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Kerogen Facies of the Cretaceous Black Shales from the Angola Basin (DSDP Site 530), South Atlantic

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앙골라분지 백악기 흑색세일의 유기물상

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Abstract

The middle Cretaceous stratigraphic section of Deep Sea Drilling Project (DSDP) Site 530 in the Angola Basin is characterized by cyclic interbeds of organic-carbon-rich black shales and organic-carbon-poor red and green claystones, namely the black shale sequence. A number of samples from the black shale sequence were analyzed for the types and distribution of insoluble sedimentary organic matter (kerogen) in order to give more information on the depositional conditions of the black shales in the Angola Basin.

The dominant type of kerogen in the black shale sequence at Site 530 is amorphous organic matter mainly of marine planktonic algal origin. It probably consists of remains of some unfossilized dinoflagellates.

The cyclic preservation of organic-carbon-rich black shales in the Angola Basin during the mid-Cretaceous could be explained by the low dissolved-oxygen concentration in the warm, saline deep and bottom waters combined with the sluggish circulation within the highly restricted basin, and the periodic high productivity in the surface waters.

요약 : 앙골라분지 심해시추연구(DSDP) 정점 530에서의 중기 백악기층은 유기탄소의 함량이 풍부한 흑색세일과 유기탄소의 함량이 빈약한 적색 및 녹색의 점토암이 주기적으로 교호한다. 이들 흑색세일층의 퇴적환경을 밝히기 위하여 이들 중에 함유된 불용성퇴적유기물(Kerogen)의 종류 및 그 분포에 관하여 분석하였다.

앙골라분지 백악기 흑색세일층에 함유된 유기물의 종류는 대부분 무정형유기물(Amorphous Organic Matter)로서, 이들의 주된 기원은 부유성 해양 조류, 즉 화석화되지 않은 해양 부유성 쌍편모충류로 추정되었다. 이들 부유성 조류는 환경의 변화에 따라 주기적으로 다량 번식하여 앙골라 심해저로 공급됨으로써, 백악기 당시 용존산소의 농도가 현재보다 훨씬 낮고 폐쇄된 환경의 앙골라 심해저에 환원환경을 주기적으로 야기시켜 유기물의 집적을 용이하게 함으로써 흑색세일층이 형성되었음이 추측된다.

INTRODUCTION

Sixteen years of Deep Sea Drilling Project (DSDP) have shown that dark-colored organic-carbon-rich sediments are common in the Cretaceous sections in many parts of the world's oceans and particularly in the North and South Atlantic basins. These sediments are often loosely described as "black shales", although they usually consist of interbedded black, green and red layers. They also differ in concentrations of organic matter.

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In the last several years, extensive interest has developed to find out the process of black shale formation in pelagic environments. However, no consensus yet exists as to their origin (e.g. Weissert, 1981; Waples, 1983). Certainly they were deposited under oxygen-deficient conditions. How such conditions were achieved has been much debated (Schlanger & Jenkyns, 1976; Thiede & Van Andel, 1977; Fischer & Arthur, 1977; Arthur & Natland, 1979; Arthur & Schlanger, 1979; Demaison & Moore, 1980).

The middle Cretaceous (refer to Late Albian to Early Santonian in this study) stratigraphic section at DSDP Site 530 in the Angola Basin shows that relatively thin layers of organic-carbon-rich (Corg-rich) black shales are interbedded with thicker layers of Corg-poor green and red claystones, namely the so-called black shale sequence (Unit 8 in Fig. 2). The purpose of this study has been to provide more information on the depositional processes of the black shales at Site 530, whose origin is still a matter of debate (e.g. Hay, Sibuet et al., 1984). Fifty samples from the black shale sequence were analyzed for the types of organic matter with light and scanning electron microscopes (Fig. 4).

Investigation of black shale is important not only for scientific questions on the paleoceanography of ancient ocean basins but also for economic purpose, because many hydrocarbon deposits are derived from Corg-rich sediments of the Cretaceous age (e.g. Bois et al., 1982).

SITE DESCRIPTION

The DSDP Site 530 is located in the southeastern corner of the Angola Basin (19° 11.26′s ; 9° 23.15′E) at a water depth of 4629 m. It is about 150 km from the base of slope of southwestern African continental margin (slope angle of 3 to 4 degrees), and about 20 km north of the eastern portion of the Walvis

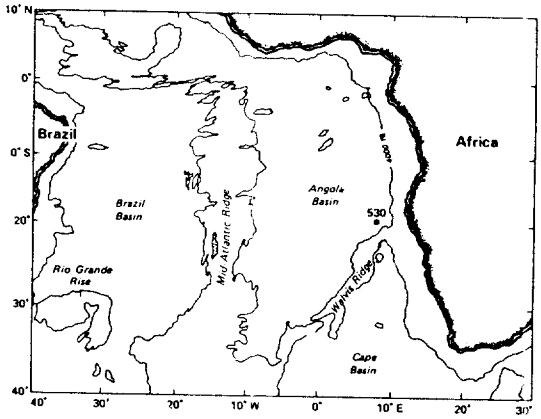

Fig. 1. Location map of DSDP Site 530. (After Dean and Parduhn, 1984).

Ridge escarpment (Fig. 1) (Hay, Sibuet et al., 1984). The site lies on the abyssal floor of the Angola Basin and is underlain by a seismic stratigraphic sequence that is typical of the entire deep part of the basin (Sibuet et al., 1984).

