5. SITE 538

SITE 538 (HOLE 538)

Date occupied: 0302 hr., 14 January 1981
Date departed: 1806 hr., 14 January 1981
Time on hole: 15.7 hr.
Position: 23°50.98' N; 85°10.26' W
Water depth (sea level; corrected m, echo-sounding): 2820
Water depth (rig floor; corrected m, echo-sounding): 2830
Bottom felt (m, drill pipe): 2822.5
Penetration (m): 6.0
Number of cores: 1
Total length of cored section (m): 6.0
Core recovery (%): 86
Oldest sediment cored:
Depth sub-bottom (m): 5.15
Nature: Nannofossil ooze
Age: late Oligocene
Measured velocity (km/s): 1.56
Basement: Not penetrated

Principal results: See Summary section.

SITE 538 (HOLE 538A)

Date occupied: 1806 hr., 14 January 1981
Date departed: 2112 hr., 14 January 1981
Time on hole: 3 days, 3.1 hr.
Position: 23°50.95' N; 85°09.93' W
Water depth (sea level; corrected m, echo-sounding): 2742
Water depth (rig floor; corrected m, echo-sounding): 2752
Bottom felt (m, drill pipe): 2801.0
Penetration (m): 322.5

Number of cores: 36
Total length of cored section (m): 332.5
Total core recovered (m): 137.67
Core recovery (%): 41
Oldest sediment cored:
Depth sub-bottom (m): 268.5
Nature: Limestone
Age: Early Cretaceous (Berriasian-Valanginian)
Measured velocity (km/s): 3.69
Basement:
Depth sub-bottom (m): 268.5-332.5
Nature: Igneous and metamorphic complex
Velocity range (km/s): 5.09
Age: Early Jurassic (~190 Ma): diabase dikes
latest Cambrian (~500 Ma): metamorphic rocks

Principal results: See Summary section.

SUMMARY

Site 538 was the third of three short holes designed to drill through a thin sedimentary section into a high-standing basement block to test the nature, age, and origin of the crust. The site is located on the top of Catoche Knoll, which lies about 25 km northeast of the Campeche Escarpment (Fig. 1). The knoll is a large topographic feature that rises over 750 m above the abyssal floor of the Gulf of Mexico (Fig. 1). Prior to drilling, this knoll was interpreted to be a large, tilted fault block. Two holes were drilled. The first hole was abandoned after only one core was taken because the sediments were too firm to spud safely. The second hole (538A) drilled through a Tertiary and uppermost Cretaceous pelagic cap and a shallow-water Cretaceous limestone sequence; it reached and penetrated 64 m of igneous-metamorphic basement. The results of 538A are summarized in Figure 2 and are discussed below.

Three major lithologic sequences were drilled as follows:
1. foraminiferal-nannofossil ooze, chalk, and limestone (0-211.5 m), late Pliocene to late Albian
2. limestone (211.5-268.5 m), Valanginian
3. gneiss and amphibolite (268.5-332.5 m) with a latest Cambrian metamorphic age (~500 Ma) intruded by diabase dikes of Early Jurassic age (~190 Ma) (Dallmeyer, this volume)

The Upper Cretaceous-Tertiary pelagic sequence consists predominantly of nannofossil-foraminiferal ooze and chalk with scattered graded ash layers. Deposition was interrupted by long periods of erosion and/or non-deposition as indicated by stratigraphic hiatuses and hardgrounds. No clear evidence for turbidites was found. However, within this pelagic sequence an interval of folded Paleocene chalk several meters thick, which oc-
Figure 1. Location map of Leg 77 sites in the western Straits of Florida. Site 538 occurs near the crest of Catoche Knoll.
Figure 2. Stratigraphic summary of Hole 538A. See Introduction and Explanatory Notes chapter (this volume) for lithologic symbols. TD = total depth.
curs between Eocene sediments, indicates slumping. Slump folds also occur in the Eocene beds. The knoll must have formed a high hundreds of meters above the abyssal plain throughout the Late Cretaceous and Cenozoic.

Late Cretaceous deposits consist of only a few meters of Santonian, Campanian, and Maestrichtian ooze/chalk with several hardgrounds and ash layers.

Valanginian limestones that occur below the pelagic sequence resemble those at Site 537. Again, we observed no top or bottom contacts and recovered only 2.7% of the formation in form of isolated fragments. These limestones could be interpreted as in situ platform deposits or as platform talus. A thin veneer of Berriasian pelagic chalk occurs on the top of basement. If one assumes that the limestones are in situ, this pelagic layer requires either (1) that basement subsided below the photic zone and was later uplifted into this photic zone or (2) that sea level dropped far enough to shift the site into the photic zone.

Base ment at Site 538 consists of 64 m of igneous and metamorphic rocks: Cambrian or older gneiss and amphibolite intruded during the Early Jurassic by diabase dikes that are fractured and partly serpentinized. The basement complex as a whole may serve as an example of "transitional" (i.e., attenuated and intruded) continental crust. Crust of this kind, with intermediate density and abnormal velocity, has been postulated for the margins of the Gulf of Mexico.

BACKGROUND AND OBJECTIVES

Site 538 (designated ENA-14A during the planning stages of this cruise) was one of several sites designed to test basement in the southeastern Gulf of Mexico in an area where inferred basement blocks occur near the seafloor and are overlain by only a relatively thin (200–300 m) sedimentary cover. This area occurs along the western part of the deep southeastern Gulf just northeast of the Campeche Escarpment in the vicinity of Catoche Knoll (Fig. 1). A more general discussion of the background and objectives of the basement sites is contained in the Introduction and Explanatory Notes chapter (this volume) and the site chapter, Site 537 (this volume).

Site 538 was drilled on the top of Catoche Knoll, located approximately 25 km northeast of the Campeche Escarpment (Fig. 1). The knoll is a large topographic feature that stands more than 750 m above the surrounding abyssal plain. The site was originally proposed as an alternate to Sites 536 and 537, but it was decided to drill here because the first two basement sites yielded considerably different sections and did not take as long to drill as anticipated.

