Hydraulic piston coring of late Neogene and Quaternary sections in the Caribbean and equatorial Pacific: Preliminary results of Deep Sea Drilling Project Leg 68

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ABSTRACT

Leg 68 of the Deep Sea Drilling Project used the newly developed Hydraulic Piston Corer (HPC) to recover two virtually continuous, undisturbed sections of late Neogene and Quaternary sediment. The sites are located in the western Caribbean (Site 502, 4 holes) and in the eastern equatorial Pacific (Site 503, 2 holes). The sediment of Site 502 is primarily foram-bearing nanno marl which accumulated at about 3 to 4 cm/thousand yr. The bottom of Site 502 (228.7 m) is ~ 8 m.y. old. The sediment of Site 503 is primarily siliceous calcareous ooze which accumulated at about 2 to 3 cm/thousand yr. The bottom of Site 503 (235.0 m) is ~ 8 m.y. old.

The magnetostratigraphy of both sites was determined on the R.V. *Glomar Challenger* with a long-core spinner magnetometer. All paleomagnetic boundaries through the Gilbert were identified in Site 502; most of them were identified in Site 503. The sediment at both sites shows a distinct cyclicity of calcium carbonate content. These relatively high accumulation rate, continuous, undisturbed HPC cores will enable a wide variety of high-resolution biostratigraphic, paleoclimatic, and paleoceanographic studies heretofore not feasible.

INTRODUCTION

The recovery of undisturbed sections of unconsolidated deep-sea sediment has long been a goal of the Deep Sea Drilling Project (DSDP). These sediments usually represent the upper 200 to 300 m of the section and contain the Quaternary and Neogene record. Unfortunately, rotary drilling usually disturbs unconsolidated sediment which renders it useless for high-resolution investigations. However, the recently developed DSDP Hydraulic Piston Corer (HPC) provides an opportunity to recover these sediments without disturbing them. An initial test of the HPC successfully recovered a varved, diatomaceous section at Site 480 (Leg 64) in the Gulf of California (Curray, Moore, and others, 1979).

We took advantage of the HPC capability and devoted Leg 68 to the recovery of two undisturbed late Neogene and Quaternary sections. We cored two sites in the Caribbean and Pacific which previously had been drilled by conventional techniques. Our major scientific objectives were to determine the high-resolution late Neogene and Quaternary biostratigraphy and magnetostratigraphy of each site and to determine the detailed oceanic record associated with events such as the closing of the Isthmus of Panama and the initiation of glaciation in the Northern Hemisphere.

DESCRIPTION OF THE HPC

The HPC (Fig. 1) consists of a 4.4-m core barrel which slides over a stationary piston assembly. The corer is "cocked" by shear pins which hold the barrel in a retracted position. The HPC is lowered down the drill string, set in the bottom hole assembly, and activated by sea water which is pumped down the drill string until the shear pins fail. The HPC then strokes out ahead of the drill bit, using the hydraulic pressure as the driving force. Once the HPC is fully extended, the hydraulic pressure is released through ports (Fig. 1). If the HPC does not fully extend, the pressure is not released. The major time consumption in using the HPC is in lowering and raising it. The complete firing sequence takes less than a minute to complete. The major advantage of the HPC is that it recovers undisturbed

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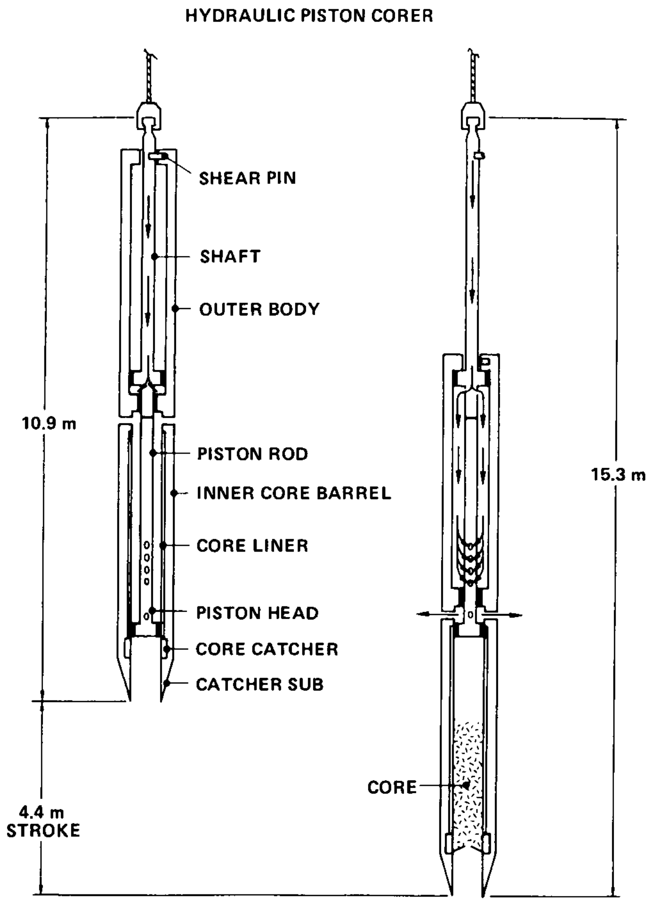

Figure 1. Operational schematics of the hydraulic piston corer. The HPC takes a 4.4-m core ahead of the drill bit.

sediments which are suitable for paleomagnetic studies as well as detailed biotic and sedimentological analyses. The undisturbed nature of these cores is illustrated by the comparison of rotary-drilled and HPC cores from the same location and stratigraphic interval (Fig. 2).

SITE OBJECTIVES AND RESULTS

Sites 502 and 503 were selected to provide continuous late Neogene and Quaternary records of the low latitude Atlantic and Pacific Oceans. We continuously cored several holes at each site and, to insure the recovery of complete sections, we overlapped the core breaks in one hole with a cored interval in an adjacent hole.

Site 502

Objectives. Site 502 is on a topographic high in the western Caribbean near Site 154 (Edgar, Saunders, and others, 1973) (Fig. 3). The site was chosen to avoid the turbidite sands encountered near the bottom of Site 154. The acoustic section has only diffuse reflectors which suggests that Site 502 lacks prominent turbidites.

The primary objectives at this site were (1) to recover a complete record of the late Neogene and Quaternary in a carbonate section with relatively high accumulation rates, (2) to obtain a detailed paleomagnetic stratigraphy to correlate with the biotic and volcanic history of the western Caribbean, and (3) to use these data to elucidate the sequence of events associated with the closing of the Isthmus of Panama.

Results. We cored four holes at Site 502 (11°29.4'N, 79°22.7'W; 3,051 m) to a maximum depth of 228.7 m (Table 1). Although recovery varied, the composite section is a virtually continuous, undisturbed record from Holocene to lowermost upper Miocene.

Lithostratigraphy. The sediment consists of foram-bearing nanno marl which grades to calcareous clay with depth. The top 7 m of the section is yellowish brown, but the remainder is various shades of gray to greenish gray. The gray colors indicate reduced conditions and, because only the upper section is oxidized, we feel that post-depositional reduction of sediment is pervasive.