LITHOLOGY

Nine lithologic units, eight sedimentary and one basalt, were recognized at Site 530 (Fig. 2). The detailed lithology is discussed in Hay, Sibuet et. al. (1982 & 1984). The black shales of Late Albian to Early Santonian age that are interbedded with red and green claystones are characterized by the basal sedimentary unit. A total of 260 individual black shale beds were recognized in 20 cores (Cores 86-105) (Fig. 3). The black shale beds constitute 8.4% of the stratigraphic section recovered and are thick 4.3 cm on average (ranging from 1 to 62 cm). The maximum amount of black shale occurs in Cores 97 and 98 (Cenomanian/Turonian), interbedded with green claystones, with about 50 and 40% of black shale, respectively. These two cores lack red claystones. Black shales have an average organic carbon (Corg) content of approximately 5 to 6% ranging from 0.57 to 25.21%. The red and green claystones are poor in Corg and have an average Corg content of 0.42% ranging from 0.08 to 1.31%

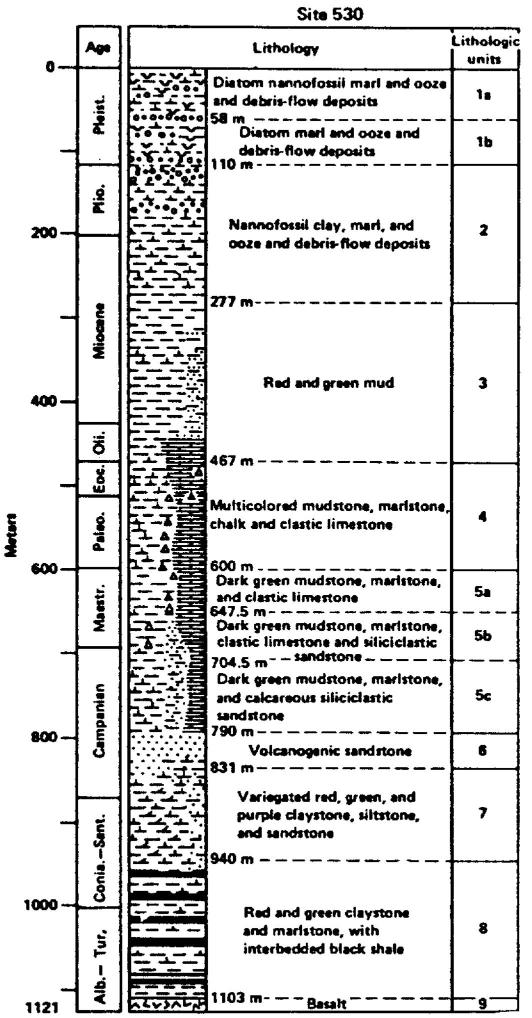

Fig. 2. Lithologic and stratigraphic column for Site 530 (Modified after Sibuet et al., 1984b, with revised stratigraphic boundaries from Stradner and Steinmetz, 1984).

(Fig. 4 and Meyers, 1984).

The red and green claystone beds occasionally contain thin (1-5 mm) turbidite layers and are usually bioturbated, although many of the red claystone beds appear to be homogenous. Some of the black shale beds contain very low amplitude ripple cross beds as well as faint, fine, horizontal lamination and bioturbation structures. They are commonly fissile and rarely massive. Bioturbation occurs throughout the sequence, most commonly in the red and green claystones, as well as in almost 50% of the black shale beds. Burrows are often smaller and more restricted in the black shales.

STRATIGRAPHY

The stratigraphy was established by Stradner and Steinmetz (1984) and Steinmetz et al., (1984) (Fig. 3). The Coniacian/Santonian boundary lies probably in Core 89. The Turonian/Coniacian boundary occurs at the bottom of Core 94. The sequence Turonian-Cenomanian-Albian, from 94 or 95 to 105, is poorly represented, and is poorly zoned as a result of the lack of useful biostratigraphic markers.

MATERIALS AND METHODS

Sixty samples from the black shale sequence at Site 530 were collected by Dr. R. Schallreuter (Geolog.-Paleontolog. Inst., University of Hamburg) during DSDP Leg 75. The samples were largely restricted to black, dark gray and green layers with exceptions of three gray marly mudstones and one red claystone (Table 1 & Fig. 3).

All types of samples investigated here were quite successfully disaggregated by the use of kerosene (Gray, 1965, p.535). The samples were treated with kerosene as outlined by Riedel and Sanfilippo (1977, p.857).

Proper amounts of sample were soaked in 40% HF overnight. HCl treatment was not carried out except for a few samples, because most samples investigated here contain little calcium carbonates (Park, 1985). The samples were washed through 63 micron sieve for convenient investigation under a microscope. The types of organic matter were identified using light (transmitted & incident) and scanning electron microscopes. Relative quantites of kerogen types were estimated semi-quantitatively from strew-mounts of residues after HF

Table. 1. Sub-bottom depth, lithology and stratigraphy of the samples from the Cretaceous black shale sequence cored at DSDP Sit 530, Angola Basin (Age after Stradner and Steinmetz, 1984).

