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The Walvis Ridge transect, Deep Sea Drilling Project Leg 74: The geologic evolution of an oceanic plateau in the south Atlantic Ocean

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ABSTRACT

Five sites were drilled along a transect of the Walvis Ridge. The basement rocks range in age from 69 to 71 m.y., and the deeper sites are slightly younger, in agreement with the sea-floor–spreading magnetic lineations. Geophysical and petrological evidence indicates that the Walvis Ridge was formed at a mid-ocean ridge at anomalously shallow elevations. The basement complex, associated with the relatively smooth acoustic basement in the area, consists of pillowed basalt and massive flows alternating with nannofossil chalk and limestone that contain a significant volcanogenic component. Basalts are quartz tholeiites at the ridge crest and olivine tholeiites downslope. The sediment sections are dominated by carbonate oozes and chalks with volcanogenic material common in the lower parts of the sediment columns. The volcanogenic sediments probably were derived from sources on the Walvis Ridge.

Paleodepth estimates based on the benthic fauna are consistent with a normal crustal-cooling rate of subsidence of the Walvis Ridge. The shoalest site in the transect sank below sea level in the late Paleocene, and benthic fauna suggest a rapid sea-level lowering in the mid-Oligocene.

Average accumulation rates during the Cenozoic indicate three peaks in the rate of supply of carbonate to the sea floor, that is, early Pliocene, late middle Miocene, and late Paleocene to early Eocene. Carbonate accumulation rates for the rest of the Cenozoic averaged 1 $g/cm^2/10^3$ yr. Dissolution had a marked effect on sediment accumulation in the deeper sites, particularly during the late Miocene, Oligocene, and middle to late Eocene. Changes in the rates of accumulation as a function of depth demonstrate that the upper part of the water column had a greater degree of undersaturation with respect to carbonate during times of high productivity. Even when the calcium carbonate compensation depth (CCD) was below 4,400 m, a significant amount of carbonate was dissolved at the shallower sites.

The flora and fauna of the Walvis Ridge are temperate in nature. Warmer-water faunas are found in the uppermost Maastrichtian and lower Eocene sediments, with cooler-water faunas present in the lower Paleocene, Oligocene, and middle Miocene. The boreal elements of the lower Pliocene are replaced by more temperate forms in the middle Pliocene.

The Cretaceous-Tertiary boundary was recovered in four sites drilled, with the sediments containing well-preserved nannofossils but poorly preserved foraminifera.

INTRODUCTION

The drilling plan for Leg 74 of the Deep Sea Drilling Project was designed to address three main scientific problems: (1) the his-

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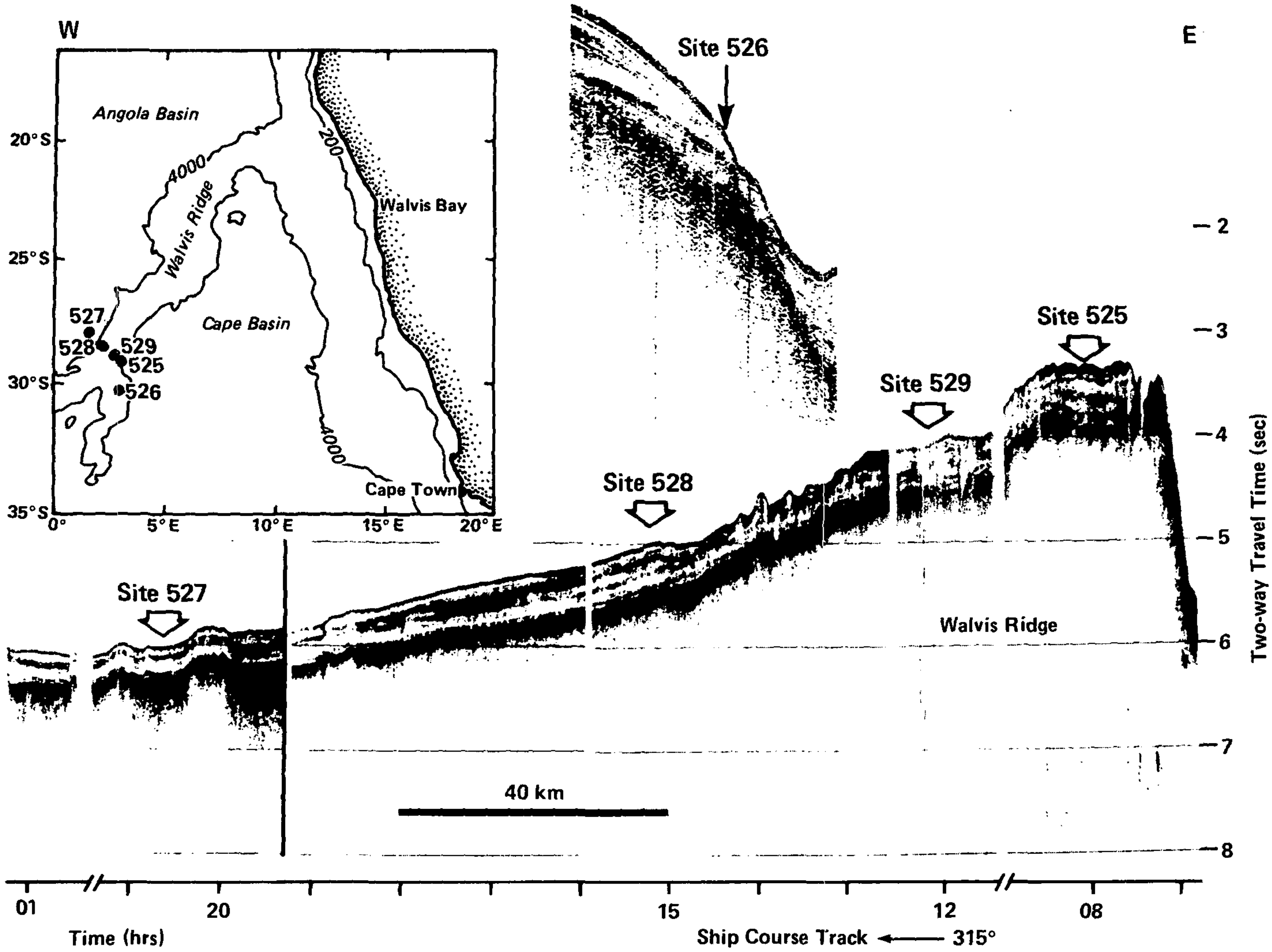


Figure 1. Site localities and index map.

tory of the deep-water circulation in the southeastern Atlantic, (2) the nature and geologic evolution of the Walvis Ridge, and (3) the biostratigraphy and magnetic stratigraphy of this region. In order to study these problems, five sites were drilled on the Walvis Ridge in June and July 1980 (Fig. 1; Table 1), extending from its crest (near 1,000-m water depth) down its northwestern flank into the Angola Basin to a depth of 4,400 m.

The sites are relatively closely spaced, encompassing a northwest-southeast transect of ~230 km. They span a water-depth range of more than 3 km and receive approximately the same rain of pelagic debris. Any site-to-site differences in average accumulation rates for a given interval of time should be a result of two main processes: (1) differences in dissolution rate as a function of depth, and (2) differences in winnowing and erosion, which may also vary as a function of depth and are likely to be important near large topographic features. Detailed stratigraphic studies and the analysis of the accumulation rates for different sized components aid in distinguishing these two processes.

The classical marine biostratigraphies have been largely established in tropical sequences (Bolli, 1957; Blow, 1969; Berggren, 1972). The transect drilled on the Walvis Ridge should help to establish biostratigraphies in more temperate latitudes. The usefulness of this sediment is enhanced by the recovery of several sections within a relatively small geographic area and by the use of the Hydraulic Piston Corer (HPC) in three of the five sites. The HPC is capable of recovering relatively undisturbed sedimentary sections and thus provides the opportunity for detailed studies of biostratigraphy, paleomagnetism, physical properties, and other biological and geological parameters. Complete coring of several sites within a small area assures nearly complete recovery of the biostratigraphic sequence and optimal preservation of both the older parts of the section (in deeper sites with less overburden and diagenesis) and the younger parts of the section (in shoaler sites with less dissolution).

The study of the evolution of the Walvis Ridge is also aided by this transect of sites. First, it allows us to date the age and subsidence history of the ridge. Second, the basement samples from this transect allow us to study the magnetic character, petrology, and chemical composition of the crustal rocks as well as the mode of emplacement of the basement complex.

OCEANOGRAPHIC SETTING

All sites lie beneath the generally northward-flowing surface currents in the eastern part of the central subtropical gyre and are ~800 km off the coast of Africa, well outside the main flow of the eastern boundary current (Benguela Current) and the associated regions of high productivity. With the possible exception of storm-induced

TABLE 1. LEG 74 CORING SUMMARY

Hole	Latitude	Longitude	Water depth*	Maximum penetration	No. of core	Metres cored	Metres recovered	Recovery (%)
525	29°04.24'S	02°59.12'E	2,467 m	3.6 m	1	3.6	3.6	100
525A	29°04.24'S	02°59.12'E	2,467 m	678.1 m	63	555.1	406.7	73
525B	29°04.24'S	02°59.12'E	2,467 m	285.6 m	53	227.0	181.7	80
526	30°07.36'S	03°08.28'E	1,054 m	6.3 m	2	6.3	3.6	57
526A	30°07.36'S	03°08.28'E	1,054 m	228.8 m	46	200.8	206.6	100+
526B	30°07.36'S	03°08.28'E	1,054 m	28.3 m	5	22.0	13.5	61
526C	30°07.36'S	03°08.28'E	1,054 m	356.0 m	21	185.0	70.9	38
527	28°02.49'S	01°45.80'E	4,428 m	384.5 m	44	384.5	243.9	63
528	28°31.49'S	02°19.44'E	3,800 m	555.0 m	47	441.0	272.8	62
528A	28°31.16'S	02°18.97'E	3,815 m	130.5 m	30	130.5	116.5	89
529	28°55.83'S	02°46.08'E	3,035 m	417.0 m	44	417.0	309.7	74
					356	2,572.8	1,829.5	71

*Water depths from sea level.

currents, near-surface conditions are rather uniform over the study area and are assumed to have remained so in the past. Even if surface-current patterns changed significantly in the past, at any given time all sites within this relatively small study area probably received a nearly uniform supply of biogenic and detrital material.

