by intense reflection 001 with d = 13.6–14.2 Å and low reflection 003 with d = 4.87 Å (in the air-dry state). Under saturation of samples with glycerin, difractogram shows close to integral series of reflections 001 with $d_{(001)}$ = 17.7 Å, and the value $d_{(002)}$ = 9.1 Å indicates the presence of about 20% micaceous type interlayers in the mineral structure; reflections d = 9.7, 4.8, and 3.18 Å corresponding to dehydrated smectite structure remain after heating at 550°C.

Kaolinite is detected on diffractograms of oriented samples owing to intense reflections with $d_{(001)}$ = 7.15 Å and $d_{(002)}$ = 3.56 Å, which do not change their position under saturation of sample with glycerin and disappear after ignition at 550°C.

Palygorskite is established based on the presence of basal reflections *hkl* 110, 200, 130, 230, 150, and 400 and corresponding values of 10.5, 6.3, 5.34, 3.65, 3.45, and 3.22 Å on difractograms of air-dry and glycerin-saturated samples.

The presence of the micaceous mineral is evident from slight reflections with $d_{(001)}$ = 9.8 Å and $d_{(002)}$ = 4.97 Å only on diffractograms of some glycerin-saturated samples. The qualitative characteristics of the mineral (its uniformity or mixed-layer structure) are impossible to determine because of overlapping of micaceous reflection $d_{(001)}$ and very intense low-angle reflections of smectite in the air-dry sample.

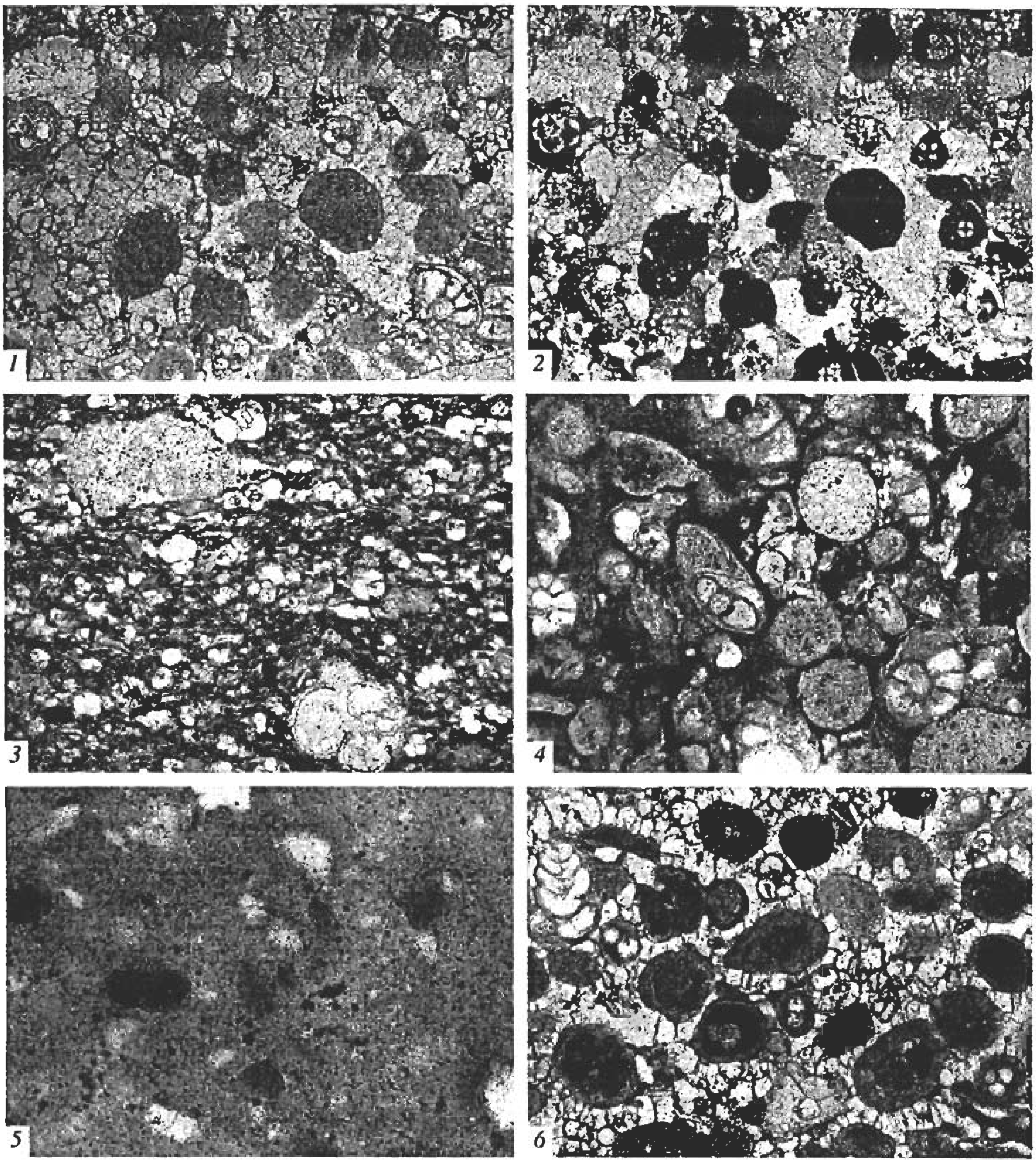

Fig. 4. SEM images of thin sections of samples from deposits drilled by boreholes BS-4 and SM-4. Limestone with phosphate grain inclusions (Ypresian, borehole BS-4, interval 52.0–52.25 m): (*1*) parallel nicols, (*2*) crossed nicols; (*3*) organogenic carbonate rock with inclusions of smaller (abundant) and larger (rare) foraminifers, phosphate grain in the upper left corner (Lutetian, borehole BS-4, interval 47.5–47.7 m); (*4*) marl with abundant inclusions of phosphate grains enclosing foraminiferal shells (the base of the Lutetian section, borehole SM-4, interval 31.5–31.75 m); (*5*) clayey rock with an admixture of quartz grains (light) and glauconite (dark), (Lutetian, borehole SM-4, interval 24.25–24.50 m); (*6*) limestone with inclusions of phosphate grains, upper part of the Lutetian section (borehole SM-4, interval 7.0–7.25 m). The horizontal side of the image is 2 mm.

