1. INTRODUCTION

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GENERAL OBJECTIVES

The principal aims of Leg 24, between Djibouti (F.T.A.I.), at the western end of the Gulf of Aden, and the island of Mauritius, at the southern end of the Mascarene Plateau, were in part dictated by the three distinct geographic areas to be examined. *Glomar Challenger* traversed the Gulf of Aden, the northwest Somali Basin, and the Mascarene Plateau–Central Indian Ridge–Chagos-Laccadive Ridge complex. Common to all sites was the study of the sediments, their sources, and the role of depositional processes in the early stages of ocean development in the Gulf of Aden, in the magnetically quiet zone of the deep Somali Abyssal Plain, in the deep region north of the Seychelles and south of the Carlsberg Ridge, and between the Mascarene Plateau and Chagos-Laccadive Ridge. Continuous coring of selected low-latitude sites has resulted in the preparation of paleontological reference columns for the western Indian Ocean. Sampling, as fully as possible, continuous sections at basement-contact zones detected late-stage volcanic effects and better established a paleontological date for any magnetic anomaly lineation recognized. Drilling in igneous rock was carried deep enough to establish whether or not the rock was "basement" and to obtain fresh (unweathered) samples. Furthermore, by penetrating more than superficially into nonpyroclastic volcanic materials, attempts were made to establish and evaluate structural and textural criteria for presumed pillow and flow occurrences, to examine thickness, jointing, and fluidity of submarine flows and to assess significance of datable or metamorphosed sedimentary inclusions or joint fillings.

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Location of sites and the summary of the lithologic logs are shown in Figures 1 and 2, respectively. The site data on precise position and recovery statistics are summarized in Table 1.

SUMMARY OF RESULTS

The Gulf of Aden Sites (231, 232, 233)

The Gulf of Aden is a young and mobile region of intermediate depth bisected from east to west by Sheba Ridge, a seismically active zone that marks the spreading center (Matthews et al., 1967). Sheba Ridge is offset by several minor transform faults and, near its eastern end, by a linear north-northeast-trending cleft, the 5360-meter-deep Alula-Fartak Trench.

Site 231

Site 231, in water about 2160 meters deep near the southern shore of the Gulf of Aden and 80 km off Somalia, was drilled at a locality where smooth acoustic basement had been profiled. It was cored continuously through entirely hemipelagic sediment of Quaternary back into middle Miocene age. The sediment section is rather uniform nanno ooze, with indications of slumped shallow-water fossils and sandy horizons in the Pleistocene deposits and several volcanic ash layers in the Pliocene sediments. Four such layers were recognized. No breaks

TABLE 1
Coring Summary – Leg 24

Hole	Dates (1972)	Location	Water[a] Depth (m)	Subbottom Penetration (m)	Cores (no.)	Cored (m)	Recovered (m)
231[b]	May 5-8	11°53.41′ N, 48°14.71′ E	2161	584	64	584	425
232[b] 232A[b]	May 10-13	14°28.93′ N, 51°54.87′ E	1758	434	49	434	252
233[b] 233A[b]	May 13-16	14°19.68′ N, 52°08.11′ E	1860	271	32	271	173
234 234A	May 19-21	04°28.96′ N, 51°13.48′ E	4738	247	15	143	90
235	May 22-26	03°14.06′ N, 52°41.64′ E	5146	684	20	190	98
236[b]	May 28-June 1	01°40.62′ S, 57°38.85′ E	4504	328	37	328	218
237	June 5-9	07°04.99′ S, 58°07.48′ E	1640	694	67	627	312
238[b]	June 15-21	11°09.21′ S, 70°31.56′ E	2844	587	64	587	425
	Totals			3,829	349	3,164	1,995

[a]Here taken as the length of drill pipe from *Glomar Challenger*'s rotary table to the mudline.

[b]Sites continuously cored.

