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# Sedimentation and Accumulation of organic carbon in the Angola Basin and on Walvis Ridge: Preliminary results of Deep Sea Drilling Project Leg 75

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## ABSTRACT

Leg 75 investigated two periods of accumulation of sediments rich in organic matter. In the Upper Cretaceous section, more than 200 beds of gray or black shale and mudstone rich in organic carbon (as much as 18%) are intercalated within a sequence of red and green mudstones that contain less than 1% organic carbon. The black shale beds are 1 to 62 cm thick and constitute less than 10% of the section in the 20 cores in which they were recovered. Both turbiditic and pelagic processes were involved in the deposition of these black shale beds. A combination of factors, including increased productivity and warm saline bottom waters, probably resulted in a delicate balance between oxic and anoxic conditions that periodically favored the accumulation and preservation of organic matter in the basinal sediments. The Pliocene-Pleistocene sediments are thoroughly bioturbated, and there is no evidence of persisting anoxia in the overlying water in spite of the high organic carbon content of the sediments. These two different periods of accumulation of organic matter both resulted in significant concentration of organic carbon (>2%, maximum 18%), but the Pliocene-Pleistocene sediments contain the greater mass of organic carbon per unit volume of the solid sediment.

## BACKGROUND

Legs 71 through 75 of the International Phase of Ocean Drilling (IPOD) of the Deep Sea Drilling Project (DSDP) were devoted to the study of the late Mesozoic and Cenozoic paleoenvironments in the South Atlantic Ocean. The scientific program of Leg 75 was designed to study the development of anaerobic conditions in the South Atlantic during the Cretaceous and to evaluate the effect of the Walvis Ridge as a barrier to deep oceanic circulation in the South Atlantic.

Sediments rich in organic carbon (>2%), and apparently indicative of a reducing depositional environment, are rare in the modern open ocean; however, the location and the extent of such deposits in the ancient record are of great interest because of their potential as source rocks for hydrocarbons. Several models have been proposed to explain such deposits in the ancient record, which in general fall into three groups: (1) Restricted water circulation leads to oxygen-deficient bottom waters which favor preservation. The important factors causing restricted circulation include the development of (a) topographic barriers (Degens and Stoffers, 1976), (b) a strong halocline (Olausson, 1960), (c) a strong thermocline (Tyson and others, 1979), and (d) a wide shelf and depression of wave action (Hallam, 1967). (2) High planktonic productivity leads to preservation of organic material where the oxygen demand exceeds the supply. In particular, high productivity may lead to an expanded oxygen minimum with anoxic bottom-water conditions occurring where this zone intersects in the sea floor (Gallois, 1976; Jenkyns, 1980; Thiede and van Andel, 1977). These variations may be related to climatic variations (Fischer and Arthur, 1977) or salinity (Arthur and Natland, 1979). (3) High rates of sedimentation, especially where there is a high input of organic-rich terrestrial matter, may lead to rapid burial and preservation of organic matter (Cornford and others, 1979; Welte and others, 1979). Today, anaerobic environments are restricted to relatively small isolated basins in which the bottom waters are renewed only very slowly, such as the Black Sea, the Cariaco Trench off Venezuela, the Orca Basin off Texas, and the Guaymas Basin of the Gulf of California, or to mid-depths along continental margins where a strong oxygen minimum is developed as a result of (a) unusually fertile conditions and

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TABLE 1. LEG 75 CORING SUMMARY

| Hole | Dates (1980) | Latitude | Longitude | Water* depth (m) | Penetration (m) | Number of cores | Metres cored | Metres recovered | Percentage of recovery |
|---|---|---|---|---|---|---|---|---|---|
| 530 | 29–30 July | 19°11.26'S | 9°23.15'E | 4,629 | 125.0 | 2 | 11.0 | 9.20 | 83.6 |
| 530A | 30 July–15 August | 19°11.26'S | 9°23.15'E | 4,629 | 1121.0 | 108 | 996.0 | 619.46 | 62.2 |
| 530B | 15–18 August | 19°11.26'S | 9°23.15'E | 4,629 | 180.6 | 48 | 180.6 | 155.08 | 85.9 |
| 531 | 19 August | 19°38.44'S | 9°35.31'E | 1,267 | 1.0 | 1 | 1.0 | 0.02 | 2.0 |
| 531A | 19 August | 19°38.44'S | 9°35.47'E | 1,267 | 1.0 | 1 | 1.0 | 0.27 | 27.0 |
| 532 | 20–21 August | 19°44.61'S | 10°31.13'E | 1,331 | 250.8 | 61 | 250.8 | 232.44 | 92.7 |
| 532A | 21–23 August | 19°44.64'S | 10°31.13'E | 1,331 | 199.6 | 47 | 199.6 | 161.15 | 80.7 |
| 532B | 23–25 August | 19°44.66'S | 10°31.13'E | 1,331 | 291.3 | 74 | 291.3 | 267.00 | 91.7 |
| | | | | | | 342 | 1859.3 | 1444.62 | 78.0 |

*Water depth from sea level.

productive surface waters, such as beneath the Benguela upwelling off southwest Africa or in the Gulf of California, or (b) where there is an outflow of oxygen-deficient waters from a hypersaline marginal sea, such as the Persian Gulf affecting the western margin of the Indian subcontinent.

These depositional environments are similar in that they are anaerobic and result in laminated sediments with a high organic carbon content. It should be possible to distinguish similar environments in the ancient record by reconstructing the paleogeographic and paleobathymetric settings and by analysis of the fossil contents of the sediments.

Conditions favorable to the development of black shales in the deep ocean occurred several times during the Cretaceous and were especially characteristic of the narrow young Atlantic Ocean. Results from Leg 40 show that the lowermost 313 m at Site 361 in the Cape Basin consist of alternating black shales, sandy mudstones, and sandstones of Aptian-Albian age. The sandstones contain black coaly and woody fragments; the shales often show laminations and have an organic carbon content averaging 3 wt %. Studies by Raynaud and Robert (1978) suggest that the shale interbeds contain some lignaceous material of terrestrial origin, but most of the organic matter in the black shales is amorphous organic material of marine origin.

No black shales were found at Site 363 on the Walvis Ridge, but 2- to 4-cm-thick beds of organic-carbon–rich (2%–3% organic carbon) black pyritic mudstones were encountered in upper Albian strata, suggesting that there must have been at least localized oxygen-deficient conditions.

At Site 364 on the continental margin off Angola, laminated black shales alternate with marly chalk and green claystone in the lower Santonian–upper Albian section, and tan organic carbon-rich laminated dolomitic marlstones alternate with black shale lacking laminations in the lower Albian–upper Aptian sequence. The organic carbon content of individual beds is commonly >10% and reaches 26%. The organic matter is characterized by amorphous sapropelic material of probable algal origin (Raynaud and Robert, 1978).

The main objective of Leg 75 was to investigate the Mesozoic paleoenvironmental history of the South Atlantic and to determine whether the Cretaceous black shales were deposited in the bottom of a barren, anoxic basin or at mid-depths within the oxygen-minimum layer of a quasi-normal oceanic basin, and whether the low-oxygen conditions were the result of an abnormally high influx of organic matter or were caused by salinity or temperature-induced stratification.

Another related objective was to study the paleoceanographic effects of the subsidence of a continuous aseismic ridge attached to a passive continental margin. Unlike the Rio Grande Rise, the Walvis Ridge has no deep passages to permit northward flow of bottom waters and may have served as a barrier to circulation and to bottom-current transport of sediments.

The D/V *Glomar Challenger* sailed on Leg 75 from Walvis Bay, South Africa, on 26 July 1980. Details of the three sites occupied on Leg 75 are given in Table 1, and their locations are indicated in Figure 1. Most of the drilling time was devoted to three holes at one site, 530, in the Angola Basin. Several holes were attempted at Site 531 on a guyot-like feature on the Walvis Ridge, but they could not be spudded in. The remainder of the time was devoted to hydraulic piston coring at Site 532, near Site 362 of Leg 40, in order to obtain a detailed history of the Benguela upwelling system.

## SITE 530

Site 530 is located in the southeastern corner of the Angola Basin, about 20 km north of the Walvis escarpment, near the eastern end of the Walvis Ridge (Fig. 1). It is on the abyssal floor of the Angola Basin and is underlain by a seismic stratigraphic sequence that is typical for the entire deep part of the basin.

Magnetic lineations of the basement are not distinct at Site 530. The M sequence (M0 to M11) has been clearly identified in the Cape Basin south of Walvis Ridge by Rabinowitz (1976). Cande and Rabinowitz (1978) interpreted the Angola Basin anomalies as suggesting that a ridge jump occurred approximately at the time of Anomaly M0 or later, so that the basement at Site 530 should be early Aptian or younger (that is, an age younger than predicted by symmetric sea-floor spreading). One of the objectives of drilling at this site was to determine the basement age and establish whether the hypothesis of a ridge jump in the southern Angola Basin is correct.