All sites are above the 5-km-deep calcium carbonate lysocline, the depth of rapid increase in dissolution rate, in this region. Only Sites 527 and 528 lie near the level of "perceptible dissolution" (R_0 level of Berger, 1977) or the calcite-saturation level of Takahashi (1975), both of which are throught to be near 4 km in the southeastern Atlantic. The shallowest site (526, at 1,054 m) lies within the depth interval presently occupied by Antarctic Intermediate Waters (AAIW). The remaining deeper sites are located at depths ranging from ~2,500 to 4,400 m (Table 1). They are well within the depth interval occupied by North Atlantic Deep Water (NADW), which now dominates the deep and bottom waters of the Angola Basin. The Walvis Ridge, together with the Mid-Atlantic Ridge, forms an effective topographic barrier that largely isolates the Angola Basin from the strong dissolution effects of chemically "older" (higher in dissolved CO_2 and nutrients) Antarctic Bottom Water (AABW) to the south and west. Only a small amount of AABW enters the Angola Basin through the two deepest passages, the Romanche Fracture Zone located near the equator (Wust, 1936) and the Walvis Passage located near the southwestern end (36°S, 7°W) of the Walvis Ridge (Connary and Ewing, 1974). Geologic evidence from previous Deep Sea Drilling Project legs (Maxwell and others, 1970; Bolli and others, 1978; K. J. Hsü and J. L. La Brecque, unpub. data) suggest that the chemical character of the deep and bottom water of the Angola Basin has changed markedly through the Cenozoic.

GEOLOGIC SETTING

The Walvis Ridge consists of offset north-northwest–trending crustal blocks connected by east-northeast–trending blocks. Together these segments form a roughly linear ridge that extends to the northeast from the Mid-Atlantic Ridge and joins the continental margin of Africa near 20°S lat. Within the area of study (Figs. 1 and 2), structural blocks tend to steeply slope toward the Cape Basin and slope more gradually northwestward toward the Angola Basin.

Until recently, it was uncertain whether or not the Walvis Ridge was an oceanic crustal feature, or a fragment of continental crust that was separated from the main continental blocks during the early phases of rifting in the South Atlantic. Seismological and gravity studies indicate that the average crustal thickness beneath the ridge is 12 to 15 km and that the seismic character of the crust is consistent with an oceanic origin (Chave, 1979; Detrick and Watts, 1979; Goslin and Sibuet, 1975). Previous investigations suggested that part of the Walvis Ridge may be a manifestation of an oceanic hot spot (Morgan, 1971, 1972; Wilson, 1963; Burke and Wilson, 1976). Other investigations have shown that ridge-crest migrations have played an important role in the evolution of this part of the South Atlantic Ocean (Rabinowitz and La Brecque, 1979). Magnetic data from a recent geophysical survey of the study area (Rabinowitz and Simpson, 1979) are interpreted as magnetic anomaly 32 (lower Maastrichtian) on the crest of the Walvis Ridge, with younger anomalies extending to the west into the Angola Basin (see Fig. 2). These results lend support to the idea that the Walvis Ridge was formed at a mid-ocean ridge by sea-floor–spreading processes.

Site 526, the shoalest site, is located near the crest of what appears to be a separate structural block. It lies to the south of the block on which the remaining four sites in the transect were drilled (Figs. 1 and 2). Site 525 is located near the crest of the more northern block, in an area having nearly 600 m of sediment. Site 529 is the next deeper site and lies on the eastern flank of a valley that forms a saddle in the ridge. Sites 528 and 527 are in progressively deeper waters and have somewhat thinner sedimentary sections.

Acoustic basement in the study area is comparatively smooth; pronounced basement highs are found most commonly in the crestal regions. There appear to be at least three sub-bottom acoustic reflectors on seismic profiles that define four sedimentary intervals that can be traced through the area. The section beneath the deepest sediment reflector thins downslope and nearly merges with the basement reflector in the area of Site 527 (Fig. 1). The next shoaler interval appears to be of approximately constant thickness throughout the transect, whereas the one above that (third from the bottom appears to pinch out between Sites 528 and 527. The shoalest interval is dissected between Sites 529 and 528 and thins between Sites 528 and 527. Evidence of erosion and slumping in the study area is seen in the reflection records taken near the edges of the crestal region and near the valley to the west of Sites 525 and 529.

Sediments of the study area are composed mainly of calcareous oozes (>90% $CaCO_3$). On account of the predominance of NADW in most of the Angola Basin, the

Figure 2. Bathymetry of Walvis Ridge. Tracklines shown are those of R/V *Thomas B. Davies*.

calcite compensation depth now lies below 5,500 m (Berger and Winterer, 1974). The noncarbonate fraction is dominated by clay with very little or no biogenic opal.

DRILLING RESULTS

Site Summaries

In the following paragraphs, the sediment and basement lithologies are summarized in order of depth of site along the transect (shallow to deep). The complete details of the cores recovered, sediment classification, physical properties, and chemical and analytical techniques used can be found in the Leg 74 Initial Core Description obtainable from the curator of the Deep Sea Drilling Project.

Site 526, on crust of anomaly 31–32 age (mid-Maastrichtian to upper Campanian), is the shallowest site drilled on the Walvis Ridge transect which had the primary objective of recovering a relatively complete and well-preserved Neogene and upper Paleocene calcareous sedimentary section (Fig. 3). The site was piston-cored to a sub-bottom depth of 229 m (Holes 526, 526A, and 526B) with a recovery rate of 98%. We rotary-cored to 356 m sub-bottom (Hole 526C), and the recovery rate averaged 38% before the hole was terminated because we encountered a thick, poorly lithified sandstone formation that created unstable hole conditions.

Five major lithologic units (Fig. 3) are observed:

Unit I. From the mud line (Holocene) to about 130 m sub-bottom (lower-Miocene)

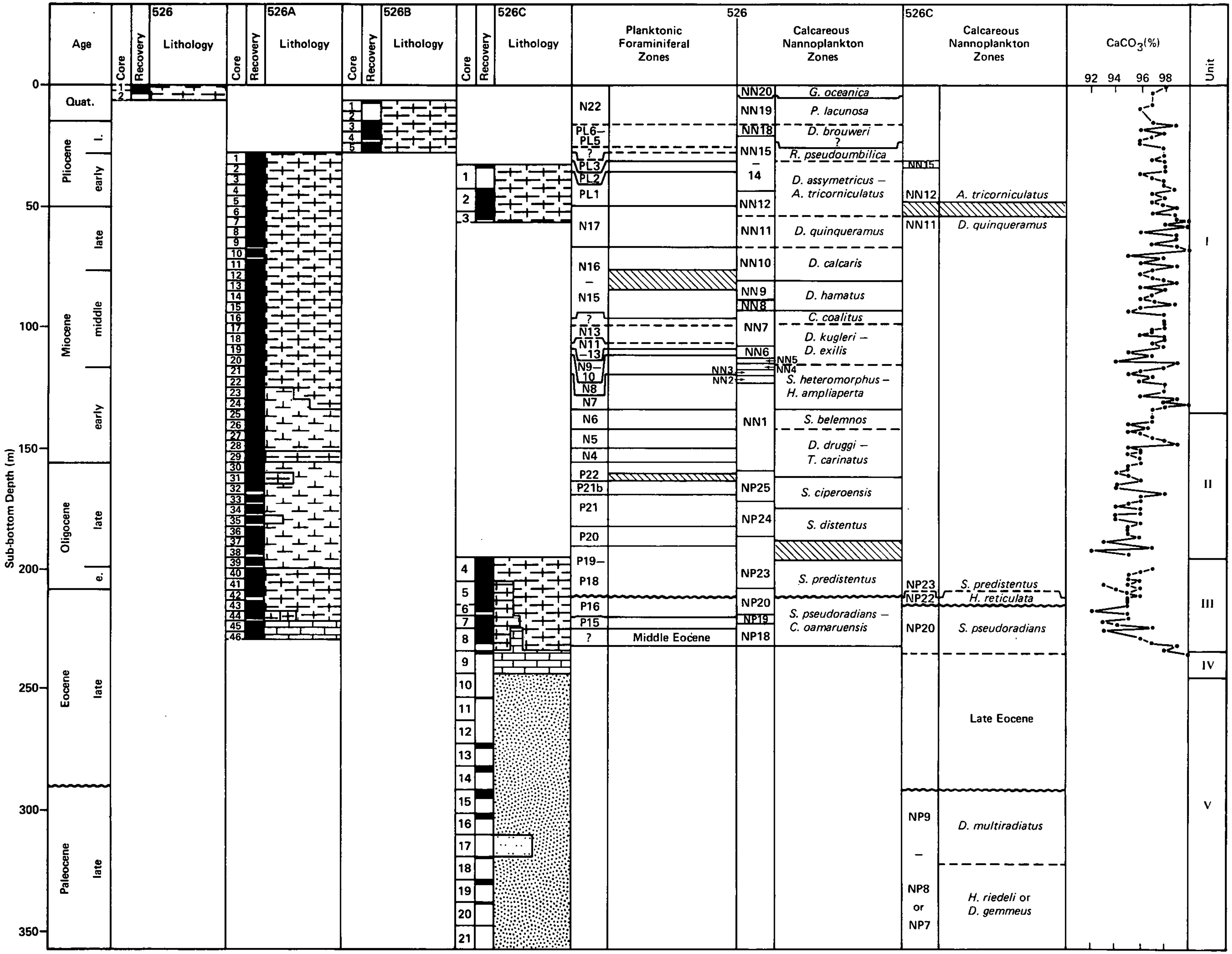


Figure 3. Site 526 stratigraphic summary.

consists of a very homogeneous white foraminifera-nannofossil ooze. Bioturbation is common. Carbonate content is ~97%.

Unit II. From 130 m to about 195 m sub-bottom (lower Oligocene) is a homogeneous very pale orange to pinkish-gray nannofossil ooze with minor chalk layers. Bioturbation is slight. Carbonate content is ~95%.

Unit III. From 195 m to about 225 m sub-bottom (upper Eocene) is a homogeneous pinkish-gray foraminiferal-nannofossil ooze. Biogenic sedimentary structures are not observed. Carbonate content is ~95%.

Unit IV. From 225 to 242 m (upper Eocene) is a thin, white, rubbly limestone layer containing oncoliths and large oyster shells. The limestone rubble is graded and probably represents a channel fill.

Unit V. From about 242 to 356 m (upper Paleocene) sub-bottom is a poorly lithified calcareous sandstone with debris of bryozoans and shell fragments of lamellibranchs and echinoids, indicating very shallow water conditions. Acoustic volcanic basement was not penetrated at this site.

Site 525, on crust of magnetic anomaly 32 age (lower Maastrichtian–upper Campanian), is located on a broad, relatively flat crest of a north-northwest–south-southeast-trending block of the Walvis Ridge. Three holes (Fig. 4) were drilled that give a complete section from the sea floor to the top of a basement complex at 574 m sub-bottom. An additional 103 m was drilled into the basement complex, and total penetration was 677 m.

Four major sedimentary lithologic units are observed:

Unit I. Consists of a very homogeneous nannofossil and foraminifera-nannofossil ooze. The base coincides with a color change and major hiatus between upper Oligocene and middle Eocene at 270 m sub-bottom.

Unit II. Consists of nannofossil and foraminifera-nannofossil oozes and chalks that terminate in the lower Paleocene at about 445 m sub-bottom. Chert fragments were found near the base of Unit II. Carbonate content in Units I and II is generally greater than 90%.