Sample No.	Core-Section (interval in cm)	Sub-bottom Depth(m)	Lithology	Age
1	86-5, 29	937.29	reddish brown claystone	Santonian Coniacian
2	-5, 33	937.33	dark gray shale	
3	-5, 35-37	937.35	dark gray & dark green shale	
4	87-1, 39-41	940.39	black shale	
5	-2, 9-10.5	941.59	black & dark green shale	
6	-4, 27-29	944.77	black & dark green shale	
7	-4, 31-33	944.81	black & dark green shale	
8	-4, 83-85	945.33	black shale	
9	88-3, 89	952.89	black shale	
10	89-1, 64	958.64	black & olive black shale	
11	-2, 119.5	960.695	black shale	
13	93-4, 41-44	994.91	olive black shale	
14	-5, 23.5-26.5	996.235	olive black shale	
15	94-1, 41	999.41	black shale	
16	-2, 37-38	1000.87	black shale	
17	95-2, 91-92	1010.41	black shale	Turonian
18	-CC,0-1	1014.50	black & olive black shale	
19	96-1, 56-58	1017.56	black shale	
20	-4, 139-141	1022.89	black shale	
21	-5, 106-109	1024.06	black shale	
22	97-1, 122-125	1027.22	black shale	
23	-2, 14-16	1027.64	black shale	
24	-2, 76.5-79	1028.265	black shale	
25	-3, 63-69	1030.63	black & dark gray shale	
26	-4, 130-132	1031.80	black & dark gray shale	
27	-CC,10.5-12	1032.305	black & olive black shale	
28	98-1, 23-25	1035.23	black & dark green shale	
30	-2, 100-102	1037.50	dark gray shale	
31	-3, 47-50	1038.47	dark gray shale	
32	-3, 126-127	1039.26	black & dark green shale	
33	-4, 23-24	1039.73	black & dark green shale	
35	99-1, 13-14	1044.13	black & dark green shale	
38	-3, 148-150	1048.48	dark gray shale	
39	-4, 0-4	1048.50	dark gray shale	
40	-5, 131-134	1051.31	dark gray shale	
41	100-1, 94	1053.94	dark gray & olive black shale	Cenomanian
42	-2, 70-74	1055.20	dark gray shale	
43	-3, 133-134	1057.33	dark gray shale	
44	-4, 33-34	1057.83	greenish gray mudstone	
45	-4, 146-150	1058.96	dark gray shale	
46	-5, 44-47	1059.44	olive black & dark green shale	
48	101-1, 84-87	1062.84	dark gray shale	
50	-2, 24-27	1063.74	light gray mudstone	
51	-4, 26-29	1066.76	dark gray shale	
53	-7, 4-12	1071.04	dark gray shale	
54	102-1, 106-107	1072.06	black shale	
55	-2, 0-7	1072.50	black shale	
57	-3, 103-105	1075.03	black shale	
58	103-1, 75-76	1080.75	black shale	Late Albian
59	-3, 58-59	1083.58	light gray mudstone	
62	-4, 78-80	1085.29	black shale	
64	104-2, 85-86	1087.35	black shale	
65	-3, 98-100	1088.98	black shale	
66	-4, 40-42	1089.90	dark green shale	
67	-5, 38	1091.38	dark green & black shale	
68	-6, 31	1092.81	dark green shale	
69	105-1, 5-7	1094.05	dark green shale	
70	-2, 139-141	1096.89	black shale	
71	-3, 77-79	1097.77	black shale	
72	-4, 7-9	1098.57	olive black shale	

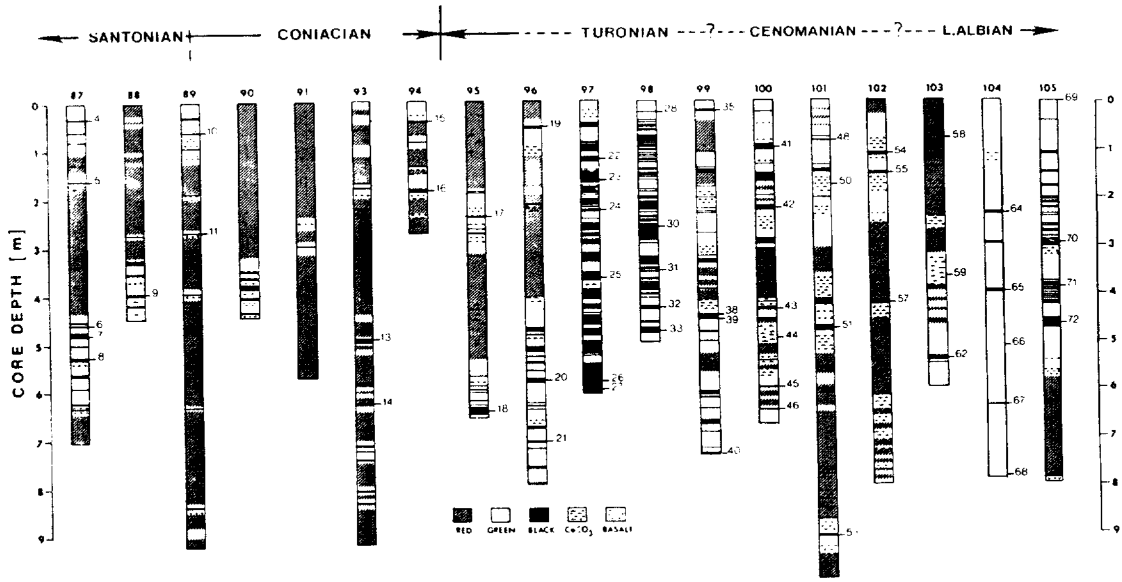

Fig. 3. Lithologies and sampling position in the Cretaceous black shale sequence at Site 530. Sample numbers 1, 2, 3 in Core 86 are not shown in this figure (Modified after Hay, Sibuet et al., 1982, with revised stratigraphic boundaries from Stradner and Steinmetz, 1984).

treatment. The strewn slides were prepared by a simple pipetting method (i.e. a small aliquot from a well-stirred sample onto a slide glass) and mounted with glycerin jelly.

The stubs for scanning electron microscopy (SEM) had been grounded with either double-faced adhesive tape or with dilute fingernail varnish; the fingernail varnish is dissolved in aceton and spread thinnly on the surface of the stub (De Weber, 1980). On the contrary to the double-faced adhesive tape, the mounting technique using fingernail varnish could prevent even very small specimens (e.g. pollen and spores) from sinking into the glue. For the investigation under SEM, a proper portion of the sample spread in suspension on the stubs and allowed to air dry. The stubs were then coated with gold by sputtering. All micrographs were taken with the Cambridge Stereoscan 180.

KEROGEN FACIES

An optical kerogen study is a vital adjunct to a geochemical investigation leading to any meaningful genetic interpretation of organic-rich sediments. In this study the results of visual kerogen analysis were compared with geochemical data from the Initial Reports of the DSDP Leg 75 (Hay, Sibuet et al., 1984).

Types and Distribution

Kerogen types were identified using criteria established by Masran & Pocock (1981). In addition, the differentiation of amorphous organic matter types was referred to the subcategories of Venkatachala (1981). Five categories of kerogen were identified from the Cretaceous black shale sequence at Site 530:

1) Structured terrestrial organic matter; woody fragments (Plate 1: 9-10).
2) Non-marine palynomorph; pollen and spores (Plate 1: 11-12).
3) Marine structured palynomorphs; dinoflagellates (Plate 1: 13-16).
4) Amorphous organic matter (AOM);
   a) Flakes and/or aggregates with irregular

shapes (Plate 1: 1-4).
b) Round bodies of amorphous organic matter (ARB) (Plate 1: 5-8).
5) Indefinable finely-fragmented organic debris.