The proportions of clay minerals vary in different parts of the section (Fig. 3). Smectite and kaolinite are present in deposits throughout the section in sufficient amount. Palygorskite, which represents one of the main components in Lower Eocene clays, disappears above the boundary between sequences at the depth of 48.5–49.0 m and occurs as an insignificant admixture only in intervals of 46.25–47.75 m and 23.5–23.75 m.

Thus, most pronounced differences exist between Ypresian and Lutetian sections (Fig. 3): Ypresian deposits are characterized by the smectite–kaolinite–palygorskite association with an insignificant admixture of mica in some samples, whereas the kaolinite–smectite association with an insignificant amount of mica and palygorskite in rare samples is typical of the Lutetian sequence; i.e., the main difference between these sequences is the significant admixture of palygorskite in the Lower Eocene deposits.

In turn, Lower and Middle Eocene sections reveal variations in the clay mineral composition although expressed in qualitative proportions. For instance, Ypresian deposits show substantial changes in the palygorskite content, from almost complete absence at the base of the section to significant values in its upper part; the kaolinite content changes in the same direction. Smectite is distributed more regularly. The lower part of the section, where the kaolinite content is maximum, is marked by an insignificant admixture of mica.

The Lutetian section is characterized by a regular increase in the kaolinite content and, correspondingly, by a decrease in the smectite content from the base upward. Mica traces are detected in basal layers of the section and in some samples from its upper part; similar behavior is characteristic of palygorskite (Fig. 3).

Such regular distribution of both mineral associations and quantitative proportions of minerals within the associations throughout the Eocene section indicate substantially different sedimentation settings in the Ypresian and Lutetian times, as well as directional changes in sedimentation conditions during the existence period of every basin.

Geochemical peculiarities of Eocene deposits. In addition to changes in the mineral composition of deposits, there are also substantial variations in their geochemical characteristics in different parts of the section. Comparison of Lower and Middle Eocene parts of the section (Fig. 3, Table) reveals two groups of elements noticeably differing in contents. In Lower Eocene deposits, contents of some elements are relatively low, whereas in Middle Eocene strata, they significantly increase. This group of elements includes C_{org}, P, Cr, V, Ni, Cu, Zn, Mo, and Ag; less distinct are differences between distribution patterns of other elements, such as Fe, Ti, Ga, B, Be, and As. The Mn behavior is quite independent: in the lower part of the section, it is present universally though in small amounts, while in the Lutetian strata, its concentrations are negligible in most of the analyzed samples (Table).

Distribution patterns of most of the elements are, to a great extent, related to the distribution of C_{org} and $CaCO_3$ through the section. The influence of C_{org} on the element behavior is determined by its geochemical activity, whereas $CaCO_3$ works usually as a dilution agent; e.g., the increase in the $CaCO_3$ content results in the decrease in contents of most chemical elements. Of interest is a similarity in the distribution of C_{org} and $CaCO_3$ in the considered section. For instance, contents of these components in Lower Eocene rocks (except for some clayey limestone interlayers in the middle of the sequence) are minimal. Their contents sharply increase in basal Middle Eocene layers and then gradually decrease upward the section (this tendency is also disturbed here only in some carbonate layers). Such similarity in behavior of C_{org} and $CaCO_3$ suggests that their accumulation in sediments was governed by common factors likely to be represented by variations in bioproductivity (in particular, of calcareous plankton) in the Eocene basin at different stages of its existence.

As noted above, the distribution of some elements (P, V, Ni, Mo, Zn, and Ag) is similar to that of C_{org}. However, only Ag shows a high degree of correlation with C_{org} in lower and upper parts of the section.

The behavior of other elements is controlled, in addition to the C_{org} content, also by other factors, which complicate their distribution patterns. For instance, the Ti, Fe, Ga, Co, and Pb contents in the Ypresian and Lutetian sequences reveal no substantial differences. Simultaneously, Ti shows the tendency for the decrease of its contents from the base of the Lower Eocene upsection and, conversely, for its increase toward the upper layers of the Middle Eocene (Fig. 3). The Ti distribution reveals a direct correlation with the content of terrigenous silt constituent in rocks and a reverse correlation with the $CaCO_3$ content. Of importance is the distribution pattern of kaolinite, which is similar to that of Ti and, probably, also reflects variations in the terrigenous material supply.

The behavior of Ga and Fe is, probably, related to the same factors. However, the Fe distribution in sections is less regular owing to its active participation in processes of diagenetic mineral formation and its presence in authigenic minerals such as glauconite and pyrite. The abnormal high Fe content (8.5%) in basal layers in borehole BS-4 is related to the bed enriched in iron hydroxides.

The P content in rocks is of particular interest because the accumulation period of the considered deposits corresponds to a terminal phase of the Late Senonian–Eocene epoch of phosphate deposition in the Arabian–African region (Pokryshkin, 1980, 1991; Slansky, 1962, 1980; and others); in some areas, phosphorite accumulations are of economic interest.

As noted above, P in the Eocene sections behaves similarly to C_{org}: low background-level contents in the Ypresian section, general increase in their concentrations in basal layers of the Lutetian section, and their gradual decrease in the upper section (Fig. 3). However, the background P distribution in the Eocene deposits is complicated by the appearance of several horizons, where petrographic and chemical studies reveal elevated phosphate contents.