Extensive multi-channel seismic surveys of the area had been carried out by the University of Texas Marine Science Institute and

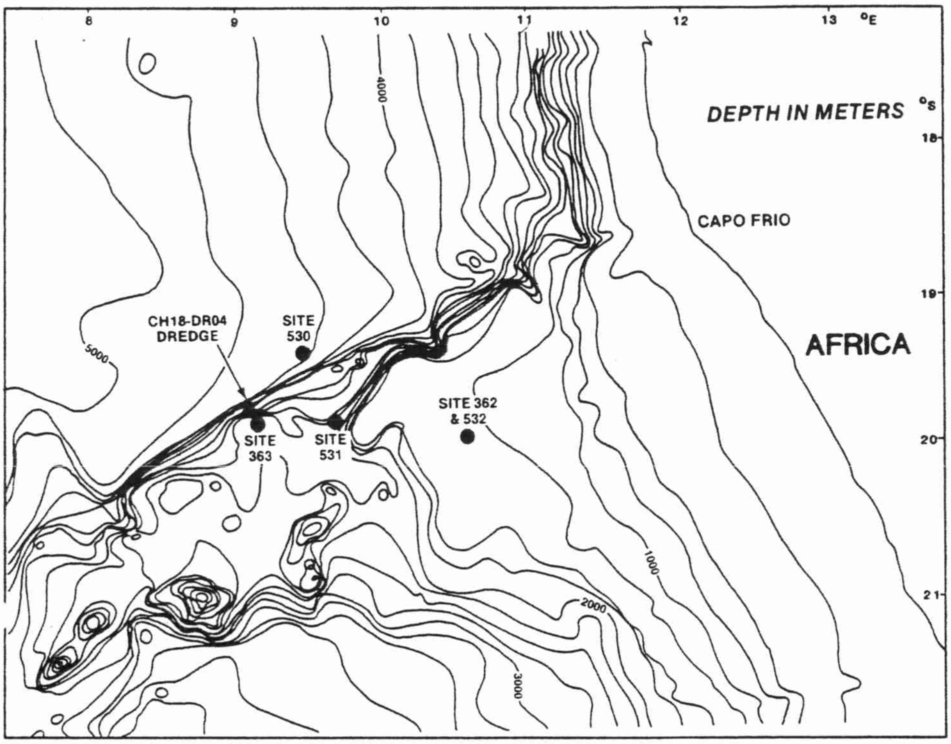



**Figure 1. Map showing the location of sites drilled on Legs 40 and 75, and of the site dredged by the R/V *Jean Charcot*.**

the Bundesanstalt für Geowissenschaften und Rohstoffe of the Federal Republic of Germany. Correlation of the results of drilling at DSDP Sites 362 and 363 with the processed multi-channel seismic-profile record (BGR-36) shows three main sequences bounded by discontinuities to be identified on the adjacent Walvis Ridge. The lowest surface of discontinuity was thought to be a paraconformity where the Cenomanian and much or all of the Turonian would be missing, as at Site 363; the middle discontinuity was expected to be early Oligocene at the top of the *Braarudosphaera* chalk, as noted at Sites 362 and 363; the upper discontinuity was expected to be middle Miocene and correspond to strata which had been drilled at Site 362. Because of differences in water depth and probable differences in sedimentary facies, it was considered speculative to extend this seismic stratigraphy to the deep Angola Basin except for the lowest discontinuity, which could be recognized throughout the area and which was thought to correspond to the Cenomanian-Turonian hiatus known to occur near the base of the upper black shale sequence at Site 364. Prior to drilling, regional seismic stratigraphic interpretation was limited to tracing the lower discontinuity in the southern Angola Basin and to studying the basal onlap of the sequence above it.

### Lithostratigraphy

Eight sedimentary units and one basalt unit were recognized at Site 530 in the southern Angola Basin (Table 2 and Fig. 2).

Unit 1 consists of nannofossil marl and ooze, diatom ooze, and debris-flow deposits; it extends from the surface to a sub-bottom depth of 110 m and represents the Holocene and most of the Pleistocene.

The sediment contains mixtures of nannofossils, diatoms, and clay, in approximately that order of abundance, and can be classified as nannofossil marl and ooze and diatom ooze. Debris-flow deposits and turbidites are interbedded with the background pelagic sediment at a number of horizons within the lithologic unit. Unit 1 is subdivided into two subunits on the basis of relative abundances of diatoms and nannofossils. Subunit 1a consists of 58 m of Holocene and upper Pleistocene sediment that is rich in both diatoms and calcareous microfossils interbedded with debris-flow deposits and diatom-rich mud turbidites. The organic-rich (>2% organic carbon) clay-diatom turbidites range from 20 to 100 cm thick and are approximately equal in abundance to organic-poor (< 2% organic carbon) pelagic ooze and marl in Unit 1a. Subunit 1b consists of 52 m of lower Pleistocene diatom-rich, carbonate-poor sediment interbedded with debris-flow deposits.

The debris-flow deposits occur at several horizons within Unit 1 and increase in thickness and abundance toward the base of the unit, where one of the flow deposits is ~6 m thick. The clasts of this thickest debris-flow deposit in Unit 1 consist of at least eight different lithologies, mainly calcareous and siliceous marl, mud, and rare sandy clasts and shell fragments, all of which can be observed in overlying and underlying sequences. The clasts are variable in size and range from ~5 mm to at least 40 cm in maximum dimension, and most are elongate and subrounded to well rounded. The clasts are in varying stages of disintegration, from those with sharp, well-defined outlines to completely smeared-out multicolored streaks and mottles. Some of the clasts are in contact with each other, but most are supported in a matrix that is dominantly a diatom nannofossil ooze. In these debris-flow deposits, the organic content ranges from 0.7% to 6.0%, according to the lithologies.

Unit 2 is composed mainly of calcareous biogenic sediments interbedded with thick debris-flow deposits and thin mud turbidites. It is 167 m thick and ranges in age from earliest Pleistocene to late Miocene. The sediment ranges in color from light greenish-gray to olive to olive-gray; the darker shades reflect an increase in clay content. The biogenic sediment is composed dominantly of nannofossils, with variable content of foraminifers and clay, and rare siliceous material. The largest debris-flow deposit encountered at

TABLE 2. COMPOSITION, CORES AND DEPTHS OF OCCURRENCE, THICKNESS, AGE, AND SEDIMENTATION RATES OF LITHOLOGIC UNITS CORED AT SITE 530, SOUTHERN ANGOLA BASIN

| Unit | Lithology | Cores | Sub-bottom depth (m) | Thickness (m) | Age | Sedimentation rate (m/m.y.) |
|---|---|---|---|---|---|---|
| 1a | Diatom nannofossil marl and ooze and debris-flow deposits | 530B, 1-14, Sect. 1 and 2 | 0–58 | 58 | Holocene to Pleistocene | 65 |
| 1b | Diatom marl and ooze and debris-flow deposits | 530B, 14, Sect. 3-27 | 58–110 | 52 | Pleistocene | |
| 2 | Nannofossil clay, marl, and ooze and debris-flow deposits | 530B, 28-48; 530A, 1-16. | 110–277 | 167 | Pleistocene to late Miocene (1.7–10 m.y.) | 20 |
| 3 | Red and green mud | 530A, 17-36 | 277–467 | 190 | late Miocene to Oligocene (10–37 m.y.) | 7 |
| 4 | Multicolored mudstone, marlstone, chalk, and clastic limestone | 530A, 37-50 | 467–600 | 133 | Eocene to Maestrichtian (37–~66 m.y.) | 5 |
| 5a | Dark green mudstone, marlstone, and clastic limestone | 530A, 50-55 | 600–647.5 | 47.5 | Maestrichtian (~66–68 m.y.) | 23.7 |
| 5b | Dark green mudstone, marlstone, clastic limestone, and siliciclastic sandstone | 530A, 56-61 | 647.5–704.5 | 57 | early Maestrichtian to late Campanian (~68–71.5 m.y.) | 16.3 |
| 5c | Dark green mudstone, marlstone, and calcareous siliciclastic sandstone | 530A, 62-70 | 704.5–790 | 85.5 | late to early Campanian (~71.5–77 m.y.) | 15.5 |
| 6 | Volcanogenic sandstone | 530A, 71-75, Sect. 1 and 2 | 790–831 | 41 | early Campanian (77–79.5 m.y.) | 16.4 |
| 7 | Variegated red, green, and purple claystone, siltstone, and sandstone | 530A, 75, Sect. 3-86 | 831–940 | 109 | early Campanian to early Santonian (79.5–84.5 m.y.) | 21.8 |
| 8 | Red and green claystone and marlstone with interbedded black shale | 530A, 87-105 | 940–1,103 | 163 | early Santonian to late Albian (84.5–96 m.y.) | 9.1 |
| 9 | Basalt | 530A, 105, CC-108 | 1,103–1,121 | 19 | | |

this site occurs near the top of this unit, and it is at least 32 m thick. The clasts in the debris-flow deposits in Unit 2, like those in Unit 1, include about eight multicolored mud, marl, and ooze lithologies, as well as rare basalt pebbles; the clasts range up to more than 60 cm in diameter. The base of Unit 2 coincides with a change in sonic velocity and density of the sediment. This or similar units containing debris-flow deposits are recognizable on seismic-reflection records in the basin adjacent to Walvis Ridge.