The site was chosen based on earlier single-channel seismic lines in the area (Bryant et al., 1969) plus more recent University of Texas multichannel lines. The formal site was located where Line SF-2 crosses the crest of the knoll (Fig. 3). The seismic data suggested that the knoll was an uplifted and tilted basement block based on the apparent asymmetry of the blocks and the adjacent sedimentary basins (Fig. 3). The strong reflector at about 4 s was inferred to be basement. Overlying basement is a thin sedimentary section some hundred meters thick that can be subdivided into two sequences separated by a prominent reflector/unconformity. The section above the unconformity was interpreted to be a thin cap of mainly Tertiary pelagic sediments and sedimentary rocks based on previous drilling in the area (Site 96; Worzel, Bryant, et al., 1973). The sequence below the unconformity was thought to consist of older Mesozoic rocks. Although the main objective of this site was to determine the nature, age, and origin of the inferred basement, data about the overlying sedimentary sequences would also provide valuable insights into the tectonic and sedimentary history of this region.

OPERATIONS

Glomar Challenger approached Site 538 (ENA-14A) on a course of about 110°, representing the shortest distance from Site 537. The 3.5-kHz and 12-kHz profilers, air guns, and magnetometer were run underway. The crest of Catoche Knoll was crossed twice and the beacon finally dropped on the northwest flank in 2882.5 m (or 2830 by the precision depth recorder) of water. This position was considered more advantageous than the higher flat top of the knoll because the cover of Tertiary sediments overlying the target reflectors was thinner. Irregular topography made it difficult to precisely determine water depth. The bottom-hole assembly was made up with a F94CK bit and the hole was spudded at 1725 hr. Because the water depth was 53 m deeper than indicated by the precision depth recorder, six water cores were taken before the mudline core was on deck. The core consisted of stiff Tertiary ooze and chalk that could not be drilled without rotating. It was decided that the sediments were too firm to spud in safely. Hole 538 was considered abandoned when the bit cleared the mudline at 1806 hr. Pipe was pulled to 2384 m, and the ship was repositioned over the flat top of a northwest-trending ridge, exactly on Line SF-2. At 0246 hr., 15 January, Hole 538A was spudded in 2801 m of water. Drilling rates were very fast in Tertiary ooze and chalk (22 cores in 21 hr.). At 211.5 m, the bit hit rubbly limestone similar to that encountered previously at Sites 536 and 537. Because this formation tended to cave in, the hole was flushed regularly with guar. Hard basement was encountered at 268.5 m. Because badly fractured formations were plugging the bit and drilling rates were reduced to 225 minutes per core, the hole was abandoned on 17 January at total depth of 332.5 m with 64 m penetration into basement. The bit was unplugged at 1407 hr.; at 2045 hr. pipe was on deck and the ship headed for Site 539. A summary of the coring at Site 538 is included as Table 1.

SEDIMENTOLOGY

The sedimentary sequence at Site 538 is divided into five units summarized in Figure 2 and Table 2 and described below.

Unit I: 0–79.1 m; 538A-1 to 538A-10-1, 60 cm; late Pliocene to late Oligocene

This unit consists predominantly of light-colored foraminiferal-nannofossil and nannofossil-foraminiferal ooze with subordinate amounts of nannofossil ooze,
Figure 3. East-west seismic Line SF-2 over Catoche Knoll showing location of Site 538 with thin sedimentary cap over acoustic basement at 4 s. See Figure 1 for location of line. MCU = mid-Cretaceous unconformity.
nannofossil marl, and clay. Two subunits are recognized.

**Subunit IA.** The characteristic feature of this subunit is the presence of nannofossil marls and a single terrigenous clay bed. The top 55 cm consist of yellowish gray foraminiferal nannofossil ooze of which the uppermost 20 cm contains angular fragments of white to very light gray chalk (less than 3 × 2 cm). These chalk fragments are speckled with black manganese and show tubular burrow sections. Below the foraminiferal-nannofossil ooze, the sediments change sharply to 140 cm of greenish gray nannofossil marl (43–53% carbonate and less than 2% quartz), then 160 cm of white, yellowish gray, greenish gray, very light gray, and light greenish gray nannofossil ooze (71% carbonate with only about 1% foraminifers). This sequence is underlain by bluish white foraminiferal-nannofossil ooze (86% carbonate, less than 20% foraminifers), then a 10-cm bed of greenish gray clay (17% carbonate, no foraminifers) that marks the base of the subunit. The sediments, although firm, are highly disturbed by drilling and no primary or biogenic structures are preserved intact.

**Subunit IB.** This subunit consists of a relatively uniform sequence of bluish white, very pale blue to very light gray, light greenish gray, and white foraminiferal-nannofossil and nannofossil-foraminiferal oozes. Eight carbonate bomb analyses were carried out and averaged 86.6%. The percentage of foraminifers varies from 10–20% in the foraminiferal-nannofossil ooze to 25–40% in the nannofossil-foraminiferal ooze; the remainder of the carbonate content is formed predominantly by coccoliths (often including abundant discoasters). The sediments are generally firm oozes but from Sections 538A-7-1 to 538A-10-1 harder, chalky horizons become more common. The homogeneous nature of the oozes makes it difficult to assess the true extent of drilling disturbance; no primary or biogenic sedimentary structures were observed.

**Unit II:** 79.1–173.5 m; 538A-10-1, 60 cm to 538A-20-1, 0.0 cm; late Oligocene to middle Eocene

This unit consists predominately of light-colored nannofossil oozes and chalks with occasional thin beds of altered, sand-sized vitric ashes and, in the lower subunit, nannofossil-radiolarian mudstones, radiolarian-nan-nofossil chalks, and nannofossil marls. The upper boundary in Unit II is taken at the top of the first ash layer. Two subunits are recognized.