Unit III. Sediments extend from the lower Paleocene to the basement complex at 574 m sub-bottom and consist of a cyclical pattern of nannofossil marly chalks and siltstones-sandstones of turbidite and/or slump origin. Included in this unit is the Cretaceous-Tertiary boundary at 452 m sub-bottom. The older sediments belong in the upper Campanian. The carbonate content of this unit is generally less than 50%. Beautifully preserved biogenic sedimentary structures are present throughout the section. At the base of Unit III and overlying the basement complex is a 6-m-thick, spectacular example of a turbidite sequence. The lithologic rock types from top to bottom in the turbidite are (1) coarse-grained, limestone-cemented conglomerates with volcanogenic intraclasts, (2) coarse- to fine-grained sandstones, and (3) siltstones and calcareous mudstones.

Unit IV. Consists of 0.2- to 2.0-m sections of bioturbated marly limestones and volcanogenic sediments interlayered within the basalt in the acoustic basement herein called the basement complex.

We drilled 103 m into the basement complex consisting of basalt with interlayered sediment (Unit IV above). The upper ~20 m is a green-gray, highly altered, vesicular, aphyric basalt. The remainder of the basalts are gray to black, moderately altered, vesicular, predominantly aphyric flows and pillows with glassy margins and numerous calcite veins. Most of the large vesicles are filled with calcite and minor amounts of pyrite. The groundmass has a subophitic texture consisting of intergrown plagioclase and clinopyroxene. The biostratigraphy and shipboard paleomagnetic results are consistent with crustal formation at the time of magnetic anomaly 32 (for example, Campanian).

Site 529, on crust of magnetic anomaly 31–32 age (mid-Maastrichtian–upper Campanian), is located near the upper part of the slope on the Walvis Ridge transect, and its primary objective was to sample complete well-preserved sections missed at other sites of the transect. The site was continuously cored to a sub-bottom depth of 417.0 m. The recovery rate was 74%.

Three major sedimentary lithologic units (Fig. 5) are observed:

Unit I. Extends from the mud line to 160 m sub-bottom (lower Oligocene) and consists of a very homogeneous white to pinkish-gray foraminifer-nannofossil ooze. Carbonate content is 95%. A hiatus is observed from lower Pliocene to middle Miocene and most probably within the middle Miocene. Slump structures occur in the lower Pleistocene, in the upper part of the lower Miocene, and in the middle Oligocene.

Unit II. Extends from 160 to about 284 m sub-bottom (upper Paleocene) and consists of pink nannofossil ooze and chalk, with relative amounts of chalk increasing with depth. Carbonate content is near 90%. Minor chert layers are observed in the bottom one-half of the unit.

Unit III. Extends from 284 to 417 m (bottom of hole–upper Maastrichtian) and consists of light to olive-gray foraminifera-nannofossil chalks. Preservation of biogenic sedimentary structures is excellent. Carbonate content is near 85%. Chert layers occur in the upper one-half of the unit. A large-scale slump deposit is present in the upper Paleocene. Other small-scale slumps are also observed, one of which is just above the Cretaceous-Tertiary boundary. Volcaniclastic sediments are abundant in the lower part of the unit. The basement complex was not reached.

Site 528, on crust of an age between magnetic anomalies 31 and 32 (mid-Maastrichtian to upper Campanian), is located midway up the western flank of the Walvis Ridge transect. Two holes were drilled that give a complete section from the sea floor to the top of a basement complex at 474 m sub-bottom. An additional 80 m was drilled into the basement complex. A good sonic velocity log was obtained in the basement hole.

Four sedimentary lithologic units (Fig. 6) are present:

Unit I. From the sea floor to about 160 m sub-bottom (lower Miocene–upper Oligocene) consists of dominantly white nannofossil and foraminifera-nannofossil oozes. Calcium carbonate is 90%.

Unit II. From ~160 m sub-bottom to 383 m sub-bottom (lower Paleocene) consists of pinkish-gray nannofossil oozes and chalks; chalks increase at depth. Chert fragments occur in the lower one-half of the unit. Calcium carbonate content is 85% to 90%.

Unit III. From 383 m sub-bottom (lower Paleocene, near the Cretaceous-Tertiary boundary) to the basement complex at 474 m sub-bottom consists of alternating sedimentary patterns of light gray to reddish-brown nannofossil chalks and greenish-gray volcanogenic sandstones and mudstones. Turbidites are present near the base of the unit. Carbonate content varies from 30% to 90%.

Unit IV. Consists of approximately 0.5- to 5.0-m sections of nannofossil chalks, calcareous mudstone, and volcanogenic sediments interbedded within the basement complex. The oldest nannofossils obtained in the sediments both above and within the basement complex are from the *A. cymbiformis* zone (Maastrichtian).

We drilled 80 m into the basement complex. Seven cooling units, ranging in thickness from 3 to 17 m, were defined, each separated by sediment as described above in Unit IV. The seven units are of two basic types. The first is a fine- to medium-grained, slightly to moderately altered, highly plagioclase, phyric basalt with sparse clinopyroxene and olivine phenocrysts. The second is

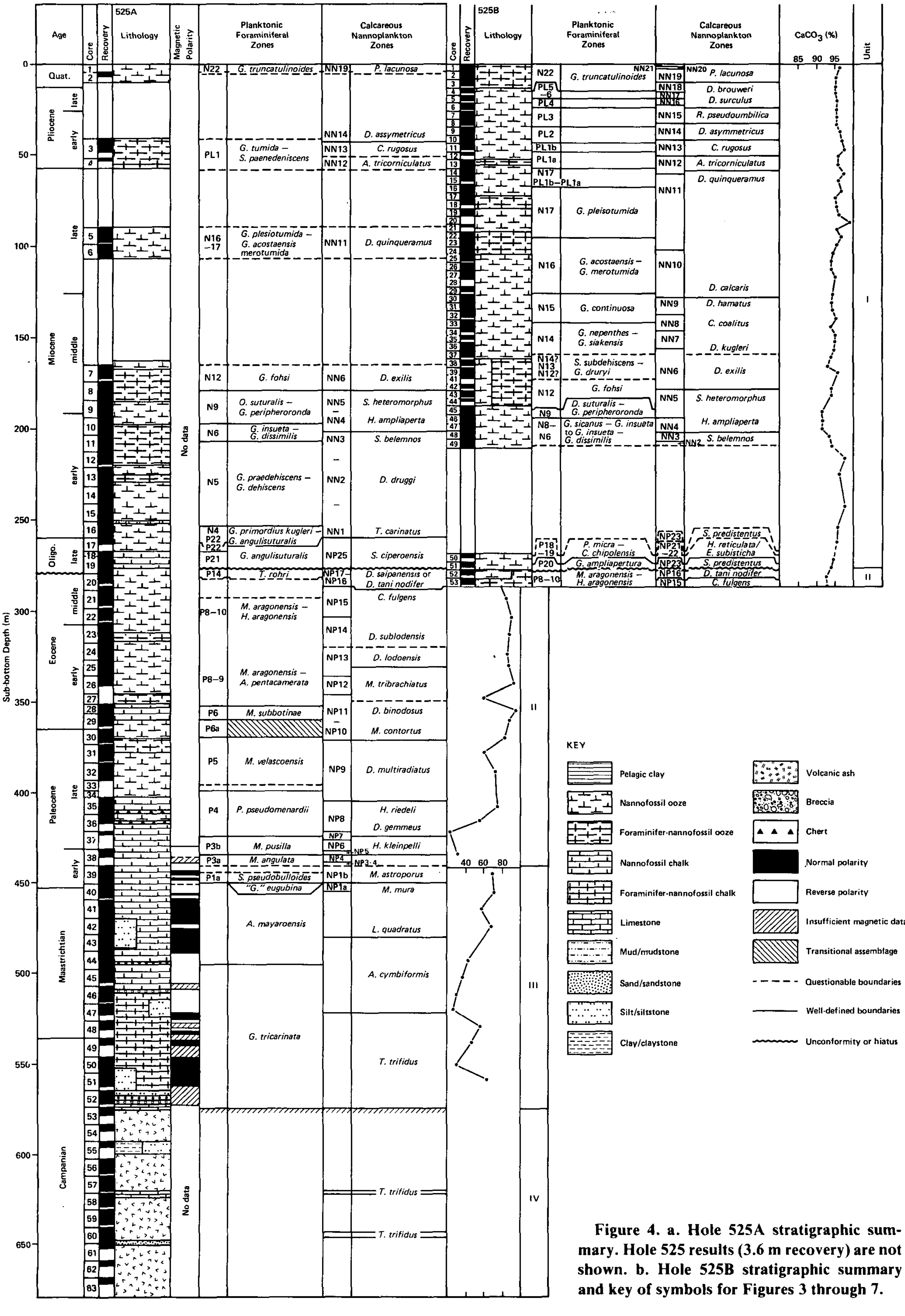


Figure 4. a. Hole 525A stratigraphic summary. Hole 525 results (3.6 m recovery) are not shown. b. Hole 525B stratigraphic summary and key of symbols for Figures 3 through 7.