Unit 3 consists of 190 m of green and red mud, very thin-bedded basinal turbidites, pelagic clay, and volcanic-palagonitic silt deposited from the late Oligocene to the late Miocene following a period of much-reduced sedimentation during middle Eocene through early Oligocene time. Seismic-reflection profiles show that the equivalent of this unit is an acoustically transparent layer that extends over much of the Angola Basin and that it is dominated by sediment input from the African continental margin. The lower Oligocene may be represented at the base of the unit by a condensed section with hiatuses. The base of Unit 3 corresponds to the widespread lower seismic discontinuity which tentatively had been identified as the Cenomanian-Turonian hiatus in seismic stratigraphic studies prior to drilling.

Unit 4 consists of 133 m of green mudstone with minor red mudstone, calcareous mudstone, marlstone, and common interbeds of nannofossil chalk and clastic limestone. The age of this unit is Eocene to Maestrichtian. The colors vary with the proportion of carbonate present and range from white and bluish-white limestone to yellowish-gray chalk, greenish- and olive-gray mudstone, dark greenish-gray mudstone, pale yellow marlstone, and brownish-gray mudstone.

The clastic limestone beds contain mainly shallow-water carbonate debris, including benthic reef foraminifers, shell debris, and fragments of calcareous algae and bryozoa, mixed with volcanic rock fragments, quartz, feldspar, glauconite, and heavy minerals. The carbonates and muds tend to occur as turbidites with sharp, scoured, and loaded bases, and more gradational bioturbated tops.

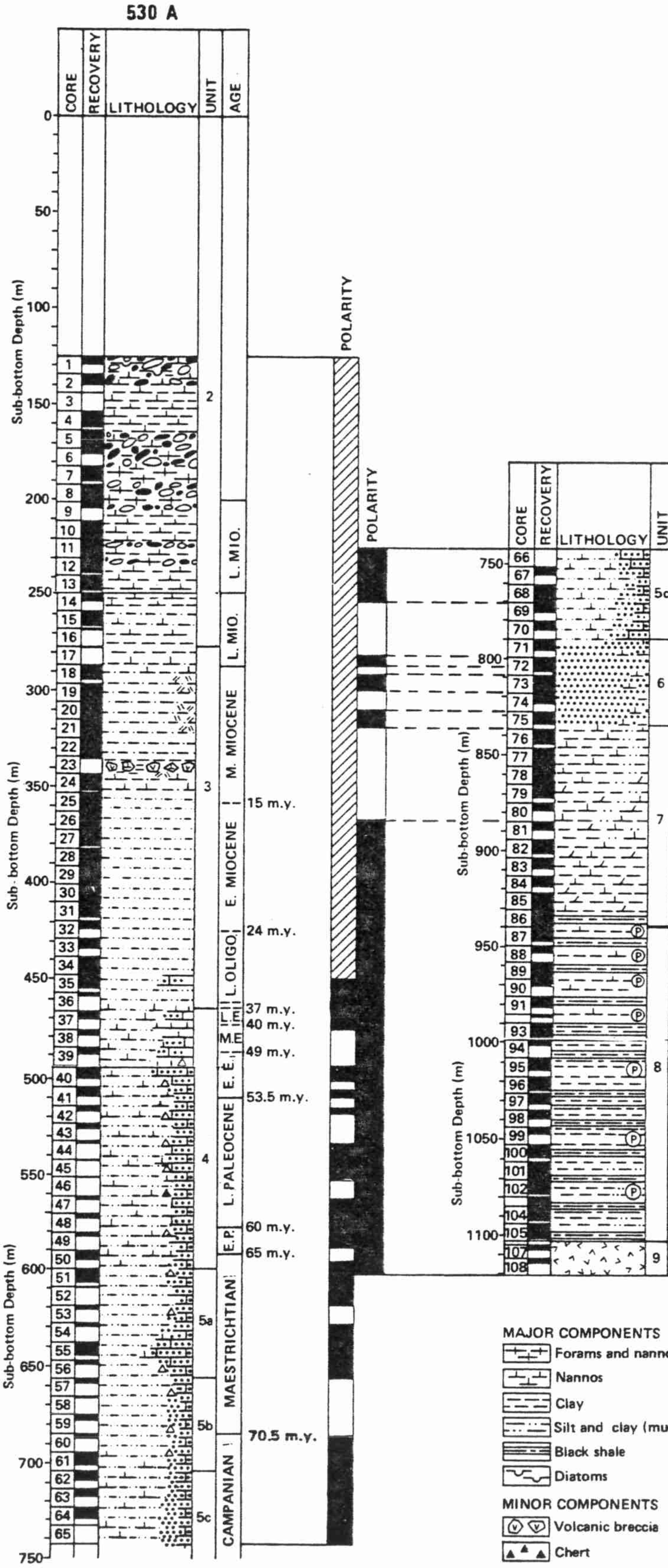
Unit 5 consists of mudstone, marlstone, clastic limestone, and siliciclastic sandstone. It is 190 m thick and ranges in age from early Maestrichtian through Campanian. The interbeds of clastic limestone become less common downward until the carbonate clastic debris is replaced by dark-colored siliciclastics and, near the base of the unit, by volcanogenic sandstone.

Fragments of the large mollusc *Inoceramus* are present in many of the cores from the Coniacian to the early Maestrichtian. The fragments consist of 0.5- to 1.0-cm-thick slabs of fibrous calcite which formed the prismatic layer of the mollusc shell. They are usually oriented parallel to stratification and often occur as continuous or partly broken layers across the entire width of the core. Most *Inoceramus* fragments of Maestrichtian age have a broken gray outer rim of varying thickness in which the calcite has been replaced by silica. *Inoceramus* are only rarely associated with turbidite deposits. This fact suggests that *Inoceramus* lived at depths of 3,500 to 4,500 m on the basis of thermal subsidence curves for oceanic crust.

There are several irregular thickening and thinning sequences of turbidites in Units 4 and 5, suggesting that these sediments may have been deposited in fan lobes and small channels.

The base of Unit 5 is marked by an increase in sonic velocity and a decrease in density, reflecting the fact that the volcanogenic sandstone of Unit 6 has a relatively high velocity but a low density. Unit 6 is made up of 41 m of carbonate-cemented greenish-black volcanogenic sandstones of Campanian age. The sandstones occur as thin (5–10 cm) to thick (1–3 m) graded turbidites that show partial or complete Bouma sequences.

The dominant lithology of Unit 7 is red claystone with interbeds of green, red, and purple siltstone and claystone and green