**Subunit IIA.** This subunit is composed mainly of white to bluish white, or very light gray or light greenish gray, nannofossil oozes and chalks with occasional thin (less than 6 cm) volcanogenic beds (see below). Between Cores 10–13 in Hole 538A, the sediments are generally firm oozes with scattered chalky bands but from Core 14 downward, chalks predominate. Carbonate contents of the oozes and chalks average about 85% (three samples); smear slides indicate that the main carbonate component is nannofossil (or crystalline) calcite. Foraminifers do not exceed 5%. As the ooze/chalk boundary was approached, the proportions of nannofossilites estimated in smear slides decreases and the amount of crystalline calcite observed shows corresponding increases. This trend suggests that the lithification of the ooze to a chalk is related to the precipitation of cements that were probably derived from the solution and reprecipitation of nannofossil calcite. Thin layers of distinctly laminated, very light gray, pale green, or light greenish gray nannofossil chalk and ooze occasionally occur within the more homogeneous sediment (e.g., in Sections 538A-10-4, 538A-11-2, 538A-12-2, 538A-14-1, and 538A-16-3). However, generally sedimentary structures are absent because of a combination of bioturbation, poor color contrasts, and drilling disturbance. Five ash beds were identified in this subunit; they have an average thickness of about 4 cm, are medium gray in color, and have a distinct hyaline appearance reflecting abundant sand-sized volcanic glass shards (average 77% in smear slide). Two of the beds (one in Section 538A-10-5, the other in 538A-12-1) are graded, with sharp bases and burrowed, transitional tops. Although there are only five distinct beds of this material in Subunit IIA, single laminae or irregular burrow-fills rich in volcanic glass are scattered throughout. Some steeply dipping, distinct laminations occur in the top part of Section 538A-16-3.

**Subunit IIB.** The boundary between Subunits IIA and IIB is taken as the top of the first pale green nannofossil marly chalk bed. Four of these marly beds occur in Sections 4 and 5 of Core 538A-16, although only one in the
latter. The uppermost two of these beds in 538A-16-4 contain thin, light gray layers (less than 0.5 cm), which are rich in volcanic glass at their lower contacts and may be graded. Sections 538A-16-4 and 538A-16-5 also contain bands of dark-colored radiolarian mudstones (less than 15 cm thick): one occurs in 538A-16-4 and is dark yellow-brown (indistinctly laminated and with lighter-colored burrow-fills), and the other two in 538A-16-5 are dusky yellowish brown to black (in part laminated and in part with lighter-colored burrows). These radiolarian mudstones contain about 30% carbonate (mostly mineralic calcite) and up to 40% silica (30% radiolarians, 10% sponge spicules). However, the predominant sediment type from 538A-16-4 through 538A-18-4 is light greenish gray to white nannofossil chalk. Several volcanogenic glassy beds occur between 538A-16-6 and 538A-17-6 (five bands averaging 3.6 cm in thickness) and are identical to those described for Subunit Ha. Only one band (in Section 538A-17-3) has a sharp base, grading, and a burrowed, transitional upper contact. Below Section 538A-18-2, the nannofossil chalk becomes progressively more yellowish gray in color, and in Section 538A-18-5 changes to a yellowish gray radiolarian-nannofossil chalk with approximately 20% radiolarians, 20% nannofossils, and 55% crystalline calcite. Between Sections 538A-19-2 and 538A-19-5 these radiolarian-nannofossil chalks contain scattered, occasional patches and thin disturbed laminae of volcanogenic material. Thin (about 2 mm) lenses of asphalt occur in Sections 538A-18-2 and 538A-19-2, and scattered specks also appear from 538A-18-2 to 538A-19-4, 5 cm. With the exception of some 25° dipping clayey laminae in 538A-17-4, few sedimentary structures were observed in Subunit IIb. Bio- turbation and Planolites type burrows were only observed in the rare cases where the color contrast between the matrix and burrow-fill was distinct.

**Unit III:** 173.5–189.2 m; 538A-20-1 to 538A-21-5, 20 cm; middle Eocene to latest Albian

This unit consists predominantly of foraminiferal-nannofossil chalks with lesser amounts of nannofossil-foraminiferous chalk and, in the lower subunit, nannofossil claystones and terrigenous claystones. The unit is characterized by its heterogeneity (both in terms of color and composition) and the presence of manganese-rich surfaces or hardgrounds (Fig. 4). The boundary with Unit II is marked by the disappearance of radiolarians and the increase in abundance of foraminifers from trace amounts (less than 1%) to 15–50%. Two subunits are recognized.

**Subunit IIIa.** The upper part of Unit III is mainly composed of very light gray, yellowish gray, pinkish gray, very pale orange, or grayish orange pink foraminiferal-nannofossil chalks. These sediments contain 78–88% carbonate, 15–20% foraminifers, and 35–80% nannofossils. There are two notable features of this subunit when compared with other parts of the sequence: (1)}
conspicuous bioturbation (dominantly unidentified or Planolites type) and (2) the occurrence of several distinct hardground horizons (the distribution of these is indicated in Fig. 4). These discontinuities are represented both as irregular bored surfaces (Fig. 5A) or as black manganese-rich crusts (Fig. 5B). The differences in ages across these horizons is usually considerable (Fig. 6; also see Biostratigraphy and the discussion part of this section). Other features indicated on Figures 4 and 6 include the distribution of manganese, microfaulted intervals, and the occurrence of rare, steeply dipping laminae. Cylindrichnus (?) or "halo" type burrows were noted in Sections 538A-20-2, 538A-20-4, and 538A-21-1, and a possible aptychus was recorded at 538A-21-2, 146 cm.

Subunit IIIb. The top of this subunit is taken at the first nannofossil claystone bed in Section 538A-21-3. This band is strongly bioturbated (Planolites, possible Chondrites), contains an unidentified back-filled burrow, is moderate brown in color, and consists of 80% clay and 20% nannofossils. Below this bed the sediments are dominantly white to yellowish or pinkish gray foraminiferal-nannofossil chalks interbedded with several claystone and ash beds (Fig. 4, and the corresponding close-ups Figs. 5C and 5D). The claystones range from dark yellowish brown through olive gray to olive black (bluish where weathered); they contain 60–99% clay, 5–10% nannofossils, and sometimes minor zeolites (less than 15%). Although their contacts are sharp, they usually contain fairly common burrows infilled with lighter-colored sediment from above (Fig. 5C). The ash bands range from light olive gray to light gray in color, have a distinct hyaline appearance, and are composed of 95–98% variably altered volcanogenic glass. Below the prominent microfault in Section 538A-21-4 shown in Figure 5D, there is an interval of pale green claystone that is altered near the fault (down to about 135 cm) to a dusky yellow, light olive brown, and dark yellowish orange color. The base of Unit III is marked by the change to dark nannofossil chalks and lighter-colored chalks and limestones (Fig. 4).