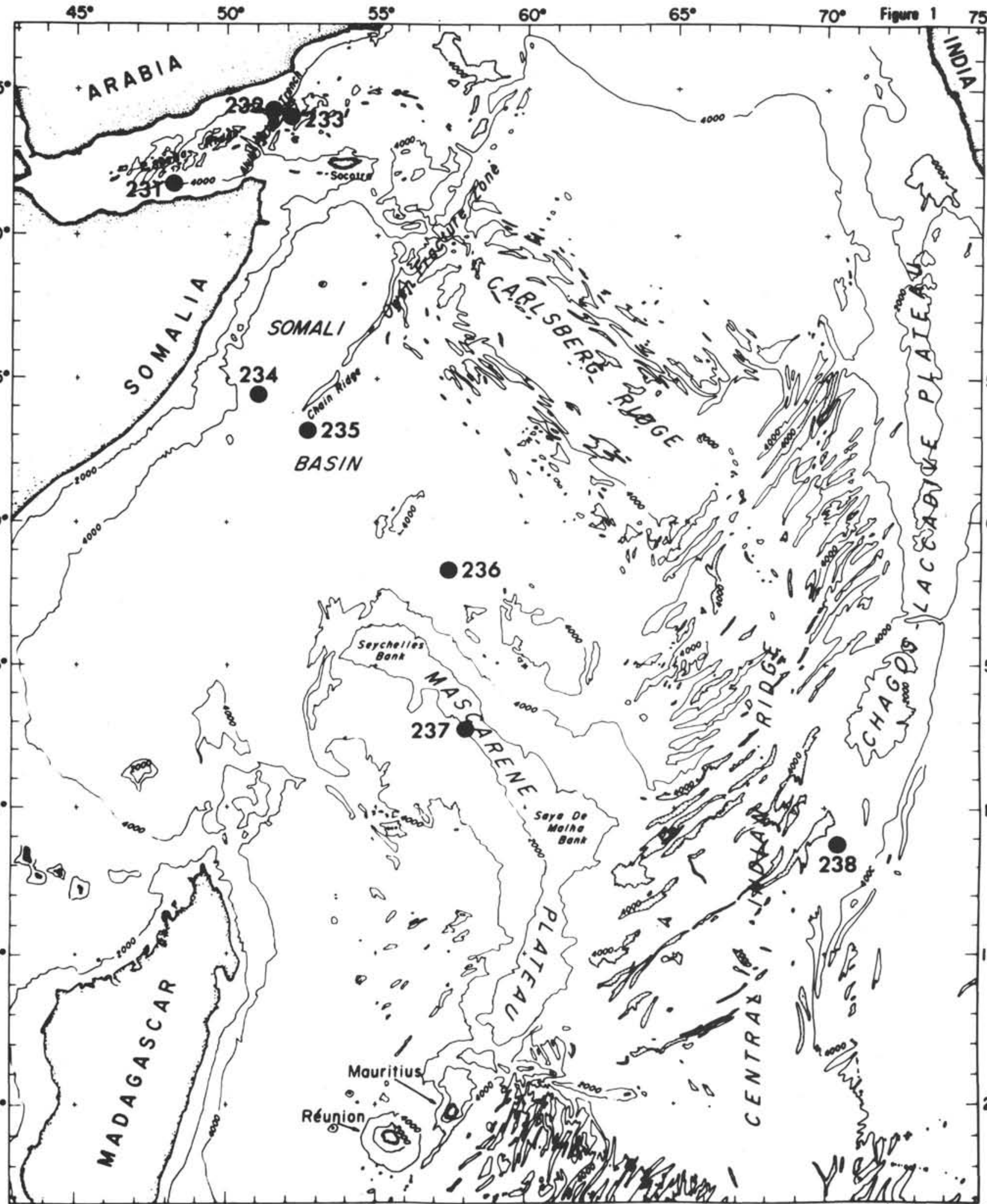

Figure 1. *Map of Indian Ocean showing location of Leg 24 sites.*

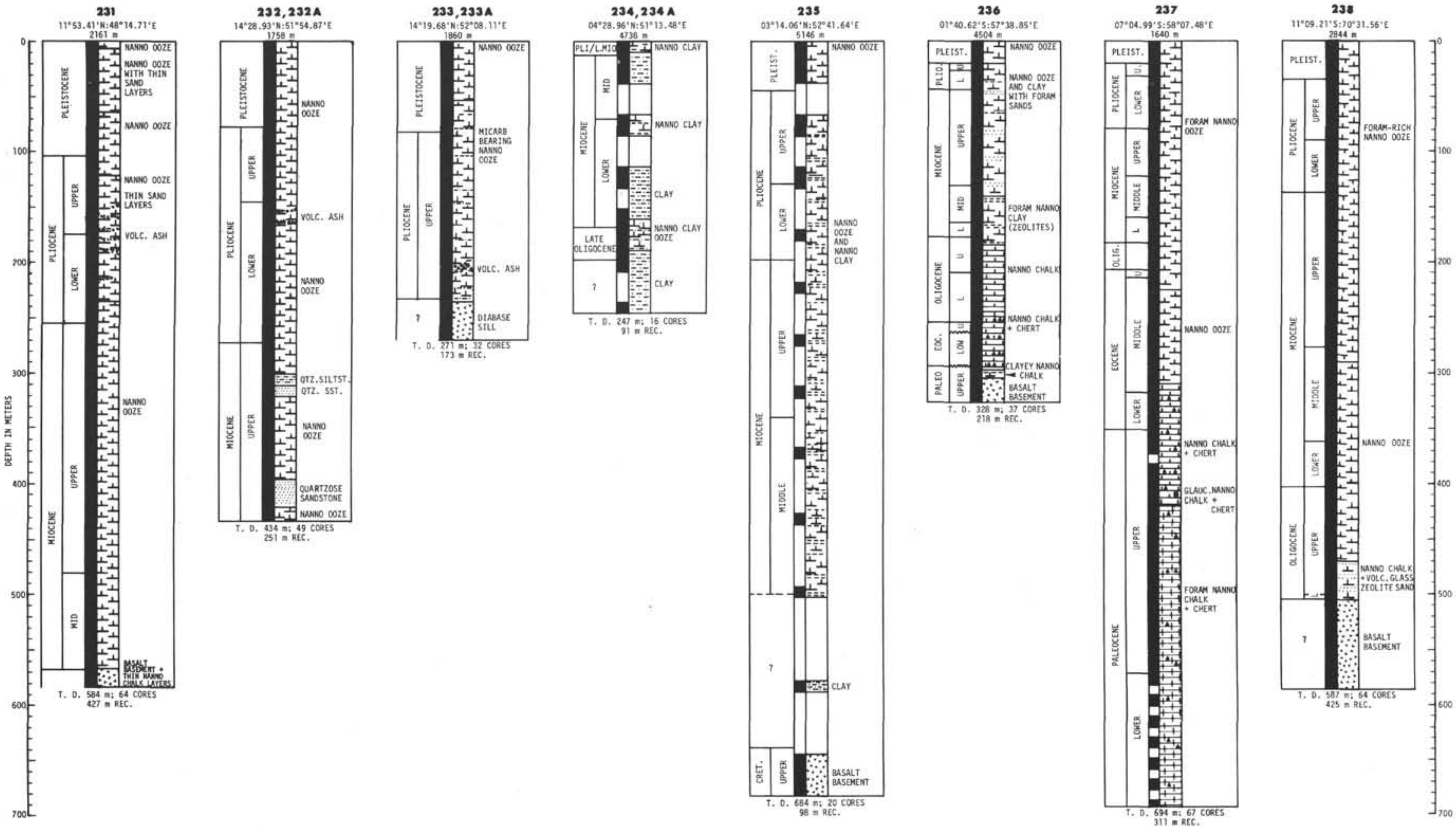

Figure 2. *Lithology and biostratigraphy of Leg 24 sites.*

were detected in the Pliocene-Pleistocene section, and we calculated a sedimentation rate of 50.8 m/m.y. Miocene sediments display rare patches of bitumen and hydrogen sulfide throughout much of the section. The rate of sedimentation for the late Miocene has been calculated as 38 m/m.y. Smooth trends in the physical properties suggest normal consolidation, which may be reflected in this lower rate for the Miocene. Igneous basement(?), here slightly altered oceanic tholeiite, was encountered at 566.5 meters and penetrated to a depth of 17.5 meters. Two nanno chalk inclusions, possibly joint fillings in the basaltic flow, are middle Miocene in age. Most basement specimens are fresh variolitic basalts containing both clinopyroxene and orthopyroxene(?); fresh glasses, in breccias, are interlayered with the granular basalts.

Uniformity throughout the sediment section suggests near constant conditions of depth, carbonate productivity, and detrital input at this locality since the inception of marine deposition in middle Miocene time. Some of the fine-grained material may be wind transported, with aridity in the probable source area of Somalia precluding large input of waterborne debris. The predrilling speculation that the basal acoustically-transparent layer might be evaporites, as in part of the Red Sea region, proved to be false. Despite a more than twofold increase in the chlorinity of interstitial water in sediments near the bottom of Site 231, there is no such direct evidence for damming of the Gulf of Aden.

Site 232

Site 232 (two holes) is near the western edge of the Alula-Fartak Trench in water about 1755 meters deep. Magnetic chronology at this site gives a basement age of about 10 m.y. The section was cored continuously to 434 meters, through "acoustic basement" and into soft sediments of late Miocene age. Six lithologic units were differentiated; three, making up more than 90 percent of the section, are hemipelagic nanno ooze with occasional quartzose sand layers. They cover the span from late Miocene to Quaternary. These suggest very constant conditions of water depth, pelagic carbonate production, and detrital sediment input, the latter probably of aeolian origin. Average sedimentation rate is 54.6 m/m.y. for the Pliocene/Pleistocene and 86.6 m/m.y. for the upper part of the late Miocene. Three acid volcanic-ash layers, found about halfway down the uppermost lithologic unit, probably correlate with similar layers in the early Pliocene of Site 231. Siltstones and sandstones, rather more lithified, calcite-cemented, thin-bedded, and highly quartzose, make up the three other units. These exhibit characteristics of shallow-water depositional environment and "continental" mineralogy, suggesting emplacement as fault or slide blocks derived from the Arabian continental margin to the northwest. We did not reach basaltic basement; so the question of the age and nature of the basin floor at this site remains unanswered.

The hemipelagic sediments accumulated at Site 232 are dominated by biogenic debris, the terrigenous fraction being rather minor. It appears that sediment input into the northern Gulf of Aden from the extensive Wadi Hadramaut-drained system has been relatively small or has all been trapped in nearshore environments.