The phosphate-bearing interlayers occur both in Ypresian and Lutetian deposits. The borehole BS-4 section incorporates at least four intervals with the elevated P contents. In the borehole SM-4 section, the elevated P content is characteristic of basal layers of the Lutetian and, in addition, at least two P-enriched levels

Results of Chemical Analyses of Eocene Deposits in Boreholes BS-4 and SM-4 from the Coastal Trench, Benin

	no.	Borehole BS-4 Interval (m)	C_{org}	CO_2	Fe	Mn	Ti	P	S	Cr	Ni	V
Lutetian	1	21.5–21.75	<0.1	10.25	5.78	0.02	0.61	0.11	1.06	330	65	240
	2	25.0–25.50	<0.1	<0.4	4.57	<0.01	0.78	0.02	0.09	670	56	375
	3	29.5–29.75	0.27	0.40	4.05	<0.01	0.70	0.05	1.22	670	77	330
	4	32.5–32.75	0.51	2.0	4.94	<0.01	0.62	0.09	1.43	480	72	460
	5	34.5–34.75	0.47	2.95	5.43	<0.01	0.53	0.08	1.82	315	80	370
	6	38.5–38.75	1.36	4.50	4.08	<0.01	0.51	0.1	1.30	665	86	610
	7	40.75–41.0	1.16	5.15	4.27	<0.01	0.52	0.1	1.02	585	92	550
	8	41.5–41.75	1.15	6.40	3.97	<0.01	0.36	0.10	1.04	425	98	410
	9	43.5–43.75	2.04	6.85	4.05	<0.01	0.42	0.13	1.48	435	107	420
	10	45.0–45.25	2.52	8.85	3.61	<0.01	0.37	0.17	1.47	442	15	360
	11	46.0–46.25	1.96	9.40	3.67	<0.01	0.34	0.33	0.20	550	115	720
	12	46.25–46.5	2.70	9.55	3.84	<0.01	0.35	0.24	1.68	440	170	990
	13	47.50–47.75	2.68	17.60	2.08	0.03	0.21	1.34	1.11	370	125	270
Ypresian	14	50.75–51.0	<0.1	<0.4	3.70	0.04	0.50	0.01	0.83	76	31	92
	15	51.75–52.0	<0.1	0.25	4.47	0.11	0.41	0.04	0.73	192	63	230
	16	55.0–55.25	<0.1	0.60	3.34	0.09	0.41	0.04	1.44	80	37	250
	17	57.5–57.75	0.27	<0.4	5.08	0.03	0.38	0.14	1.67	124	44	245
	18	58.25–58.5	<0.1	36.50	2.61	0.30	0.16	0.03	0.31	37	11	30
	19	61.25–61.5	0.14	26.5	3.22	0.12	0.23	0.04	0.59	49	17	83
	20	61.75–62.0	<0.1	12.0	2.97	0.07	0.38	0.11	0.93	93	38	220
	21	64.5–64.75	<0.1	0.40	3.0	0.02	0.67	0.06	0.28	118	62	220
	22	67.75–68.0	<0.1	1.00	2.96	0.03	0.83	0.03	0.36	95	42	128
Thanetian (?)	23	69.25–69.5	<0.1	2.0	3.70	<0.01	0.84	0.07	0.25	165	60	208
	24	69.5–69.75	<0.1	1.40	3.88	0.06	0.84	0.16	0.37	118	72	140
	25	69.75–70.0	<0.1	3.80	8.35	0.14	0.81	0.13	0.23	88	38	112
	no.	Borehole SM-4 Interval (m)	C_{org}	CO_2	Fe	Mn	Ti	P	S	Cr	Ni	V
Lutetian	1	9.25–9.50	0.27	4.00	4.60	<0.01	0.55	0.30	n.d.	230	115	470
	2	10.5–10.75	1.36	12.70	1.40	<0.01	0.33	1.71	1.12	125	45	220
	3	11.0–1.25	0.42	30.55	1.21	0.10	0.16	1.82	n.d.	130	42	40
	4	11.5–11.75	0.43	16.35	1.14	0.01	0.38	0.18	1.04	110	26	105
	5	14.75–15.0	0.68	4.60	4.36	<0.01	0.50	0.26	n.d.	285	50	260
	6	15.5–15.75	0.42	5.85	3.94	<0.01	0.46	0.37	"	335	54	200
	7	16.25–16.5	0.68	9.35	1.70	<0.01	0.20	5.61	"	290	65	120
	8	20.5–20.75	1.22	8.4	3.33	<0.01	0.33	0.09	"	410	80	560
	9	26.25–26.5	3.25	15.50	2.58	<0.01	0.24	0.32	"	455	150	550
	10	31.0–31.25	2.15	22.65	1.29	0.02	1.17	2.08	"	295	70	340
	11	31.5–31.75	1.23	21.15	1.12	0.04	0.10	1.45	"	165	60	120
Ypresian	12	35.0–35.25	<0.1	<0.4	3.63	0.06	0.38	0.01	"	88	40	110
	13	37.75–38.0	<0.1	<0.4	3.91	0.06	0.44	0.02	"	87	50	155
	14	42.5–42.75	<0.1	0.50	5.30	0.05	0.61	0.05	"	110	45	220

Note: C_{org}, CO_2, Fe, Mn, Ti, P, S, Cl in %, other elements, in ppm.