Unit IV: 189.2–211.5 m, 538A-21-5, 20 cm to 538A-24-1, 0.0 cm; latest Albian

Because of poor recovery in this unit (7.6%), few if any original lithologic contacts were preserved in the cores. The lithologies recovered include nannofossil chalks, limestones, marly limestones, and chert, but these may be unrepresentative of the unit as a whole. Because of the poor recovery, the position of the lower boundary of this unit was inferred from a decrease in the drilling rate (Fig. 2). The nannofossil chalks observed in this unit range in color from white to light greenish or light brownish gray; one darker band in 538A-21-5 contains common phosphatic (fish scale?) debris. The limestones range in color from light gray, light olive gray, yellowish gray, or medium light gray and are variably laminated and banded or bioturbated. They show some moldic porosity (including occasional, small, ammonite molds). Thin sections indicate that these limestones are radiolarian or foraminiferal-radiolarian mudstones and packstones in which...
the skeletal material is generally recrystallized to sparite. Some of these limestones contain thin lenses of pale green clay similar to that at the base of the overlying unit. The cherts are either black or dark yellow brown to light olive or yellowish gray and some are laminated in part. Intercalated within these limestones and cherts are two intervals of very soft, white calcareous oozes showing well-preserved foraminifer and nannofossil assemblages. The curious lack of cementation in this material contrasts sharply with the rather advanced lithification of the other lithologies observed in the unit.

Unit V: 211.5-268.6 m; 538A-24-1 to 538A-30-1, 5 cm; early Berriasian to Valanginian

Rocks recovered from Unit V consist of white and grayish orange oolitic, skeletal, and oncotic limestones, most of which are grainstones and packstones. Rare patches of wackestones are scattered throughout samples from the lower two-thirds of the unit. Oolitic limestones occur in the upper third of the unit and consist of well-sorted, medium sand-size ooids and skeletal grains in a fibrous or bladed calcite cement interpreted to be of marine origin. Skeletal grains include echinoderm fragments, composite grains, peloids, and rare benthic foraminifers. Ooid cortices are preserved as concentric micritic laminae with rare dolomite rhombs (about 50 μm on an edge) replacing portions of the ooid coatings. Erosional horizons occur in the oolites, horizontally and evenly truncating and cement across the width of a thin section. These horizons are in turn overlain by oolite cemented in a more open-marine environment.

Composite grains and small oncites (0.5-2 mm) are the characteristic grains below the oncitic limestone, with echinoderms, coral, peloids, and foraminifers forming the majority of other grain types. Unusual but distinctive grains in this oncitic facies include echinoderm spine fragments and trochoinid foraminifers. Cement is again common, and wackestone fills both pockets and borings in the specimens. Calpionellids are rare. The cement encloses layers of peloids, which may form geopetal surfaces and, in some instances, display reverse grading.

Porosity is estimated to be between 10 and 20%, derived mainly from dissolution of originally aragonitic grains. Micropor or blocky calcite apparently replaced some aragonite. Primary pore space is largely filled with cement, although patches of preserved primary porosity exist throughout the unit.

At the base of the unit, a chalk crust, 1-2-mm thick, coats the surface of the underlying metamorphic basement rock. The crust contains coccoliths, nannoconids, and nannoconid debris, but is composed primarily of fine calcite silt of indeterminate origin.

Discussion

The oldest sediments recovered in Hole 538A were the limestones of Unit V and the thin pelagic chalk on the uppermost piece of basement. Although the very poor recovery of this unit (about 3%) places considerable constraints on the elucidation of the early geologic history at this site, sufficient data are available to propose two alternative sequences of events.

The material from the lower two-thirds of Unit V, the oncitic facies, is similar in facies and age to that of Unit II at Site 537. As with that material, this sediment is probably derived from an open-marine part of a carbonate platform (upper forereef or deeper platform terrace). Like the material from Site 537, it is possible that the oncitic, oncitic, and skeletal limestones at Hole 58A have been redeposited in deeper water.

The oncitic limestone from the top of Unit V is also a sediment characteristic of carbonate platform margins. Such facies often occur just a few kilometers bankward of the shelf margin or, more infrequently, on bank interiors characterized by low sedimentation rates. The oncitic represents a more shallow-water facies than the underlying oncitic facies. We found no evidence of distinct clast margins in the recovered material, which would suggest that these rocks are redeposited clasts of shallow-water limestone. Distinct layers of pelvic sediment are absent from recovered rocks of Unit V. Such layers are characteristic of Unit III at Site 536, present both within and between core segments of shallow-water debris.

Although pelagic sediment layers seem to be absent from the unit, planktonic skeletal material is scattered throughout the interval, as might be expected on an isolated knoll in the deep southeastern Gulf of Mexico. In particular, scattered planktonic foraminifers and calpionellids occur in areas of fine-grained matrix and are incorporated in the coatings of oncites. Calpionellids, which occur in all cores, suggest the unit is Berriasian to Valanginian in age and the probable occurrence of three calpionellid zones in sequence supports the in situ origin of the unit.

In Hole 538A, the contact between oolite and oncitic facies is gradational over several tens of meters. Thin sections from Cores 25 through 28 contain both oncites and ooids. Oolitic limestone occurs as deep as Core 28 and oncites occur as shallow as Core 25, but the unit is clearly an oncitic limestone at the top and an oncitic limestone at the base. The gradation between these facies suggests one continuous unit, not two units with a hiatus between them.

Although it is unlikely that Unit V is redeposited platform talus, the possibility cannot be eliminated. Intercalated layers of soft pelagic sediment may occur in the unit but were not recovered. It is possible that the rocks recovered were redeposited in deep water as clastics and that these clasts have never been firmly cemented. Redeposition would have to be periodic, so that biostratigraphic stages were not mixed. (For further discussion, see Schlager et al., this volume).