We divided the section into four lithostratigraphic sub-units, based on differences in color, foraminifera content, and the occurrence of siliceous microfossils (Table 2). Layers of volcanic ash are common in the early Pliocene and late Miocene and are distinctive enough to be reliable lithostratigraphic marker horizons. Shear strength

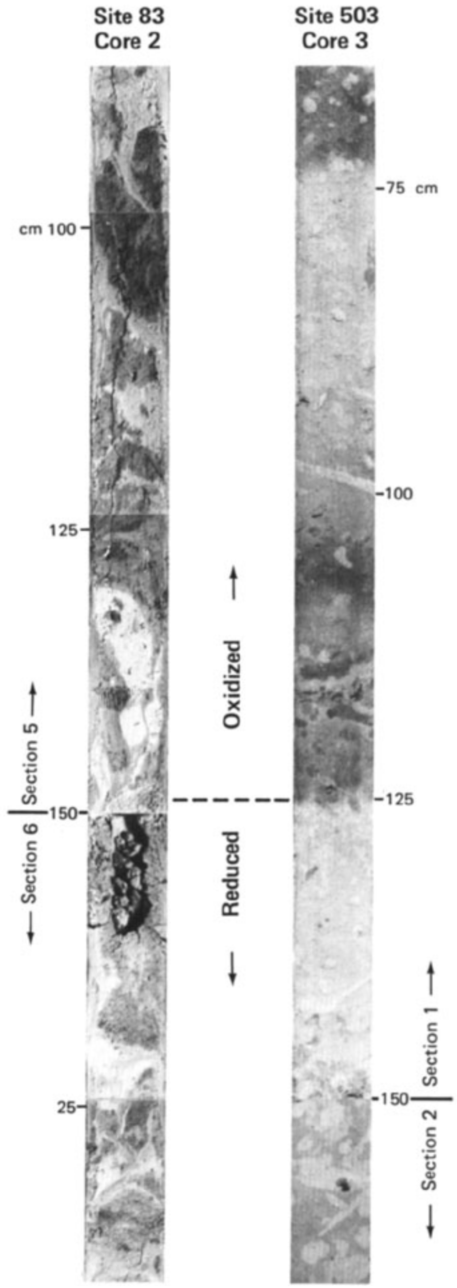

Figure 2. Equatorial Pacific sediments recovered by conventional rotary drilling (Site 83) and the hydraulic piston corer (Site 503). These sections represent the same interval and illustrate the undisturbed nature of HPC cores (note worm burrows in Core 3).

increased uniformly from 100 g/cm^2 near the surface to a maximum of 3,185 g/cm^2 at 193.9 m with rapid increases at 88 m and 110 to 130 m (Fig. 4). We found distinct cyclic variations in carbonate content, foram abundance, and physical properties superposed on the dominant lithology.

Shipboard analyses of percent carbonate by the bomb technique were made at 30-cm intervals, estimated to represent 12.5

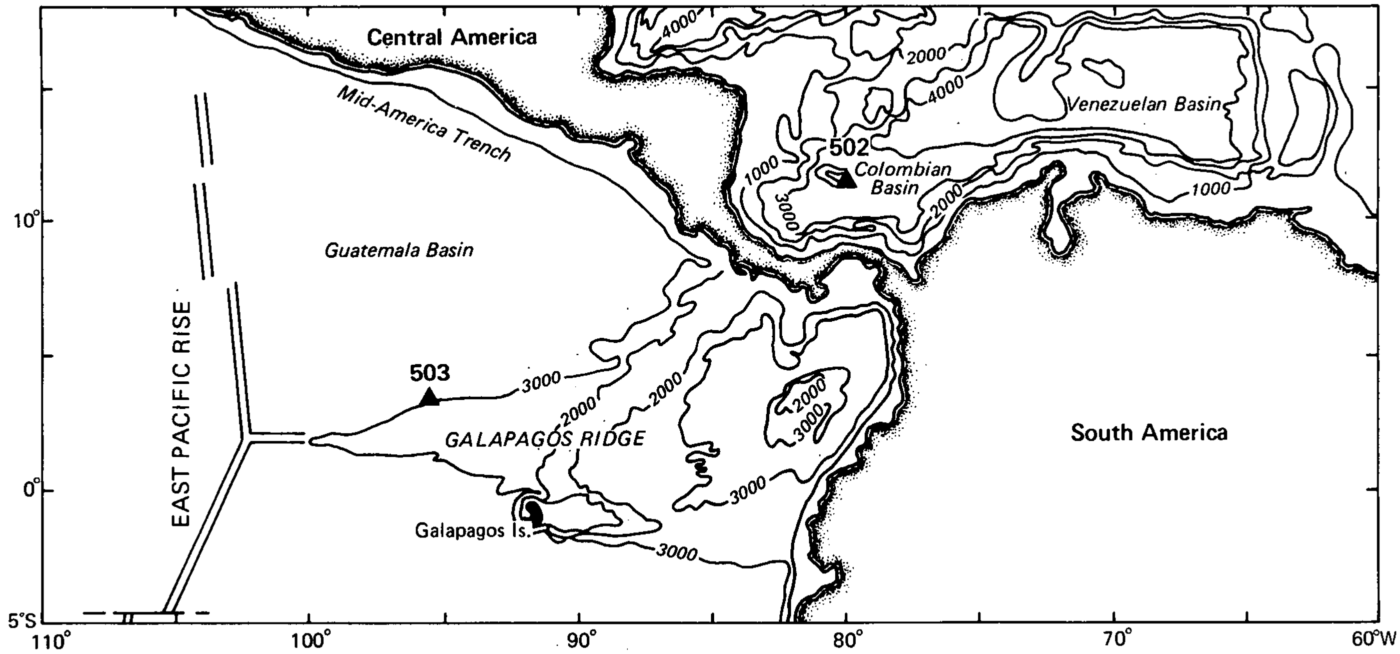

Figure 3. Location map of Site 502 and Site 154 (Leg 15) in the western Caribbean and Site 503 and Site 83 (Leg 9) in the equatorial Pacific. Sites 154 and 83 lie within the symbols for Sites 502 and 503, respectively.

thousand yr (Fig. 5). Preliminary results from holes 502 and 502A suggest that sediment recovered from the Brunhes epoch is virtually complete. This conclusion is based on the correlation of 19 carbonate stages between holes 502 and 502A with well-established oxygen isotope stages (Shackleton and Opdyke, 1976) (Fig. 5). All stages are identified, and none was missed because there was no loss of sediment between cores. The largest gap occurs in hole 502A and is 50 cm in length (~20,000 yr).

Although their amplitude varies, we find that these carbonate cycles extend back through early late Miocene sediments. Climatic variations which affected terrigenous dilution, productivity, and dissolution controlled the carbonate fluctuation during the Quaternary of the Caribbean (Cline and Hays, 1976; Prell, 1978). The carbonate record of Site 502 indicates that similar climatic variation has occurred continuously since the early late Miocene, which supports the observations of Dean and others (1977).

Magnetostratigraphy. The high accumulation rate and long record (~8 m.y.) of Site 502 provide a unique opportunity to significantly increase the resolution of paleomagnetic stratigraphy. We identified all 19 major paleomagnetic events of the Pliocene and Quaternary in this section (Figs. 6A and 8) on the basis of data generated aboard ship from the long-core spinner magnetometer. Although the record continues into the Miocene, shore-based work is necessary to resolve the details of the period because of reduced natural remanent magnetism (NRM) and secondary remanent magnetism. In addition to the major paleomagnetic events, preliminary examination of the data suggests several excursions of the field within the Matuyama epoch near the Jaramillo event. These normal polarity excursions appear to be real

TABLE 1. SUMMARY OF INTERVAL CORED AND SEDIMENT RECOVERED

Hole	Number of cores	Cored interval	Sediment recovered (m)	Sediment recovered (%)	Disturbed sediment (m)	Undisturbed sediment (%)
502	50	0–214.1	156.24	72.9*	18.0	88.5
502A	68	0–214.8	179.81	83.7†	15.6	91.3
502B	23	0–99.7‡	88.05	88.3	10.6	88.0
502C	37	32–144.2 210.2–228.7	114.36	87.5†	12.5	87.1
503	1	0–4.78	4.78	100.0	0.0	100.0
503A	54	0–235	146.94	62.5**	28.9	80.9
503B	26	0–112.8	96.49	85.5††	13.8	85.7

* Recovery is low because at depths >110 m, we washed down a full 4.4 m even though the HPC did not penetrate the full interval. Thus, the percent recovery below 110 m is not a true reflection of the HPC's capability for continuous coring.