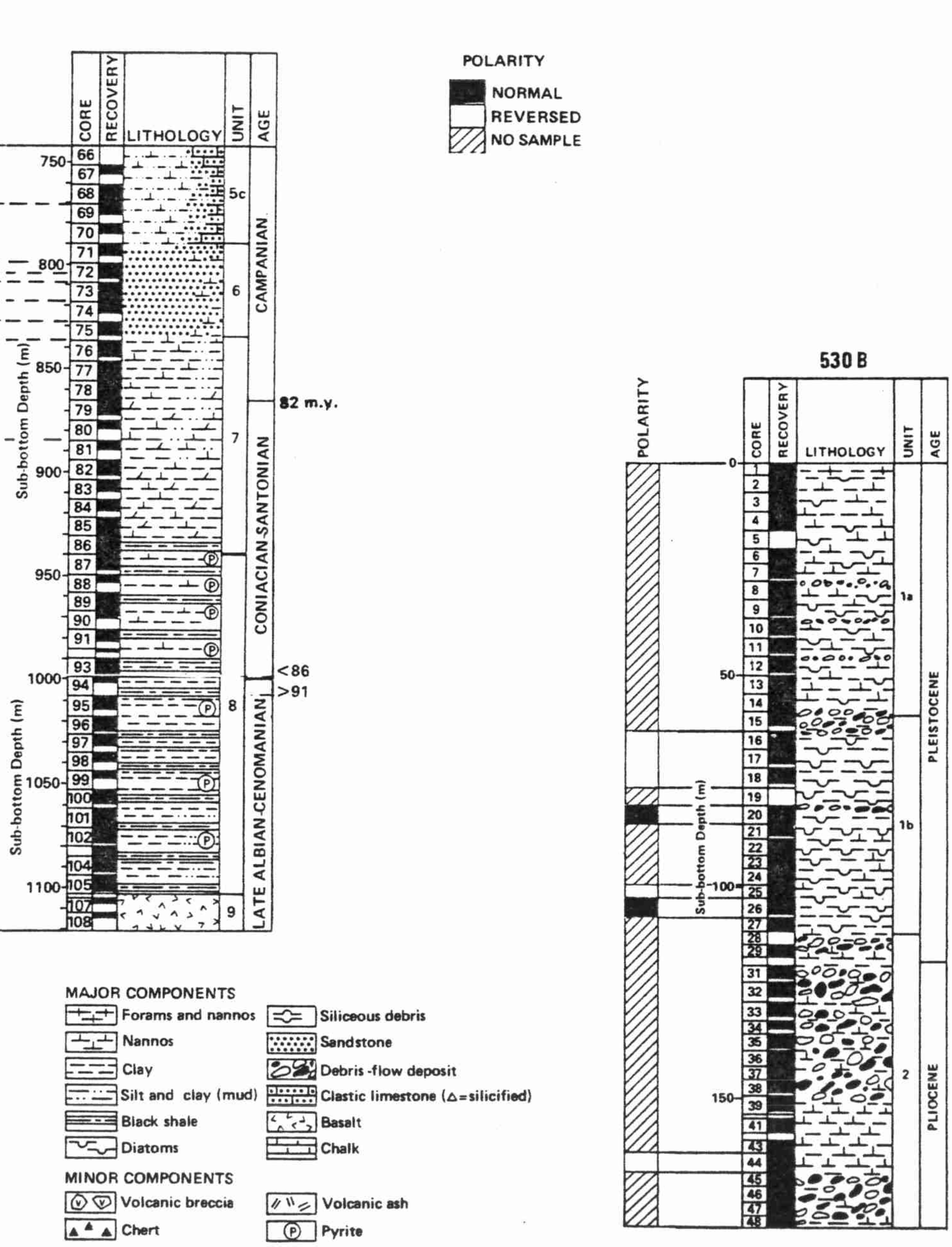




**Figure 2. Lithologic columnar sections for holes drilled at Site 530. Conventional coring below 125 m sub-bottom. Hole 530B, hydraulic piston coring of the upper 180.6 m sub-bottom.**

sandstone in numerous repeated turbidite sequences. The green beds are the result of reduction of iron in the red claystone, usually on either side of a thin silt lamina or layer. The unit is 109 m thick and ranges in age from early Campanian to early Santonian.

In Unit 8, the basal sedimentary unit, the dominant lithologies are red and green claystone with beds of black shale. The greenish-gray and grayish-red claystone beds have some faint horizontal lamination and low-angle ripple cross-lamination, suggesting that they include fine-grained turbidites interbedded with dominant basinal pelagic sediments. The unit is 163 m thick and ranges in age from early Santonian to late Albian.

A total of 260 individual black shale beds were recognized in 20 cores taken within 160 m of stratigraphic section (see Fig. 3). The black shale beds have an average thickness of 4.3 cm (range of 1 to 62 cm), constitute 8.4% of the stratigraphic section recovered, and have an average organic carbon content of 5.7% (range of 1.4% to 18%).

Some of the black shale beds contain very low amplitude ripples as well as faint, fine, horizontal lamination and bioturbation structures. They are commonly fissile; more rarely, they appear to be massive. Bioturbation occurs throughout the sequence, most commonly in the red and green claystone but also in almost 50% of the black shale beds. Burrows are often smaller and more restricted in the black shales, but, nevertheless, suggest that bottom conditions were oxic or never very far from oxic.

Paleontologic evidence indicates that a hiatus representing the Turonian is present within this unit, but it does not have any pronounced physical expression.

Unit 9 is a medium-gray, fine-grained basalt containing veins and vugs filled with calcite; 19 m of basalt were cored before the drilling rate became so slow that the hole had to be terminated. The contact between the basalt and red mudstone of Unit 8 occurs in the core catcher of Core 530A-105. Here, the basalt is light gray with a thin, white, altered glassy layer immediately below the mudstone. White veins and veinlets of calcite extend from the basalt into the overlying reddish mudstone for a distance of ~5 cm. The mudstone appears to be either hydrothermally altered or baked for a distance of about one metre above the contact with basalt.

**Principal Results**

The oldest sedimentary rocks recovered at Site 530 are late Albian-Cenomanian. Extrapolating the previous sedimentation rate, an age of 96 m.y. is suggested. Using this age estimate, and assuming a constant rate of sea-floor spreading for the creation of the oceanic crust older than Anomaly 34 (79 m.y.), an age of 106 to 108 m.y. (that is, early Albian) is predicted for the oldest oceanic crust at the ocean-continent boundary to the east. This supports the hypothesis of a ridge crest jump toward the African margin in latest Aptian, as proposed by Cande and Rabinowitz (1978). This ridge jump occurred just after salt deposition in the northern part of the basin and explains both the lack of salt deposits in the southeastern Angola Basin and the relative eastward shift of the Anomaly 34 lineation with respect to the axis of symmetry of the South Atlantic.

The basal sedimentary sequence, Unit 8, is made up of red, green, and black mudstones, marlstones, and rare limestones (Fig. 3). The interpretation of these interbedded lithologies is complex.

The red mudstones and marlstones make up about 44% of the unit and were deposited in a relatively deep (3.5 km), narrow ocean basin by pelagic, hemipelagic, and turbiditic processes under oxygenated bottom water. The green mudstones and marlstones, constituting about 47% of the unit, are closely associated with the black shales and were deposited in the same manner as the red mudstones. There are two possible interpretations for the green coloration: either it is the result of diagenetic reduction of iron in red muds around layers rich in organic matter, or the result of iron reduction during deposition of sediments in poorly oxygenated bottom waters.

In the first interpretation, the high biological and chemical oxygen demand of the organic carbon-rich (black shale) layers produced reducing conditions in the underlying and overlying sediments for a period of time before oxidizing conditions were re-established. This resulted in black shale "sandwiched" by green in a red-mudstone sequence, or, with closely spaced black shales, in the common sequence of alternating black and green beds. The accompanying migration of iron and sulfate ions toward the organic-rich beds concentrated FeS locally at the black-green boundary. In time, this was converted to the pyrite commonly observed at the contact between a black shale and underlying green mudstone.

In the second interpretation, the green mudstones represent a transition (commonly through a gray, more organic-rich layer) to reducing bottom-water conditions in which organic matter was preserved as black shale.

These two interpretations are not mutually exclusive, and both may have operated. An increase in organic productivity and supply of organic matter to the sediments would place an increased oxygen demand on the water column as well as on the sediments. If the bottom waters were delicately poised at a low oxygen level, an increased oxygen demand could result in anoxic bottom water to help preserve the organic matter. The common interbedding of red, green, and black layers, and the bioturbation of much of the sediment but its absence in parts of the black shales, suggest that there was a delicate balance between oxidizing and reducing conditions in the Angola Basin and sediments at this time.

There are three groups of factors affecting oxygen concentrations that are related to black shale deposition at Site 530:

1. Factors acting to reduce sea-water oxygen content: (a) the relatively small, silled basin restricted circulation and tended toward salinity stratification; (b) relatively warm bottom water contained less oxygen; (c) transgression over low-lying land areas may have transported more terrestrial plant material seaward, and wide shelves may have stimulated production of marine plankton, both factors tending to produce poorly oxygenated shelf waters; (d) increased evaporation over wide shelves produced dense saline waters poor in oxygen which would have spread oxygen-depleted waters and increased stratification; (e) local restricted shelf basins and coastal lagoons or swamps may have been anoxic and provided sinks for organic matter; (f) turbidity currents may have transported warm, saline, oxygen-depleted waters to the basin as well as organic-rich sediments.

2. Factors acting to increase sea-water oxygenation: (a) wind-forced advection of water masses; (b) geothermal heating of the basin; (c) circulation and overturn by saline water and turbidity current movement.

3. Factors affecting oxygen content of sediments: (a) oxygen content of overlying sea water; (b) rate of supply of organic matter, rate of burial, and rate of consumption by aerobic benthic organisms and chemical oxidation.