The preferred interpretation of Unit V is that it was deposited in place, on a raised basement block. Deposition commenced with pelagic sediment, the pelagic crust, on a surface swept free of any preexisting sediment by currents or by slumping or faulting, perhaps during the uplift of the block. The sediments on the block record deposition in decreasing water depth. The chalk was prob-
Figure 5. Details of sedimentary structures and features in Unit III. Scales in cm. A. 538A-20-2, 60–95 cm; irregular, bored surfaces and burrows in Unit IIIa. B. 538A-21-1, 50–85 cm; manganese-rich crust at 538A-21-1, 56–59 cm, Unit IIIa. C. 538A-21-4, 50–85 cm; interbedded dark claystone at 75–78 cm and foraminiferal-nannofossil ooze at 78–85 cm, Unit IIIb. D. 538A-21-4, 85–120 cm; interbedded chalk, ash, and claystone faulted over green claystone, Unit IIIb.
Figure 5. (Continued)
ably deposited in bathyal depth, the oncolite facies probably in the depth range of 50–200 m, followed by the oolite (which may represent deposition in as little as a few meters of water). Shoaling water may have resulted from continued relative uplift of the basement block, sea level fall, or a combination of the two. Sometime in the Valanginian, the block was submerged more deeply, resulting in nondeposition or erosion.

During the late Albian, the pelagic sediments of Unit IV were deposited. Poor recovery hinders the interpretation of this unit. The change from the oolitic grainstones at the top of Unit V to the chalks, limestones, and cherts of Unit IV occurred at some point within the Valanginian through Albian interval. Depending on whether the platform hypothesis or the talus hypothesis is correct, this transition may represent either: (1) drowning of a shallow-water platform and transition to a relatively deeper, more pelagic environment, or (2) rapid decline of sediment influx from platforms into the deep basin. This decline may have been caused by drowning or backstepping of carbonate platforms, or it may be related to a change in the topography of the seafloor.

Unit IV is late Albian in age, and this implies a considerable hiatus between Unit IV and the underlying Valanginian limestones of Unit V. The unit consists of two suites of lithologies. Light, massive limestone and dark-laminated, hard limestone; dark carbonaceous marl; and black chert compose the dominant group (nearly identical with coeval rocks at Site 540), and represent sediments in an advanced stage of diagenesis. Two short sections of very soft, white carbonate ooze, on the other hand, appear to have undergone hardly any diagenesis at all and show no transitions to the limestone lithologies. Well-preserved biota in both lithologic groups clearly indicate the same age. The alternation of these lithologies in one core is very puzzling. In the North Atlantic, un lithified, white Albian ooze has been recovered from shallow positions on the continental slope, for instance the Blake Nose (Benson, Sheridan, et al., 1978; Sites 390, 392), whereas dark sediments, normally lithified, occupy the abyssal areas below 3200 m. Tucholke, Vogt, and others (1978) postulated a body of stagnant deep water to explain this facies pattern. Catoche Knoll may have been located near a similar boundary of water masses. Short-term fluctuations of this boundary could explain the change from white ooze to darker, laminated, carbonaceous sediment and back to white ooze. To explain the difference in lithification, depositional environment and sediment facies must play an important role during burial history in controlling the progress of diagenesis.

Unit III appears to be a pelagic sequence composed predominantly of foraminiferal-nannofossil chalks, but it is complicated by the presence of several omission surfaces and a major slump unit (see Figs. 4 and 5). The base of Subunit IIb is marked by pale green and yellowish (altered) claystones of latest Albian age separated from the overlying chalks, interbedded ashes, and dark claystones by a conspicuous fault. Despite the sharp change in lithology across this fault, detailed biostratigraphic sampling indicates that sediments of latest Albian age
occur on both the upthrown and downthrown sides, although the overlying sediment is mainly Santonian and Campanian in age (see Fig. 6). The evident stratigraphic hiatus is not, therefore, produced by the faulting (which is probably small scale), and the Cenomanian to Coniacian interval appears to have been lost by erosion and/or nondeposition. The same is partly true for the Santonian and Campanian intervals, which are both abbreviated and incomplete (see Biostratigraphy section).

The dark mudstones in the Santonian-Campanian probably represent altered, fine-grained volcanic ashes. The mudstone layers exhibit bored surfaces, and one appears to correspond with the Maestrichtian/Campanian boundary and another with the Campanian/Santonian contact.

An additional interesting feature of Unit III is the presence of apparently "shallow-water" foraminifers in the Campanian foraminiferal-nannofossil chucks. Some of this material is coeval with the matrix and has not been reworked from other, Unit V type sediments exposed elsewhere. It may indicate that the site, although raised above the surrounding seafloor, was still within reach of turbidity currents.

At the top of the lower Maestrichtian interval in Core 538A-21, there is a manganese-encrusted omission surface which is capped by a thin layer of lower Eocene chalk, suggesting condensing and loss of the upper Maestrichtian and Paleocene sections. However, above the 25 cm of lower Eocene chalk there is an approximately 7.2-m thick section of Paleocene sediment topped by a hardground and overlain by lower middle Eocene chalk. This reversal of stratigraphic order indicates that slumping has taken place (see Fig. 4), and this is supported by the deformation of the lowest ± 30 cm of the allochthonous unit. Several important points are evident:

1. In the autochthonous sequence at Hole 538A there was either minimal deposition during the Paleocene or most Paleocene sediment was removed by slumping.
2. The slump took place between the early and early middle Eocene, at which time the slumped sediment must have been relatively cohesive.
3. Prior to displacement, the omission surface at the top of the slump unit may have merged laterally with the one at its base.

Schlager and others (this volume) consider this slump to have been triggered by tectonics rather than sediment loading.