† When the HPC did not fully extend 4.4 m, we used the recovered core length to determine the interval penetrated. In most cases, this agreed with the mud line on the core barrel. Thus, we have defined our recovery as ~100%.

‡ Hole 502B was terminated because of mechanical failure.

** Low recovery was caused by the repeated failure of the core catcher and numerous cracked core liners.

†† We attribute the higher recovery in hole 503B to using one small shear pin (that is, activation of the HPC at lower pressures) and modification of the core catcher.

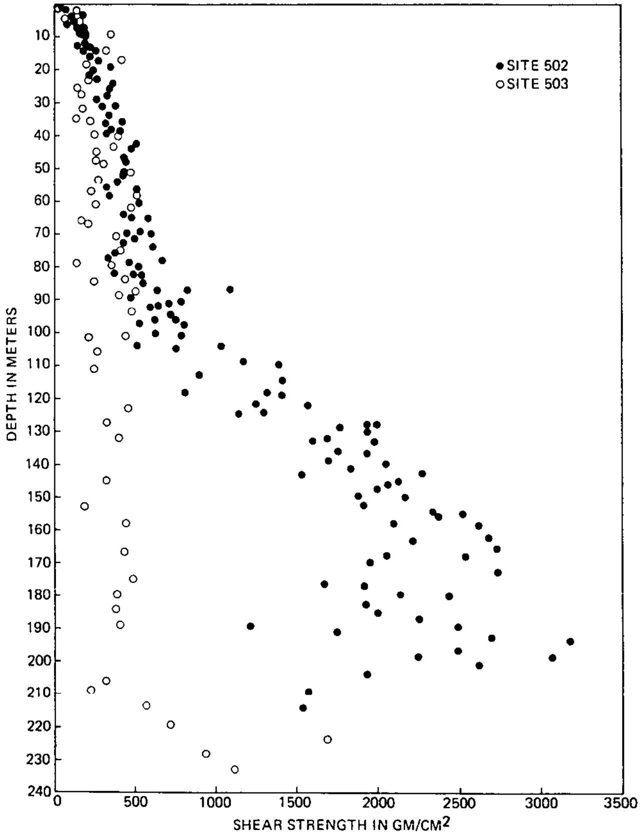

Figure 4. Shear strength (g/cm²) for sediments at Holes 502A, 503A, and 503B. Note the increase of shear strength with depth at Site 502 and the constant values of shear strength to almost 200 m at Site 503.

TABLE 2 LITHOLOGICAL SUMMARY, SITES 502 AND 503

Sub-unit	Hole, cores	Sub-bottom depth (m)	Age	Description
IA	502, 1-3 502A, 1-3 502B, 1-2	0–7	Holocene–upper Quaternary	Foram-bearing nanno marl; yellowish brown to light brownish gray; generally structureless.
IB	502, 3-25/27 502A, 3-24/27 502B, 2-23 502C, 1-16/18	7–110	Upper Quaternary–lower Pliocene	Foram-bearing nanno marl; gray to olive gray; generally structureless with occasional ash beds, foram cycles and foram content greater than 10%.
IC	502, 25/27-50 502A, 24/27-67 502C, 16/18-27	110–210	Lower Pliocene–upper Miocene	Foram-bearing nanno marl; to calcareous clays, light gray to olive gray to dark greenish gray; foram content less than 10%; pyritic ash layers and distinct burrowing are common.
ID	502A, 68 502C, 28-37	210–228*	Upper Miocene(?)	Calcareous and ash-bearing clay, pale green to grayish green; pyritic ash layers are common and biosiliceous remains are present.
IA	503A, 1-2 503B, 1-3	0–8.45	Holocene–upper Quaternary	Siliceous calcareous ooze and siliceous calcareous marl, oxidized dark brown and orange; cyclic; highly bioturbated; manganese and iron oxides-hydroxides common.
IB	503A, 4-52 503B, 3-26	8.45–226.2	Upper Quaternary–upper Miocene	Siliceous calcareous ooze and siliceous calcareous marl; reduced dark greenish to very pale greenish-yellow; gradational from dark at the top to light at the base; cyclic; highly bioturbated.
IC	503A, 53-54	226.2–235.0*	Upper Miocene	Siliceous calcareous ooze and siliceous calcareous marl; reduced dark greenish yellow; cyclic; highly bioturbated; pyrite common; greater than 25% clay.

* Deepest penetration.