Cu	Co	Pb	Ga	Ge	Mo	Zn	Sn	Ag	As	Be	Cl	B
20	9	18	16	1.3	6.0	100	3.5	0.06	7	n.d.	0.04	40
32	16	19	28	<1.0	4.7	128	6.1	0.12	5	2.3	n.d.	n.d.
24	16	21	32	<1.0	5.6	190	4.2	0.15	8	2.0	0.03	19
22	17	17	29	1.0	7.9	290	5.1	0.30	8	3.2	n.d.	n.d.
20	24	20	22	1.0	5.8	235	4.8	0.16	7	n.d.	0.04	33
24	14	14	25	1.0	11.5	278	5.4	0.46	8	1.8	n.d.	n.d.
24	11	15	26	<1.0	9.5	235	3.9	0.58	8	2.1	″	″
33	11	17	20	1.0	7.6	195	3.5	0.50	7	n.d.	0.02	35
40	9	16	18	1.0	7.3	210	3.5	0.55	7	″	0.04	33
44	9	14	18	1.0	27.0	178	4	0.65	7	″	0.04	30
31	10	8	17	<1.0	16	345	3.0	1.10	28	2.4	n.d.	n.d.
55	18	10	14	1.0	6.0	350	4.0	0.94	7	n.d.	0.06	30
30	5	7	10	<1.0	<1.0	88	1.8	0.94	7	″	<0.01	27
20	12	6	10	<1.0	2.5	50	1.7	0.11	6	2.3	n.d.	n.d.
19	29	14	24	<1.0	2.0	78	2.5	0.08	5	n.d.	″	32
18	12	15	18	1.3	1.0	90	1.8	0.09	6	″	0.03	30
27	14	12	17	1.2	3.5	118	2.6	0.14	6	2.0	n.d.	n.d.
5	<5	<5	<3	<1.0	2.3	25	1.4	0.06	<1	n.d.	0.01	10
12	6	<5	5	<1.0	2.7	25	1.5	0.17	4	2.3	n.d.	n.d.
22	15	11	17	1.0	<1.0	78	2.1	0.14	6	n.d.	0.03	26
40	30	22	23	1.0	21.5	100	3.0	0.06	n.d.	″	<0.01	35
16	16	16	18	<1.0	2.2	125	2.4	0.09	7	2.5	0.03	26
23	16	23	31	1.0	2.4	120	4.7	0.11	17	2.8	n.d.	n.d.
24	24	16	22	<1.0	2.5	122	2.4	0.1	8	3.0	″	″
27	15	12	18	<1.0	3.2	140	2.4	0.14	8	3.2	″	″

Cu	Co	Pb	Ga	Ge	Mo	Zn	Sn	Ag	As	Be	Cl	B
33	<5	21	21	1.6	6.0	520	2.7	0.55	n.d.	n.d.	n.d.	n.d.
22	6	8	8	1.0	12.5	150	1.2	0.35	″	″	″	″
15	<5	6	4	1.0	5.7	65	1.2	0.28	″	″	″	″
16	7	5	6	<1.0	10.0	55	1.2	0.10	″	″	″	″
25	9	17	26	<1	9.0	210	5.5	0.16	″	″	″	″
20	<5	14	16	1.3	6.1	110	3.5	0.09	″	″	″	″
26	<5	8	6	1.0	20	85	1.5	0.45	″	″	″	″
33	7	17	24	1.0	17.7	195	6	0.37	″	″	″	″
40	<5	9	10	1.0	1.3	240	2.7	1.10	″	″	″	″
25	5	<5	<5	<1	7.5	80	1.6	0.80	″	″	″	″
20	<5	<5	<5	<1	3.2	43	<1	0.55	″	″	″	″
15	11	13	19	<1	4.5	65	3.3	0.05	″	″	″	″
18	16	14	14	<1.0	<1.0	110	1.8	0.05	″	″	″	″
18	18	21	17	1.3	<1.0	80	3.0	0.05	″	″	″	″

occur in the upper half of the section (Table; Fig. 4, Images *4*, *6*).

In the Ypresian section, one of the interlayers of dolomitized micrite, as well as the underlying interlayer with phosphate micronodules and phosphotized coprolites, are characterized by high P_2O_5 contents amounting to 16.8 and 5.5%, respectively (according to data reported by the BREDA Company). Phosphate-bearing rocks of the Ypresian age mostly occur in the eastern areas of the trough (Slansky, 1962).

The Lutetian section encloses several phosphate-bearing layers. Elevated phosphate contents are usually characteristic of basal horizons of the sequence. In borehole BS-4, these deposits are represented by the light brown sand layer (several centimeters thick with phosphate micronodules and coprolites). Phosphate-bearing layers inside the Lutetian sequence are commonly composed of sandy–marly rocks with coprolites. The P_2O_5 content in them varies from several percent to 15–17%, rarely higher. Of particular interest is the presence of a sandy material in phosphate-bearing interlayers; the sand content experiences significant lateral variations throughout the trough (in different boreholes). Some of these interlayers in the central part of the trough are represented by brecciated limestone. In the northern part of the trough, the abundance of the phosphate-bearing layers decreases. The thickness of these interlayers usually does not exceed several dozens of centimeters.

Thus, available data on the background P distribution in sections of the boreholes considered and the distribution of P_2O_5-enriched layers indicate that the Eocene basin was intermittently characterized by environments favorable for the formation of elevated phosphate contents in sediments against the background of its generally low concentrations.

Very similar distribution patterns of the considered elements in both the sections studied (Table, boreholes BS-4 and SM-4) suggest that revealed tendencies objectively reflect changes in deposition settings in these shelf areas.

Paleoecological environments in the Eocene basin. To estimate paleoecological environments in the Eocene basin, which occupied the modern Coastal Trough of Benin, a study of distribution and relationships of different forms of benthic and planktonic foraminifers, as well as other organisms, was carried out (determinations by V.N. Ben'yamovskii).