Unit II is a fine-grained pelagic deposit that contains two particularly interesting features; these are the apparent episode of a higher radiolarian productivity during the middle Eocene (Subunit IIb) and the thin, sandgrade, vitric ash beds. When not disturbed by bioturbation or drizzling, several of the ash beds reveal sharp bases, grading, and bioturbated transitional upper contacts. Because we observed no evidence for traction current deposition (e.g., winnowed sand layers, ripple cross lamination) in these beds, we believe that they were produced by the settling out of volcanogenic particles deposited from atmospheric ash clouds rather than deposition from turbidity currents.

Unit I is also a purely pelagic deposit, although the upper subunit is less pure, containing marls and even a clay layer. The latter lithologies may suggest an increase in the amount of suspended clay materials entering the basin. At least two of the more clayey bands contain a small amount of sand-size quartz grains (less than 2%) and it is possible that the top of the knoll was not totally beyond the influence of large turbidity currents at this time. The Tertiary pelagic sequence in Hole 538A is capped by a chalky hardground of late Pliocene age.

**Biostratigraphy**

**Summary**

Most of the biostratigraphic data at Site 538 have been collected from Hole 538A, which penetrated 267 m of sediments ranging in age from Holocene to late to early(? ) Berriasian and resting on older metamorphic and igneous basement rocks. Sediments recovered in Hole 538 add some information only about the uppermost part of the sedimentary sequence.

Sedimentologically, five discrete units have been recognized at this site. The upper four units are predominantly pelagic in origin (ooze and chalk), whereas the fifth unit is mainly composed of skeletal-ooid limestone in which pelagic sediments are a minor component.

Biostratigraphically, the pelagic sequence that represents the bulk of the sediments recovered at Site 538, can be subdivided into specific intervals, characterized by peculiar composition or preservation of the biota. In very few cases do these intervals coincide with main changes in lithology.

These biostratigraphic intervals are as follows (from top to bottom):

1. **The uppermost interval**, about 20 m thick, corresponds to the uppermost part of Lithologic Subunit Ia (Core 538-1; 538A-1 to 538A-2, 10 cm) and is characterized by large hiatuses marked sometimes by indurated crusts (top of Core 538-1) or by questionable glauconitic ash layers (538A-1, CC). The ages of the recovered sediments are late Pliocene (Hole 538: nannofossil Zone CN12a, foraminiferal nannofossil Chalky Zone CNP12); early Pliocene (Hole 538: Zones CN10c, CN10d, CN9, CN7b, CN7b, CN11b, CN11d); middle Miocene (Hole 538A: Zones CN5, CN6, CN12a, CN12b, CN12c, CN12d); and middle Miocene (Hole 538A: Zones CN5, CN6, CN12a, CN12b, CN12c, CN12d). Except for the upper Pliocene assemblages, all other planktonic foraminiferal faunas, and in some cases nanofloras, are affected by dissolution.

2. **The second interval** (538A-2, CC; 538A-2-2, 11 cm through 538A-11) is characterized by a continuous sequence of upper Oligocene sediments deposited at a rate of 19.36 m/Ma. However, lower rates of sedimentation (9 m/Ma) are reported between 28 and 26 Ma in Zone P21b. In this specific interval, planktonic foraminiferal faunas are dissolved to varying degrees. Such an event can be correlated with an important cooling event on a global scale.

3. **The next lower interval** (47.5 m thick), from Cores 538A-12 through 538A-16 (most of Unit IIA), ranges in age from early to late Oligocene through early middle Eocene and is characterized by a period of low depositional rates, interrupted by discrete hiatuses that appear not
to exceed 2-Ma duration. The biozones represented in this interval are: foraminiferal Zones P20-P18 and nannofossil Zones CP17-CP16 in the Oligocene; foraminiferal Zone P15 and nannofossil Zone CP15 in the upper Eocene; foraminiferal Zones P14-P13 and nannofossil Zone CP14 in the middle Eocene.

4. The interval from Core 538A-17 through 538A-20-2, 75 cm—about 30 m thick—(Unit IIB) is characterized by predominant radiolarians. The entire interval is within the 1-Ma long nannofossil Zone CP12b of early middle Eocene age. The abundant of radiolarians in this interval (they are scarce in other parts of this sequence) is in our opinion a reflection of the high biogenic silica production similar to that at Site 537 as well as at many other oceanic areas during the middle Eocene (e.g., Horizon A in the western North Atlantic).

5. About 30 Ma of the geologic history of the area is represented by only 12.45 m from 538A-20-2, 75 cm to 538A-21-4, 110 cm (Unit III). The sequence is characterized by large hiatuses frequently marked by conspicuous hardgrounds. The youngest sediments recorded in the interval are of early Eocene age (Morozovella aragonensis Zone P8; Discoaster lodoensis Zone CP11). They are overlain abruptly by about 6 m of sediments of late Paleocene age. This stratigraphic repetition is interpreted as a slump that took place in late early Eocene, approximately 51-49 Ma. Other sediments recorded in the sequence are: (1) upper Paleocene, just below the hardgrounds at the bottom of the lower Eocene sediments in 538A-21-1, 58-63 cm associated with some volcanic glass and exotic lithotypes; (2) lower Maestrichtian (538A-21-1, 62 cm to 538A-21-2, 125 cm), beginning just below the mentioned hardgrounds; (3) lower upper Campanian (538A-21-2, 126 cm to 538A-21-4, 75 cm), separated by a hiatus of at least 1 Ma from the lower Maestrichtian; (4) lower Santonian in 538A-21-4, 78-110 cm.

This interval contains the longest record of the Upper Cretaceous sediments ever recovered in this area of the Gulf of Mexico, and it contains the youngest influx of reefal, shallow-water debris from the Early Cretaceous carbonate platform, as well as neritic benthic forms of late Campanian age that display affinities to similar forms in Texas. Reworked and displaced material occurs at the bottom of the recovered upper Campanian pelagic sediments. The lowermost interval—22 m thick, corresponding to Unit IV, from 538A-21-1, 110 cm through Core 23—spans the whole Planomalina buxtorfi Zone of latest Albian, whose duration is about 2 Ma. Hard limestones in between the nannofossil chalk and marly limestones are dominated by radiolarians, but foraminifers are poorly preserved and sparse.