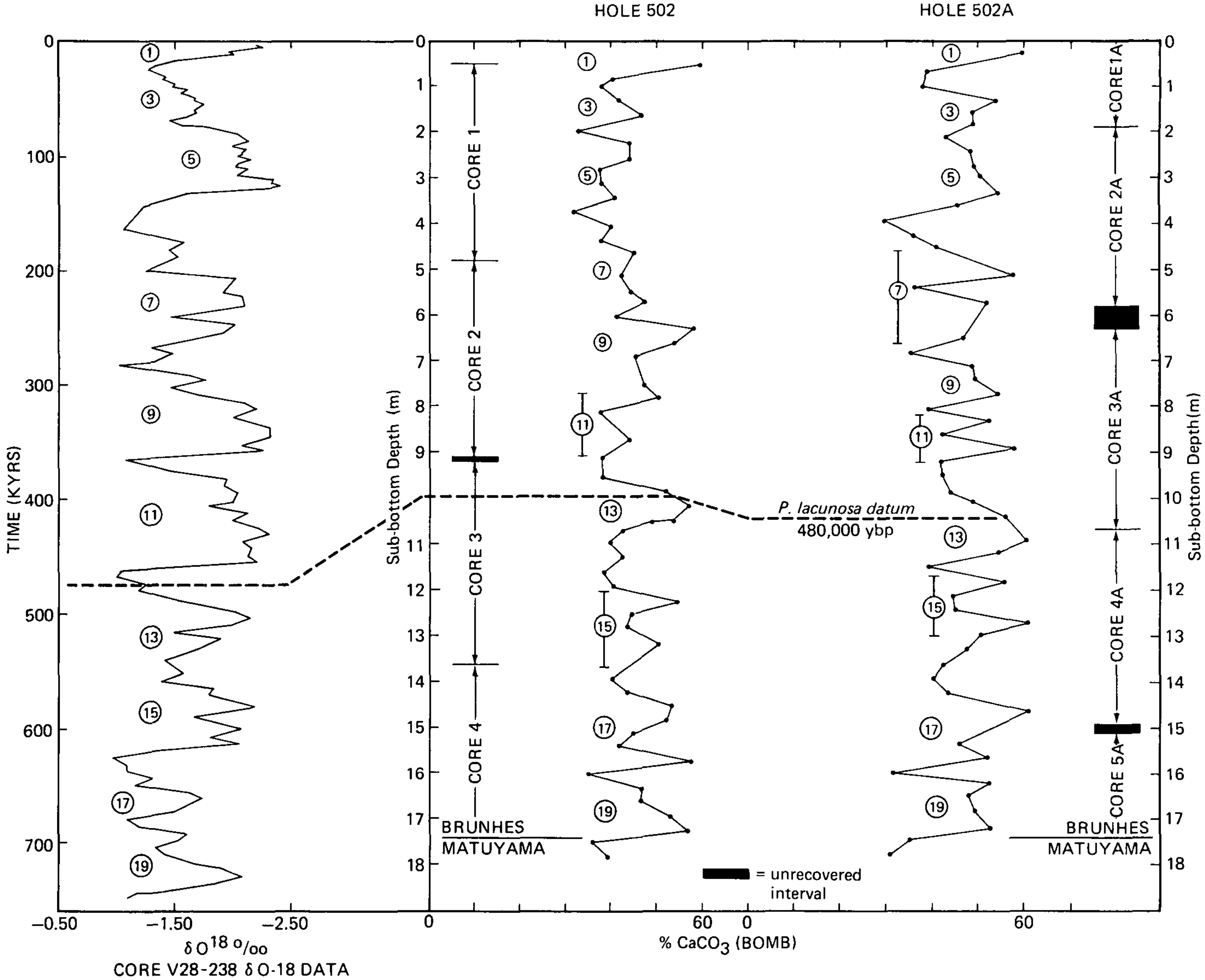

Figure 5. Correlation of carbonate content in Holes 502 and 502A with the oxygen isotope stratigraphy of core ***Vema*** 28-238 (Shackleton and Opdyke, 1976). Cores are numbered, and intervals of no recovery are shown in black. Isotope and carbonate stages are numbered 1 to 19, following Shackleton and Opdyke (1976). The oxygen isotope record is plotted versus time. The carbonate curves are plotted versus depth in the hole. Preliminary shipboard biostratigraphy places the extinction of ***Pseudoemiliani lacunosa*** in the upper part of Stage 13 in Holes 502 and 502A (dashed line). This extinction occurs in Stage 12 in ***Vema*** 28-238 (Thierstein and others, 1977). Examination of carbonate stages reveals the same pattern of variation and number of stages as the well-known oxygen isotope stratigraphy for the Brunhes epoch. Despite the variation of sampling interval in the carbonate data (the oxygen isotope record is sampled at a density three times that of the carbonate records), the identification of all stages and the continuity of the carbonate curves indicate that no significant sediment has been lost between successive cores with full recovery. Small gaps occur where less than 4.4 m was recovered. We attribute these gaps to failure of the core catcher.

(several are 30 cm long and are found in two of three holes) and, if verified, may provide new paleomagnetic data. The magnetostratigraphy should provide a new high-resolution standard for age calibration of biostratigraphic horizons.

Biostratigraphy. We found calcareous microfossils of Site 502 to be generally well preserved and diverse. Nannofossils are abundant, but planktonic foraminifera are sometimes rare because of carbonate dissolution and terrigenous dilution. Despite these problems, we recognized all of the standard late Neogene and Quaternary nannofossil and planktonic foraminiferal zones, which provide excellent biostratigraphic resolution (Fig. 8).

The planktonic foraminiferal assemblages are tropical throughout the section. However, below about 115 m, we found *Neogloboquadrina pachyderma* (sinistral) associated with a predominantly tropical assemblage. The sinistral coiling form is the coldest phenotype of this species in modern waters. This same association was noted by Keigwin (1978) at nearby Site 154. To our knowledge, consistent abundance of this

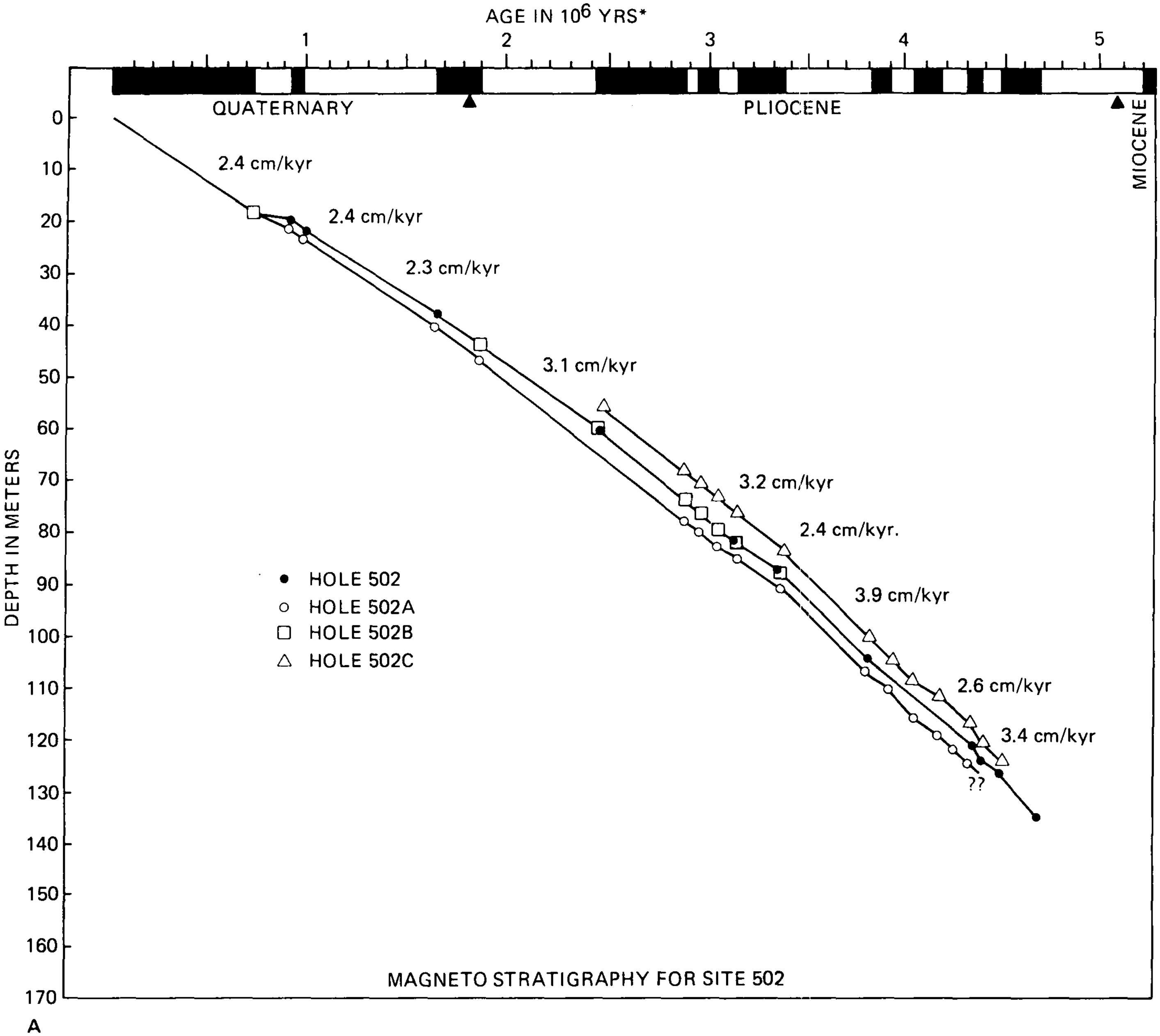

Figure 6A. Age versus depth in hole for magnetostratigraphic boundaries in Site 502.

species in a predominantly warm-water assemblage has not been described elsewhere. One interpretation of this relationship is that the early sinistral form of *N. pachyderma* was not restricted to cold waters.