Site 233

Site 233 was drilled in about 1860 meters of water on the back side of the eastern flank of the Alula-Fartak Trench. Only about 30 km southeast and across the trench from Site 232, basement at Site 233 has been tagged as Anomaly 3 in age. Here two drill holes using the same beacon were overlapped to provide continuous coring from the sea floor to 271 meters. We encountered the discrete, widespread, and easily recognized acoustic basement, a diabase sill perhaps 8 to 37 meters thick, at 234.5 meters, and recovered 2.6 meters of slightly altered diabase of uniform doleritic texture and, apparently, no great age. Markedly increased drilling rates deeper in the hole indicated soft sediments below this "basement reflector" but diabase found wedged in the drill bit precluded recovery of any material penetrated below 243 meters and necessitated pulling the drill string at 271 meters. The sedimentary sequence consists of micarb-bearing nanno ooze and nanno chalk; baking occurs just above the intrusive. Late Pliocene and Pleistocene rates are 117 and 45 m/m.y., respectively. Acid volcanic glass again is found in the Pliocene section. If the quartzose sand layer at 209.5 meters correlates with similar material at Site 232 across the cleft, opening of the Alula-Fartak Trench may postdate the early Pliocene. However, benthic forams indicate a bathyal environment throughout, with no evidence of downslope transport from shallow regions.

The Northwest Somali Basin (Sites 234, 235)

The western Somali Basin (Bunce et al., 1967) is a magnetically quiet zone containing ponded sediments, 2 to 3 km thick, that appear similar in aspect on widely separated reflection profiles, with an acoustically transparent layer separating the upper and lower stratified (partly turbidite) sequence. The western pond forms the Somali Abyssal Plain and is bounded on the north and west by the Somali continental rise and marginal ridges; to the east by Chain Ridge, which is a possible age discontinuity; and to the south by a subsurface feature that probably is the buried continuation of Chain Ridge. While the extreme sediment thickness below the already deep abyssal plain surface prevents drilling to basement in much of the area, both older sediments and basement might be sampled at the borders where deeper sediments do onlap basement slopes beneath thinning younger layers.

Site 234

Site 234 was selected in a region of onlap near the western margin in an attempt to reach the older sediments, to obtain basement rock for comparison with that dredged from Chain Ridge, and to determine, from turbidite mineralogy, African source areas and their tectonic history. Two holes were drilled, using the same beacon, in about 4740 meters of water; the second of these, 234A, was abandoned after a single core. The pair, cored intermittently, reached only 247 meters below the sea floor; drilling was terminated there because of repeated seizing and sticking of the drill string. The cored sediments, extending downward from Pliocene back to Oligocene(?), consist largely of nanno clay and ooze, and are generally lacking in sand-sized components or turbidites. Fossil identifications are fragmentary but infer sedimentation rates of about 1.0 m/m.y. for post middle Miocene time, with evidence of oxidizing conditions, about 13.0 m/m.y. for the early and middle Miocene horizons, under more reducing conditions, and about 7.0 m/m.y. for the late Oligocene.

A few conclusions may be drawn from the partly cored sections: (1) the etched and corroded calcareous nannofossils and poorly preserved foraminifers indicate that the site must have been close to carbonate compensation depth (CCD) throughout the time of deposition; (2) minor amounts of zeolitic sand do suggest important volcanic input to this offshore region; (3) clay sediments of yet undetermined origin dominate; and (4) this site seems to have been well removed from the African landmass, or at least effectively inaccessible to slumped material or turbidity currents during the intervals represented by the sediments recovered.

Site 235

Site 235 was drilled in about 5140 meters of water at the westernmost edge of the abyssal plain that onlaps the east flank of Chain Ridge. It was cored intermittently from the sea floor to basement, which was encountered at 651.5 meters, and then continuously to hole bottom at 684 meters. The sediments recovered are mainly nanno ooze with some calcareous clay-bearing intercalated sand layers and some traces of volcanic glass.

Extensive calcium carbonate solution makes foraminifera rare to absent, but the calcareous sediments are rich in moderately well-preserved nannofossils. Chiefly characteristic are high clay-mineral content, presence of finely laminated silty sand horizons, and the evidence of oxidizing conditions just above basement. Sedimentation rates for Pleistocene back to middle Miocene average 37 m/m.y. However, sediment pods at the upper basement contact contain Cretaceous (late Maestrichtian) nannofossils. Basement, which provides the only firm acoustic-lithologic correlation, was penetrated for 32.5 meters, with 13 meters of core recovered. It consists principally of massive to somewhat fractured basalt with obvious porphyritic texture, oxidized at the upper surface and between lower flows. Brecciated glasses occur in the middle of the basement section. Dark brown spinel is present as a minor mineral in these basalts; its association here with olivine suggests a deep magmatic source.

From the sediment column at Site 235, one might conclude that (1) fluctuations in the CCD have occurred while the sedimentary milieu has evolved from an oxidizing environment toward more reducing conditions; and (2) minor turbidite deposits may have originated from Chain Ridge or slopes above the northern margin of the abyssal plain.

The Mascarene Plateau–Central Indian Ridge–Chagos-Laccadive Ridge Complex (Sites 236, 237, 238)

Site 236

Site 236, in water about 4500 meters deep, was drilled into basement in the sedimented outer foothills southwest of Carlsberg Ridge and about 270 km northeast of Seychelles Bank. Lying between anomalies 26 and 27, it is near the oldest cycle of an ancient magnetic-anomaly pattern associated with Carlsberg Ridge or a proto-Carlsberg Ridge (Fisher et al., 1968). It was cored continuously from the sea floor to 306 meters, where basement, here a veined and chloritized basalt, was encountered and thence 21.5 meters into igneous rock. The section recovered represents a complete sequence from late Paleocene through Quaternary horizons with hiatuses in the Eocene and uppermost Paleocene; it contains common to abundant calcareous planktonic fossils typical of a low-latitude open-ocean environment. Thin volcanic ash layers and some chert occur in the Eocene nanno ooze. Clayey nanno chalks overlying the basaltic basement are higher in clay minerals. iron oxides, and pyrite, suggesting weak posteruptive hydrothermal activity. Average accumulation rates increase from about 3.3 m/m.y. for the interval late Paleocene through early Miocene to 11.3 m/m.y. for the interval middle Miocene to Quaternary. The increase reflects the presence in quantity of foraminifera and siliceous fossils in the later strata. Basement basalts display two facies: the upper part is olivine-bearing tholeiite, and the lower four-fifths of the igneous section is a subalkalic melano-basalt enriched in clinopyroxene. From the rather complete paleontological record at Site 236, and an assumption that this site does indeed lie between anomalies 26 and 27, there are some slight discrepancies (up to 7-8 m.y.) in the several magnetic time scales so far proposed. Some reexamination of profiles is indicated, but this date suggests that India and the Seychelles-Mascarene Plateau region may have been sundered–if they were once one–rather later than is currently believed.

Site 237

Site 237, which was terminated short of the basement because chert dulled the bit, was drilled in 1630 meters of water in the intermediate-depth saddle joining granitic Seychelles Bank to volcanic(?) Saya de Malha and the shoal areas to the southwest. Except for one 9.5-meter joint, coring was continuous from the sea floor to 585 meters; from that depth to hole bottom at 693.5 meters, alternate joints were cored. The sedimentary lithologic units differentiated represent a sequence of primary nanno ooze from the present back through early Paleocene. Late Eocene and Oligocene are condensed; middle and early Eocene and Paleocene are very thick. The lower 273 meters consists of altered and recrystallized nanno chalk with cherty horizons. Although pelagic sediments dominate the entire section and deep-water indicators are present throughout, evidences of shallower water interludes in Paleocene and Eocene time are indicated by the presence of glauconite, lensing and lamination of sedimentary structures, and by reef debris, probably brought to this locality by slides or slumping from nearby banks or shoals. If the basal sediments were deposited in depths as shoal as 500 meters, the site has sunk, relative to present sea level, about 2 km in 60 m.y. Apparent sedimentation rates through time differ widely. From middle Miocene to the present, with sediments being foraminiferal nanno ooze, the average rate is 11.3 m/m.y. From Oligocene through early Miocene, the oozes accumulated at the average rate of 2.0 m/m.y. Rates for Eocene and Paleocene intervals, with pelagic carbonate ooze being deposited, are very much higher, being as high as 60.2 m/m.y. in the early Paleocene. This again indicates that extensive early Tertiary slumping moved fine-grained carbonates to this locality and is responsible for the great thickness (300 m) of Paleocene deposits. Finally, we did not fulfill our main objective: this site did not yield either the age or petrologic character of the basement between 600 m.y. old granitic Seychelles Bank and Saya de Malha.