Unit V, the lowest sedimentary unit overlying the metamorphic and igneous rocks (Core 538A-24 through 538A-30-1, 0-4 cm) consists primarily of oolitic, skeletal, and oncotic limestones with pelagic limestone as a minor component. However, the latter lithotype contains age-diagnostic calpionellids. Based on the occurrence of the various species belonging to this pelagic fossil group, the limestone sequence can be dated as early Valanginian to late-early(?) Berriasian.

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Foraminifers and Calpionellids

**Hole 538**

The 6 m (Core 1) of nannofossil ooze (Unit I) recovered in Hole 538 range in age from late Pliocene to late Oligocene, and the sequence is characterized by important hiatuses.

The uppermost 53 cm in Section 538-1-1 contain a rich planktonic foraminiferal fauna of late Pliocene age. The concurrence of Globorotalia puncuticulata and Sphaeroidinellopsis ssp. in the absence of G. margaritae allows us to attribute this interval to Zone MPL4.

The color change at 538-1-1, 54 cm coincides with a hiatus of less than 1 Ma. At this level, a rich, moderately preserved planktonic foraminiferal fauna of early Pliocene age occurs. The assemblage, belonging to Zone MPL2 and characterized by G. margaritae associated with Globigerina nepentes, occurs through 538-1-4, 10 cm. Faunas become progressively more dissolved downwards. At 538-1-4, 10 cm, another abrupt change in both color (bluish) and lithology (more chalky) corresponds to another hiatus—one of about 20 Ma. In fact the remainder of Core 538-1 contains a diversified assemblage of the G. angulisuturalis Zone (= P22) of late Oligocene age.

**Hole 538A**

On the basis of the fossil content, the sequence recovered at this hole can be subdivided in two parts: (1) an upper portion consisting dominantly of foraminiferal-nannofossil ooze or nannofossil chalk, rich in planktonic organisms, but characterized by large hiatuses (Units I through IV) and (2) a lower unit (Unit V) of mainly oolitic, skeletal, and oncotic limestone with minor pelagic limestone.

In Core 1, the first sediments encountered are already late Miocene in age and are indurated at their top. According to the nannoplankton data (foraminifers were not processed in this interval), most of Core 1 belongs to the upper Miocene Zones N17 through N16. The core catcher sample contains a largely mixed assemblage of different ages, which includes upper Miocene Zone N17 elements (dominant), middle Miocene forms possibly belonging to Zone N12, and some undifferentiated upper Oligocene forms. Planktonic foraminiferal faunas are partially dissolved. Some glauconite grains also occur.

Most of Core 2 contains a middle Miocene Zone N12 assemblage, but it bottoms in upper Oligocene sediments of the Globigerina angulisuturalis Zone (= P22). The same zonal assemblage occurs in Cores 3 through 5. Cores 6 through 7 yield a rich assemblage attributable to the upper part of the Globorotalia opima Zone (= P21b), characterized by the concurrence of the zonal marker with Globigerina angulisuturalis. The lower part of the G. opima Zone (= P21a) is represented in Core 8 through 11. It is within this interval that sediments are more lithified (Unit II). The next older zone, G. ampliapertura Zone (= P20), occurs apparently only in Core 12. Core 13 contains a planktonic foraminiferal assemblage characteristic of the upper part of the Pseudohas-
tigerina micra/Cassigerinella chipolensis Zone (= P19), whereas Core 14, core catcher excluded, seems to contain the lower part of the same zone (= P18), which represents the lowermost zone of the lower Oligocene. Thus, the Oligocene sequence appears to be almost complete in Hole 538A. Planktonic foraminiferal faunas are well preserved in the upper part of the Oligocene but display a progressive deterioration downwards because of dissolution effects. The environment change implied would account for the clearly low rate of sedimentation of the lower portion.

A hiatus probably occurs in Core 14 and spans the Oligocene/Eocene boundary and part of the upper Eocene. However, poor recovery (less than one section) prevents a definite conclusion. Sample 538A-14,CC belongs to the lower upper Eocene Globigerinatheka semi-involuta Zone (= P15).

Cores 15 and 16 yielded relatively well-preserved faunas of the upper middle Eocene Truncorotaloides rohri and Orbulinoides beckmanni Zones (= P13, P14), respectively. Core 17 contains a planktonic assemblage of lower middle Eocene Hantkenina aragonensis Zone. Thus, the middle part of the middle Eocene is missing at Hole 538A. Radiolarians from Core 17 downwards become predominant, and preservation of planktonic foraminifers progressively deteriorates, so no specific age assignment on the basis of foraminiferal content can be made for Cores 18 to 20. Nannofossil assemblages suggest that the whole interval has the same age as Core 17.

A conspicuous hardground at 538A-20-2, 76 cm is the sedimentary expression of a hiatus of about 7 Ma, spanning the whole lower Eocene and the uppermost Paleocene (Morozovella velascoensis Zone = P5). The hardground truncates sediments containing a planktonic foraminiferal fauna of the upper Paleocene Planorotalites pseudomenardii Zone (= P5). The same zonal assemblage is recorded in most of Core 20 through 538A-20-2, 112 cm. The bottom part of Core 20 and the uppermost 32 cm of 538A-21-1, contain rich planktonic faunas of the lower Paleocene "Subbotina" pseudobulioides Zone (P1c). Manganese coating marks a hiatus of more than 6 Ma. The lower Paleocene pink chalk rests unconformably on 25 cm of whitish foraminiferal chalk of the lower Eocene M. aragonensis Zone (= P8). Consequently, the upper and lower Paleocene strata are interpreted as a slump formed sometime after the M. aragonensis Zone (early Eocene) and before the middle Eocene.