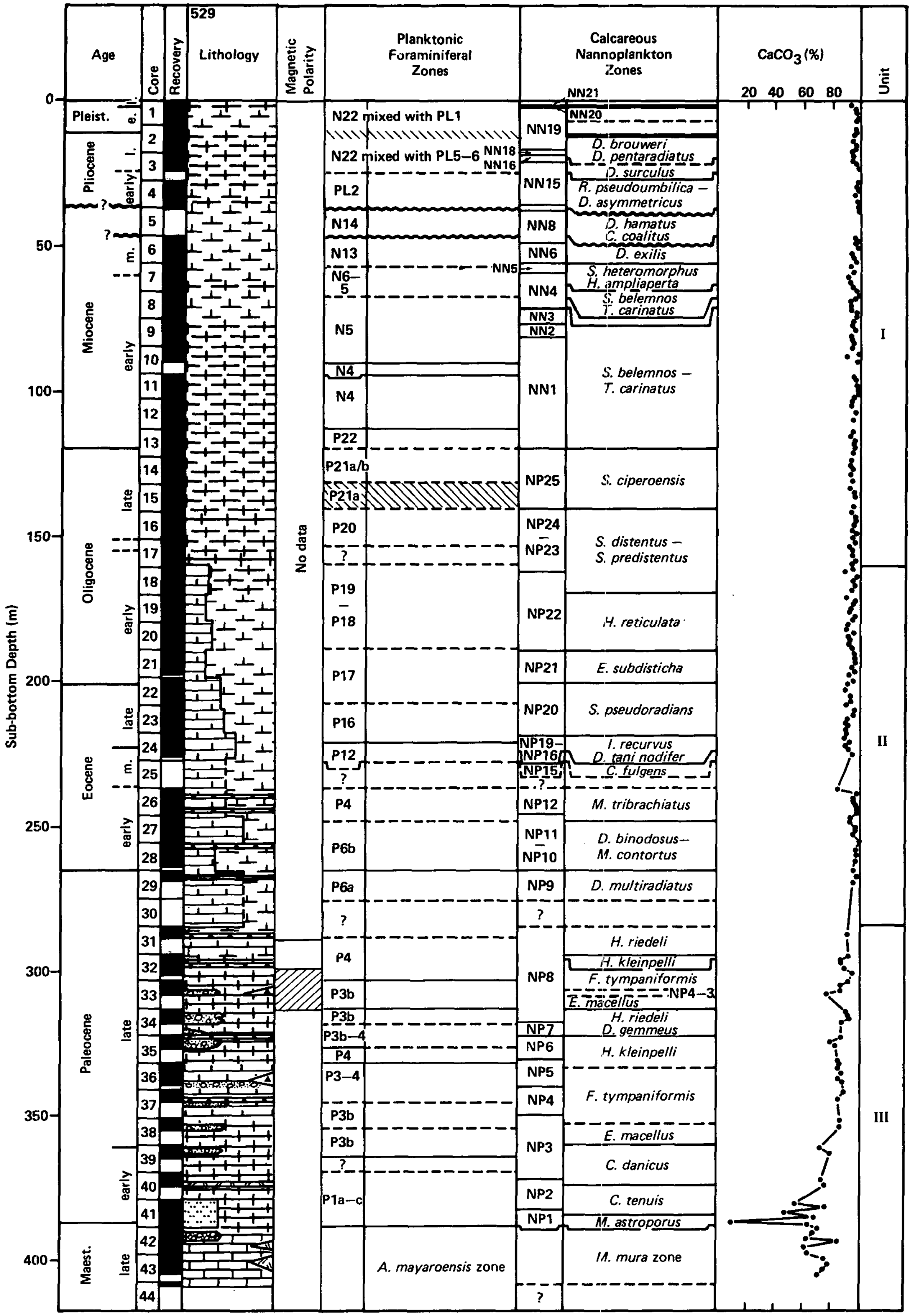


Figure 5. Site 529 stratigraphic summary.

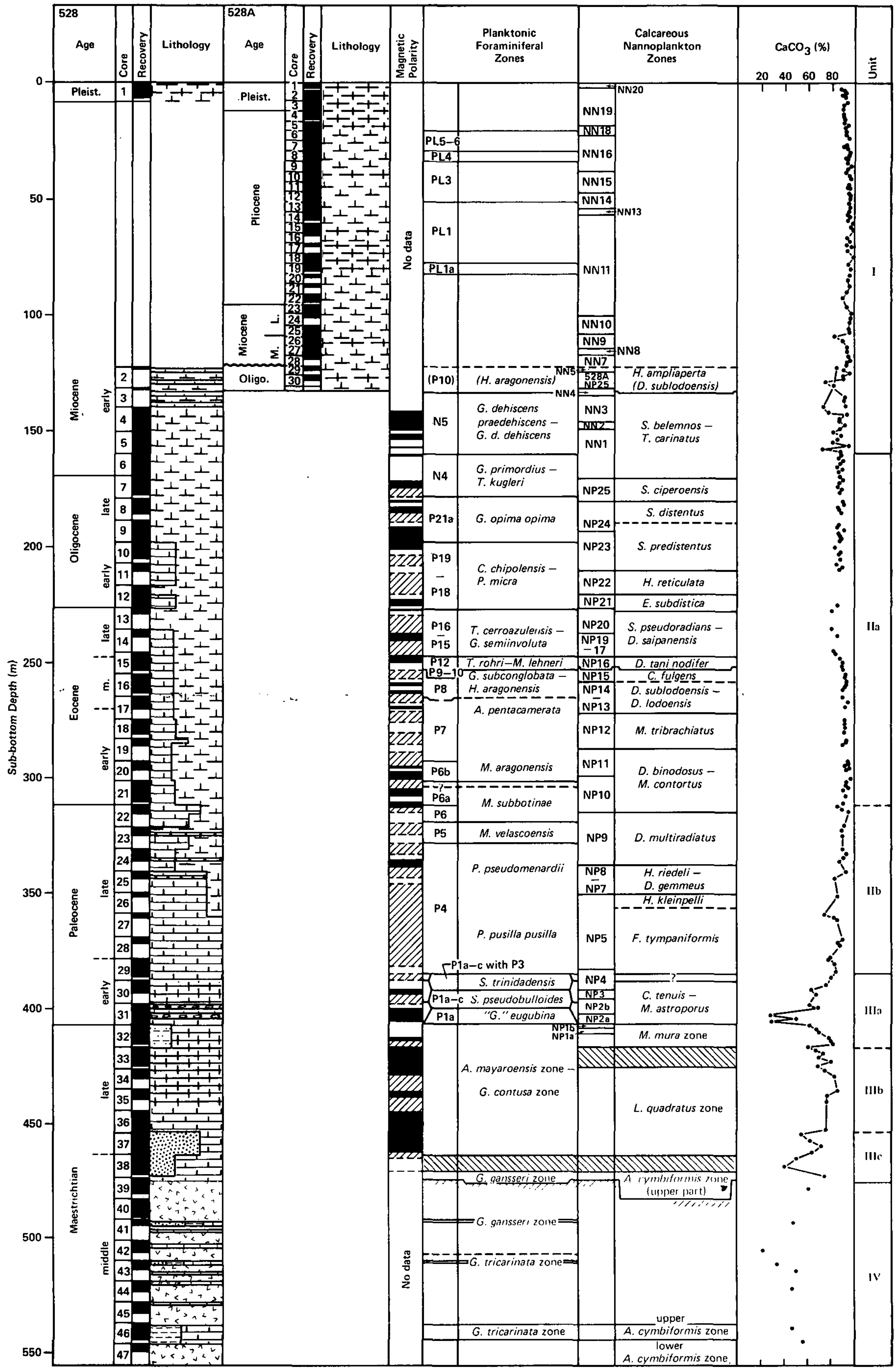


Figure 6. Site 528 stratigraphic summary.

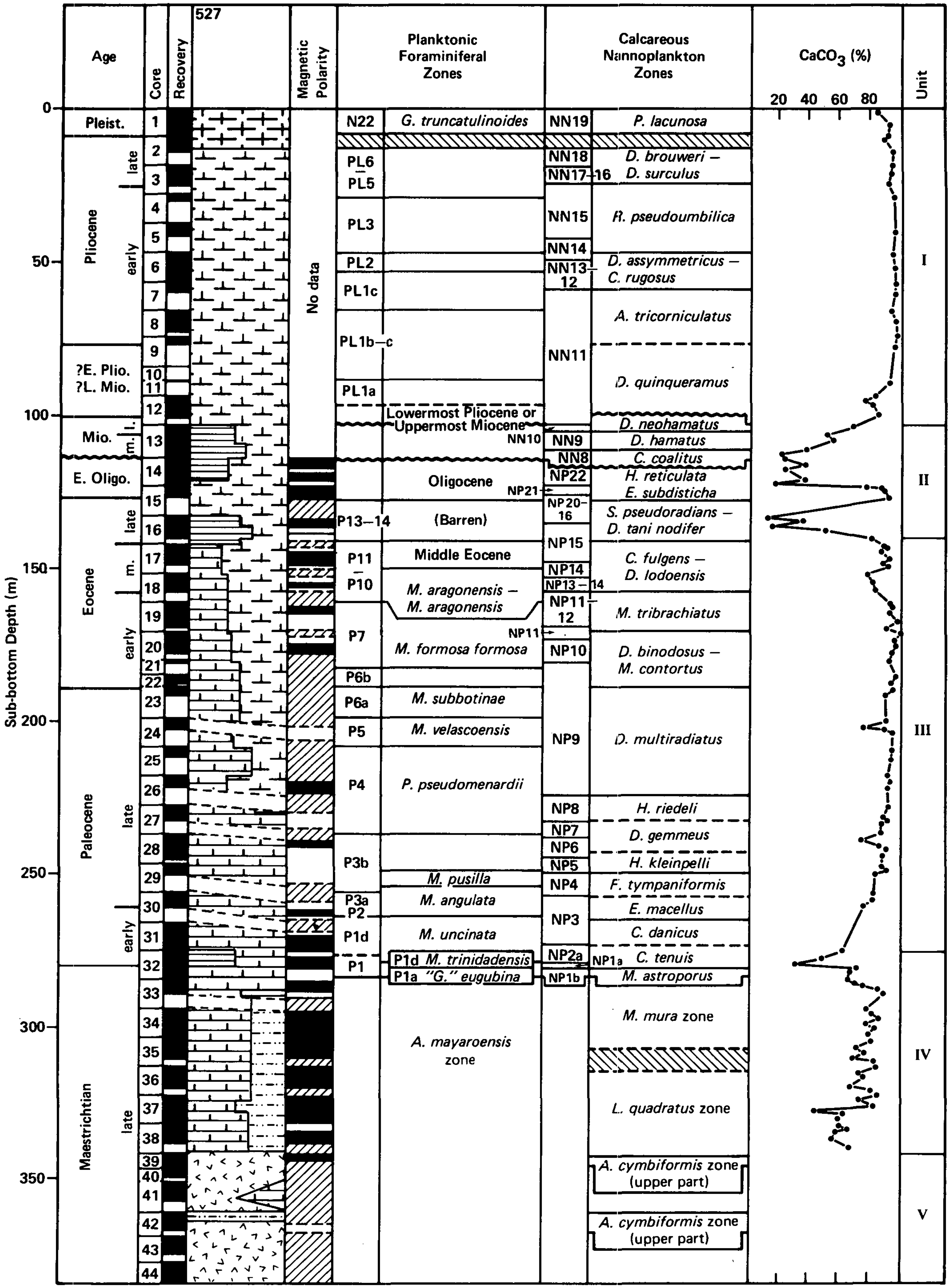


Figure 7. Site 527 stratigraphic summary.