The relative amounts of various types of organic matter (Fig. 4) were confined to the fractions larger than 64 micron on the basis of following results from the observations of the Corg-rich and Corg-poor samples under the light and scanning electron microscopes:

A) The fractions larger than 63 micron of the Corg-rich samples are mostly composed of flakes, aggregates and round bodies of amorphous organic matter (more than 95%), whereas the fractions smaller than 63 micron are composed of abundant minerals with a small amount (less than 10%) of indefinable finely-fragmented debris of organic matter. The latter seem to be disintegrated or fragmented debris of the large amorphous organic matter during sedimentation and partly from the process of sample preparation. Palynomorph extracts by acetolysis from the finer fractions are generally very rare or absent from structured matter such as dinoflagellates, spores and pollen.

B) The amounts of kerogen isolated from Corg-poor samples were occasionally insufficient for quantitative microscopic investigation. Some of the Corg-poor samples are mostly composed of very small amounts of carbonized woody fragments.

Since the identification of kerogen types was largely confined to the coarser fractions which are not necessarily representative and their abundance expressed as percentages, the results of visual kerogen analysis are compared with organic carbon values to assess the variations in net organic matter abundance between the Corg-rich and Corg-poor samples (Fig. 4).

As stated previously the organic matter in the Corg-rich black and dark gray shales at Site 530 is characterized by amorphous organic matters. They occur in the forms of flakes, aggregates, and round bodies. It amounts to more than 95% of the total organic matter in the fractions larger than 63 micron of the Corg-rich samples (AOM & ARB in Fig. 4). Structured terrestrial organic matter such as woody fragments occurs mostly in carbonized forms (charcoal). They are rare to barren in the Corg-rich black shale samples (CWF in Fig. 4). The relative abundances of charcoal in the Corg-poor samples amounted to from 30 to 100%. The high percentages of charcoal in the Corg-poor samples may have resulted from survival of this refractory organic matter under oxidizing conditions where other labile amorphous organic matter had been partially or severely destroyed.

As amorphous organic matter is the dominant type of organic matter in the black shales at Site 530, the correct identification and accurate assessment of this organic matter are crucial in order to obtain information on the origin of black shales. In the following section the origin of amorphous organic matter will be discussed in detail.

Origin of Amorphous Organic Matter

Amorphous organic matter (AOM) is completely transformed material into structureless matter where all recognizable cellular structure has been lost. This type of organic matter may result from biodegradation and geopolymerization of various kinds of organic matter derived from either marine or terrestrial source (Venkatachala, 1981). Visual observation fails adequately to distinguish the source of this material. However, examination and correlation with associated fossil contents and physicogeochemical data may shed some light on its source.

Except for the round bodies of amorphous organic matter (ARB), most of the amorphous organic matter at Site 530 occur as