Site 238

Site 238 is located in about 2840 meters of water at the extreme northeast end of Argo Fracture Zone, within a partly buried transform-fault cleft athwart the seismically active and spreading Central Indian Ridge. The hole was cored continuously from the sea floor to 506 meters where basement was encountered conformably overlain by Oligocene sediments. Basement was then continuously cored for 80.5 meters to hole bottom at 586.5 meters. Three sedimentary lithologic units were distinguished, all nanno ooze or nanno chalk with greater foraminifer admixture in the later, more reduced strata. In the oxidized lowermost unit, there are intercalated horizons of volcanic debris, clays, and zeolite sands, plus fragments of quartz, mica, and feldspar, manganese micronodules, and bits of hard limestone. Such coarse material would have been deposited in an early structural trough, between igneous walls, then existing between the facing scarps of the transform fault. Apparent sedimentation rates are high for post-early Miocene time, averaging 25.9 m/m.y. Rates average 8.7 m/m.y. in Oligocene through early Miocene time and amorphous iron oxides from this interval are less diluted. In the lowest unit, sedimentation rates are high in volcanic debris and iron oxide zones, low in the intervening nanno chalks. One might conclude that this area always lay above the CCD and was in a highly productive region, as attested by the overall richness of the three pelagic microfossil groups and by iron oxides increasingly diluted with time. The incidence of volcanic material in the lower sedimentary unit shows that the after effects of volcanism persisted long after the final extrusion of basement basalts—in fact, until the site had migrated away from the spreading center. The igneous basement is composed of dense gray basalt, very little altered and commonly vesicular, emplaced as flows. Selvages of glass occur at pillow edges and seams, and the lower section contains inclusions of metamorphosed sediments with relics of foraminifers and radiolarians. Petrographically, the basement of Site 238 is very uniform tholeiite, some with minor olivine, very much like that at Site 231.

At Site 238, one ancient end of Argo Fracture Zone, and not as it turned out, incontrovertibly on the southern end of Chagos-Laccadive Ridge, we fulfilled our objectives only in part. It provided abundant sedimentary and igneous material to document the winding down of a crustal rupture. The date of supposed sundering of the Chagos-Diego Garcia region from Cargados Carajos/Nazareth Bank has been moved back in time, perhaps to the early Oligocene. This calls for reexamination of magnetic lineations between Anomaly 5 and the boundaries of transform-faulted blocks.

EXPLANATORY NOTES

Organization of This Report

This volume is divided into three parts. The introductory chapter presents the scientific rationale for drilling this area of the Indian Ocean, a preliminary scientific summary of results at each of the eight sites occupied, and notes on procedures and conventions employed aboard *Glomar Challenger* and in describing the specimens examined. Further, in this initial section, the site reports are presented in Chapters 2 through 9, according to a standard schedule:

Site Data
Background and Objectives
Operations
Lithologic Summary
Biostratigraphic Summary
Sediment Accumulation Rates
Physical Properties
Interstitial Water Chemistry
Correlation of Reflection Profiles and Lithology
Summary, Conclusions, and Speculations

In the second part appear the more specialized studies made ashore subsequent to the cruise, both by shipboard scientists and by other specialists who were not in the field program. In this section appear the reports of the designated shore-based laboratories.

The third portion synthesizes the scientific results and conclusions from overall lithostratigraphy and biostratigraphy.

Responsibility of Authorship

The site reports are coauthored by the shipboard scientific party. The abstracts and the background-objectives were written by Robert L. Fisher and Elizabeth T. Bunce, or vice versa, depending on the particular site; the operations by Fisher and Lamar P. Hayes; lithologic summaries variously by David Cronan, Vincenzo Damiani, David J. J. Kinsman or Jorn Thiede, with petrology by Leonid V. Dmitriev and R. L. Fisher; biostratigraphy by Edith S. Vincent, Peter Roth, William Riedel, and Annika Sanfilippo; physical properties by Paul Cernock; interstitial water chemistry by Kinsman; correlation of profiles and lithology by Bunce, and the conclusions-speculations by Bunce or Fisher with input from all.

Jorn Thiede was responsible for the compilation ashore of the sediment core summary forms and their redrafting.

Site Surveys Prior to Leg 24

Indian Ocean sites proposed for drilling on the basis of profiler records obtained by Lamont-Doherty Geological Observatory (*Conrad*-12, 1969), Scripps Institution of Oceanography (CIRCE, 1968), and Woods Hole Oceanographic Institute (*Chain*-43, 1964) had been scouted in detail by E. T. Bunce (R/V *Chain*, Cruise 100, 1971: Sites 234, 235) and R. L. Fisher (R/V *Melville*, ANTIPODE expedition, 1971: Sites 236, 237, 238). In the Gulf of Aden, where reconnaissance work had been done by R.R.S. *Discovery* in 1967, it was necessary to make preliminary passes to ensure that the point selected for drilling met the objectives and essentially matched the descriptions provided by A. S. Laughton and D. G. Roberts of the Institute of Oceanographic Sciences, Wormley, Surrey, United Kingdom.

Underway Observations

Glomar Challenger's underway geophysical measurements were obtained with a Varian proton-precession magnetometer, a 12-kHz bathymetric system employing a Gifft GDR-1C-19 recorder, and a seismic reflection profiler system with various streamers made up to meet current needs. The reflection profiling generally included two PAR 600A airguns firing simultaneously, one operating at 20 cu.in., the other at 10 cu.in., an EVP-23 hydrophone array, two Edo Western recorders and Bolt PA-7 bandpass filters normally operated at 40-160 Hz. The recorders were operated at two different sweep rates, 10 sec and 3-4 sec (with minor exceptions) full scale, the latter for higher resolution of shallow features.

Wide-angle reflection-refraction measurements using sonobuoys as receivers were made, or attempted, at each site. After recovery of drilling gear, the technique was to steam away from the beacon on a course reciprocal to that to the next site, meanwhile streaming seismic gear and checking its operation, then to reverse course and drop the sonobuoy. In principle, seismic propagation would then occur across the drill site. Ship speed was maintained at 5-6 kn for the approximately two hours of useful data acquisition. The oblique or wide-angle reflection data obtained will be useful for the sediment column interval velocities; the expected refraction information did not materialize due to the high low frequency cut off of the sonobuoy receiver. The underway geophysical observations are presented in Chapter 10 of this volume.

Navigation was based on satellite fixes with later processing by techniques customary to the Scripps Institution of Oceanography Underway Data Processing Group and to the DSDP where the detailed information is available.

Bathymetric charts prepared aboard *Glomar Challenger*, such as those appearing in the site reports, as well as the more extensive plots used as base maps in broader studies, are contoured in "Matthews-corrected meters" from soundings adjusted for the velocity of sound in seawater according to the tables of Matthews (1939).