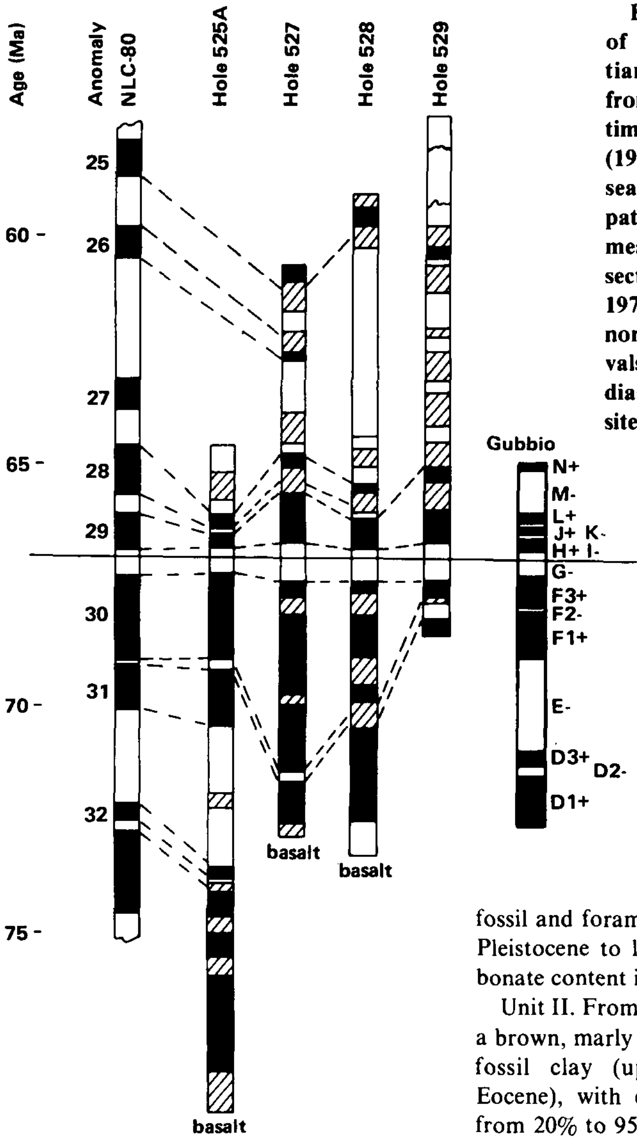


Figure 8. Summary diagram of Late Cretaceous/early Tertiary paleomagnetic results from four Leg 74 sites using the time scale of Ness and others (1980), with comparisons to the sea-floor-spreading anomaly pattern and the paleomagnetic measurements of the Gubbio section (Alvarez and others, 1977). Black intervals indicate normal polarity; white intervals indicate reversed polarity; diagonal line intervals (Leg 74 sites) are areas of no recovery.

fine-grained, moderately altered, vesicular aphyric to sparsely plagioclase phyric basalt flows. Both types have subophitic textures.

The biostratigraphy and shipboard paleomagnetic results (Fig. 6) are consistent with crustal formation between the times of magnetic anomalies 31 and 32 (middle Maastrichtian–upper Campanian).

Site 527, on crust of magnetic anomaly 31 age, is the deepest site drilled on the western flank of the Walvis Ridge transect. One rotary-drilled hole provided a complete sedimentary section from the sea floor to the top of a basement complex at 341 m sub-bottom. An additional 44 m was drilled in the basement complex. A density log was run before the hole caved in.

Five major sedimentary units were observed (Fig. 7):

Unit I. From 0 to 102 m sub-bottom consists of a very homogeneous white nannofossil and foraminifera-nannofossil ooze of Pleistocene to late Miocene age. The carbonate content is near 95%.

Unit II. From 102 to 142 m sub-bottom is a brown, marly nannofossil ooze to nannofossil clay (upper Miocene to upper Eocene), with carbonate content ranging from 20% to 95%. Quasi-cyclic patterns in carbonate sedimentation begin in this unit. A major decrease in sedimentation rates or a hiatus is observed between mid-Miocene and lower Oligocene sediments in this unit.

Unit III. From 142 to 275 m sub-bottom consists of alternating beds of nannofossil chalks and oozes, with chalks increasing with depth. Carbonate content is near 85%.

Unit IV. Extends from near the Cretaceous-Tertiary boundary at about 275 m sub-bottom to the top of the basement complex at 341 m and is a reddish-brown, muddy nannofossil chalk. Noncalcareous components consist mainly of volcanogenic sediments.

Unit V. Consists of 0.02-, 0.60-, and 3.50-m-thick sections of nannofossil limestone and carbonate mudstones interbedded within the basaltic basement complex. A very sharp increase in calcium and a decrease in magnesium within the pore fluids are observed here. The oldest sediment obtained both above and within the basement complex is mid–upper Maastrichtian.

We cored 44 m into the basement complex and were able to define five basalt units separated by sediment interlayers. The upper four are medium-grained plagioclase-olivine-clinopyroxene phyric basalt with large plagioclase and altered olivine phenocrysts. The lower basalt unit is a more altered aphyric basalt. All units are massive flows.

The biostratigraphy and shipboard paleomagnetic results are consistent with crustal formation at the edge of magnetic anomaly 31 for Site 527.

In summary, five closely spaced sites were drilled in water depths ranging from 1,054 to 4,428 m. Although some obvious differences are observed between the shallowest and deepest sites, the sediment lithologies are generally uniform from site to site. From top to bottom, nannofossil and/or foraminifera-nannofossil oozes grade into ooze and chalk sequences with a decreasing ratio of ooze to chalk with depth and a final predominance of chalks. Volcaniclastic sedimentation increases near basement. Within the basaltic basement complex, interbedded nannofossil chalks, limestones, and volcaniclastic sediments are observed. The carbonate content is high (>90%) throughout most of the lithologic columns but tends to drop near the bases of the columns. In addition, biogenic and primary sedimentary structures are generally poorly preserved to absent near the tops of the columns but tend to be preserved deeper in the sections. In particular, graded turbidite sediments are found near the bottoms of the columns. All of the basement sites have basalt flows with intercalated sediment. The basalts range from aphyric to plagioclase-olivine-clinopyroxene phyric.

Paleomagnetic Results

The results of the paleomagnetic measurements are included in Figures 4 to 8. The white, unlithified oozes of Pliocene to mid-Miocene age at all sites proved to be too weakly magnetized for measurement even with a super-conducting rock magnetometer. The remaining Neogene material was contaminated by a strong viscous remanence acquired during sample handling that could not be reliably removed. Thus, an analysis of paleomagnetic results for the HPC material is not reported, and detailed study was confined to undisturbed Paleogene rotary-drilled cores, especially the lithified lower Paleocene to Cretaceous interval at Sites 525, 527, 528, and 529. The lower Paleocene–Cretaceous proved to be quite stably magnetized, with median demagnetizing fields of 200 to 300 Oe and directional change of less than 20° over a 600-Oe coercive force range. Forty-three pilot samples were selected and given detailed AC demagnetization in order to determine the optimum field for cleaning treatment of samples. The results show a record that is completely consistent with the paleomagnetic reference section at Gubbio, Italy (Alvarez and others, 1977). The Cretaceous-Tertiary boundary occurs near the top of the reversed interval between magnetic anomalies 29 and 30. The complete Paleocene-Cretaceous sequence of anomalies 28 to 31 was recognized at all four sites, and anomalies 25, 26, 27, and 32 are seen at some sites. Figure 8 shows a summary diagram, along with the preferred time scale of Ness and others (1980). The basement ages derived from these magnetic measurements indicate that at Site 525 the basement is of anomaly 32 age; at 527 and at 528, anomaly 31 age. These data are consistent with the biostratigraphic ages and the mapped crustal anomalies, which suggest that the Walvis Ridge was formed by sea-floor–spreading processes at a mid-ocean ridge.

IGNEOUS PETROLOGY

Although aphyric basalts occur at all three sites at which basement was penetrated, moderately to highly phyric varieties are restricted to the two flank sites. Significant compositional differences exist between these two types. Representative major-element analyses (Richardson and others, in press, a) appear in Table 2. These serve to illustrate some features of a probable over-all compositional trend from the ridge crest down into the adjacent ocean basin. The sample from the ridge crest Site 525 is an aphyric basalt from a glassy pillow margin. It has the chemistry of a mildly quartz-normative tholeiite with high K_2O, TiO_2, P_2O_5, and FeO contents similar to those encountered in more evolved examples of mid-ocean ridge basalt (MORB) from East Pacific spreading centers (Clague and Bunch, 1976). The sample from the deepest Site 527 is a highly plagioclase phyric basalt from a flow interior. Its chemistry is that of a mildly olivine-normative tholeiite with K_2O, TiO_2, and P_2O_5 contents similar to those in typical MORB, although higher FeO and lower MgO indicate a somewhat more evolved magma.

The major-element chemistry of basalts from the Walvis Ridge crest resembles neither that of typical MORB previously recovered from the South Atlantic (Frey and others, 1974) nor that of alkalic basalts on the spatially associated island of Tristan da Cunha (Baker and others, 1964). In addition, the ridge-crest basalt trace-element and Nd-Sr-Pb isotopic characteristics (Richardson and others, in press, b) are unparalleled among ocean-floor tholeiites. The closest analogues are the tholeiitic basalts of the Ninety East Ridge in the Indian Ocean (Hekinian, 1974), which have similar Sr isotopic characteristics (Whitford and Duncan, 1978). The incompatible trace-element and isotopic systematics of the Walvis Ridge basalts suggest derivation by partial melting of mantle that had become heterogeneous due to the ancient introduction of small-volume melts and metasomatic fluids (Richardson and others, in press, a). The relatively low compatible trace-element contents of the Walvis Ridge basalts indicate that they further evolved by fractional crystallization prior to eruption (Richardson and others, in press, a).

TABLE 2. REPRESENTATIVE AVERAGE XRF ANALYSES OF BASALTS FROM THE LEG 74 WALVIS RIDGE TRANSECT (in percent)

Sample no.	525A-59-4, 25	527-41-4, 10
Depth*	61	14
SiO_2	50.20	48.82
TiO_2	2.49	1.17
Al_2O_3	13.95	16.91
Fe_2O_3	12.92	10.79
MnO	0.19	0.17
MgO	5.33	5.86
CaO	9.49	12.66
Na_2O	2.49	2.52
K_2O	1.03	0.17
P_2O_5	0.31	0.10
LOI	0.90	0.19
H_2O^-	0.51	0.93
TOTAL	99.82	100.29
CIPW Norms†		
Q	2.97	0.00
OR	6.08	1.00
AB	21.05	21.30
An	23.83	34.31
WO (DI)	8.84	11.60
EN (DI)	4.44	6.16
FS (DI)	4.19	5.07
EN (HY)	9.05	5.03
FS (HY)	8.55	4.14
FO (OL)	0.00	2.51
FA (OL)	0.00	2.28
MT	2.63	2.20
IL	4.47	2.23
AP	0.72	0.23

*Depth below top of basement in metres.
†Norms computed on basis of $Fe^{2+}/(Fe^{2+} + Fe^{3+}) = 0.86$.

Sedimentation History

The sediments of Walvis Ridge are dominated by biogenic carbonate. Only in the upper Maastrichtian and lower Paleocene are the sediments rich in volcanogenic material, apparently derived from active centers on the ridge itself. This activity was particularly great during the latest Maastrichtian, dropped markedly in the early Paleocene, and disappeared from the record in younger times.

Carbonate preservation and accumulation varied greatly through the Cenozoic. This is indicated by changes in estimates of preservation of the calcareous assemblages and variation in the average carbonate-accumulation rates in the study area (Figs. 9a, 9c). The average accumulation rates for any given interval are found using the expression

$$\frac{\frac{100-P}{100} \times \text{sediment thickness (cm)}}{\text{time } (10^3 \text{ yr})} \times \text{average grain density (g/cm}^3\text{)}$$

where

P = porosity in percent.

A summary of the physical properties needed to calculate the accumulation rates and other important physical property measurements are given in Table 3.