Black shales were formed in the South Atlantic during two

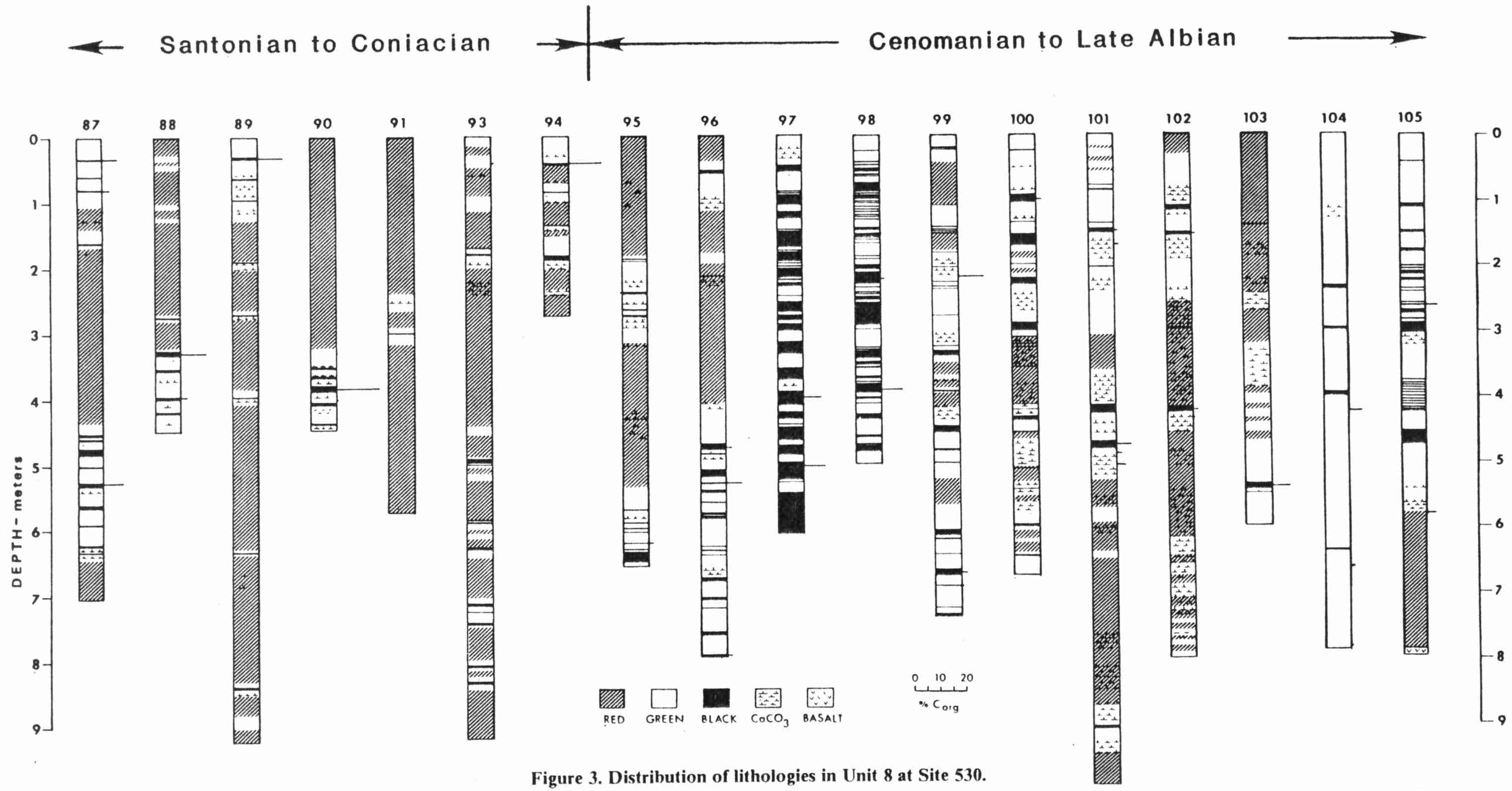



Figure 3. Distribution of lithologies in Unit 8 at Site 530.

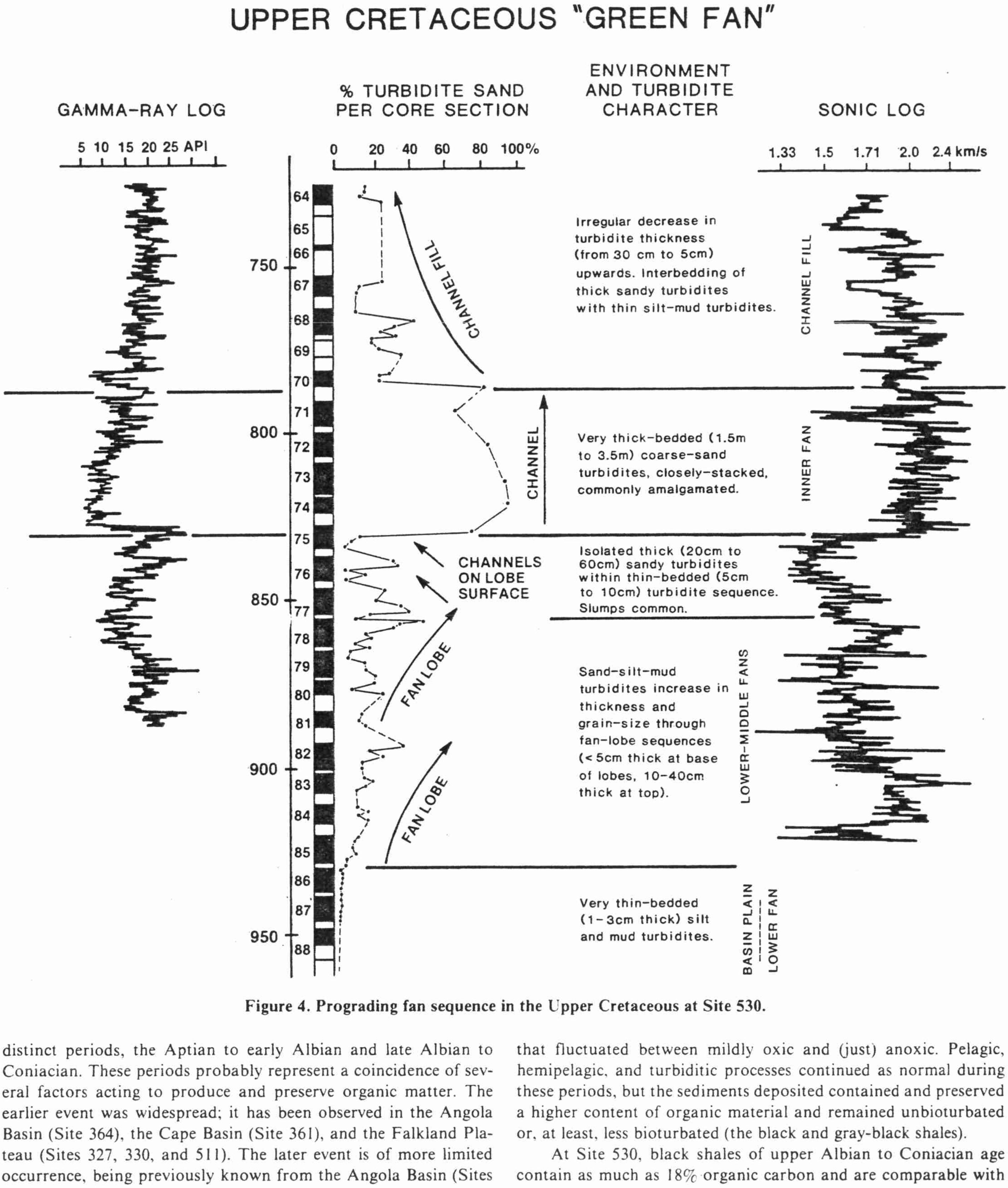



**Figure 4. Prograding fan sequence in the Upper Cretaceous at Site 530.**

distinct periods, the Aptian to early Albian and late Albian to Coniacian. These periods probably represent a coincidence of several factors acting to produce and preserve organic matter. The earlier event was widespread; it has been observed in the Angola Basin (Site 364), the Cape Basin (Site 361), and the Falkland Plateau (Sites 327, 330, and 511). The later event is of more limited occurrence, being previously known from the Angola Basin (Sites 363 and 364) and the northern slope of the Rio Grande Rise (Site 516).

The Angola Basin was sufficiently oxygenated during *most* of the Upper Cretaceous to support an active benthic infauna. There were periods of shorter and longer duration when several of the factors noted above combined to produce bottom-water conditions that fluctuated between mildly oxic and (just) anoxic. Pelagic, hemipelagic, and turbiditic processes continued as normal during these periods, but the sediments deposited contained and preserved a higher content of organic material and remained unbioturbated or, at least, less bioturbated (the black and gray-black shales).

At Site 530, black shales of upper Albian to Coniacian age contain as much as 18% organic carbon and are comparable with those of similar age from Site 364. Shipboard analyses show that the organic matter in the black shales is derived mainly from marine organisms, but a few samples also contain organic matter of terrestrial origin. If shore-based studies corroborate these preliminary findings, then the formation of black shales at Site 530 may be very similar to that at Site 364, where the upper Albian-Coniacian black shales contain organic matter either of marine origin or of mixed marine-terrestrial origins with as much as 8% plant debris. In contrast, the organic matter of the earlier Aptian–Albian black shales at Site 364 was derived wholly from marine sources. All of the organic matter within the black shales is immature, as shown by the low production index, the temperature of the maximum hydrocarbon production during Rock-Eval pyrolysis, and the absence of significant levels of gaseous hydrocarbons formed by diagenetic processes.

As shown in Figure 4, the sediments in Units 8 through 6 comprise a classic progradational submarine fan sequence grading from basinal (Unit 8) and lower-fan deposits (Unit 7), through middle-fan lobe and channel sediments (Unit 7), to thick upper-fan channel sandstones (Unit 6). These were followed by a thinning and fining-upward channel-fill sequence (Unit 5c). The coarse-clastic turbidites consist mostly of shallow-water debris. These different materials, first volcanogenic sand, then siliciclastic sand, and finally carbonate sand, were progressively supplied to Site 530 either by change in sediment type in the same general source area or by contributions from several different sources.