The nannofloral assemblage is tropical through the Quaternary and late Pliocene. Assemblages from lower Pliocene and upper Miocene sediment may reflect somewhat cooler waters. However, preservation of nannofossils in this interval is also somewhat poorer than in the younger sediment. Well-preserved siliceous microfossils are found in the top few metres of the section and then not again until lower upper Miocene sediments. Very rare fragments of radiolaria, sponge spicules, and diatoms do occur throughout the entire section, which suggests that silica dissolution has been pervasive throughout most of the late Neogene and Quaternary. We do not observe enhanced preservation of silica in association with volcanic ash.

The basal sediments of the section recovered at Site 502 are early late Miocene (~8 m.y.) on the basis of the presence of nannofossils (*Discoaster neohamatus* Zone, *Discoaster bellus* Subzone), radiolaria (*Ommatartus antepenultimis* Zone), and diatoms (occurrence of *Nitzschia porteri* and *Thallassiosire burckliana).*

Accumulation History. Linear accumulation rates remain fairly constant, between 2.4 and 3.9 cm/thousand yr. Mass accumulation rates have been calculated using the scheme of van Andel and others (1975) together with our extensive physical property measurements. These calculated mass accumulation rates represent fluxes and reflect the complex interaction of carbonate productivity, carbonate dissolution, terrigenous influx, and tectonic uplift. The bulk rates decrease from late Miocene to Quaternary with an interval of high ac-

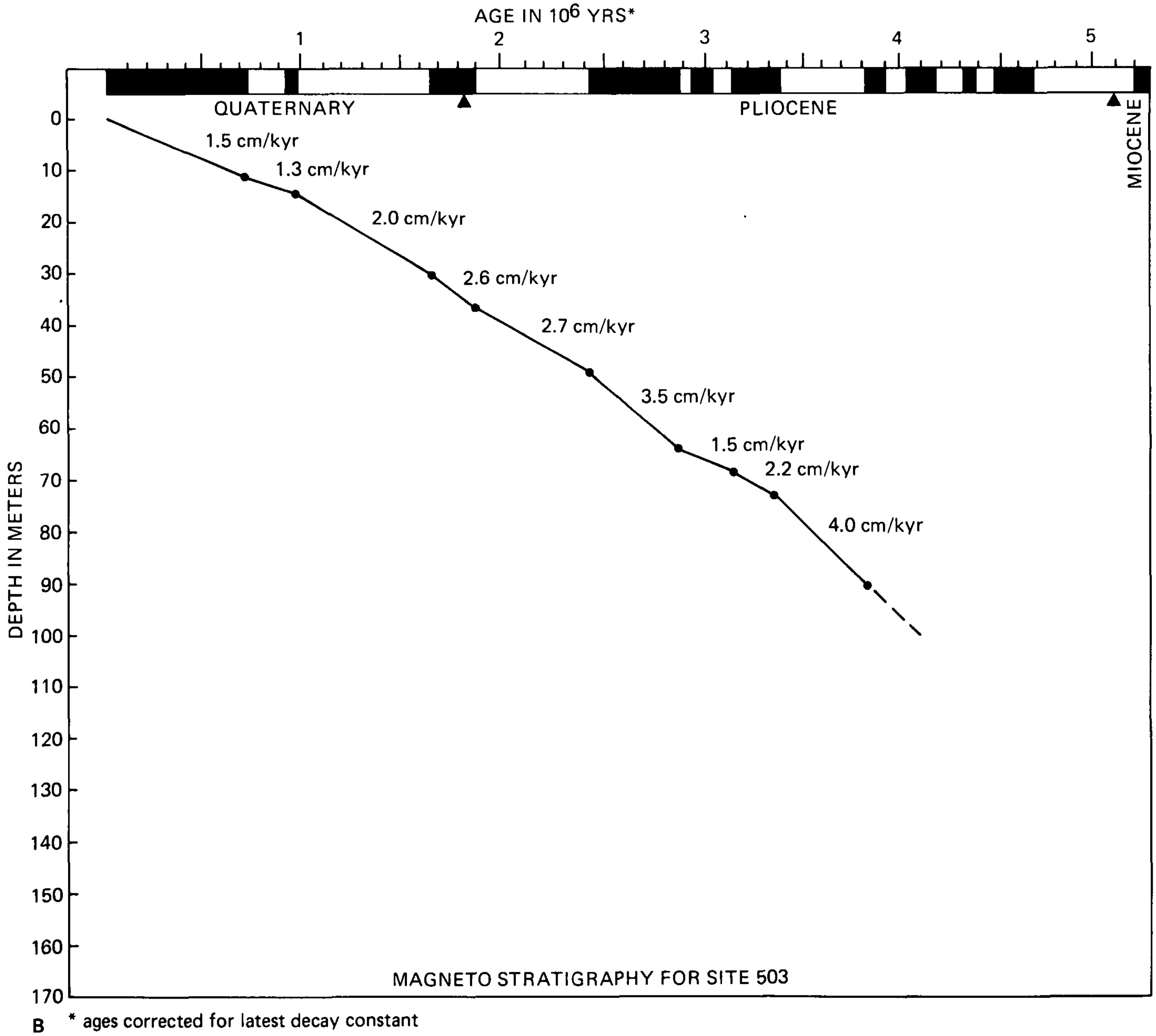

Figure 6B. Age versus depth in hole for magnetostratigraphic boundaries in Site 503.

cumulation at ~ 3.6 m.y. and a rapid decrease from 2.1 m.y. to the Quaternary (Fig. 7). The ratio of noncarbonate to carbonate flux decreases from late Miocene to about 3.6 m.y. and then remains constant through the rest of the Pliocene and throughout the Quaternary.

The decrease in accumulation of noncarbonate (mostly clay) sediment may be explained by a decrease in the supply of clay or by uplift of the site above the level of lateral near-bottom transport. Comparison of the reflection profiles across Site 502, Site 154, and the adjacent basin indicates that turbidite deposition has been active in the Colombia Basin from late Miocene through Holocene time. The sediment at Site 502 indicates that this area was already above the level of turbidite sand deposition prior to 8 m.y. This uplift substantially predates the uplift of Site 154 which is located on a much smaller ridge to the west between Site 502 and Central America. We interpret the onset of constant noncarbonate-carbonate flux to reflect the time (~3.6 m.y.) when the site was elevated above the level of major near-bottom clay transport. The timing is significant because it falls within the period that the Isthmus of Panama is thought to have closed, based on planktonic foraminiferal biostratigraphy (Kaneps, 1970; Saito, 1976; Keigwin, 1978). The volcanic ash in the late Miocene and early Pliocene of Site 502 may be related to the earlier phases of the tectonic evolution of the isthmus.

Site 503

Objectives. Site 503 was cored in the eastern equatorial Pacific near Site 83 (Fig. 3). Prior work at Site 83 indicates that the region experienced almost continuous pelagic sedimentation of all major microfossil groups from middle Miocene through Holocene time (Hays and others, 1972).