Drilling Operations

Drilling attempts were routinely successful; they are chronicled in the site reports. It was necessary to make a second penetration at only three sites and especially at (1) Site 232, where a special instrument case parted and the untethered core barrel fell to the bottom of the string and was retrieved only by pulling out; and (2) Site 234, because of an inability to rotate the drill string in the stiff clays. No tools were lost in the course of penetrating 3829 meters, coring 3164 meters, and recovering 1994 meters: this program included coring 163 meters and recovering 74.1 meters, of basaltic or diabasic material, primarily basement.

Configuration of the bottom hole assembly (BHA) used throughout Leg 24 was as follows, from the bit up: (1) 10 1/8" tungsten carbide button bit, (2) 8 1/4" float sub, (3) 8 1/4" core barrel, (4) Three 8 1/4" drill collars, (5) Two 8 1/4" Baash Ross bumper subs, (6) Three 8 1/4" drill collars, (7) Two 8 1/4" Baash Ross bumper subs, (8) Two 8 1/4" drill collars, (9) 7" drill collar, and (10) 5" joint of heavy wall drill pipe.

Shipboard Laboratory Procedures

Basis for Numbering Sites, Holes, Cores, and Sections

The ensuing discussion of this topic, and the one on handling of sediment cores that follows, draws in part from the excellent exposition of these subjects in Burns, Andrews et al. (1973), which covers Leg 21 procedures on sediment cores.

A site number refers to a single hole or group of holes drilled essentially in the same position using the same acoustic beacon. The first hole at a site (for example, Site 232) was given the number of the site (Hole 232). Second holes drilled by withdrawing from the first hole and redrilling were labeled "A" holes (Hole 232A).

A core was usually taken by dropping a core barrel down the drill string, and coring for 9.5 meters as measured by the lowering of the drill string before recovery. The sediment was retained in a plastic liner 9.28 meters long inside the core barrel and in a 0.20 meter long core catcher assembly below the liner. The liner was not full in the usual case.

On recovery, the liner was cut into 1.5-meter sections as measured from the lowest point of sediment within the liner (Figure 3); this yielded a maximum of six 1.5-meter lengths and an upper 28-cm stub.

In general, the top of the core did not coincide with the top of a section. The sections were labeled from 1 for the top (incomplete) section to a figure as high as 6 for the bottom (complete) section, depending on the total length of core recovered.

In the event there were gaps in the core resulting in empty sections, these were still given numbers in sequence. Core catcher samples were always considered to have come from the bottom of the cored interval regardless of the depth assigned to the adjacent section above.

On occasion, over 9 meters of core were recovered. The small remainder was labeled Section 0 (zero), being above Section 1.

All samples taken from cores, before being processed, were numbered according to the following system: Example, 24-231-3-2, 75 cm refers to Leg 24 Hole 231, Core 3, Section 2, sampled at 75 cm from the top of that section. The label "24-231-3, CC" refers to the core catcher sample at the base of Core 3 in the same hole.

It is appreciated that with this labeling system the top of the core material recovered may be located at, for example, 1.3 meters below the top of Section 1 and bottom will be at 1.5 meters in, say, Section 2 (if the total recovery is 1.7 meters). In relating this to downhole depths, there is an arbitrariness of several meters. However, it is impossible to assess where exactly in the hole the sample came from. Sometimes the core barrel will jam up with a hard sediment after sampling a few meters; this then will really represent the first few meters penetrated. At other times, the

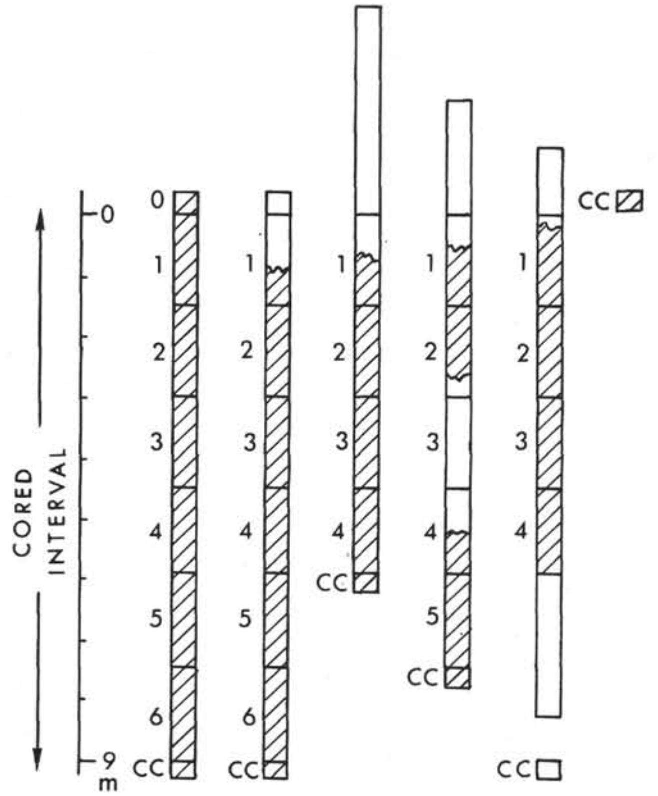

Figure 3. *Method of labeling sections of cores when recovery is complete, incomplete, and divided. The cores have been lined up so that the top of Section 1 is always coincident with the top of the cored interval, according to the method of calculating down-hole depth of samples. Core-catcher samples are always considered to have come from the bottom of the cored interval regardless of the depth assigned to the adjacent section above.*

circulation of water may wash away the upper softer part of a core and recovery will represent the lower part. Separated lengths of core in a core liner may result from the drill bit being lifted away from the bottom of the hole during coring in rough sea conditions. Similarly, there is no guarantee that the core catcher sample represents the material at the base of the cored interval.

The labeling of samples is therefore rigorously tied to the position of the samples within a section as that position appears when the section is first cut open and as logged in the visual core description sheets. The section labeling system implies that the top of the core is within 1.5 meters of the top of the cored interval. Thus, the downhole depth of "24-231-3-2, 75 cm" is calculated as follows. The top of the cored interval of Core 3 is 15 meters. The top of Section 2 is 1.5 meters below the top of the cored interval, that is, at 16.5 meters. The sample is 75 cm below the top of Section 2, that is, at 17.25 meters.

For the purposes of presenting the data for the entire hole in the hole summary sheets, where 1 meter is represented by less than 1 mm, the top of the recovered sediment is always drawn at the top of the cored interval. The error involved in this presentation is always less than 1.5 meters compared with depths calculated from the sample label.

On Leg 24, considerable interest was attached to recovery of igneous rock or basement in quantity. Volcanic or intrusive rock inherently is texturally and structurally less amenable than soft sediments to the procrustean sectioning techniques outlined above. Hence modifications were made. For example, on occasions when hard rock was encountered, drilling was suspended and the core recovered when less than 9.5 meters penetration had been achieved. In most cases, rapid inspection of this shortened core indicated the bit was still sound, so coring with a new liner was resumed. With regard to the present questions of section inventory, however, it was soon realized that no virtue attaches to having a hard-rock core catcher specimen logged and preserved separately from the equally disassociated stubby igneous links immediately above it in the lowermost portion of the liner. Hence, while the just-extricated liner still lay horizontal in its rack on deck, any coherent sample, commonly a cylinder, that was recovered from the core catcher assembly was inserted, in its proper vertical orientation, into the lower end of the core liner. Ordinarily little or no force was required; the core overall was abundantly fragmented. Then the rock-in-liner was examined and measured in a preliminary way and the plastic liner cut and capped at convenient intervals, approximately 140-150 cm, where the enclosed rock need not be sawed. Again, limited efforts were made to allow any jumbled and attenuated rock zones to reassume their in situ relations, as attested by color, vein, or fracture, before the liner was segmented.