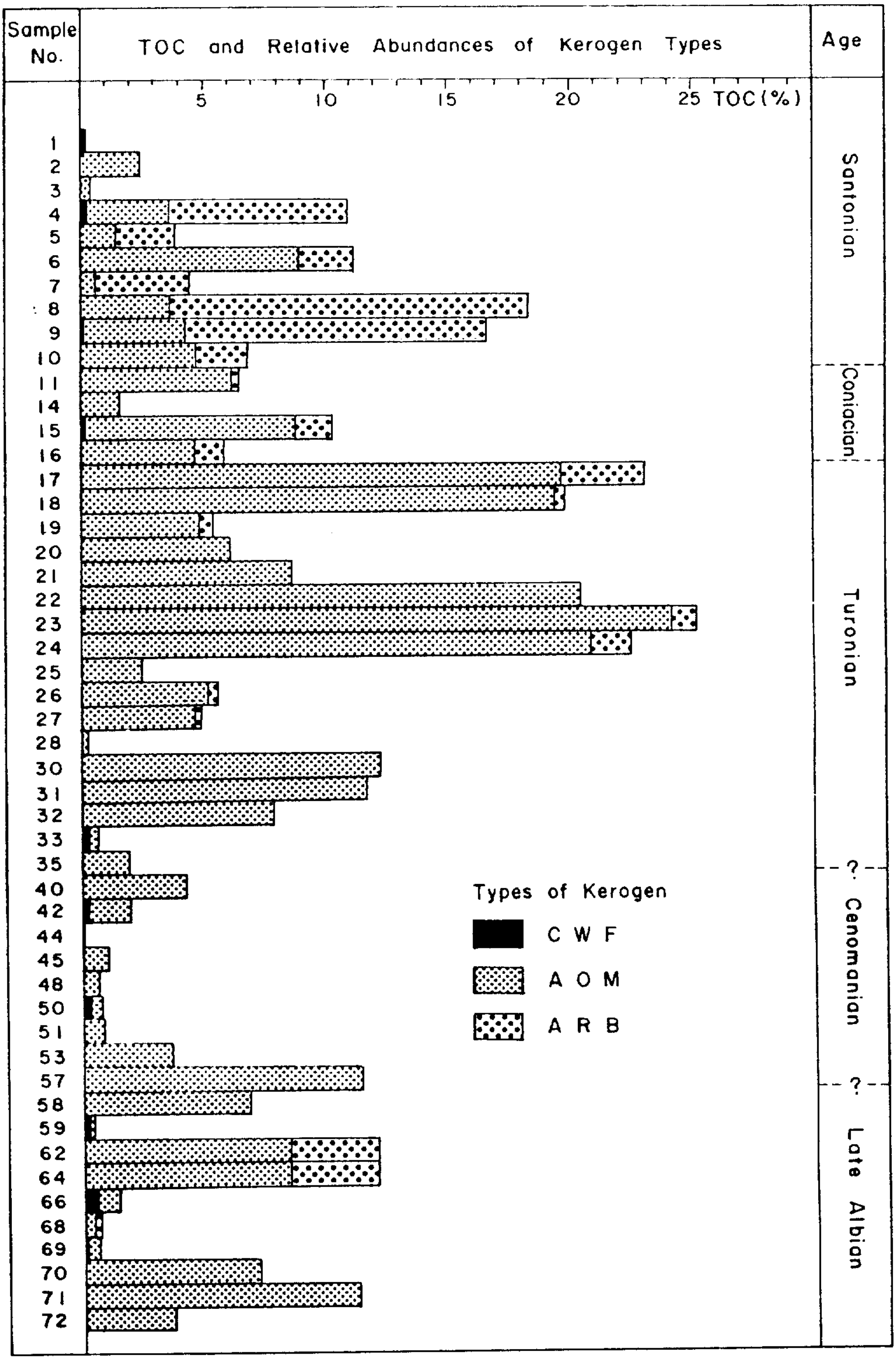

Fig. 4. Total organic carbon (TOC) and kerogen distribution of the samples from the Cretaceous black shale sequence at Site 530, Angola Basin (TOC data from Emeis, in press). Types of kerogen: CWF = Carbonized Woody Fragments; AOM = Amorphous Organic Matter with irregular shapes; ARB = Round Bodies of Amorphous Organic Matter.

flakes and/or aggregates with irregular shapes. The aggregates are completely structureless under the light microscope. Under the SEM, however, many of them show a flaky structure of the dominant organic matter (Plate 1: 4 & 8).

The Corg-rich black and drak gray shales containing abundant amorphous organic matter are generally barren of microfossils (Park, 1985). Some of them contain rare to few, relatively well preserved, marine microfossils such as radiolarians, diatoms, dinoflagellates, ichthyoliths, and pyritized worms. On the other hand, the Corg-poor green claystones and gray marly mudstones contain common to abundant radiolarians and few to common planktonic foraminifera respectively. The microfossil assemblages both in the Corg-rich shales and Corg-poor claystones show no remarkable evidence of redeposition of shallow-water microfossils into the deeper water (Park, 1985), suggesting that the AOM are largely of pelagic origin. The organic geochemical analyses of the black shales at Site 530 (e.g. Meyers, 1984; Brassel, 1984) also show that the organic carbon is mainly of marine origin.

The fluorescence analysis is particularly useful to distinguish the source of AOM: the AOM of algal or microbial origin shows a bright fluorescence, whereas the AOM derived from the terrestrial plants is nonfluorescent or weakly fluorescent (e.g. Tissot and Welte, 1984, p. 503). The AOM extracted from the black shale samples showed a strong bright fluorescence (see also Meyer et al., 1984c, p. 357), which verifies that the AOM may be of algal or microbial origin. Brassel, at the Colloguium on Black shales held in Hamburg, 1985, reported that the lipid components found in the Cretaceous black shales at Site 530 reflect the significant contribution of dinoflagellates to the Corg-rich sediments. Chappe et al. (1982) identified archaebacterial alkanes, in particular of methanogens, from the Cretaceous black shales at Site 530, however, their volumetric contribution to the total amounts of organic carbon should be very small.

Microscopic examination indicates that the amorphous aggregates did not originate from zooplankton fecal pellets. They show no distinctive forms of fecal materials and their sizes are too large for zooplankton fecal pellets (cf. Porter & Robbins, 1981; Habib, 1982a & 1982b). Honjo (1980) observed amorphous, loosely aggregated organic matter as large as several millimeters (ranging from 0.5 to 10 mm) from sediment trap samples collected from the meso- and bathypelagic regions. The large amorphous aggregates could have mainly originated from "marine snow (fragile macroscopic amorphous aggregates)" rather than from fecal pellets. Fecal pellets are believed to be important for the bulk of organic flux in the anoxic basins of the shallow marine waters, inland seas, and lakes (Porter and Robbins, 1981; Iovino and Bradley, 1969). However, they account for only a small fraction of the total organic flux for deep water. The bulk of organic flux precipitating in deep water is thought to be amorphous fine particles, not in the forms of fecal pellets. The fine particles are suspected of being remnants of fragile, large amorphous aggregates, i.e. marine snow (Honjo et al., 1982 & 1984). The agglutination of small, dense particles such as clay minerals onto the marine snow probably increases the density of the matrix and cause it to sink (Honjo et al., 1984). On the other hand, amorphous round bodies (ARB), which are common in about one third of the samples investigated here (Fig. 4) have distintive elliptical forms with a uniform size (mostly ca., 0.5 to 1.0 mm) (Plate 1: 5 & 7). The uniformity of size and shape suggests that they may well be produced in fecal pellets of some deposit-feeders such as polychaetes and holothurians. The occurrence of fecal pellets of benthic organisms together with burrows, bioturbation and pyrite worm tubes (Plate 1: 17-19) suggest that bottom conditions must have been relatively well oxygenated during the deposition of the black shales at Site 530.

On the basis of the informations from the above, it could be concluded that the amorphous organic matters in the black shales at Site 530 are principaly the remains of certain microscopic open-sea planktonic algae, probably the remains of some dinoflagellates which were not fossilized. The cyst-producing (and thus fossilizable) species of dinoflagellates form only a minor part of the extant dinoflagellates flora. If the proportions of the fossilizable to the unfossilizable species in the Cretaceous ocean were similar to those in the mordern oceans, then the sharp increase in the fossilizable species during the middle Cretaceous would have been matched by a proportional and therefore much greater diversification of the open-ocean nonfossilizing flora (Habib, 1982a, p. 124; Tappan, 1980, p.352).

MID-CRETACEOUS SOUTH ATLANTIC

Since the type of sedimentation was profoundly influenced by the paleoenvironmental conditions existing at that time, the middle Cretaceous environment of the South Atlantic is reviewed in the following sections to provide informations on the depositional conditions of black shales at Site 530.

With the exception of a few aseismic ridges, the entire basin of the South Atlantic was created by normal sea floor spreading. Initial rifting in the South Atlantic probably began during the late Jurassic (Oxfordian-Kimmeridginan) (Sibuet et al., 1984a) and subsequently, rift valleys were formed. The initial opening of the South Atlantic appears to have occurred approximately 130 m.y. ago (Berriasian/Valanginian) (Rabinowitz & La Brecque, 1979; Larson & Ladd, 1973).