In the lower, Ypresian part of the section, foraminifers are scarce. Of all the samples studied, relatively abundant planktonic and rare benthic species occur only in samples collected from depths of 67.25, 57.25, and 21.75 m. Among planktonic forms, representatives of *Subbotina, Acarinina, Pseudohastigerina (Globanomalina), Chiloguembelina*, and, probably, *Morozowella* genera were determined. Most common are subbotinids accompanied by less common, but permanent acarininids and pseudohastigerinids. *Chiloguembelina* and *Morozowella*(?) species are registered only in samples from a depth of 52 m. Benthic forms probably belong to the *Bolivina, Bulimina*, and *Robulus*(?) genera.

The Middle Eocene deposits contain both planktonic and benthic foraminifers. Planktonic species belong to the *Subbotina, Acarinina*, and *Morozowella* genera. Their assemblage includes *Subbotina* sp., *S. eocaenica, S. inaequispira, S. pseudoeocaena pseudoeocaena, S. pseudoeocaena trilobata, S. hevensis, S. aequensis, Acarinina* sp., *A.* cf. *convexa, A.* ex gr. *multicamerata, A. marksi, Morozowella* sp., and *M* cf. *subbotinae*. Benthic foraminifers are represented by *Robulus*(?) sp., *Uvigerina* sp., *Bulimina* sp., *Bolivina* sp., *Rotalia* sp., and *Nonion* sp.

In the interval of 24.25–27.50 m, foraminifers are very rare. Only rare, poorly preserved specimens of *Subbotina (?)* spp. occur in depth intervals of 25.50–26.0, and 24.75–25.0 m. In samples from the interval of 24.0–24.25 m, foraminifers are absent but ostracods are relatively abundant.

By the benthos/plankton ratio, three types of paleocenoses can be distinguished: (1) benthic paleocenosis with the preponderance of benthic foraminiferal species (>90%), (2) planktonic–benthic paleocenosis with the share of planktonic forms amounting to 20%, and (3) paleocenosis with equal proportions of planktonic and benthic species. By the ratio between representatives of planktonic genera *Subbotina* and *Acarinina*, paleocenoses are subdivided into four types: (1) *Subbotina* (completely composed of subbotinids); (2) *Acarinina–Subbotina* (dominated by subbotinids); (3) *Subbotina–Acarinina* (with preponderance of acarininids); and (4) paleocenosis with equal proportions of representatives of both genera.

Low abundance and diversity, as well as small dimensions of planktonic foraminifers, indicate the unfavorable living environments apparently resulting from shallow depths and oxygen deficiency in the water column.

Benthic foraminifers form four biocenoses dominated by species of one or two genera: (1) *Rotalia*; (2) *Nonion–Rotalia*; (3) *Rotalia–Nonion*, and (4) *Nonion–Bulimina* paleocenoses. In the first cenosis, the main share belongs to the *Rotalia* species (77–96%). The remaining part of the assemblage consists of *Bolivina* (2–10%), *Bulimina* (8%), and *Uvigerina* (1–5%). In the *Nonion–Rotalia* cenosis, the share of *Rotalia* representatives decreases to 66–70% and the remaining part belongs to common *Nonion* (25–34%) and rare *Bolivina* forms. The *Rotalia–Nonion* paleocenoses is marked by the further increase in the *Nonion* share (to 72%) accompanied by common *Rotalia* species (28%). The content of *Nonion* representatives is also high (72%) in the *Bulimina–Nonion* paleocenosis; other important constituents of the latter cenosis are *Bulimina* (25%) and *Rotalia* (3%).

The cited data on benthic foraminifers indicate a strong preponderance of either *Rotalia* or *Nonion* genera. Such impoverished assemblages of benthic foraminifers with the prevalence of certain species adapted to unfavorable conditions also suggest a relatively shallow basin and oxygen deficiency in its waters.

The distribution patterns of fossils through the section and their composition indicate significant changes in paleoenvironments at different stages of evolution of the basin of the Coastal Trough of Benin. The absence of fossils in the greater part of the Ypresian section and their occurrence only in separate horizons testifies to extremely unfavorable habitat conditions. The latter ameliorated intermittently during inflow of normal sea waters into the basin, which resulted in its elevated bioproductivity. In the Lutetian time, habitat conditions were more favorable, which led to a relatively high bioproductivity of the basin. However, oppression features are generally typical of fauna at that time as well. Some episodes of the upper Lutetian sequence formation were, probably, marked by changes in water salinity, which resulted in the almost complete replacement of foraminifers by ostracods.

The appearance of conditions unfavorable for life was apparently common in this region. For instance, the analysis of benthic foraminifer distribution in the Upper Cretaceous deposits of the adjacent region (the Benue depression) revealed the preponderance of sediments formed in marsh settings, shallow-water freshened basins, and also in basins with anoxic conditions (Petters, 1983).

DISCUSSION

The Eocene deposits of Benin are interesting in many respects. First of all, for example, there is the structure of the Eocene sequence. The latter reflects the unstable regime of sedimentation: deposition periods alternated with periods of nondeposition and partial erosion of accumulated sediments. For instance, it has been established that the Late Paleocene (late Thanetian) sedimentation corresponding to the CP8a nannoplankton subzone (no material was available from underlying deposits) was followed by an erosion period, which is indicated by the absence of CP8b and CP9a subzones. The duration of a hiatus is about 2 Ma. The following Ypresian sedimentation stage lasted, as evident from preserved deposits, about 1 Ma. It should be noted, however, that the subsequent relatively long-lasting erosion period resulted in partial elimination of deposited sediments, and, thus, the Ypresian sedimentation period could be slightly longer. A hiatus corresponds to the middle–late Ypresian and earliest Lutetian time.

The duration of the Lutetian sedimentation stage (CP12b and CP13a subzones) was probably not less than 2.5 Ma. It undoubtedly terminated somewhat later because Lutetian sediments were partly eroded during the subsequent long erosion period. The latter continued till the Late Oligocene, i.e., lasted not less than 17–18 Ma. As seen, sedimentation on the Atlantic paleoshelf of the considered region was discrete and alternated with periods of sea regression and nondeposition (erosion).