Since the interfragmental relationships or packing of sphenoidal pieces of hard rock determine the core's apparent length with more variation and less certainty than in the case of aligned cylindrical slugs of hard rock or sediment, the question of the uniqueness of the lengths recorded is not resolved. More to the point than positions comparable over vertical distances of meters or tens of meters—as would be required to establish rates of sedimentation, for example—are the more localized thicknesses and orientation of glassy margins, or zones of vesicles, oxidation, or phenocrysts. Such interfragmental relationships are preserved by numbering the fragments in sequence downward within any section of 140 to 150 cm, or whatever. Nevertheless, in nearly all instances the preliminary measurements recorded on deck were very close in total length to the more precise measurements made on the geologically reconstructed and realigned cores as laid out for labeling and photography in *Glomar Challenger*'s laboratory.

Handling of Cores

On Leg 24, the occurrence of interstitial gas was minor except at Site 231. A check for such gas was made immediately upon laying the cored sediment, still in its liner, on the deck rack. Megascopically, this gas manifests itself in three ways: (1) the sediment will be effervescing at the time of recovery; (2) elongated gas pockets appear, coalesce and grow, pushing apart slugs of sediment; or (3) once the core has been sectioned, capped, and laid in the core racks, the end caps start bulging and may pop off if not punctured to relieve the pressure. When gas was suspected or evidenced as in (1) or (2) above, the core liner was immediately capped unsectioned and the chemist sampled it for gas, analyzing the specimens on a gas chromatograph. Of particular interest was the methane-ethane ratio; a consistent decrease in CH_4/C_2H_6 may signal the possible presence of heavier hydrocarbons, which in turn may indicate the approach to a natural gas pocket. Gas samples were taken by puncturing the core liner with a spitcock apparatus to which a hypodermic needle was attached, with the needle discharging into a 23cc evacuated tube (vacutainer). Customarily, two samples were taken at each point where the liner was punctured, and the core was sampled at two or three points along its length. At least one sample per core was analyzed on a Carle basic gas chromatograph (Model 6500) before penetration was resumed. Detection limits were determined at approximately 10 ppm for methane and 50 ppm for ethane. The obvious presence of gas at Site 231 did not modify drilling procedure; continuous coring already was standard for that hole.

The first assessment and age determination of the core material was made immediately on sediment samples from the core catcher. After a core section had been cut, sealed, and labeled, it was brought into the core laboratory for processing. The core section was first weighed for mean bulk density measurement. Then GRAPE (gamma ray attenuation porosity evaluation) analysis was made for detailed bulk density determination.

After the physical measurements were carried out, the core liner was cut on a jig using Exacto-type blades, and the end caps cut by knife. The core then was split into halves with a cheese cutter if the sediment was a soft ooze. At times, when compacted or partially lithified sediments were included, the core had to be split by a machine band saw or diamond wheel.

One of the split halves was designated a working half. Sonic velocity determinations, using a Hamilton frame, were made on pieces from this half. Samples, including those for grain size, X-ray mineralogy, interstitial water chemistry, and total carbonate content, were taken, labeled, and sealed. Larger samples were taken from suitable cores for organic geochemical analysis. The working half then was sampled by the paleo technician; materials for shipboard and shore-based studies of nannoplankton, foraminifera, and radiolarians were taken. The other half of a split section was designated an archive half. The cut surface was smoothed with a spatula to bring out more clearly the sedimentary features. The color, texture, structure, and composition of the various lithologic units within a section were described on standard visual core description sheets (one per section) and any unusual features noted. A smear slide was made, usually at 75 cm if the core was uniform. Otherwise, two or more smear slides were made, each for a sediment of distinct lithology. The smear slides were examined microscopically. The archive half of the core section was then photographed. Both halves were sent to cold storage on board after they had been processed.

Material obtained from core catchers–and not used up in the initial examination–was retained for subsequent work in freezer boxes. Sometimes significant pebbles, small manganese nodules or cherty bits, were extracted from the core and stored separately in labeled containers. On other occasions, the liners would contain only sediment-laden water. This was usually collected in a bucket and allowed to settle, the residue being stored in freezer boxes.

Igneous rocks, characteristically basalts, were obtained at five sites, and were subjected to velocity measurement, megascopic description, and thin-sectioning aboard ship. The original plastic liners brought in from the deck were cradled for splitting longitudinally so that the uncut rock fragments lay exposed. Where possible, the fragments were arranged in their original relative orientation. Each separate core fragment of more than shard size was numbered from the top downwards and labeled with India ink on paint; its vertical orientation was indicated by an upward pointing arrow and its horizontal relation to adjacent fragments by a small keying line. Fragments selected for thin-sectioning on the basis of freshness, homogeneity, composition, or abundance ordinarily were the same as those chosen for velocity measurements. Such fragments were sliced longitudinally; one half was returned immediately to the archive array. The "working" fragment was sawed and shaped for velocity and petrographic examination; any excess material not needed for initial studies was returned to the array. On Leg 24, paired thin sections were prepared; in all, about 225 to 230 were cut. Following photography and before sealing the hard-rock cores for storage horizontally, any gaps or voids that would promote jumbling were packed with plastic or paper fillers.

All samples are now deposited in cold storage at the DSDP West Coast Repository at the Scripps Institution of Oceanography, La Jolla, California. These samples may be obtained for further study.

Interstitial Water Chemistry

Immediately upon arrival of cores in the shipboard sediment processing area, 10-cm-long sections, at intervals of 10 to 20 meters down the sedimentary column, were removed and squeezed before the material could warm to laboratory temperature. After the water had warmed to laboratory temperature (25°C), determinations of *p*H, alkalinity, and salinity were made. The remainder of the extracted pore water was sealed in polyethylene vials for later onshore analysis. All shipboard sampling and analysis was performed by the chemistry technician.

Salinity was determined at 25°C by refractometry and the data have a probable precision of ±0.5 percent. The relationship of refractive index to salinity, at constant temperature, is a function of total dissolved solids content, but this measure does not differentiate between changing ion ratios. It is thus not necessarily a measure of gross dilution or concentration. For example, drastic reduction of $SO_4^=$ is a commonly recorded phenomenon in marine sediment pore waters, and a 50 percent reduction of $SO_4^=$ (1300 ppm $SO_4^=$) would be expressed by refractometry as a "salinity" decrease of 3-4 percent. Changing ratios of alkalinity and other ions relative to chloride generally will have a rather smaller effect.

*p*H measurements were made at 25°C using either a combination, flow-through, or punch-in electrode. Measurements are thought to be ±0.1 *p*H units. However, the difference between values recorded with any two electrodes on the same sample is commonly more than ±0.2 *p*H units. The reason for these differences is not obvious.

Alkalinity titrations were made with HCl to an end point at *p*H 4.5. Consultations with Dr. Joris Gieskes of Scripps Institution have suggested that our alkalinity values determined on board ship are 28 ±5 percent too high. This conclusion was reached after comparing our Indian Ocean surface seawater alkalinities with the probably rather more precise determinations of alkalinity made by Gieskes on surface Indian Ocean seawater on Leg 25. Therefore we have decreased all our alkalinity values by 28 percent. Our alkalinity data are thus somewhat suspect, but the trends are still correct. If the correction factor is truly appropriate, then perhaps our revised alkalinity values have a precision of about ±5 percent.

A further program of onboard measurement by the chemistry technician consisted of the determination of water content, porosity, and bulk density of the sediments. Syringe sample plugs of a known volume, between 0.25 and 0.5 cm^3, were taken, weighed wet, dried at 110°C, reweighed and then water content, porosity, and density calculated. These data have a probable error of ±2 percent.