During Aptian-Albian time the South Atlantic was a unique pair of narrow, linked, and highly restricted ocean basins (the Angola-Brazil and Cape-Argentin Basins), constricted at the middle by the Walvis-Sao Paulo Ridge complex (Fig. 5-A). These basins were closed to the north by the bulge of West Africa and to the south by Falkland Plateau which formed effective barriers between the North Atlantic and the Antarctic-Indian Ocean until the Late Albian (e.g. McCoy and Zimmerman, 1977). About 90-95 m.y. ago (Cenomanian-Turonian), the bulge of Africa was separated from South America, allowing North-South Atlantic surface water mass exchange for the first time (Fig. 5-B) (Berggren & Hollister, 1974). Four distinct basins (Angola, Brazil, Cape, and Argentin Basins) were forming during Coniacian-Santonian time at a depth greater than 4 km, separated meridionally by the Mid-Atlantic ridge and latitudinally by the Walvis-Sao Paulo Ridge complex (Fig. 5-C) (Le Pichon et al., 1978, p.32). Deep water circulation between Angola/Brazil and Cape/Argentine Basin was established by Campanian time (about 70-75 m.y. ago). However, the Walvis-Sao Paulo Ridge complex remained effective barriers to flow of bottom waters (Berggren and Hollister, 1977, p.15). Deep water connections (deeper than 3 km) between the North and South Atlantic Oceans occured in the Maastrichtian or Early Paleocene (Van Andel et al., 1977; Sclater et al., 1977).

During the early and middle Cretaceous the northern part of the South Atlantic was located within the tropics, but hot and arid and the southern part at cool, temperate latitudes. (Morgan, 1978; Roth & Bowdler, 1981). Thus the waters of Angola/Brazil basin should have been considerably warmer, more saline and denser than waters of the Cape/Argentine basin. Circulation at this time may have behaved similarly to that bet-

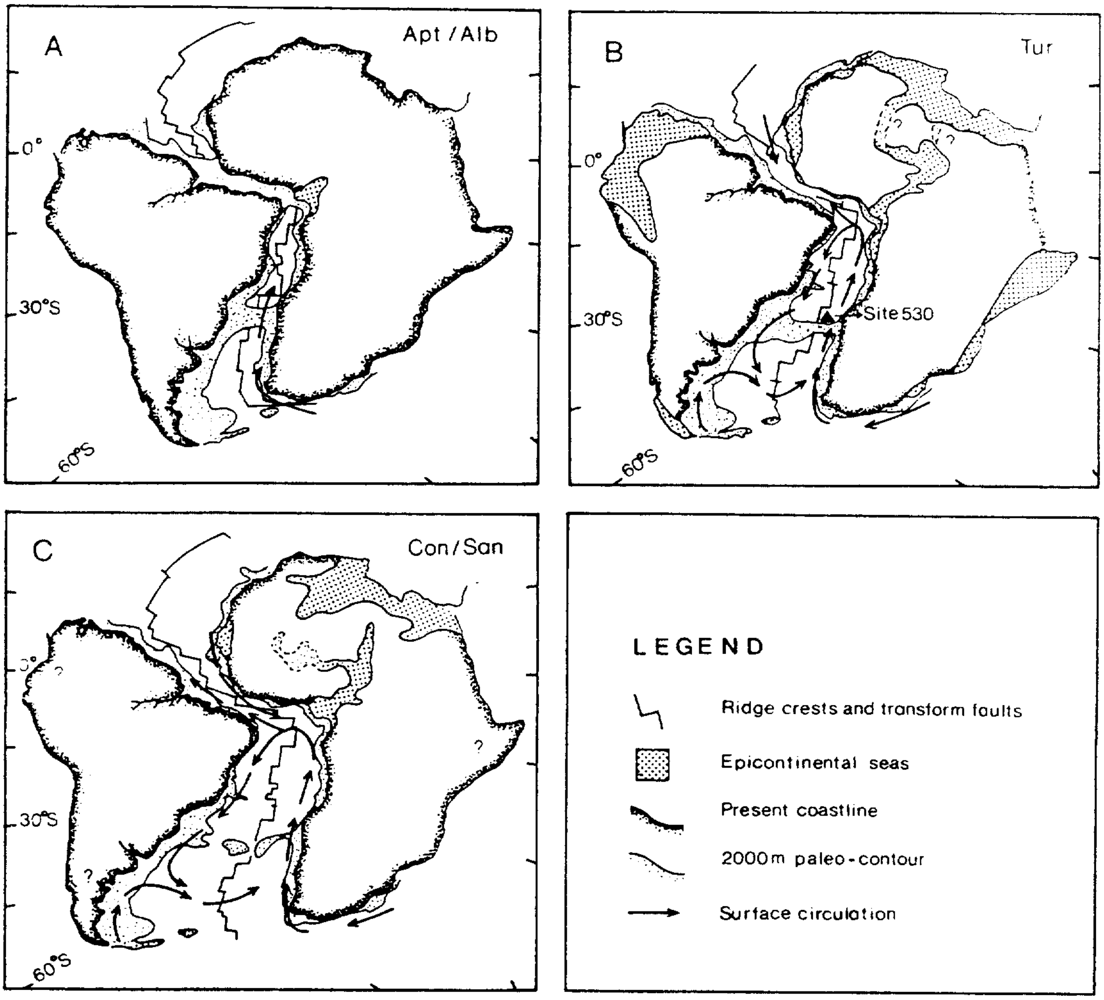

Fig. 5. Paleogeography, paleocirculation, and the extent of epicontinental seas during the middle-Cretaceous South Atlantic (Paleogeographic reconstruction after Sclater et al., 1977 :Extent of epicontinental seas after Reyment and Tait, 1972, Reyment et al., 1976, Reyment, 1980, ect.: Paleocirculation after Berggren and Hollister, 1974, McCoy and Zimmerman, 1977, and Natland, 1978).

ween the present Red Sea and Gulf of Aden, i.e. arid circulation (Natland, 1978). High evaporation rates in the northern end of the South Atlantic produced saline dense waters that sank to the bottom of the Angola/Brazil Basin. It was then forced to cross the Sao Paulo-Walvis Ridge resulting in slight upwelling on the northern side of the ridge with increased mixing of deep and surface water, and finally descended into the Cape/Argentin Basin (McCoy & Zimmerman, 1977; Arthur & Natland, 1979).