The following should be noted when interpreting factors responsible for the discrete patterns of sedimentation. Biostratigraphic studies of Paleogene deposits in southern Russia and neighboring regions (Muzylev, 1980, 1996) revealed alternating periods of sedimentation and hiatuses similar to those in the Benin section (Fig. 2). A similar situation is also peculiar to Paleogene sections in spacious areas of West Europe (Aubry, 1985, 1986; Pomerol, 1989) and Turkey (Varol, 1989). Paleogene sections of the Atlantic coast of the United States are marked by the pre-Lutetian hiatus (Poag and Ward, 1987), which was considered as being worldwide (Vail *et al.*, 1977).

Thus, taking into consideration the similar structure of Eocene deposits in distant sections, one can suggest that the dynamics of deposition were controlled by eustatic sea level fluctuations. The duration of periods of sedimentation and hiatuses allows them to be estimated as fluctuations of the third order. Sedimentation environments were substantially different at different stages of the Eocene sequence formation, which is evident from virtually all the characteristics of deposits: mineral composition, geochemical parameters, and distribution of fossils through out the section.

The Ypresian stage was characterized by specific conditions, first of all, by the arid climate. As was shown, fossils are absent in deposits of this age: the impoverished assemblage of benthic foraminifers occurs only in some carbonate interlayers. These latter associate with rare phosphate-enriched horizons. The mineral composition of deposits is characterized by abundant palygorskite.

The absence of both planktonic and benthic organisms in most of the Ypresian deposits most likely indicates poor connections of this part of the shelf basin with the open ocean and, probably, the existence of lagoonal-marine settings. Penetration of normal sea waters into this area was, evidently, intermittent, which is confirmed by the presence of interlayers of carbonate sediments and the appearance of the marine, although impoverished, fossil assemblages within the low-carbonate section.

The aforesaid allows us to suggest that the Coastal Trough of Benin in the considered area was occupied by the shallow well-heated sea basin with the elevated salinity of waters. The arid basin environment was unfavorable for organism development but suitable for the formation of authigenic palygorskite (Strakhov, 1962; Rateev, 1964; Millot, 1968; and others) and partial dolomitization of carbonate rocks. The suggestion that palygorskite is authigenic and was not transported from eroded land is supported by the fact that the terrigenous material provenance remained constant during the Ypresian and Lutetian, whereas the mineral composition in deposition basins was substantially different. Unfavorable environments in the basin were responsible for low bioproductivity, absence or minimal concentrations of organic matter in sediments, and, correspondingly, for low contents of some elements, which are characterized, as a rule, by close correlation with C_{org}. The contents of elements connected with the terrigenous admixture are generally below background values. To a certain extent, such an interpretation of sedimentation environments is discordant with relatively low Cl contents in rocks (see table). However, taking into consideration the high mobility of Cl in different postsedimentary processes, one can suggest its removal from sediments in the course of their diagenetic compaction and with squeezing out of porous waters (or technogenic removal during drilling operations).

High palygorskite contents in Ypresian deposits of Benin and Togo were noted earlier (Viss, 1954; Slansky *et al.*, 1959; Slansky, 1962). Slansky also registered another maximum in palygorskite distribution in the Upper Paleocene. Further studies showed that palygorskite and locally (e.g., in Senegal and the Côte d'Ivoire) sepiolite are widespread in Paleocene–Middle Eocene deposits of West African sedimentary basins (Millot, 1968), as well as in Cenozoic sedimentary basins of Spain (Galan, 1984; Adatte *et al.*, 1998) and Armorican Massif (Esteoule-Choux, 1984).

Based on studies of clay minerals, Millot noted that in the succession kaolinite–montmorillonite–palygorskite–sepiolite, kaolinite is of clastic origin and is characteristic of coastal deposits, whereas other minerals prevail in off-shore areas. The regular distribution of clay minerals in the lower (Thanetian (?)–Ypresian) part of the section penetrated by borehole BS-4 can indicate the migration of shoreline during the corresponding time period, i.e., the transgressive–regressive cycle. It is characterized first by the upsection decrease in the kaolinite content and increase in the palygorskite concentrations and then, in the upper part of the section, by the reversed tendency. As Millot (1968) noted, the major Eocene transgression was complicated by two regressive episodes (prior to the Ypresian and at the Ypresian–Lutetian boundary), which is reflected in the distribution of layered magnesian aluminosilicates.

It is interesting, that epochs of the palygorskite clay development on the African continent correspond to the appearance of palygorskite in the deep-water oceanic sediments of the Central Atlantic (Timofeev *et al.*, 1982; and others). Established regularities in the distribution of magnesian silicates are supported by recent data obtained by deep-sea drilling near the Benin coast on the continental slope in the northern part of the Guinea Gulf (Leg 159 *JOIDES Resolution*, 1995). There, abundant palygorskite in the clay mineral association appears in the Lower Eocene interval of Holes 959–962 (Mascle *et al.*, 1996).

With regard to the origin of Eocene palygorskite clays of the Eastern Atlantic, there is an opinion that they were formed as a result of transformation of the finely dispersed alkali-basalt vitroclastic material under influence of hydrothermal Mg-fluids (Lomova, 1979). However, it is difficult to share this hypothesis, because, in particular, it does not explain the close correlation between palygorskite clay accumulation in oceanic and terrestrial domains although it is undoubted that these processes are interrelated.