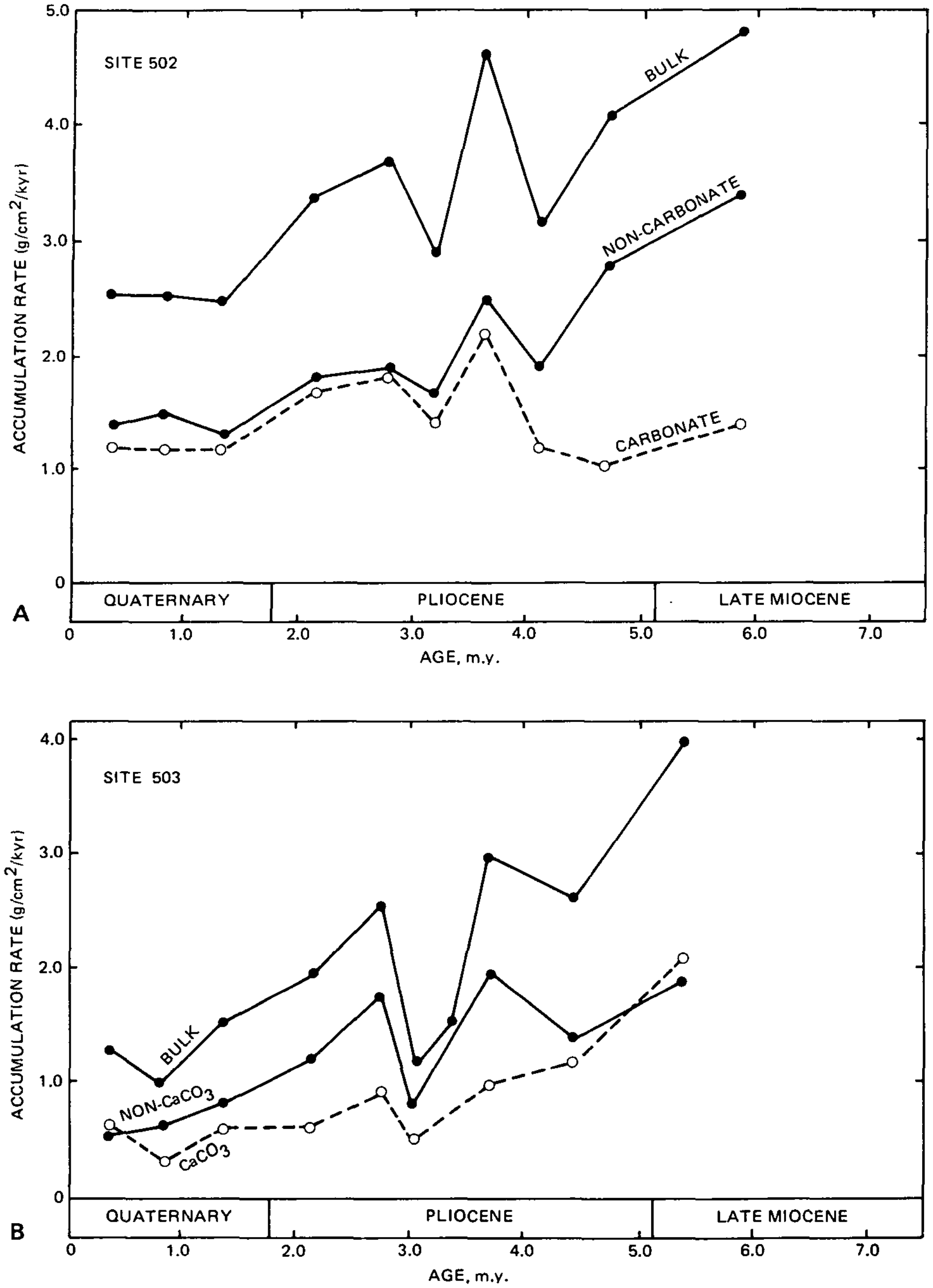

Figure 7. Mass accumulation rates (g/cm²/10³yr) for the bulk, noncarbonate, and carbonate sediment of (A) Site 502 and (B) Site 503. The magnetostratigraphy was used as time control, and accumulation rates were calculated after van Andel and others (1975).

Unfortunately, the sediment recovered at Site 83 was badly disturbed by drilling (Fig. 2).

Our primary objectives were (1) to recover a complete, undisturbed late Neogene and Quaternary section; (2) to compile a high-resolution intercalibration of biostratigraphy and magnetostratigraphy; and (3) to elucidate the detailed history of Neogene oceanographic conditions as revealed by fluctuations in stable isotope ratios, carbonate and opal contents, and changes in faunal and floral assemblages.

Results. We cored two holes (4°4.04′N, 95°38.21′W; 3,672 m depth) to a total depth of 235.0 m (Fig. 3 and Table 1) and recovered a section which represents approximately the past 8 m.y. The upper 100 m (Holocene through mid–early Pliocene) is virtually complete, whereas below 100 m (mid–early Pliocene through late Miocene), we recovered 70% of the section (Fig. 9, Table 1).

Site 83 was reported to be on the east flank of the East Pacific Rise; an age of 11 m.y. was given to the basal sediments (Hays and others, 1972). Van Andel and others (1975, Fig. 7) imply that Site 83 is actually located on the north flank of the Galapagos Ridge, and they reported an age of 8.2 m.y. for the crust. Bathymetry, of the detail available for both sites, cannot easily resolve which of these two interpretations is correct. The basement magnetics, however, can define which flank was sampled. The shipboard magnetometer data showed no magnetic anomalies as we steamed west-southwest to Site 503. However, we observed anomalies on our east-southeast transit to Ecuador. This pattern of anomalies suggests that we were over the northern flank of the Galapagos Rise.

Lithostratigraphy. The section at Site 503 consists of a uniform siliceous calcareous ooze with only minor compositional changes (Table 2). Carbonate and color cycles are apparent throughout the entire section and have periodicities which range from 20,000 to 40,000 yr per cycle. Curiously, we found very little volcanic glass and no zeolites. The sediment changes from an oxidized to a reduced state at 8.45 m and is reduced throughout the remainder of the section. Open burrows were observed from 9.3 to 64.0 m. Nodules composed of carbonate and/or silica(?) which formed around burrows occur from 13.5 to 235 m and are common from 13.5 to 60 m. Clay content is low and fairly constant down to 226 m, where it abruptly increases to greater than 25%. This increase in clay content occurs within about 20 m of the basement and may be the result of hydrothermal activity and/or weathering of the igneous basement.

Detailed measurements of shear strength, sonic velocity, bulk density, water content, porosity, and penetration (by needle penetrometer) were made on the sediment. The section proves to be highly undercompacted. Shear strengths vary around 400 g/cm² from 15 to 210 m (Fig. 4). Similar values were obtained at 25 m depth at Site 502 but continued to increase with depth (Fig. 4). The maximum value at Site 503 is only 1,686 g/cm². Porosities average about 90%, water contents about 80%, and sonic velocities about 1,510 m/sec down to a depth of 210 m. Velocities and shear strengths increase and porosity and water content decrease below 210 m (Fig. 4). A possible explanation for the undercompaction of these sediments was suggested by Lee (1973). He found shear strengths of only 300 to 400 g/cm² at depths greater than 275 m for diatomaceous sediments from the Bering Sea; he attributed this phenomenon to the presence of abundant diatom frustules. The frustules seem to be deposited in a closely-packed network and