Eustatic sea-levels during the middle and late Cretaceous were generally high, leading to broad shallow continental shelves (e.g. Vail et al., 1977). The computed sea-level curve presented by Pitman (1978), based on rates of seafloor spreading and resultant volumes of mid-oceanic ridges, indicates that sea level may have been 350 m higher than the present at 85 m.y. ago. Kominz (1984) has recently repeated Pitman's (1978) calculation and found that the most probable sea-level stand may be 230 m above the present at 80 m.y. ago, but large uncertainties allow a possible range of 45 to 365 meters.

Major eustatic rise in sea level occurred during the Late Cenomanian, that reached a maximum in the Turonian (vail et al., 1977). During the short time (Early Turonian) tectono-eustatic high sea level caused a brief marine connection between the South Atlantic and Tethys by way of a shallow transitional transcontinental sea across North Africa (Fig. 5-B) (e.g. Reyment, 1980a & 1980b).

BLACK SHALE MODEL AT SITE 530 -DISCUSSIONS AND CONCLUSIONS

Any model for the Cretaceous black shale deposition at Site 530 needs to explain the common cyclic interbedding of Corg-rich black and Corg-poor red and green layers. The variation in sediment color from red to green to black indicates that there was a delicate balance between oxidizing and reducing conditions in the Angola Basin. In order to explain this cyclicity environmental variables important in controlling the amounts of organic matter are discussed. Three main variables are supply of organic matter (from land and/or from surface water productivity), sedimentation rate, and oxygen concentration in bottom waters. These variables are greatly influenced by climatic, oceanographic, geographic and tectonic factors (e.g., Demaison & Moore, 1980; Bois et al., 1982; Arthur et al., 1984).

Productivity

Generally the primary productivity in the mid-Cretaceous Angola Basin should be low due to the arid circulation pattern (Fig. 6); the arid basin might be characterized by downwelling, hence low fertility (Seibold & Berger, 1982, p.175). However, the wide shelves including epicontinental seas and lagoons may have stimulated production of marine plankton. Another possible area of high productivity is on the northern side of Walvis Ridge, where the slight upwelling occurred. The hot and arid climate may have inhibited the formation of dense vegetation onshore and may explain why little terrestrial organic matter was observed at Sites 530 and 364 in the Angola Basin: The sequence at Site 364 on the Angola Basin slope (Fig. 6) is very similar to that at Site 530 with maximum black shale development that is approximately synchronous (Stow & Dean, 1984).

Bottom-water oxygenation

Oxygen isotopic measurements from Inoceramus show that the bottom water temperature in the Angola Basin during the Coniacian-Santonian was about 15°-23°C (Saltzman & Barron, 1982; Barron et al., 1984). The high bottom water temperatures may have been caused by sinking warm and heavy saline waters produced in the surrounding shelves by evaporative processes, i.e. haline circulation. For water temperature between 15° and 20°C the saturation values for oxygen are near 5.5 ml/l. A typical actual value near 2 ml/l for the deep Cretaceous ocean might be expected after subtracting an oxygen consumption through decay of organic matter (Seibold & Berger. 1982, p.224; Wilde & Berry, 1982).

The rare, well preserved, pyrite worm tubes (Plate 1: 17-19) and relatively common occurrence of fecal pellets of some deposit feeders (ARB in Fig. 4), and the common presence of bioturbation and burrows in many of the black shale layers (Hay, Sibuet et al., 1982) indicate that the organic rich sediments at Site 530 were deposited under bottom waters that contained at least some dissolved oxygen, probably not more than 1 or 2 ml/l of O_2. In the oxygen range 0.1 to 1.0 ml/l, termed

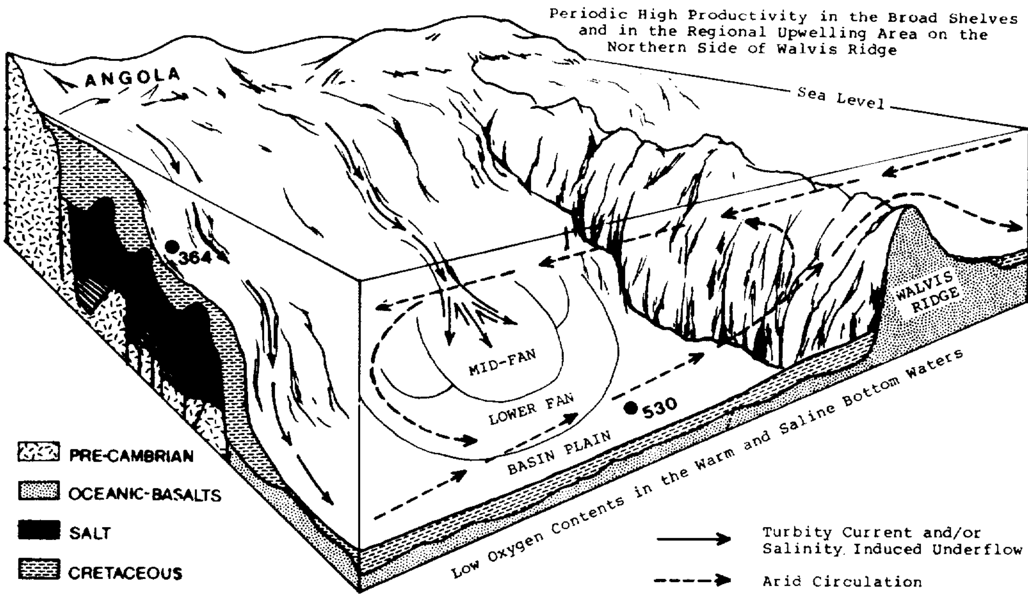

Fig. 6. Depositional environment of the Cretaceous black shale sequence at Site 530 (Sub-bottom structure modified after Beck and Lehner, 1974).