We believe that synchronism in magnesian clay accumulation in substantially different facial settings was controlled by the following factors. Accumulation of palygorskite and, locally, sepiolite clays initially occurred on continents under arid climatic conditions (Ypresian age) in shallow shelf basins and some inner basins of West Africa. In these basins, authigenic formation of magnesian silicates took place. However, the sedimentation regime was, probably, unstable, and relatively low-magnitude sea level fluctuations resulted in local draining of shelf areas and erosion of deposited sediments. These deposits were probably subjected to fluvial erosion by permanent and intermittent flows, but under arid conditions, its role was apparently insignificant. Much stronger denudation was caused by wind erosion. Deposits that occurred in subaqueous environments only a while back and were yet free of vegetation were readily blown out and transported by permanent easterlies into the Atlantic Ocean. At the end of the Ypresian, when the sea level dropped by almost 100 m (Haq *et al.*, 1987) and spacious shelf areas became land (Fig. 2), the process of eolian erosion of palygorskite clays was at its maximum, which resulted in transport of significant amounts of magnesian aluminosilicates into the ocean. Maps compiled by Lisitsyn (1978) and quantitative estimates of the modern eolian transport of the material from the African land to the Atlantic cited by this author show that this process is also significant nowadays. As for the Ypresian–Lutetian boundary, the combination of spacious eustatic regression and arid climate favored the particularly intense eolian erosion; the subsequent Lutetian transgression and further increase of climate humidity substantially reduced the eolian transport of the sedimentary material. The pelitic palygorskite material accumulated in the ocean could further be subjected to diagenetic transformation, which resulted in the appearance of signs of authigenic neogenic minerals.

The post-Ypresian stage of the Coastal Trough development is also characterized by some interesting features. The arid climate was replaced by the humid one. Probably, this stage was marked by certain geological reorganization in the region and the appearance of the sublatitudinal uplift in its southern part. Similarly to regression, the transgression was fast and of high magnitude. The sea level rose quickly and significantly, thus resulting in transformation of the Benin territory into the basin partly separated from the open sea by the morphological barrier. The depth of the basin is estimated to be several dozens meters. The upsection increase in the silt and kaolinite contents can probably be considered as indicative of gradual shoaling of the basin as a result of its compensatory filling with sediments. Later stages of the Lutetian basin development were marked by intermittent changes in environments, which resulted in a sharp reduction of foraminifer abundance and the appearance of numerous ostracods.

The basin was initially characterized by high productivity, which determined the accumulation of carbonate ooze, whereas stable sedimentation conditions favored preservation of organic matter in sediments. The process of compensation filling of the basin with sediments and its shoaling was apparently accompanied by deterioration of ecological conditions, which resulted in reduction of the background bioproductivity and decrease in the $CaCO_3$ and C_{org} contents in sediments. The formation of this part of the section was only sometimes interrupted by a sharp increase in the intensity of carbonate accumulation and the formation of limestone interlayers.

Most of minor elements reveal a noticeable increase in their concentrations in Lutetian sediment as compared with those in the Ypresian section. The behavior, at least, of some of them (V, Ag, Mo, Ni, and others) is closely related to that of C_{org}. Therefore, the fall of C_{org} concentrations on moving upward in the Lutetian section is accompanied by the reduction in contents of these elements as well. The behavior of other elements, such as Ti, Ga, Fe, Cr, and Pb (and probably some others), was mainly controlled by the terrigenous material supply, which determines the increase (contrary to the previous group of elements) in their contents further upward in the section.

Special attention should be paid to Mn behavior in Eocene basins. Both sections considered are characterized by similar patterns in the Mn distribution: the Mn contents that are generally at the Clarke level in Ypresian deposits become minimal and, sometimes, negligible in most of the Lutetian samples. Such distribution patterns of Mn are most likely to be related to changes in deposition settings in basins; there are no grounds to relate them to variations in the composition of the sedimentary material transported into the basin of the Coastal Trough from land.

It is known that Mn^{2+} is characterized by high mobility and is removed from marine muds under reductive conditions. This property is most probably responsible for the Mn absence in sediments, at least, of the lower part of the sequence with noticeable C_{org} concentrations. In the uppermost layers of the Lutetian deposits, C_{org} contents are very low, but the presence of small segregations of sulfide minerals indicates the former existence of reductive environments in sediments of this part of the section as well.

Moreover, even in sediments enriched in organic matter but deposited under conditions of the open shelf with active hydrodynamics, the Mn contents are noticeably higher than in the Lutetian deposits of Benin (Brongersma-Sanders *et al.*, 1980; Lukashin *et al.*, 1994; and others).

An additional factor, which complicated the process of Mn accumulation in sediments was probably an abnormal gas regime in the Lutetian basin of the Coastal Trough. The restricted water exchange of the basin with the open ocean due to the morphological barrier could result in weak hydrodynamics, formation of temperature and density stratification, and appearance of environments with the abnormal gas regime (decrease in O_2 content in bottom waters). This assumption is supported by the above-cited data on the occurrence of impoverished and suppressed assemblage of benthic and planktonic foraminifers in the Lutetian deposits, which was apparently caused by suboxic environments in the basin at that time.

Kholodov and Nedumov (1991) showed that the Mn/Mo ratio in rocks can be used for interpretation of the gas regime in waters of the sedimentation basins. Such an approach provides quite a satisfactory tool for recognizing anoxic environments in ancient sedimentation basins as well (Gavrilov *et al.*, 1997; Nedumov, 1994). As evident from the above-mentioned data (see table), the minimal Mn concentrations in Lutetian deposits are accompanied by elevated Mo contents, which favors, in combination with paleoecological data on benthic and planktonic organisms, the abnormal (suboxic) gas regime in the Lutetian basin of the Coastal Trough.

If this scenario of the evolution of sedimentation settings is true, then it can be suggested that in marginal areas of the basin, i.e., in zones of shoals and more active hydrodynamics, Mn could precipitate from waters of the Lutetian basin to form elevated concentrations in sediments. It is also inconceivable that Mn could be concentrated in higher horizons of the Lutetian sections, which were deposited at the terminal stages of the Eocene basin development, but, were eroded during the prolonged erosion period.