The fact that we commonly observed massive or interlaminated mixtures of siliciclastic and carbonate sands suggests that they were supplied from the same general source area. It is possible that one or more volcanic islands or seamounts with shallow-water platforms may have been present to supply the volcanogenic sand, but the only existing bathymetric evidence for these features is some 200 km to the southwest.

Obtaining a section across the Cretaceous-Tertiary boundary was one of the ancillary objectives of Leg 75. The Cretaceous-Tertiary boundary occurs in Unit 4 and is documented by moderately preserved to well-preserved, common to abundant nannofossils in Core 50, Section 2, at ~593.0 m sub-bottom. They reveal that the boundary, as far as can be judged by calcareous nannoplankton, lies between 14 cm and 53 cm in Core 50, Section 2. Paleontologically, the boundary is not a sharp break between Maestrichtian and Paleocene assemblages, and there may be some interlayering or mixing. Paleomagnetic studies show a shift in polarity at 63 cm, just below the paleontologic boundary; polarity is normal above and reversed below.

The coarse-grained siliciclastic turbidites of the progradational fan sequence in Unit 6 are gradually replaced by coarse-clastic limestone turbidites through Unit 5 so that the top of Unit 5 and all of Unit 4 are dominated by coarse-clastic limestone interbedded with finer-grained chalk and marl. There are several irregular thickening and thinning sequences in Unit 4 that may have been deposited on fan lobes and small channels.

The red and green clays of Unit 3 represent several marked changes in sedimentation. First, the mud turbidites of Unit 3 suggest that from late Oligocene through the late Miocene (30 to 10 m.y.) turbidity currents were still supplying fine-grained background sediment from the African continental margin, although the supply of coarse-clastic debris had stopped. Second, the almost complete lack of carbonate in the muds of Unit 3 indicate that at this time (30 to 10 m.y. ago) the site was below the calcite compensation depth (CCD). Unit 3 is therefore unique in the section recovered at Site 530 in that it is the only one that does not contain carbonate.

The marked increase in carbonate accumulation as nannofossil marl and ooze of Unit 2 beginning in the late Miocene was probably the result of a combination of rapid deepening of the CCD and increased productivity as the Benguela upwelling system came into being. Turbidity currents supplied fine-grained clastics that formed clay-marl-ooze cycles in Unit 2, but most of the sediment that accumulated was pelagic nannofossil debris.

The oldest unequivocal evidence of sediment supplied from the Walvis Ridge is recorded by the debris-flow deposits that began to accumulate in Unit 2 during the late Miocene. The clasts within the debris-flow deposits were derived from approximately contemporaneous sediments on Walvis Ridge. The larger flows can be seen on seismic-reflection profiles to have moved downslope 15 to 20 km. The clay-diatom turbidites were probably also derived from Walvis Ridge, where similar materials of the same age were recovered at Sites 362 and 532.

Maximum diatom productivity occurred during the Pliocene, associated with the maximum extent of upwelling conditions off the coast of southwest Africa, and was accompanied by shoaling of the CCD, as indicated by low to nil concentrations of carbonate.

Nannofossil and foraminifer abundance in the upper part of Unit 1 records deepening of the CCD during the late Pleistocene and Holocene.

The series of late Miocene to Pleistocene calcareous and siliceous biogenic oozes recovered using the hydraulic piston core at Sites 530 contain high concentrations of organic carbon (as much as 6%), although they show evidence of extensive bioturbation. The organic matter is predominantly of marine origin and certainly related to the high productivity of the Benguela upwelling system (see Fig. 5). A calculation of the mass of organic carbon in Unit 8 (Cretaceous) gives a total of 0.37 kg/cm$^2$ for the lower 240 m of the sediment column. The Pleistocene and Pliocene sediments have a mass of >0.40 kg/cm$^2$ in the upper 200 m of sediment. The upper sediments have a porosity of ~60% and the Cretaceous strata of Unit 8 have porosities of ~35%, so that the Pleistocene-Pliocene mass accumulation is actually much greater than the Cretaceous mass accumulation.

Sedimentation at Site 530 in terms of the paleolatitude at which the different deposits accumulated is shown in Figure 6. The most interesting feature is that the turbidites are associated with a paleolatitude within the mid-latitude humid climatic belt. As the site moved into the arid subtropical zone, the sedimentation regime shifted to become predominantly basinal. Thus, it appears that

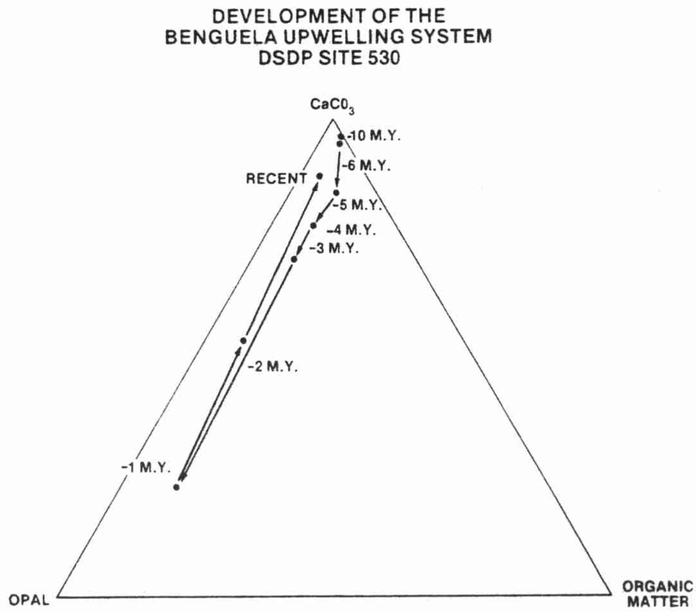



**Figure 5. Development of the Benguela upwelling system as reflected in changing nature of the Miocene to Recent biogenous sediment components at Site 530.**

broad-scale climatic conditions affected the history of continental-margin sedimentation. The discovery of *Inoceramus* in the deep ocean (3,500–4,500 m paleodepth) greatly extends the depth habitat from that described previously from DSDP cores.

## SITE 531

Knowledge of the subsidence history of Walvis Ridge is critical to interpretation of the paleoceanography of the southwest Atlantic. Adjacent parts of the Walvis Ridge and Angola Basin seem to lie within a similar age range, the difference not exceeding 10 m.y. (Goslin and Sibuet, 1975; Detrick and Watts, 1979), and the subsidence rate is expected to be similar to that of oceanic sea floor.

The BGR-36-processed multichannel-seismic profile shows a flat-topped platform at this site. Because this "guyot-like" structure is at a water depth of only 1,300 m, it was anticipated that this feature subsided below sea level more recently than other deeper parts of the ridge; preliminary estimates suggested that it subsided below sea level about 20 m.y. after the formation of the adjacent ocean crust and would provide precise calibration for the ridge subsidence curve.

Two attempts to spud in at this site failed because the bottom was hard. Two cores were attempted. Both recovered a small amount of Pleistocene-Holocene foram ooze, but the second core taken at Site 531A contained a single small rock fragment about 1 cm across.