Physical Properties

Bulk densities were measured by the standard GRAPE device. Small bulk density samples of the soft nanno ooze were taken by the syringe method. When the sediment was too firm to obtain these samples, water content samples were taken.

The GRAPE device was calibrated after each core by means of two aluminum standard rods (density = — g/cm^3); a 1.0″ diameter rod provided a 1.00 g/cm^3 — position, and a 2.6″ diameter rod yielded a 2.60 g/cm^3 — position. Shorebased data reduction was by the Whitmarsn Iteration of Leg 12. However, aboard ship an Evans (1965) "corrected" density was obtained by linear interpolation between the standards, and used in acoustic impedance data. These two techniques differ by 0% to 10%.

Porosity values corresponding to each bulk density measurement were obtained by: (1) assuming the density of the interstitial pore water is 1.03 g/cm^3 and (2) assuming the average density of the sediment solids is 2.70 g/cm^3. Since most of the smear slides made for the lithologic description of the nanno ooze showed approximately 80 percent calcium carbonate material and density of calcite = 2.71 g/cm^3, the latter assumption is reasonable. The conversion formula obtained from these data is:

Porosity (in %) = 161.7–59.9 (bulk density)

Sonic velocities were measured by the Hamilton frame device using the first negative peak response method (Cernock, 1970). The acoustic impedance (*pv*) determined for each measurement was obtained by multiplying the bulk density by the sonic velocity.

Basis for Age Determination

The planktonic foraminiferal zonation used throughout the report is the letter-number system developed by Banner and Blow (1965) and Blow (1969) for the late middle Eocene to Holocene, and by Berggren (1971), as modified from Bolli (1966), for the Paleocene to middle Eocene. No attempt was made, however, to differentiate Zone N.19 from Zone N.20; these two zones have been combined. The nannofossil zonation applied in this report is one discussed in Roth (1973), with minor modifications. The radiolarian zonation utilized is that developed by Riedel and Sanfilippo (1970, 1971).

Various planktonic microfossils zonation schemes and time-stratigraphic boundaries have been calibrated by Berggren (1969, 1972) who developed a Cenozoic radiometric time scale. Berggren's scale (1972) and its revised late Neogene version (Berggren and Van Couvering, 1974) forms the basis for age determination of biostratigraphic levels encountered on Leg 24 and provides the standard for calculating average sedimentation rates. Throughout this report, such rates, which were calculated without taking into account changes of compaction, are expressed in meters per million years.

Lithologic Classification and Nomenclature (Sediments), and Symbols

Holes drilled on Leg 24 in the Gulf of Aden and the northwestern Indian Ocean penetrated mostly hemipelagic and pelagic sedimentary sequences. The nomenclature applied to these sediments follows classification rules developed by Weser (1973) of the Deep Sea Drilling Project and adopted for use throughout the Indian Ocean cruises of *Glomar Challenger*. It differs from classifications proposed by Olausson (1960) and refined by Berger and von Rad (1972) mainly in abandoning use of the terms *marl* and *chalk* to signify different amounts of calcareous microfossils. It attempts to employ simple sediment names and to avoid long complex terms. Ordinarily, the main constituents of sediments were determined in smear slides (smear slide analyses are given in the graphic core descriptions of the individual sites and, in a few cases, in the site reports as well). Color was determined by comparison with the "Rock Color Chart" (Goddard et al, 1951) and, if mentioned, precedes the sediment name. The classification and nomenclature rules applied to the sediments in this volume are, in brief:

Major Constituents

1) Sediment takes the name of those constituents present in major amounts (major defined as >25%).

2) Where more than one major constituent is present, the one in greatest abundance is listed last. In order of decreasing abundance, the remaining major constituents are listed progressively farther to the left.

3) Class limits, when two or more major constituents are present in a sediment, are based on intervals of 25 percent: 0-25, 25-50, 50-75, 75-100.

Minor Constituents (appear in sediment name only if very characteristic)

1) Constituents present in amounts of from 10 to 25 percent are prefixed to the sediment name by using the term *-rich*.

2) Constituents present in amounts of from 2 to 10 percent are prefixed to the sediment name by using the term *-bearing*.

Biogenous Constituents

1) The term *Nannofossil* is applied only to the calcareous tests of coccolithophorids, discoasters, etc.

2) The term *spicule* is applied to sponge spicule, and *silicoflagellate* to silicoflagellate deposits.

3) The term *calcareous* or *siliceous*, depending on skeletal composition, is applied where no attempt is made to identify individual taxonomic groups. Where this distinction is made, the appropriate fossil name is used.

4) Non-current-transported fossil tests are not qualified by a textural term.

5) The term *ooze* follows a microfossil taxonomic group whenever it is the dominant sediment constituent.

Volcanic/Constituents – Pyroclastics are given textural designations:

Volcanic Breccia: > 32 mm
Volcanic Lapilli: 32 → 4 mm
Volcanic Ash: < 4 mm

Authigenic Constituents

1) Authigenic minerals enter the sediment name in a fashion similar to that outlined under "major constituents". Normally, the authigenic minerals are not given a textural designation.

2) The terms *ooze* and *chalk* are applied to carbonate minerals of all types, using the same rules as those that apply to biogenous constituents.

3) *Ferruginous* is the term applied to the microscopic translucent subspherical iron oxide minerals.

Detrital Constituents

1) When detrital grains are the sole constituent of a sediment, a simple textural term suffices for its name (*sand, silt, clay*). Such a textural term can be preceded by a mineralogical term when this seems warranted.

2) When occurring together with detrital grains, the tests of a fossil biocoenosis or authigenic minerals are not given a textural designation. Note however, that the detrital material is classified texturally by recalculating its size components to 100 percent. With the presence of other constituents in the sediment, the detrital fraction now requires a compositional term. For this purpose the term *detrital* is employed.

3) Redeposited fossil tests become a detrital component and as such are given a textural designation. In addition, particularly for microfossils, it is essential that they be identified taxonomically in the sediment name. Consequently, the textural term is preceded by the appropriate term identifying the fossil constituents.

4) The distinction between detrital and nondetrital fossil material is often not clear in the deeper pelagic realm. Therefore, fossil material receives a textural designation, if, and only if, there is evidence of *obvious* and *significant* current transport. Similar considerations apply to volcanic material.

5) There are, at present, fine-grained carbonate particles which by virtue of their unknown origin cannot be classified as either biogenic, detrital, or authigenic. Such particles are prefixed by the term *micarb.* Because they also do not exhibit evidence of obvious and significant current transport, they are not given a textural designation—consequently, the terms *ooze* and *chalk* should be applied to them where appropriate.

Classification of the carbonate sediments is set forth in Table 2.

In most cases, no problems occurred when applying this nomenclature to the sediments of Leg 24. However, these

TABLE 2
Classification of Carbonate Sediments

		Unconsolidated	Consolidated	Indurated (Cemented)
Identifiable fossils	Transported:	Foram sand Nanno silt	Foram sandstone Nanno siltstone	Foram sandstone Nanno siltstone
	In situ:	Foram ooze Nanno ooze	Foram chalk Nanno chalk	(Foram) limestone (Nanno) limestone
Genetically unidentifiable carbonate	Transported:	Carbonate sand	Carbonate sandstone	Carbonate sandstone
		Carbonate silt	Carbonate siltstone	Carbonate standstone
	In situ:	Micarb ooze	Micarb chalk	(Bio) Micrite

rules seem perhaps less well established with respect to different types of hemipelagic sediments, especially if benthic fossils occur in great abundances and possibly are being redeposited.