The limited available factual data on the lateral distribution of phosphate-bearing horizons prevents us from a detailed consideration of the problem of their origin. Simultaneously, the distribution patterns of background P contents and occurrence of phosphate-rich horizons allows the most plausible hypotheses of their formation to be outlined.

Distribution of dispersed P contents in Eocene deposits reveal their stable correlation with C_{org} and $CaCO_3$, i.e., with components of the biogenic origin. This indicates that supply of sediments of the Eocene basin with P occurred as a result of burial of planktonic and benthic organisms and was directly related to the basin bioproductivity: growth or fall of bioproductivity resulted in a corresponding increase or decrease in P concentrations in sediments. This tendency is particularly manifested in Middle Eocene deposits. In the Middle Eocene basin, bioproductivity substantially increased against the background of fast transgression; after stabilization of the sea level, bioproductivity gradually decreased. It is pertinent to note that the Middle Eocene transgression demonstrates the close relation between some fast transgressions and bioproductivity of the basin accompanied by accumulation of the elevated contents of organic matter in sediments (Hallam and Bradshaw, 1978; Gavrilov *et al.*, 1997; and others). Depending on the facial settings, though synchronously, either high-carbonaceous or phosphate-bearing deposits are formed; sometimes, they occur together.

As was noted above, the distribution of phosphate-enriched interlayers in the Eocene section is irregular. For instance, in the Lutetian deposits, accumulations of phosphate segregations are noted at certain levels in the upper part of the Lutetian section, in addition to phosphate-enriched interlayers in its lowermost portion (at the base and slightly higher). Moreover, these interlayers are marked by the elevated content of the silty or even sandy material. If phosphate accumulations are confined to carbonate interlayers, these latter are often brecciated. Thus, phosphate-bearing interlayers are confined to deposits accumulated at the early stages of the Lutetian transgression and at the stage of the gradual shoaling of the basin that resulted from this transgression (uppermost layers). It is pertinent to note that the Lutetian eustatic transgression accompanied by phosphate accumulation in Benin was responsible for relatively large-scale phosphate manifestations in the spacious areas of West Africa, i.e., in the Senegal, Togo–Nigerian, and Mali–Nigerian basins (Slansky, 1980; Pokryshkin, 1987) as well as in the Central Asian region (Boiko *et al.*, 1982; Boiko, 1987) and some areas of the northern Caucasus (data obtained by N.G. Muzylev). Thus, the Lutetian eustatic transgression not only marked the beginning of the new stage of sedimentation on the oceanic shelf and in epicontinental seas but also determined the similarity of the mineral and geochemical composition of accumulated sediments.

The increase in the silt content in the phosphate-bearing horizons of Benin and their local brecciation suggest certain activation of the hydrodynamic regime during their formation. Taking this into consideration, it can be suggested that reworking of sediments generally containing the background-level phosphate segregations (microconcretions, phosphatized coprolites, and shells of skeletal organisms) and the subsequent concentration of phosphates in some thin interlayers can represent one of the possible mechanisms of the formation of phosphate-bearing horizons.

Another scenario, which takes into account the specific gas regime in the Lutetian basin of Benin, can be as follows. The development of the reductive environments in sediments of the basin and suboxic conditions, at least in some layers of the water column, could provide favorable conditions for P mobilization from sediments and its accumulation in excessive amounts in bottom waters. As noted by Baturin (1978), the distribution of phosphates in the southeastern Atlantic is contrary to the oxygen distribution: maximum contents are characteristic of waters impoverished in oxygen. In the Lutetian basin, activation of hydrodynamics, water mixing, and their aeration could result in intense P supply into sediments (from different sources). Mechanisms of phosphate accumulation in basins with abnormal gas regime have been considered (Boiko, 1987; Kholodov, 1997; and others). Since the Lutetian basin of Benin was relatively shallow-water and anoxia was low, the enrichment of muds with P during such episodes was insignificant. Probably, both these mechanisms operated simultaneously.

It should be noted that episodic distribution of phosphate-bearing interlayers, their confinement to certain levels in the Middle Eocene section (to the basal and upper parts), and also the somewhat restricted water exchange between the sedimentation basin of the Coastal Trough with the open ocean in the Eocene make, from our point of view, the participation of an upwelling mechanism in the formation of phosphate-bearing sediments unlikely. The analysis of formation environments of modern phosphate-bearing sediments on the West African shelf also reveals no relation to upwelling (Summerhayes *et al.*, 1972).

Despite the different sedimentation environments in the Ypresian basin as compared with those in the Lutetian, phosphate-bearing deposits in the Ypresian section are also confined to the interval with marl interlayers and related to changes in the deposition regime, which were probably determined by sea level fluctuations of a sufficiently high order.

CONCLUSION

Paleocene–Eocene sedimentation on the African shelf in the Guinea Gulf depended on many different-scale factors. The discrete patterns of sedimentation recorded throughout the alternation of deposition and nondeposition periods were determined by transgressions and regressions. The existence of similar regularities in the structure of sedimentary sequences of the coeval age in some areas of Europe, Asia, and North America allows the transgressive–regressive cycles to be considered as reflecting eustatic sea level fluctuations.

The mineral and geochemical composition of Ypresian and Lutetian deposits of Benin formed during different transgressive–regressive cycles substantially differs, which is related to peculiarities in sedimentation basins (in particular, their bathymetry, water exchange with the open ocean, climatic variations) and to the influence of some local factors.

The enrichment of Ypresian, as well as Thanetian (Slansky, 1962), deposits of Benin in palygorskite reflects specifics in sedimentation environments peculiar of the spacious African–Arabian and some adjacent regions. Eocene phosphate accumulation in Benin, although of a limited scale, was related to synchronous and much more intense processes of phosphorite formation in the African–Arabian region and also in some areas of Central Asia and the Northern Caucasus.

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