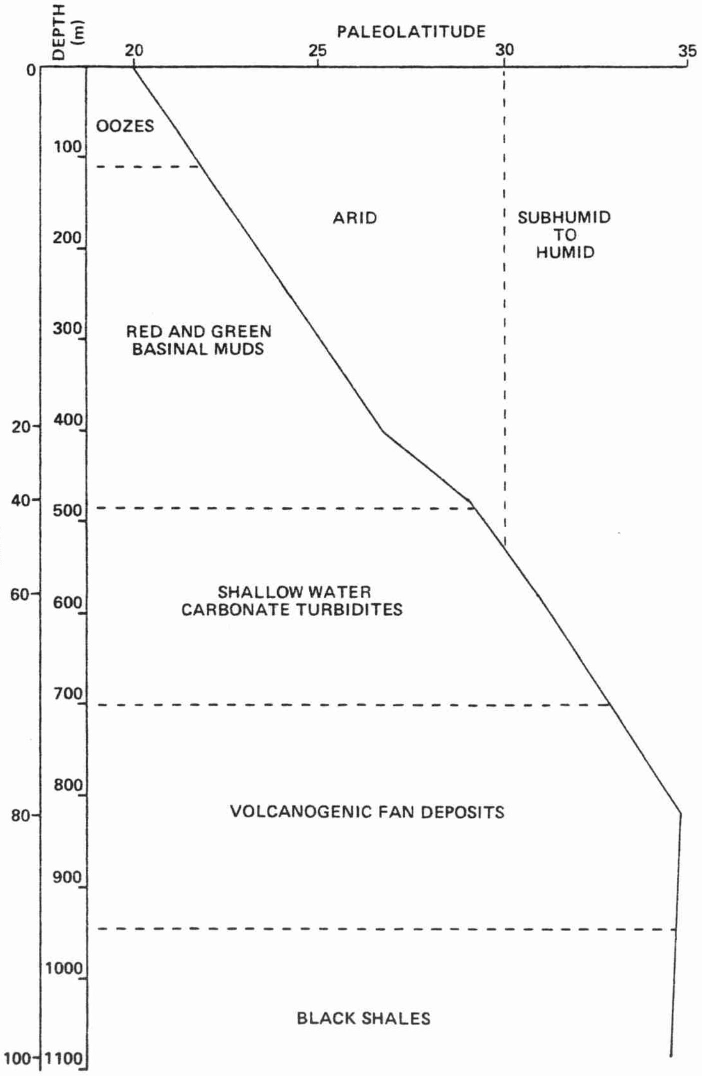



**Figure 6. Paleolatitude of deposition of the major lithologies encountered at Site 530.**

### Lithostratigraphy

The rock fragment consists dominantly of rounded to subrounded coarse-sand sized fragments of volcanic rocks, red coralline algae, molluscs, and possibly coral cemented by calcite. The red coralline algae are predominantly *Archaeolithothamnium* (John L. Wray, 1981, personal commun.), which has a range from Late Jurassic to the present and therefore cannot be used to date the time of subsidence. Coralline algal fragments are approximately 70% of the total. Much of the biogenic material is replaced by cryptocrystalline calcite, although the cellular structure of the red algae is well preserved. The sediment is well sorted, and the rock is grain-supported with sparry calcite cement in the intergrain spaces.

### Principal results

The shallow-water indicators found at this site are considerably better preserved than the recrystallized, rounded grains which had been collected at Site 362 during Leg 40. The virtual absence of younger sediments suggests that at least the edges of the plateau have been swept clean by currents. If the subsidence history is correct, this reef-like accumulation extends the maximum southern limit of southern-hemisphere Cretaceous reefal carbonates plotted by Habicht (1979) by about 4° to 5°. However, *Archaeolithothamnium* may not have been restricted to tropical and subtropical climates.

## SITE 532

After attempting to spud in at Site 531, hydraulic piston coring at a relatively shallow site was deemed the best use of the available time remaining. Operations at Site 530 had yielded the unexpected result that the Pliocene and Pleistocene sediments were rich in diatoms and organic carbon and reflected a Benguela upwelling system that was more active than at present. However, the stratigraphic record at Site 530 has been obscured by turbidite and debris flows, so that details of the history of upwelling were difficult to ascertain.

The upper part of Site 362 was continuously cored by rotary drilling during Leg 40 in 1975, but all of the cores taken above a sub-bottom depth of 200 m were badly disturbed by the drilling processes. The cores were noted, however, to be rich in diatoms, calcareous plankton, and organic carbon (Erdman and Schorno, 1978). It was recognized by the Leg 40 scientists that the sediments were a product of the Benguela upwelling system which started in the Miocene (Bolli, Ryan, and others, 1978; Siesser, 1980). Because this site yielded a section of great interest, it was decided to return to it to take hydraulic piston cores through the upper part of the section, from which only disturbed cores had been available previously.

Site 532 was located on the eastern part of the Walvis Ridge in a trough with relatively thick sediment fill, about 1.1 nautical miles from Site 362. Three parallel sets of hydraulic piston cores were taken at this site. In Hole 532, 61 cores were taken, reaching a sub-bottom depth of 250.8 m. Hole 532A was offset several hundred metres to the southwest, and 47 cores were taken to a sub-bottom depth of 199.6 m for geotechnical studies proposed by the JOIDES Sedimentary Petrology and Physical Properties Panel. The cores from Hole 532A were sealed and only the core-catcher samples were examined aboard ship. Hole 532B was offset slightly, and 74 cores were taken, reaching a sub-bottom depth of 291.3 m. Cores 1–56 in Hole 532B were not opened but were frozen to be used later for organic geochemical studies. The remainder of the cores were studied in the usual manner.

Recovery with the hydraulic piston corer was good to excellent, but in those we opened, the top 50–150 cm of nearly all of the cores in the upper 100 m were badly disturbed. Below 100 m, the disturbance was less common, although parts of cores were gas-cracked.

### Lithostratigraphy

The sediments recovered at Site 532 are calcareous and siliceous, biogenic, open-marine pelagic deposits with variable amounts of terrigenous clay and a high organic-carbon content (see Figs. 7A and 7B). They accumulated at rates between 25 and 60 m/m.y. The variations within the single lithologic unit recognized are as follows: color varies from light olive in the uppermost Pleistocene, becoming generally darker olive in the mid-Pleistocene with individual dark layers increasing in intensity and frequency; the color then becomes lighter into the upper Miocene part of the section. Foraminifers are common in the upper Pleistocene but decrease to generally less than 10% in the lower Pleistocene and older sediments. Nannofossil abundance is generally 20% to 50%, becoming less in the upper Pliocene strata. Diatoms become significant (10%–40%) only in the upper Pliocene. The carbonate content decreases from 60% to 70% in the Pleistocene to 20% to 40% in the upper Pliocene, then increases again into the upper Miocene sediments. Organic-carbon content averages about 3% to 4% in the Pleistocene, increasing to 3% to 6% in the upper Pliocene, then decreasing to 1% to 2% in the upper Miocene strata. The clay content increases with depth, from 10% to 20% in the Pleistocene to 50% to 60% in upper Miocene beds. The salinity, chlorinity, $Ca^{++}$, and $Mg^{++}$ of the interstitial waters decrease with depth; pH and alkalinity increase with depth. Sedimentation rates in the Pleistocene are 40 m/m.y., increasing to 62 m/m.y. in the Pliocene, and decreasing in the latest Miocene to 25 m/m.y.

### Discussion

Our results are in general agreement with those from the drilling during Leg 40, but we recovered 235 m of Pleistocene and Pliocene sediments, as opposed to a total thickness of 169 m for those sediments reported at Site 362. This difference in thickness is based on paleontologic evidence and is not apparent on the seismic-reflection profiles which indicate horizontal layering over the entire area.

The changes in sedimentation at Site 532 can be interpreted in terms of (1) biotic productivity, (2) terrigenous input, and (3) early diagenesis within the sediment. All of these factors are related to changes in the Benguela upwelling system and the underlying causative climatic changes.

As noted by Siesser (1980), the upwelling system began in the late Miocene. Its development becomes apparent in a plot of the three biogenic components, shown in Figure 8. There was an increase in productivity from the late Miocene to a maximum in the late Pliocene and a slight subsequent decrease. This is clearly