The lithologic symbols used in the core and hole summaries of Leg 24 are reproduced in Figure 4. Complex lithologies have been represented on the core summary forms using a vertical striping system. To do this, the constituents are divided into the following percentage classes: 0-2, 2-10, 10-25, 25-50, 50-75, and 75-100. The lithologic column is subdivided into five subcolumns, their boundaries being the midpoints of the percentage classes (Figure 4). Percentages under 10 percent cannot be represented this way. For constituents between 2 and 10 percent, a letter or other symbol can be sparsely overprinted on the main symbols. Constituents under 2 percent are ignored in the lithology columns. They are, however, mentioned in the text in the smear slide compositions.

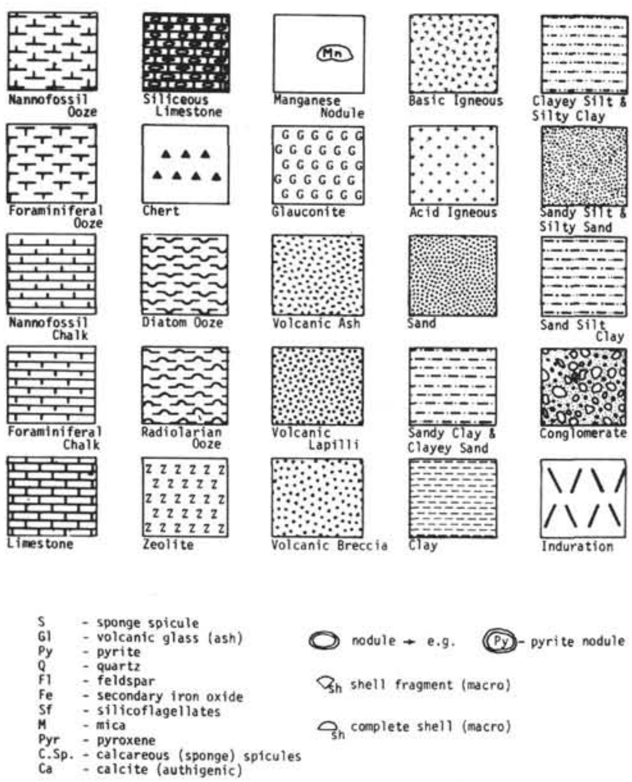

Figure 4. *Standard symbols used to illustrate lithology.*

Grain-Size Analysis

Discussions of this topic, and the two that follow, draw very heavily on material prepared for earlier initial reports by DSDP shore lab specialists. Grain-size distribution was determined by standard sieving and pipette analysis (Krumbein and Pettijohn, 1938). The sediment sample was dried, then dispersed in a Calgon solution. If the sediment failed to disaggregate in Calgon, it was dispersed in hydrogen peroxide. The sand-sized fraction was separated by a 62.5-micron sieve with the fines being processed by standard pipette analysis following Stokes settling velocity equation. Step-by-step procedures are described in Appendix III of Volume IV, Initial Reports of the Deep Sea Drilling Project (Bader, R. G., Gerard, R. D., et al., 1970). In general, the sand-, silt-, and clay-sized fractions are reproducible within ±2.5 percent (absolute) with multiple operators over a long period of time. Tabulated results of grain-size analysis and carbon-carbonate analysis are presented in Appendix I of this volume.

Carbon and Carbonate Analysis

The carbon-carbonate data were determined by a Leco induction furnace combined with a Leco acid-base semiautomatic carbon determinator. Normally the more precise seventy-second analyzer is used in place of the semiautomatic carbon determinator, but it was not used for these samples because of malfunctions.

The sample was burned at 1600°C, and the liberated gas of carbon dioxide and oxygen was measured volumetrically in a solution of dilute sulfuric acid and methyl red. This gas was then passed through a potassium hydroxide solution which preferentially absorbs carbon dioxide and the volume of the gas was measured a second time. The volume of carbon dioxide gas is the difference of the two volumetric measurements. Corrections were made to standard temperature and pressure. Step-by-step procedures are outlined in Appendix III of Volume IV, Initial Reports of the Deep Sea Drilling Project, and a discussion of the method, calibration, and precision was presented by Boyce and Bode (1972).

Total carbon and organic carbon (carbon remaining after treatment with hydrochloric acid) are determined in terms of percent by weight, and the theoretical percentage of calcium carbonate is calculated from the following relationship:

Percent calcium carbonate ($CaCO_3$) =
(%total C – % C after acidification) ×8.33

However, carbonate sediments may also include magnesium, iron, or other carbonates; this may result in "calcium" carbonate values greater than the actual content of calcium carbonate. In our determinations, all carbonate is assumed to be calcium carbonate.

Precision of the determination is as follows:

Total carbon (within 1.2 to 12%)	= ±0.3% absolute
Total carbon (within 0 to 1.2%)	= ±0.06% absolute
Organic carbon	= ±0.06% absolute
Calcium carbonate (within 10-100%)	= ±3% absolute
(within 0-10%)	= ±1% absolute

X-Ray Methods

Samples of sediment were examined using X-ray diffraction methods at the University of California at Riverside, under the supervision of Harry E. Cook.

Treatment of the raw samples was by washing to remove seawater salts, grinding to less than 10 microns under butanol, and expansion of montmorillonite with trihexylamine acetate. The sediments were X-rayed as randomized powders. A more complete account of the methods used at Riverside is presented in Appendix III of Volume IV of the Initial Reports of the Deep Sea Drilling Project.

Data from X-ray analysis are briefly described and tabulated in Chapter 18 of this volume. In that tabulation columns one and two contain the core numbers and the depths of the cored intervals (in meters below the mudline). The third column gives the depths of the composited sample intervals or the depths of single samples. Column 4 contains the percentage of the diffuse scattered X-rays. The amorphous scattering percentage in column 5 is derived from the data of column 4 by a simple conversion based on the ratio of Bragg and diffuse scattering in pure quartz. It is a measure of the proportion of crystalline and amorphous materials in the sample. The remaining columns contain crystalline mineral percentages computed by the method of mutual standards using peak heights.

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Referenced geophysical data, most especially continuous seismic reflection profiles, were made available to DSDP by John Ewing and associates of Lamont-Doherty Geological Observatory and their counterparts at Scripps Institution of Oceanography (SIO), Woods Hole Oceanographic Institution (WHOI), and the Institute of Oceanographic Studies of the United Kingdom. Additional more detailed data came from the 1971 site surveys aboard R/V *Chain* (WHOI) and R/V *Melville* (SIO); these efforts enabled us to occupy the intended sites expeditiously and saved our time for the main purposes of drilling and coring.

Captain Loyd E. Dill, his crew of *Glomar Challenger,* Superintendent Cotton Guess and the drilling teams, with Lamar Hayes, Cruise Operations Manager, made the cruise productive and efficient.

Michael Lehmann, Laboratory Officer, and all the DSDP marine technicians unstintingly, ingeniously, and enthusiastically performed the routine tasks involved in the shipboard data assimilation, instructed Leg 24 participants in the ways of *Glomar Challenger*, and adapted with patience and forbearance to the special procedures or requirements of the underway geophysical watch.

Lillian Musich of the DSDP staff, not a shipboard participant on Leg 24, assumed most competently the scientific editorial duties for preparation of this volume. Barbara Long and associates of DSDP and Stuart Smith and Uta Albright of the S.I.O. Underway Data Processing Group prepared plots and corrected tabulations of the geophysical measurements and navigational data.

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