The preservation of the calcareous faunas and floras generally parallels changes in the CCD (that is, deeper CCD, better preservation). From the middle to late Eocene through the Oligocene, microfossils are generally poorly preserved; those of the late Oligocene to late Miocene are moderately well preserved, and those of the latest Miocene through Quaternary are well preserved. Preservation in the lower Paleogene was poor to moderate, with diagenetic alteration in the thicker sections (shallower sites) having the greatest over-all effect on the assemblages. Hiatuses are most common in the late Eocene through late Oligocene parts of the sites (Fig. 9b). In this interval, they do not appear to have a clear depth dependency; breaks in the record are found in both the deepest site (527) and the shallower sites (525, 526) but not in between. However, this interval of abundant hiatuses has a lower accumulation rate, with poorer microfossil preservation at all sites. The increased frequency of hiatuses in the mid-Paleogene is probably related to a relatively

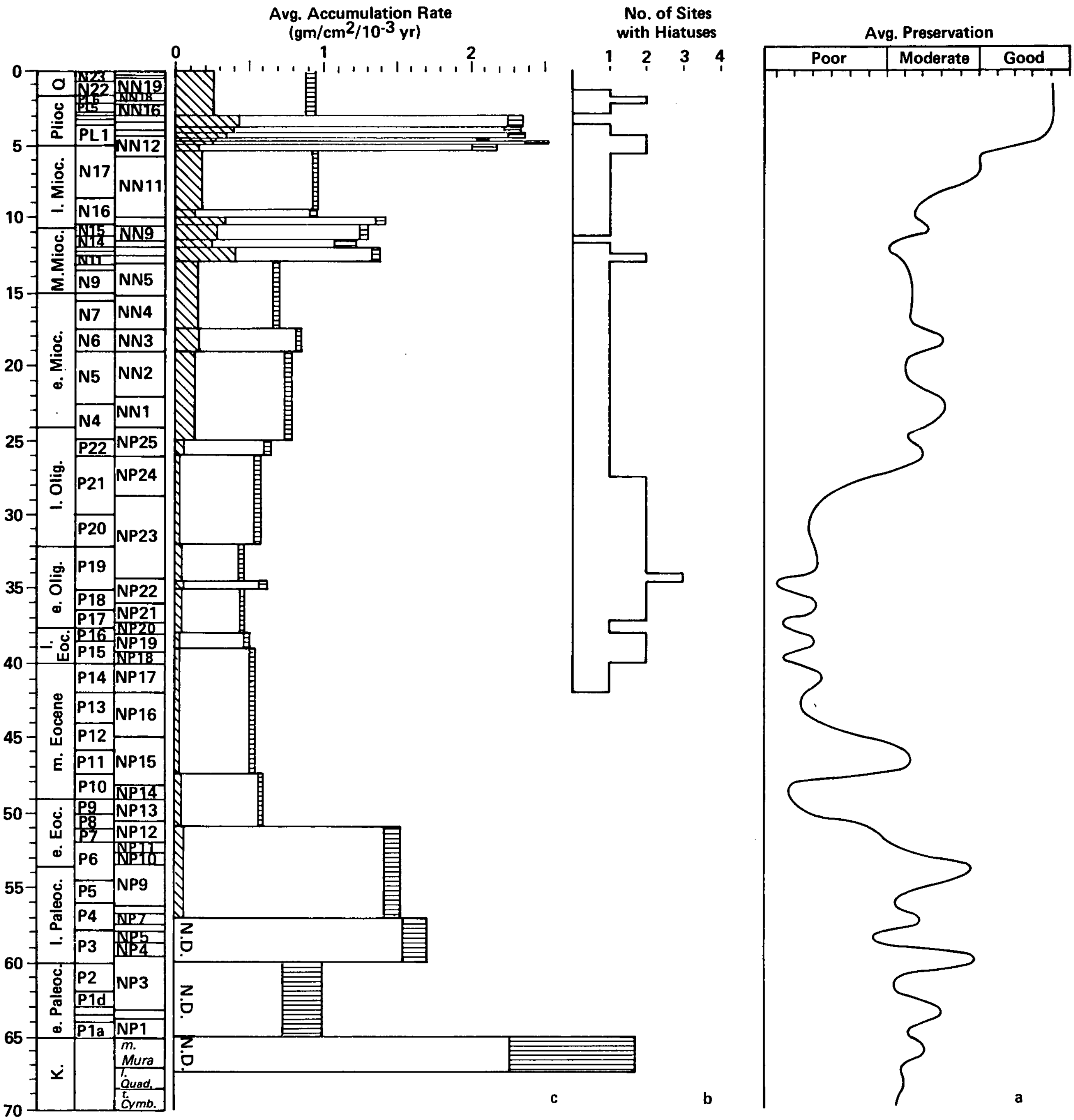


Figure 9. a. Average foraminifera preservation. b. Abundance of hiatuses. c. Average sediment accumulation rates for Leg 74 sites. Preservation is a subjective estimate; each estimate is given a numerical code and averaged over all five sites. Hiatuses in the sections were considered present only when both calcareous nannofossils and foraminifers indicated that one or more biostratigraphic zones were not represented. Accumulation rates were calculated for three separate components: coarse-grained (> 63 μ) material (dominated by foraminifera and indicated by diagonal shading); fine-grained carbonate (< 63 μ, dominated by calcareous nannoplankton and indicated by unshaded areas); and noncarbonate sediments (indicated by shading). Accumulation rates for each component were averaged over all intervals recovered. Hiatuses were excluded in the calculation of averages, as were the shallow-water sediments of Site 526 (Fig. 10). "N.D." indicates "not determined" and corresponds to lithified intervals where sediments could not be separated into size fractions.

high ratio of dissolution to supply rates. Hiatuses in the late Neogene occur in the mid-depth sites (528, 529). They are closely associated with slump deposits and occur near times of peak accumulation rates (Fig. 9c); thus, they are more likely linked with slumping and erosion than with dissolution.

The record of average accumulation rates from sites in this region shows the same general features. Carbonate accumulation averaged about 1 $gm/cm^2/10^3$ yr during much of the Cenozoic. There are four maxima in average accumulation: (1) in the late Maastrichtian, when volcanic debris was an important sedimentary component and contributed nearly 1 $gm/cm^2/10^3$ yr to the sediments; (2) in the late Paleocene to early Eocene, where hiatuses were not found; (3) in the latest mid-Miocene; and (4) in the earliest Pliocene. Of these four peaks in average accumulation rate, the early Pliocene appears to be the largest. The two Neogene peaks in sediment accumulation rate occur at all five sites. Their presence in the shallowest site (526), where dissolution effects are thought to be negligible, suggests that these maxima result from increased carbonate productivity during the late middle Miocene and early Pliocene.

One of the chief purposes of drilling this suite of sites over a wide depth range was to investigate, in more detail than is generally feasible, the history of calcite dissolution in the water column. Figure 10 shows the estimated accumulation rates of sediment broken into three components: greater than 63 μ (almost entirely foraminifera), less than 63 μ (largely coccoliths), and the noncarbonate residue. It is apparent from this figure that the accumulation rate of foraminifera was generally highest at the shallowest site; we interpret the reduced accumulation of foraminifera at deeper sites as a measure of the loss by dissolution. The accumulation of fine-grained material was low at the shallowest sites, high at intermediate depths, and, during parts of the record, low again in the deepest sites. We interpret this as a result of winnowing, which preferentially inhibits the accumulation of fine material on the rises, and of dissolution, which has a significant impact only on coccoliths near the CCD.

The recovery of one exceptionally shallow section (Site 526) serves as a standard that has no (or minimal) dissolution effects, against which the deeper sites can be compared. A comparison of the accumulation rates of Site 526 (at 1,054 m) with that at the next shoalest Site 525 (at 2,467 m) indicates that the difference in the coarse fraction accumulation rates at the two sites (indicative of differences in dissolution rates) was greater during the intervals of maxima in the over-all accumulation rate (for example, the early Pliocene and middle Miocene) than during times of more normal total accumulation rates (for example, in the late Miocene). This suggests that carbonate-dissolution rates were highest during times of relatively high carbonate supply (productivity). Thus, the changes in dissolution rates extend upward to at least 2,500 m and are strongly linked to large-scale changes in productivity. If the carbonate-dissolution rate at 2,500-m water depth had been as high in the late Miocene as it was during the early Pliocene or during the mid-Miocene (intervals of rapid carbonate accumulation), no foraminifera would have survived, whereas we see that the late Miocene foraminiferal accumulation at 2,500 m (Site 525) was similar to that at 1,000 m (Site 526).

Figure 11 shows, for three selected time intervals, the magnitude of these dissolution effects. Here, we have divided the foraminifera into two fractions on a 150-μ sieve and the coccoliths from the foraminifera on a 63-μ sieve. In the Pleistocene, the accumulation of larger foraminifera is only significantly affected by dissolution (seen as a reduction in accumulation rates) at the deepest site (527), but the accumulation of smaller foraminifera is reduced by a factor of 2 between Sites 526 (1,000 m) and 525 (2,400 m), a surprising find, considering that the CCD was deeper than 4,400 m throughout the interval. The effects of winnowing are shown by the coccolith accumulation, which was reduced by at least a

TABLE 3. SUMMARY OF PHYSICAL PROPERTIES

	Site	Oozes: 0 to 50 m sub-bottom	Oozes: Below 50 m	Clay and clayey oozes
Wet Bulk density (g/cc)	525	1.67→1.71	1.75	. .
	526	1.7	1.7 →1.75	. .
	527	1.62→1.75	1.75	1.75
	528	1.62→1.73	1.73→1.81	. .
	529	1.75	1.75	. .
Wet water content (%)	525	36→34	33→30	. .
	526	40→34	34→30	. .
	527	40→33	34	35
	528	42→34	34→31	. .
	529	33	33	. .
Porosity (%)	525	60→57	56	. .
	526	60	60→53	. .
	527	64→57	57	57
	528	65→56	56→53	. .
	529	55	55	. .
(Horizontal) sonic velocity (km/s)	525	1.6	1.6	. .
	526	1.6	1.6	. .
	527	1.53	1.53	1.55
	528	1.55	1.55	. .
	529	1.6	1.6	. .
Shrinkage (% vol.)	525	7→6	6→5	. .
	526	5	6	. .
	527	12→9	(10)	15
	528	8	8→5	. .
	529	7→5	5→4	. .
Vane shear strength (g/cm^2)	525	50	30	. .
	526	. .	< 50	. .
	527	< 100	< 100	800
	528	40	50→200	800
	529	50	50	. .

TABLE 3. (*Continued*)

Transition ooze/Chalk		Chalks	Basement: Sediments	Basement: Basalt	Site
1.75→2.05		2.05	(1.93)	2.47	525
..		..	..	..	526
1.75→1.9		1.9→1.95	(2.05)	2.64	527
1.81→2.0		2.0→2.05	2.05	2.85	528
1.75→1.9		1.95→2.2	..	..	529
30→22		22→16	(28)	8	525
..		..	..	..	526
34→28		28→25	(21)	5	527
31→24		24→20	22	4	528
33→26		26→15	..	..	529
50→40		40→35	(53)	20	525
..		..	..	..	526
55→50		47	(42)	13	527
53→45		45→41	43	10	528
55→45		45→31	..	..	529
1.6→1.9		1.9→2.6	1.8	3.9	525
..		..	..	..	526
1.55→1.7		1.7	1.9	4.4	527
1.56→1.9		1.9→2.0	2.4	4.9	528
1.6→1.8		1.8→2.5	..	..	529
3.5	0		Physical Properties		
..			of Lithologic Units		
6→0			(estimated averages)		
5→0					
4→0					
50→ >200					
..			65→56 = trend top → bottom of unit		
150→ >400			55 = no trend visible		
30→ >300			(10) = only few or one values		
50→ >600					

factor of three at Site 526, compared to the deeper sites.