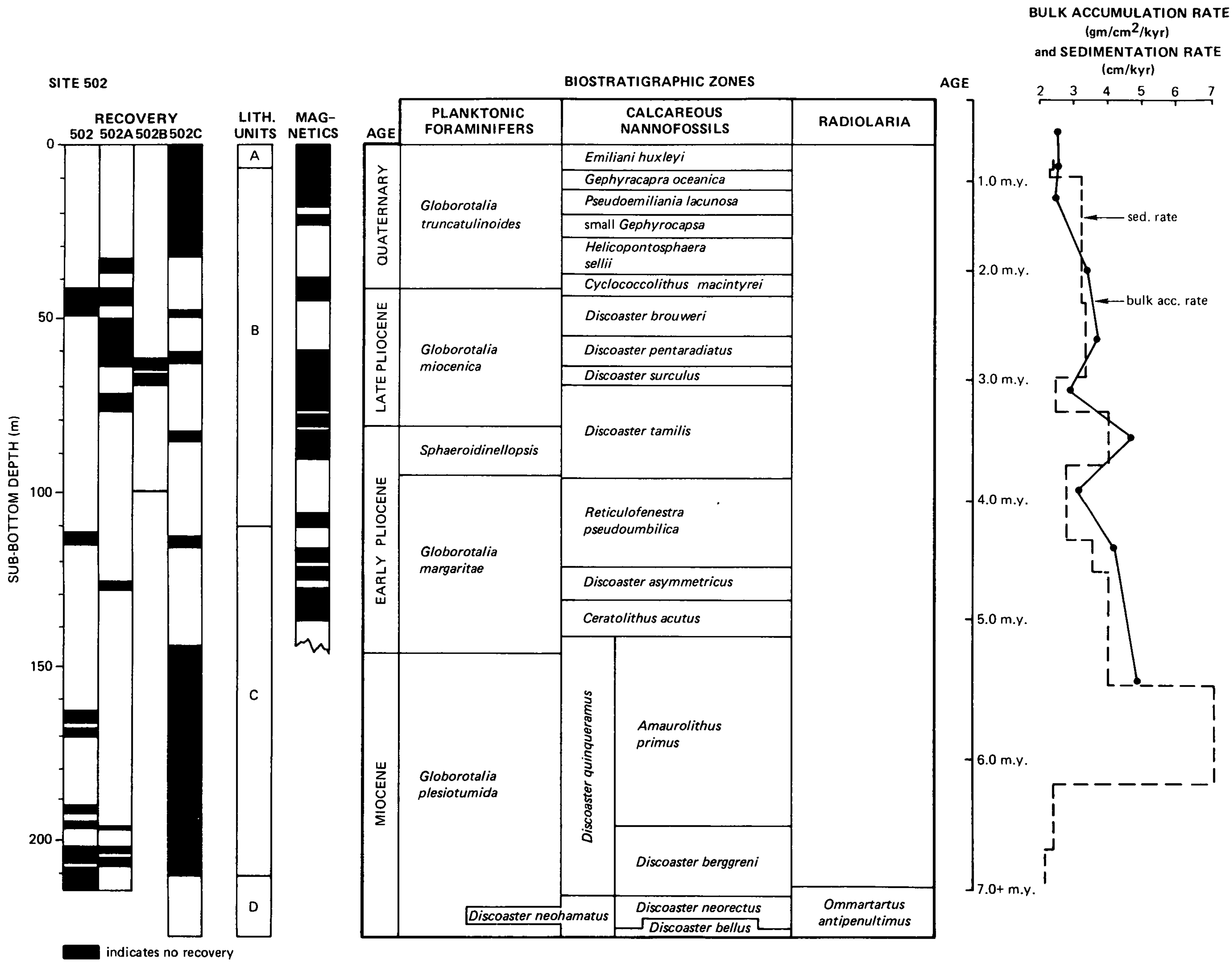

Figure 8. Summary of the recovery, lithostratigraphy, magnetostratigraphy, biostratigraphy, and sediment accumulation rates for Site 502.

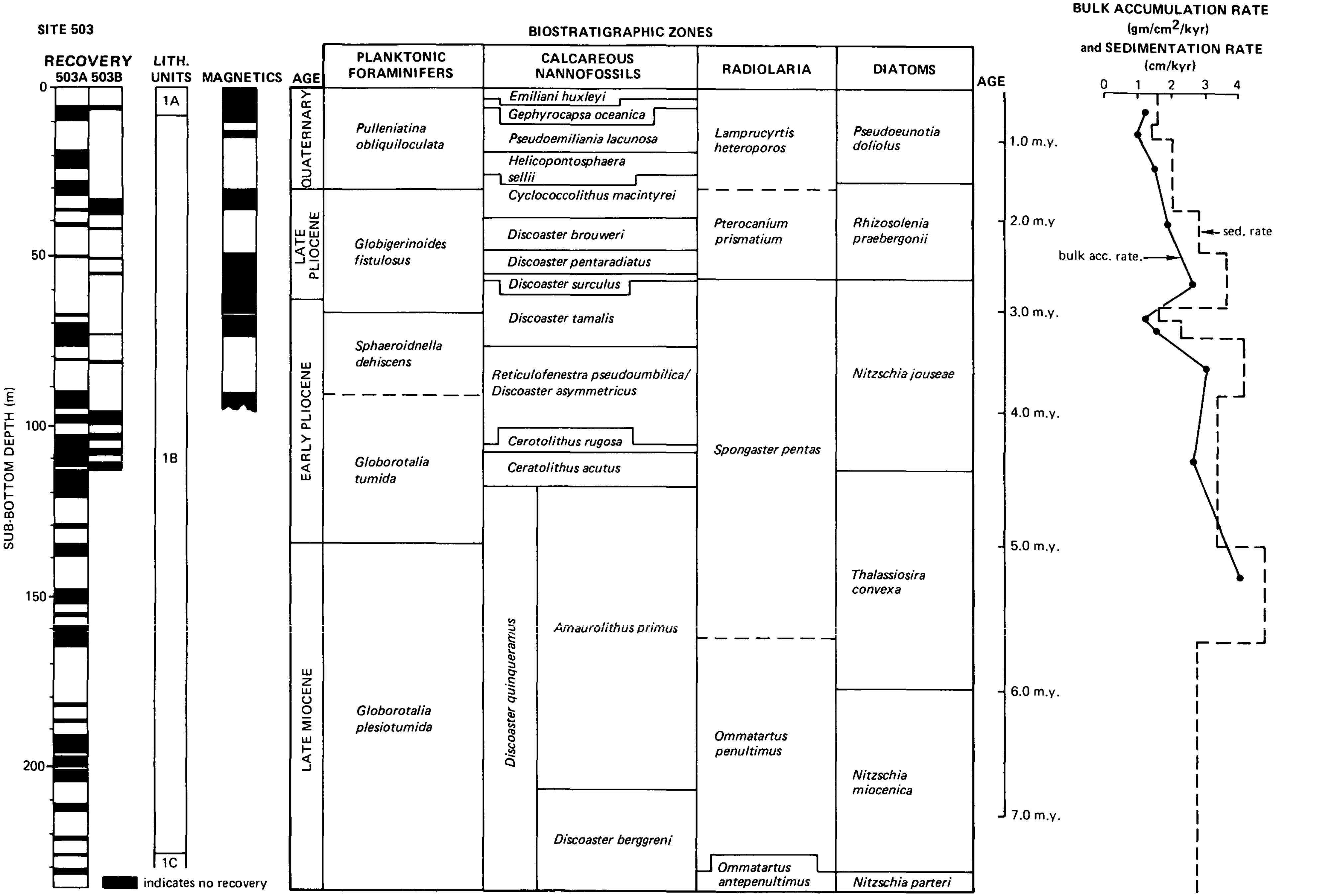

Figure 9. Summary of the recovery, lithostratigraphy, magnetostratigraphy, biostratigraphy, and sediment accumulation rates for Site 503.

are essentially incompressible at these lithostatic pressures. The high void ratios of diatoms account for the high porosity and water content. Even though the sediment from Site 503 is not diatom ooze, it contains appreciable quantities of diatoms and radiolaria, and we believe they are the cause of the undercompaction.