"dysaerobic" by Rhoads and Morse (1971), the soft-bodied infaunal polychaetes and nematodes and the poorly calcified crustaceans become the dominant components of the benthos, in sharp contrast to the calcified epifauna which dominate in normal aerobic ranges, i.e. 2.0-7.0 m*l*/1 (Byers, 1977, p.8). The benthos in such dysaerobic conditions stir the uppermost sediment, feeding on deposits, leaving bioturbation and burrows but essentially no hard parts. Preservation of organic matter is not normally good in such dysaerobic conditions unless sufficiently large amounts of organic material are buried quickly enough to consume the limited oxygen available in sediment pore waters.

Sedimentation rate

During the deposition of Corg-rich black shales at Site 530, sedimentation rates varied from 9 to 14.6 m/m.y., which are relatively low (Dean et al., 1984). High TOC values and low sedimentation rates may indicate environment of deep-water anoxia (Stein, 1986; Stein et al., 1986). Hence, the rate of organic carbon supply and/or preservation under low-oxygen conditions might be more important than bulk sedimentation rate in causing enhanced organic carbon accumulation in mid-Cretaceous Angola Basin.

From the above discussion, it appears that the bottom waters in the highly restricted Angola Basin were relatively well oxygenated during most of the middle Cretaceous to support the active infauna and to remove most of the organic carbon supplied. The common cyclic interbedding of reduced and oxidized strata at Site 530, therefore, are interpreted as being mainly the result of cyclic variations in diagenetic redox conditions within the sediments in response to variable rates of supply of organic matter to the basin as suggested by Dean and Gardner (1982) and Dean et al.

(1984): When the rate of supply of organic matter is low, the bottom waters are relatively well oxygenated, and the oxidation-reduction boundary is at some distance below the sediment-water interface so that red, oxidized sediments accumulated. When the rate of supply of organic matter is higher, the bottom waters are still more or less well oxygenated but increased oxygen demand in the sediments, mainly from the increased decomposition of the organic matter, has resulted in a oxidation-reduction boundary at or near the sediment-water interface, and in the accmulation of green, less reduced sediments. When the rate of supply of organic matter is much higher, the bottom waters become anoxic or near-anoxic, and the oxidation-reduction boundary may be some distance above the sediment-water interface so that black, reduced sediments accumulated. Stow and Dean (1984) observed that in the transition from green claystone to black shale the burrows commonly become smaller and less abundant upwards, which suggests that periodic deep-basin oxygen-deficient conditions occurred there.

One problem with this model is to provide a mechanism that will produce a cyclic supply of organic matter to the deep basin. As discussed previously, black shale beds represent episodes of large inputs of marine organic matter into a more or less well oxygenated sedimentary environment. Such input would be met, either by periodic downslope redeposition in the deep-basin by turbidity flow of Corg-rich shelf and slope sediments, or by periodic increase in surface productivity. Stow (1984b) estimated that only about 5 to 20% of the black shale sequence at Site 530 was deposited by turbidity currents as part of distal fan facies. The microfossil assemblages in the black shale sequence showed also no remarkable evidence of redeposition of shallow water microfossils into the deep basin. Organic matters in the black shales at Site 530, therefore, are largely a pelagic contribution to the sediments from the overlying waters. Figure 6 summarizes the interrelationship of main environmental variables that may have operated in controlling the accmulation of organic matter in the mid-Cretaceous Angola Basin. The Corg-rich sedimentation in the middle Cretaceous Angola Basin could be explained mainly by a combination of a large input of organic matter related to a periodic high productivity of surface waters and enhanced preservation under reduced oxygen level in warm, saline bottom waters.

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PLATE 1

In each SEM photo the magnification is indicated in micron for distance between the white marks. All specimens in this plate were treated with HCL/HF.

Figs.

1-4. Amorphous Organic Matter (AOM) with irregular shapes. They show commonly flaky or splintered structure, rarely spongy structure of organic matter. Fig. 4 is close-up of the AOM in fig. 3, showing the flaky structure of organic matter.

5-8. Round bodies of Amorphous Organic Matter (ARB) which may be produced in fecal pellets of some deposit feeders. Fig. 6 is detail of the ARB in fig. 5, which shows the growth of framboidal pyrite in the organic matter. Fig. 8 is close-up of the ARB in fig. 7, showing the flaky structure.

9-10. Woody fragments.

11. Fern spore; Gleicheniidites (?) sp.

12. Conifer pollen; Cicatricosisporites sp.

13-16. Dinoflagellates.
- 13. Cribroperidinium sp.
- 14. Fragmenting of dinocysts.
- 15. Danea chibanis (?)
- 16. Cleistosphaeridium (?) sp.

17. Pyrite worm tube with a smooth, granular surface.
18. A cross section of a specimen similar to fig. 17.
19. Detail of the hole at the center of fig. 18, which shows clearly the growth of framboidal and tabular pyrite crystals within the hole. This example shows a burrow filled with pyrite crystals.

Note: Figs. 1, 5, 6 from sample no. 4 (DSDP Leg 75-530A-87-1, 39-41 cm; black shale; Early Santonian): Figs. 2, 3, 4 from sample no. 70 (75-530A-105-2, 139-141 cm; black shale; Late Albian): Figs. 7, 8 from sample no. 9 (75-530A-88-3, 89 cm; black shale; Santonian/Coniacian): Figs. 9, 10, 11, 12, 14, 16 from sample no. 48 (75-530A-101-1, 84-87 cm; dark gray shale; Cenomanian): Figs. 13, 15 from sample no. 50 (75-530A-101-2, 24-27 cm; light gray mudstone; Cenomanian): Figs. 17, 18, 19 from sample no. 27 (75-530A-CC, 10.5-12 cm; black shale; Turonian).

PLATE 1