In the late Pliocene, the pattern was somewhat similar to the Pleistocene situation, except that even the larger foraminiferal fraction is affected by dissolution at 2,500 m (Site 525).

We also show data from the mid-late Miocene (zones NN9 and NN10), at which time the CCD evidently was not much deeper than the depth of Site 527. Much of the foraminiferal carbonate has been removed at Site 528, whereas at Site 527 foraminiferal accumulation is nil, and the coccoliths are noticeably reduced.

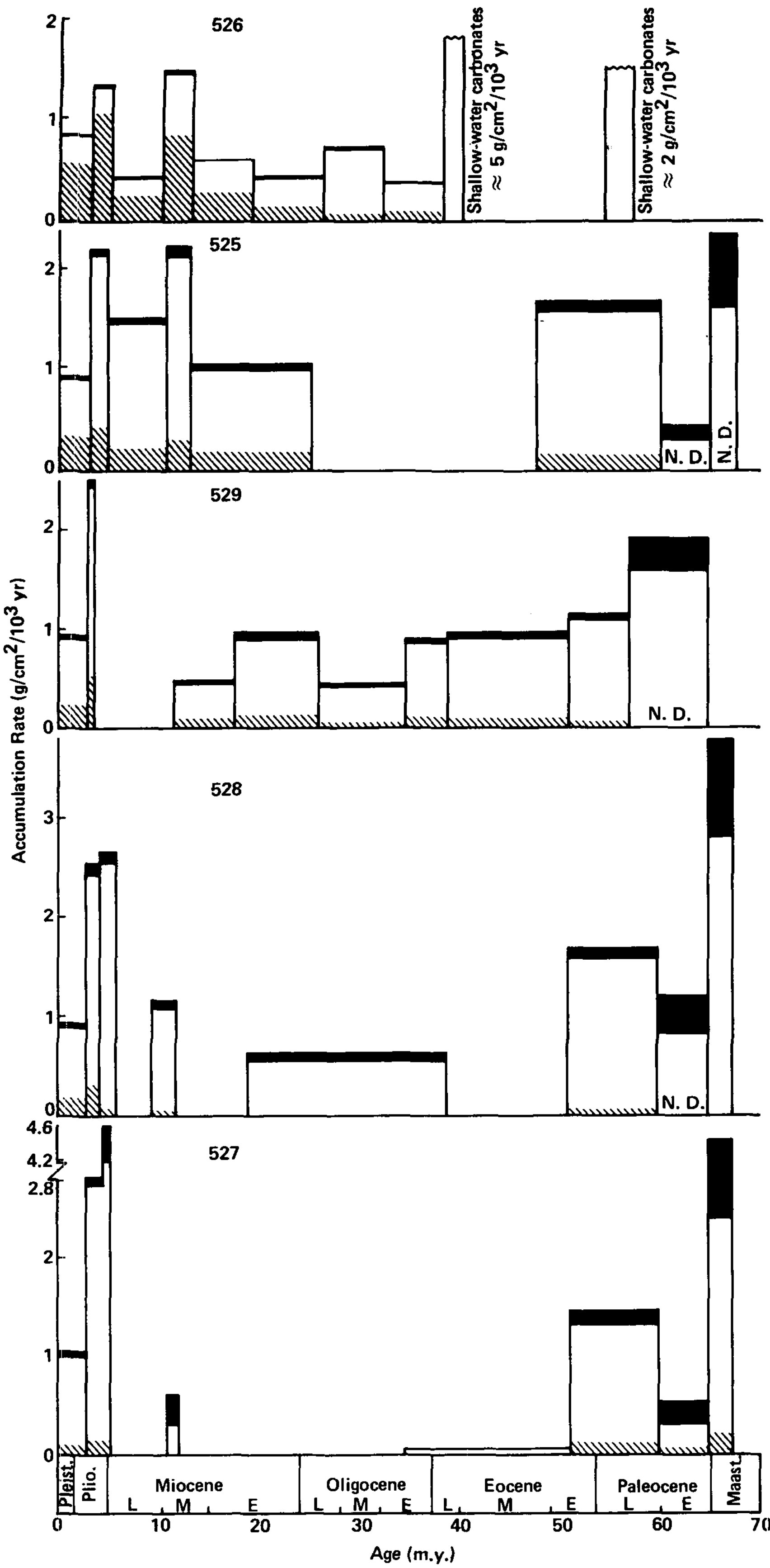
Biostratigraphy and Evolution of Walvis Ridge Floras and Faunas

Within the Leg 74 area, sedimentation commenced upon the Walvis Ridge in the early Maastrichtian (*Gtr. tricarinata* foraminiferal zone or *T. trifidus* nannofossil zone). Sediments were deposited between basaltic lava eruptions. Shallow-water faunas and turbidites from shallow pinnacles containing *Inoceramus* are in places abundant. Benthic faunas and the ratio of the planktonic to benthic foraminifera in these sediments confirm the same approximate depth of basalt eruption predicted by normal thermal-subsidence models (Table 4). The correlation of standard nannofossil zones to magnetic data also was possible in the Walvis Ridge sites. Nannoplankton and planktonic foraminifera of the Maastrichtian are typical of middle latitudes. Preservation varies among the sites and appears to be strongly affected by the amount of sedimentary overburden. Nannofossils are moderately preserved throughout, but foraminifera are poorly preserved at the shallow Site 525 and the intermediate Site 529; the best-preserved faunas are found at the deepest Site 527.

The Cretaceous-Tertiary boundary interval is included in four continuous sedimentary sequences that contain diverse nannofossil and foraminiferal biotas. Substantial volcanic material was added to sediments below the boundary at all sites, and into the Paleocene at Site 525. Just below the boundary, there is a thin zone of blue-gray sediment containing a warmer-water foraminiferal fauna than those in cores below, implying the incursion of slightly warmer surface waters into this area just before the terminal Cretaceous event. All sediments are calcareous oozes with moderately well-preserved nannofossils, but not particularly well-preserved foraminifera.

The basalt Tertiary *G. eugubina* zone was recovered, attesting to the relative completeness of the sedimentary section. Paleocene faunas are typical of middle latitudes, and floras contain temperate water-mass indicators. The shallowest Site 526 probably was close to sea level at this time and contained a carbonate shelf fauna. Sedimentation through the Paleocene appears to have been more continuous at the deeper than at the shallower sites, in that several foraminiferal zones are not identified at Sites 525 and 529 near the end of the early Paleocene. However, no significant breaks were found in the nannofossil biostratigraphic sequence of the early Paleocene. Average accumulation rates (Figs. 9 and 10) were lower in the early Paleocene than in the late Maastrichtian. Some of the best-preserved nannofossils are found in the upper Paleocene of Site 529, despite the large overburden at this site. The Paleocene-Eocene boundary was easily recognized by the disappearance of the benthic foraminifera *Gavelinella beccariformis*, and by the first appearance of the calcareous nannofossil *Discoaster diastypus*.

Early Eocene faunas are relatively well preserved at all sites, and benthic foraminifera indicate deposition at intermediate water depths. Planktonic faunas contain sufficient warmer-water elements to indicate warmed surface waters in this area. Preservation worsens markedly, and the South Atlantic episode of poorly preserved middle Eocene sediments (Boersma, 1977) is evidenced here on the Walvis Ridge. Few well-preserved sequences from the middle into upper Eocene were found at any site. By late Eocene time, Site 527 was approaching the



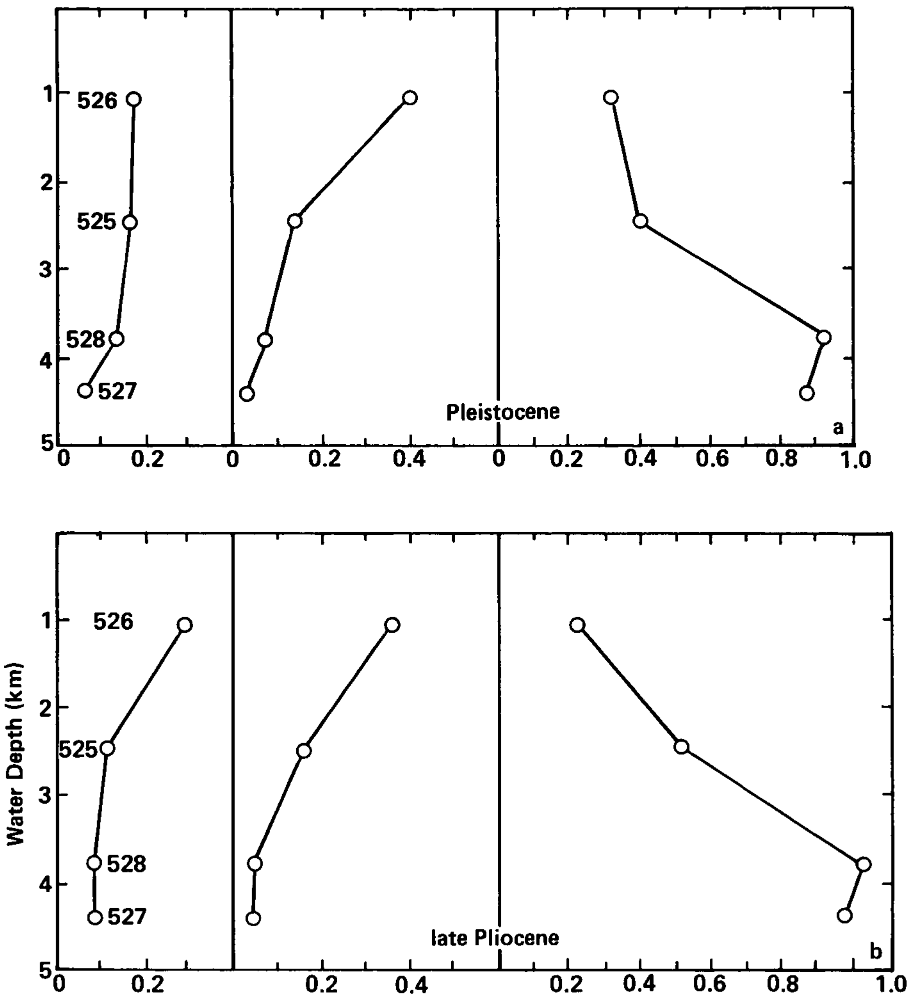
paleo-CCD, and most of the foraminifera were dissolved. Nevertheless, the nannoflora was useful for the zonation in this interval. Little upper Eocene was recovered at any of the other sites. The faunas contain typical middle-latitude species, and sediments are nearly all carbonate oozes. At this time, the shallowest Site 526 lay near the shelf-slope transition; planktonic oozes contain large amounts of shallower-water sediments and fossils. The preservation of the calcareous nannofossils is poor through the Eocene interval; only large species are present.