Biostratigraphy. Ages of microfossil assemblages range from Quaternary through late Miocene. Both calcareous and siliceous microfossils are sufficiently numerous and well preserved for detailed stratigraphic interpretation (Fig. 9). Cyclic zones of carbonate dissolution principally occur in the Quaternary but are also apparent in the Tertiary section. Planktonic foraminifera are rare to absent during dissolution intervals. Reworked assemblages of nannofossils and an assemblage dominated by *Thallassionema* and *Thalassiothrix* species occur in the late Miocene. These diatom assemblages have been interpreted to indicate upwelling (Jouse, 1971; Bukry and Foster, 1973). Radiolaria and diatoms show effects of dissolution in Quaternary sediment, but preservation is good in the Tertiary section.

Magnetostratigraphy. We were able to identify most of the magnetostratigraphic boundaries above the Gauss-Gilbert boundary (Fig. 6B) with the long-core spinner magnetometer, even though rust contamination from the drill pipe was a serious problem, especially in Hole 503A. Uncontaminated cores show clear cycles of NRM intensity with wavelengths comparable to the carbonate cycles. We see a decrease in the NRM intensity during the lower Gilbert epoch as was found at Site 502 in the Caribbean.

Accumulation History. Linear accumulation rates are about 4 cm/thousand yr from lower Pliocene through mid-Pliocene but decrease to 1.5 to 2.5 cm/thousand yr from mid-Pliocene through Holocene. Mass bulk accumulation rates that were calculated on the basis of paleomagnetic boundaries and our physical properties data generally decrease from late Miocene to late Quaternary with a distinct interval of high accumulation rates in the mid-Pliocene followed by a period of low accumulation rates (Figs. 7 and 9). The fluxes of both carbonate and noncarbonate (principally biogenic silica) show similar trends, suggesting pelagic sedimentation modified by dissolution and productivity.

CONCLUSIONS

We can make several observations from our shipboard analyses.

1. The combined magnetostratigraphy and biostratigraphy of Sites 502 and 503 will provide the most detailed, high-resolution stratigraphy for the late Neogene and Quaternary yet recovered. To our knowledge, these cores represent the only continuous sections containing all of the paleomagnetic boundaries from the Brunhes-Matuyama boundary through the bottom of the Gilbert.
2. Oxidized sediment occurs only in the uppermost 8 to 10 m of each section, and the remainder of the section has reduced states. This suggests pervasive, post-depositional reduction at both locations.
3. Our preliminary analyses support others in their contention that the Isthmus of Panama emerged between 3.6 and 3.2 m.y. ago.
4. The close similarity of the calculated accumulation-rate curves from Site 502 and 503 suggests a major event of reduced accumulation in the middle Pliocene.

In addition to the above scientific results, we were able to evaluate the performance of the HPC. We conclude the following:

1. The HPC can collect undisturbed, continuous sections of unconsolidated sediment. The HPC should be considered to be a routine sampling tool.
2. The penetration limits of the HPC (on the basis of Site 502 data) may be summarized as follows: the HPC fully extends in sediments with shear strengths $\leq$1,200 g/cm^2, regularly penetrates 1 to 3 m in sediments with shear strengths of 1,200 to 2,400 g/cm^2, and recovers $\leq$1 m in sediments with shear strengths of >3,000 g/cm^2. The HPC fully extended throughout Site 503.
3. Little to no sediment is lost between successive HPC cores in the same hole when full recovery is achieved. This continuity of section is best illustrated by the continuous carbonate curves in Holes 502 and 502A (Fig. 5).
4. The strategy of overlapping HPC cores in adjacent holes virtually assures recovering a complete section (Figs. 5, 8, and 9). The major obstacle to complete recovery is the failure of core catchers and core liners.
5. On the basis of Leg 68 results, the present HPC should recover between 80% and 90% of the section cored, and 85% to 90% of that section should be undisturbed. Recovery on Leg 68 varied in individual holes for a variety of reasons (see Table 1 for details). We expect recovery to improve to > 90% with the redesign of the core catcher.
6. The availability of the newly designed HPC offers a unique opportunity to recover continuous, undisturbed sections of the upper several hundred metres of the sea floor. These cores will make possible a wide variety of detailed studies which were heretofore not feasible.

ACKNOWLEDGMENTS

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REFERENCES CITED

Bukry, D., and Foster, J. H., 1973, Silicoflagellate and diatom stratigraphy, Leg 16 Deep Sea Drilling Project, *in* van Andel, Tj. H., Heath, G. R., and others, Initial reports of the Deep Sea Drilling Project: Washington, D.C., U.S. Government Printing Office, v. 16, p. 815–871.

Cline, R. M., and Hays, J. D., eds., 1976, Investigations of late Quaternary paleoceanography and paleoclimatology: Geological Society of America Memoir 145.

Curray, J. R., and Moore, D. G., and others, 1979, Leg 64 seeks evidence on development of basins: Geotimes, v. 24, no. 7, p. 18–20.

Dean, W. E., and others, 1977, Cyclic sedimentation along the continental margin of northwest Africa, *in* Lancelot, Y., Seibold, E., and others, Initial reports of the Deep Sea Drilling Project: Washington, D.C., U.S. Government Printing Office, v. 41, p. 965–989.

Edgar, N. T., Saunders, J. B., and others, 1973, Initial reports of the Deep Sea Drilling Project: Washington, D.C., U.S. Government Printing Office, v. 15, p. 1137.

Hays, J. D., and others, 1972, Initial reports of the Deep Sea Drilling Project: Washington, D.C., U.S. Government Printing Office, v. 9, 1205 p.

Jouse, A. P., 1971, Stratigraphic and paleogeographic investigations in the northwest part of the Pacific Ocean: Moscow, Akad. Nauk SSSR, 198 p.

Kaneps, A. G., 1970, Late Neogene (late Miocene to Recent) biostratigraphy (planktonic foraminifera), biogeographic, and depositional history, Atlantic Ocean, Caribbean Sea, Gulf of Mexico [Ph.D. thesis]: New York, Columbia University, 185 p.

Keigwin, L. D., Jr., 1978, Pliocene closing of the Isthmus of Panama, based on biostratigraphic evidence from nearby Pacific Ocean and Caribbean Sea cores: Geology, v. 6, p. 630–634.

Lee, H. J., 1973, Measurements and estimates of engineering and other physical properties, Leg 19, *in* Creager, J. S., Scholl, D. W., and others, Initial reports of the Deep Sea Drilling Project: Washington, D.C., U.S. Government Printing Office, v. 19, p. 701–720.

Prell, W. L., 1978, Upper Quaternary sediments of the Colombia Basin: Spatial and stratigraphic variation: Geological Society of America Bulletin, v. 89, p. 1241–1255.

Saito, T., 1976, Geologic significance of coiling direction in the planktonic foraminifera *Pulleniatina:* Geology, v. 4, p. 305–309.

Shackleton, N. J., and Opdyke, N. D., 1976, Oxygen-isotope and paleomagnetic stratigraphy of Pacific core V28-239 late Pliocene to latest Pleistocene, *in* Cline, R. M., and Hays, J. D., eds., Investigation of late Quaternary paleoceanography and paleoclimatology: Geological Society of America Memoir 145, p. 449–464.

Thierstein, H. R., and others, 1977, Global synchroneity of late Quaternary coccolith datum levels: Validation by oxygen isotopes: Geology, v. 5, p. 400–404.

van Andel, Tj. H., Heath, G. R., and Moore, T. C., Jr., 1975, Cenozoic history and paleoceanography of the central equatorial Pacific Ocean: Geological Society of America Memoir 143, 134 p.

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