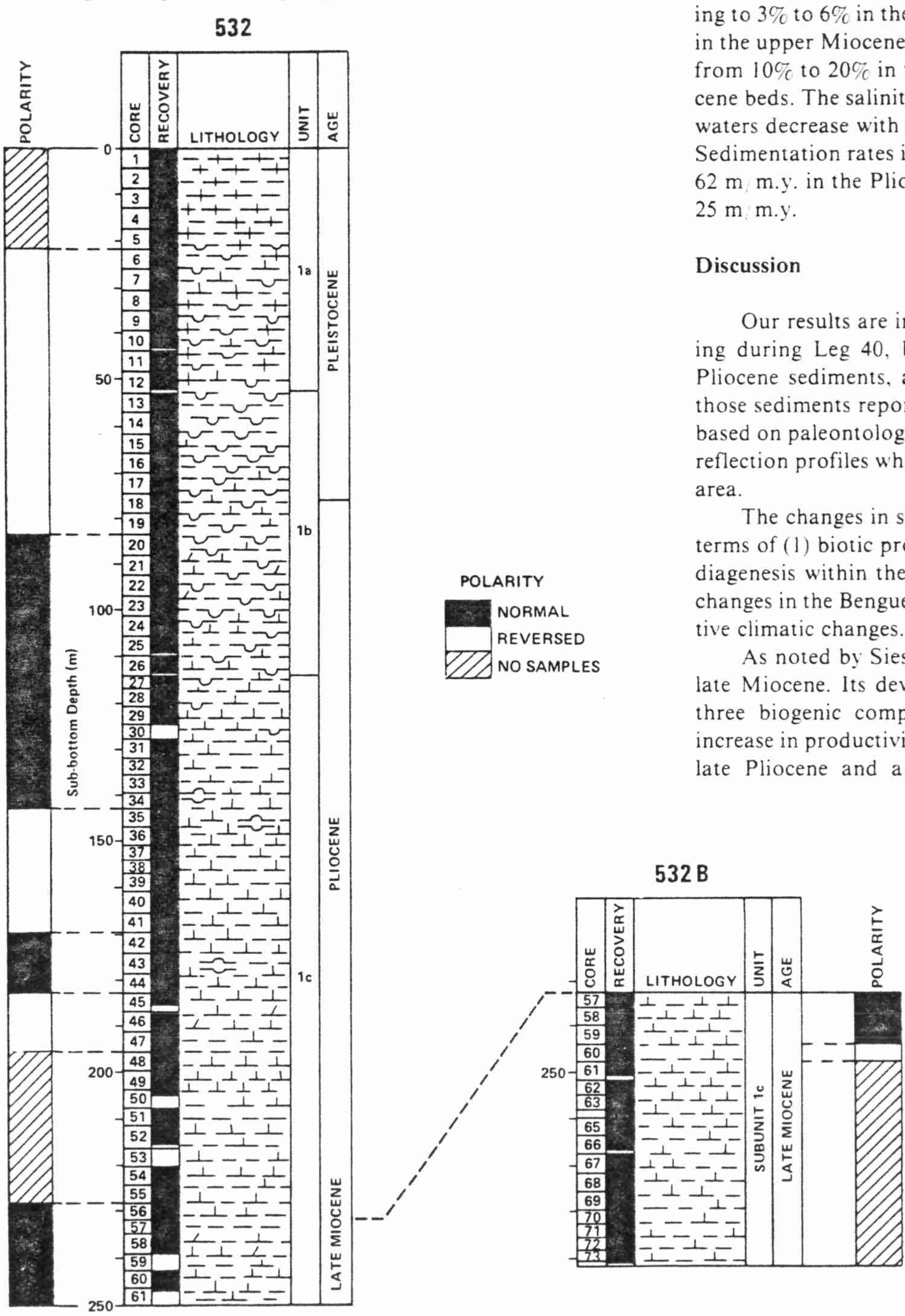



**Figure 7A. Lithologic columnar sections for holes drilled and cored by the hydraulic piston corer at Site 532.**

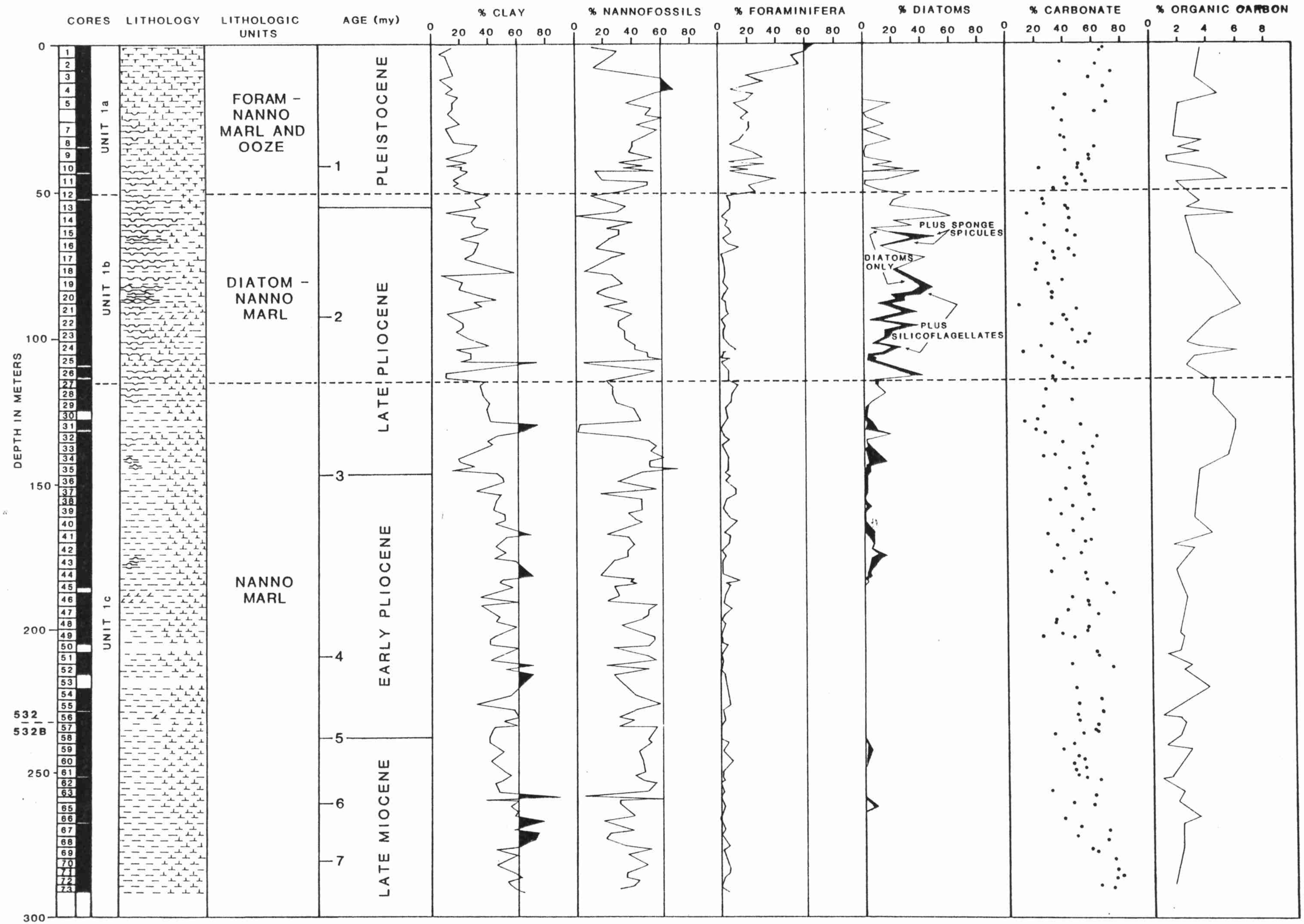



Figure 7B. Composite lithologic columnar section of cores from Holes 532 and 532B; lithologic units, age, and abundance of the major sediment components.

reflected by the sediment color, organic carbon content, and siliceous biogenic component, but the total accumulation rate for biogenic sediment increased by only about 25%. The increase in pH and alkalinity with depth reflects sulfate reduction in the sediments accumulating beneath the high-productivity area. The increase in productivity may be related to climatic cooling through the Pliocene, producing higher wind stress and intensification of upwelling, and to the northward drift of Site 532, in a region more prone to upwelling.

The drastic decrease in quantity of planktonic foraminifera in the older Pleistocene and the occurrence of broken tests through the older sequence are partly attributable to selective carbonate dissolution but may also reflect exclusion of the planktonic foraminifera from the upwelling area. The carbonate content of the sediment remains high and generally increases with depth through the Pliocene. Some recrystallization of nannofossils was observed in the upper Miocene sediments. Authigenic dolomite was noted in some samples below 100 m, while apatite or carbonate-apatite and pyrite are present throughout, suggesting that the sediments beneath this upwelling system may be a significant sink for phosphorous. The formation of these minerals is in part correlated with the loss of $Mg^{++}$ and $Ca^{++}$ cations from the interstitial water.

Alterations of light and dark sediment over a distance of 1–3 m occur throughout the section but are especially obvious in the Pliocene. These light-dark cycles occurred over an estimated average time span of 30,000–50,000 yr. The dark layers are richer in organic carbon, clay, and pyrite. One explanation for this cyclicity might be periodic increases in productivity, leading to relative increases of planktonic species without preservable skeletons and their rapid sedimentation as fecal pellets and eventual preservation as the darker sediment layers. The increased nonbiogenic component of the dark layers may be, in part, due to an increased terrestrial (wind-borne) input of clay-sized material. There is little evidence that the light-dark cycles were caused by carbonate dissolution within the sediment.

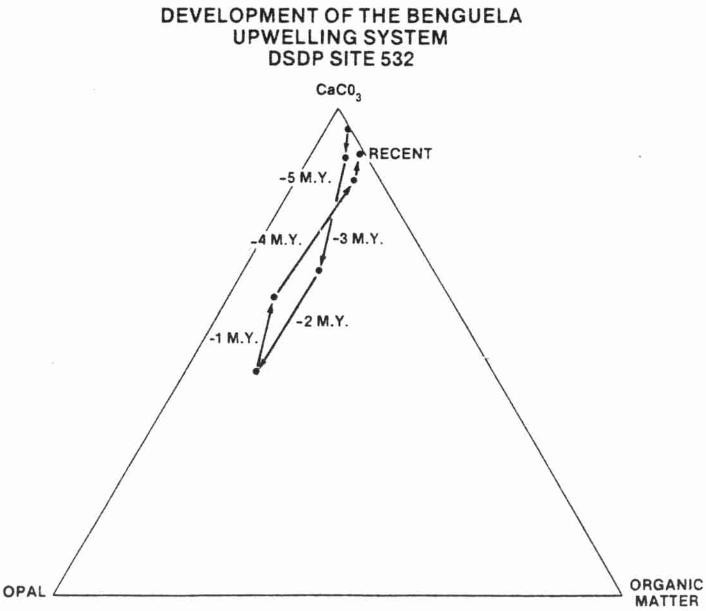



**Figure 8. Development of the Benguela upwelling system as reflected in changing nature of the Miocene to Recent biogenous sediment components at Site 532.**

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