The Eocene-Oligocene boundary is well preserved and appears continuous at Site 529, where a long transition zone containing moderately to well-preserved biotas was recovered. According to the calcareous nannofossil study, a very condensed interval containing the Eocene-Oligocene boundary is also present at Site 528. At the shallowest site (526), a regression and consequent sediment removal are indicated at this time.

The Oligocene planktonic biotas recovered at Site 529 included several boreal types, but mostly temperate species, which are moderately well preserved. *Chiasmolithus altus*, an Oligocene nannofossil species preferring cooler water masses, was also commonly found only at Site 526. A nearly complete section occurs at the shallower Site 526, which benthic uvigerinid faunas indicate must have lain at depths from 600 to 1,000 m during the Oligocene. Shallow-water materials were transported into this area during the middle Oligocene, which is marked by increased sediment erosion and by the presence of bryozoan and mollusc debris and a *Uvigerina semivestita* fauna. This may represent the large eustatic sea-level fall indicated by Vail and others (1977) at 29 Ma. Other sites apparently lay too deep to demonstrate the effects of the regression. Site 527 lay below the CCD for foraminifera through the middle Oligocene.

KEY
■ = non-carbonate
□ = fine (63) carbonate ["coccolith"]
▨ = coarse (63) carbonate ["foram"]
N. D. = not determined (i. e. "foram" not separated)

Figure 10. Sediment accumulation rates for the Leg 74 sites, arranged according to water depth from shallow (top) to deep (bottom). Shading and notation as in Figure 9.



Only at Site 526 was an interval of abundant *Braarudosphaera* detected within the Oligocene zone (NP23).

The Oligocene/Miocene boundary was cored at four sites; only Site 527 was below the CCD at this boundary time. The boundary is based primarily on the last occurrence of the calcareous nannofossil species *Sphenolithus ciperoensis*, and the *T. kugleri–G. primordius* concurrent ranges. Foraminifera and nannofossils were moderately well preserved except where adjacent to hiatuses. Benthic foraminifera indicate that sediments were nearly all from intermediate depths, except for Site 527, which contained red clays with no foraminifera and few nannofossils.

It is difficult to establish a zonation within the upper lower to middle Miocene interval using foraminifera, due to the lack of tropical-index fossils, although the nannofossils present are generally amenable to a tropical zonation. The build-up of the Antarctic ice sheet coincident with the zone NN5-NN6 boundary is evidenced by a large influx of keeled globorotaliids and forms of *Globigerinoides*, suggesting increased niche differentiation and possibly density stratification at the eastern margin of the South Atlantic gyre.

Carbonate oozes of late Miocene age contain middle-latitude and temperate-water floras and faunas; the sections are relatively complete, and preservation is moderate.

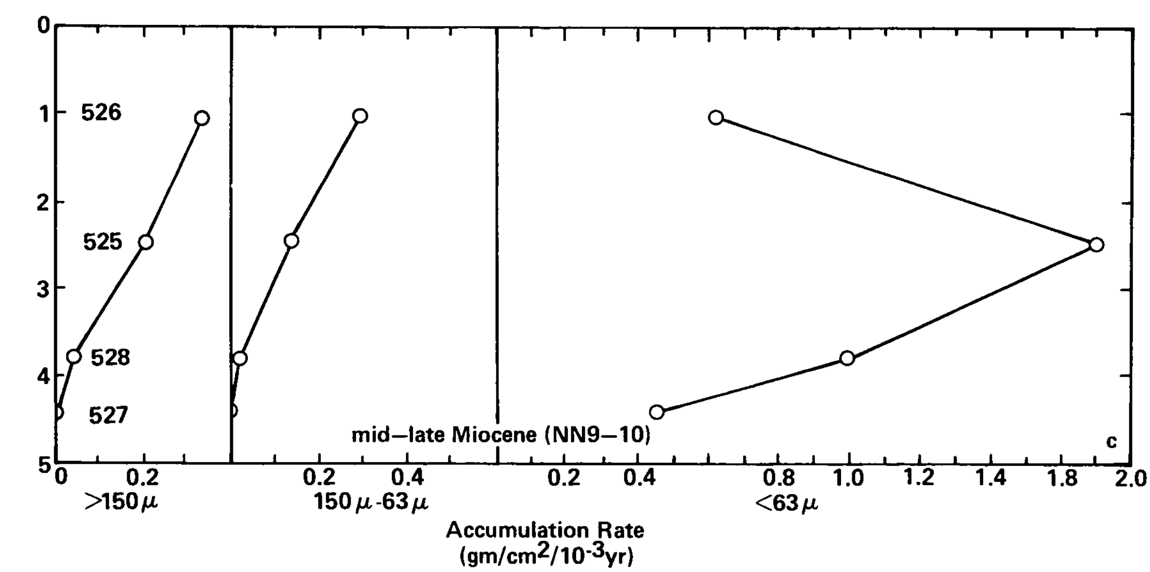


Figure 11. Average accumulation rates of three carbonate-sized fractions (< 150 μ, 150–63 μ, and < 63 μ). Data from Site 529 are excluded from these plots because slumping in the section gives anomalous accumulation rates.

TABLE 4. FOSSIL CRITERIA FOR PALEOENVIRONMENTAL AND PALEODEPTH ESTIMATION OF BASAL, CRETACEOUS-AGE SEDIMENTS AT LEG 74 SITES

Site	Age/zone at hole bottom	Paleoenvironment	Fossil criteria
525	*Gtr. tricarinata*	Slope	Large lenticulinids *Palnula* sp. Abundant *Inoceramus* *Gavelinella* cf. *velascoensis*
526	Late Paleocene	Carbonate platform or shoal	Coral and invertebrate sands *Rotalia* sp. *Asterocyclina* sp. Large lenticulinids
527	*A. mayaroensis*	Bathyal	*Gavelinella* cf. *velascoensis* *Nuttalides truempyi* *Gyroidina* spp. *Inoceramus*
528	*Gtr. tricarinata*	Bathyal	*Gavelinella* cf. *velascoensis* *Nuttalides truempyi* Gyroidinids *Inoceramus*
529	*A. mayaroensis*	Bathyal	Gyroidinids *N. truempyi* *Gavelinella* sp.

Three very well-preserved and apparently complete Pliocene sections containing boreal and temperate planktonic fossils were recovered. A marked decrease in boreal species and their replacement by a typical middle-latitude fauna is indicated in all of the mid-Pliocene faunas coincident within the extrapolated base of the Gauss Chron. The CCD sank below the deepest site (527) near the base of the Pliocene; thus, this site also contains fossils that are sufficiently well preserved for detailed climatic studies. This site is on the northwestern end of the transect (Fig. 1). That it may have lain under a slightly different surface water mass in the Pliocene is demonstrated not only by differing planktonic foraminiferal faunas, but also by a different sequence of changes in these faunas through the Pliocene. Although a Pliocene section was recovered at Site 529, active slumping has disturbed the upper Neogene sequence there. The upper Pliocene section accumulated at slower rates and is consistently thin at all sites drilled.

Portions of the early to late Pleistocene contained well-preserved temperate floras and faunas in coarse-grained foraminifera-nannofossil oozes. Slumping of the Pliocene into the lower Pleistocene was found at Site 529.

SUMMARY AND CONCLUSIONS

1. As suggested by crustal magnetic-anomaly patterns and igneous petrology, this drilled section of the Walvis Ridge was initially formed at a mid-ocean ridge spreading center at an anomalously shallow elevation. The age of the basement rocks is ~69 to 71 m.y. (time of magnetic anomaly 31 to 32), with the deeper sites slightly younger than the sites upslope.

2. The basement is composed of basaltic pillowed and massive flows intercalated with nannofossil chalks and limestones containing a significant volcanogenic component. The major-element chemistry shows a change from quartz tholeiitic basalt at the ridge crest to olivine tholeiitic basalt down the northwestern flank. The chemistry of these crestal magmas differs from that of mid-ocean ridge basalt previously recovered from the South Atlantic.

3. The lithology of the sections is dominated by carbonate oozes and chalks. Dissolution had a marked effect on accumulation in the deeper sites, particularly during the upper Miocene, Oligocene, and middle to upper Eocene.

4. Volcanogenic material is common in the Maastrichtian and lower Paleocene sediments and was probably derived from sources on or near the Walvis Ridge.

5. During the Cenozoic, average accumulation rates in the sites drilled suggest that there were three peaks in the rate of supply of carbonate to sea floor: one during the early Pliocene, one in the late middle Miocene, and one in the late Paleocene to early Eocene. During much of the rest of the Cenozoic, carbonate accumulation averaged 1 $gm/cm^2/10^3$ yr.

6. The rates of dissolution as a function of depth can be calculated by using data from all of the sites of the transect. Initial results of such an analysis indicate that the shoaler sites (for example, 525) showed greater carbonate dissolution during times of high carbonate accumulation (production). Even when the CCD was below 4,400 m, a large amount of carbonate was dissolved in the upper part of the water column. This may render the "lysocline" and "R_0 level" concepts of Berger (1977) inapplicable for at least some parts of the studied record.

7. The effects of winnowing on the sediments are shown by a systematic downslope increase in the clay (noncarbonate fraction) and coccolith (< 63-μ size fraction) accumulation rates. The coccolith accumulation rate is lowered in the deeper sites only during intervals of intense dissolution.

8. Standard zonatons for the foraminifera and calcareous nannofossils could be used through much of the section; however, many of the foraminiferal species commonly used in tropical zonations are absent in this area, and in some cases, the ranges of species appear to be diachronous through latitude. Standard foraminiferal and nannofossil zones of the Maastrichtian are correlated to paleomagnetics for the first time.

9. The faunas and floras of the Walvis Ridge sites are temperate in nature. An indication of warmer faunas is found in the latest Maastrichtian and early Eocene, and cooler faunas in the Oligocene, middle Miocene, and early Pliocene. The boreal elements of the lower Pliocene faunas are replaced by more temperate forms in the mid-Pliocene.

10. The Cretaceous-Tertiary boundary was represented in four of the five sites drilled, with sediments containing well-preserved nannofossils but poorly preserved foraminifera. The basal Tertiary *G. eugubina* zone was recovered consistently, although it was poorly preserved.

11. The shallowest site (526) did not sink below sea level until the late Paleocene. Here, benthic faunas are distinctly different from the deeper sites and from sites on continental slopes at similar depths.

12. At Site 526, the effect of a middle Oligocene regression is recorded by the benthic foraminifera, which indicate a rapid shoaling followed by a deepening. Other sites were deep enough so that no change was noted in the benthic fauna.

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