The 25 cm of lower Eocene sediments lie upon an irregular, manganese-rich burrowed surface or hardground (4 cm thick). Elements of the hardground are a chalky sediment, now manganese impregnated, of late Paleocene age (P. pseudomenardii Zone), fragments of altered volcanic glass, clay minerals, chert, and other rock fragments. No Upper Cretaceous microfaunas occur in that layer. A very irregular and indurated upper surface of the grayish foraminiferal-nannofossil chalk that underlies the Mn-rich hardground may represent a second hardground. This lower unit, encountered at 538A-21-1, 62 cm, contains a rich foraminiferal assemblage attributable to the lower Maestrichtian Globotruncanata tricarinata Zone; the same assemblage is recorded through 538A-21-2, 125 cm. At that level, no lithologic break occurs to account for the absence of the upper Campanian G. calcarea Zone, G. subspinosa Zone, and possibly the top part of the G. elevata Zone. The planktonic faunas are older than these zones or parts of zones and can be attributed to a generalized medial part of the G. elevata Zone, still of Campanian age. The same assemblage continues downwards as far as 538A-21-4, 75 cm. The allochthonous benthic foraminiferal faunas contain forms indicating a lower bathyal environment. Some omission surfaces in this interval have been suggested by sedimentologic observations, but the poor resolution of planktonic foraminifers prevents the detection of such minor hiatuses.

The lower part of the upper Campanian sediments recovered in 538A-21-4, 10–75 cm is much coarser than the overlying chalk. This layer contains fragments of altered ash layers, neritic benthic foraminifers of late Campanian age, shallower-water skeletal debris of Early Cretaceous age, and finally an early Santonian planktonic foraminiferal assemblage. The allochthonous material is very abundant at 538A-21-4, 72–75 cm and at 538A-21-4, 53 cm. It decreases gradually upwards to 538A-21-4, 29 cm, where it is a minor component. This suggests that this upper Campanian interval may contain originally graded turbidites with shallower-water material that was largely destroyed by burrowing and are thus not recognizable in the cores.

A rich, diversified planktonic fauna occurs in 538A-21-4, 78–110 cm. The assemblages contain several specimens of Dicarinella concavata and of various species of Marginotruncana. The concurrence of those forms dates this interval as early Santonian within the D. concavata Zone. The allochthonous benthic foraminiferal assemblages are characteristic of a dominantly lower bathyal environment; however, shallow-water Lower Cretaceous benthic foraminifers and debris also occur within this interval.

Another hiatus and possible hardground occurs at 538A-21-4, 110 cm. The underlying yellowish to green claystones are barren. In 538A-21-5, 18–23 cm, a light brownish gray nannofossil chalk contains only a very large amount of fish debris. Rich and well preserved, planktonic foraminiferal faunas of the uppermost Albian Planomalina buxtorfi Zone, occur in several layers from the core catcher sample of Cores 21 through 23. The benthic foraminiferal assemblages are characteristic of the middle bathyal zone. The most prominent species belong to the genera Praebulimina, Ellipsoidella, Osangularia, and Gaudryina. Shallow-water benthic foraminifers are mixed in the assemblages. Fish debris is a relatively common component of the residues.

The limestone (Unit V) recovered at Hole 538A contains two different assemblages: (1) a shallow-water assemblage from a carbonate platform very similar in aspect as well as in biogenic components to that recovered in limestones at Site 537; (2) a pelagic assemblage constituted by calpionellids (Cores 538A-25 through 538A-30-1, 0–4 cm).

The shallow-water material of Core 24 has the same composition as underlying cores and as the material re-
covered at Site 537 in the same stratigraphic position. The major difference is that, at Site 538, biogenic components, such as *Troccholina*, occur mainly as nuclei of ooids, whereas in the deeper cores they are mainly found as separate sediment particles. We believe that *Troccholina* in Core 24 are reworked from older parts of a shallow-water sequence.

Besides the shallow-water components, the interval from Core 538A-25 through 538A-30-1, 0-4 cm contains several layers with abundant calpionellids (see 538A-27-1, 4-5 cm). Based on their occurrence, this interval can be dated as a succession of three biozones, ranging from early Valanginian (Core 25) to possibly early Berrissian (Core 30) at the bottom. Specifically, Cores 25 and 26 can be attributed to Subzone D3 of calpionellid Zone; Cores 27 and 28 to Subzone D2 on the basis of the occurrence of *Calpionellopsis simplex*, the zonal marker; and finally Cores 29 and 30 to Subzone D1, which straddles the upper/lower Berrissian boundary, on the basis of the occurrence of *Calpionella elliptica* and the absence of the former index species. The shallow-water assemblages are very monotonous.

**Calcareaous Nannofossils**

**Hole 538**

Core 1 recovered an approximately 520-cm sequence of pelagic calcareous oozes ranging in age from late Pliocene to late Oligocene. In addition, a small amount of soupy, brown, calcareous ooze was recovered washed along the liner in 538-1-1, 0-120 cm. This soupy material contains a mixture of Neogene and Upper Cretaceous nannofossils with species of the *Emiliania huxleyi* Zone (CN14—late Pleistocene through Holocene) most abundant. Interval 538-1-1, 0-53 cm contains assemblages with *Discoaster tamalis*, *D. surculus*, *D. brouweri*, and *Cyclicargolithus abisectus*. This interval is assigned to the *D. tamalis* Subzone (CN12a) of late Pliocene age. Separated from this interval by a sharp lithologic break are nannofossil oozes of the *Amaurolithus tricorniculatus* Zone (CN10) of early Pliocene age. This lower Pliocene interval (from 538-1-1, 54-55 cm to 538-1-4, 8-9 cm) contains *D. asymmetricus*, *D. surculus*, and *A. tricorniculatus*. The core interval from 538-1-4, 10-11 cm through 538-1, CC contains an assemblage of the *Sphenolithus ciperoensis* Zone (CP19) of late Oligocene age. Species present include *S. ciperoensis*, *S. moriformis*, and *Cyclicargolithus abisectus*.

**Hole 538A**

Drilling in Hole 538A penetrated approximately 267 m of Tertiary and Cretaceous sediments before entering older metamorphic and igneous rocks. Cores 1 through 21 (partim) contain Tertiary sediments, and Cores 21 (partim) through 30 (partim) contain Cretaceous sediments.

The interval from Core 538A-1 through 538A-2-3, 20 cm contains sediments of Miocene age. Core 1 is topped by a hardground developed in upper Miocene sediments. The interval 538A-1-1, 0-27 cm contains *Discoaster quinqueramus*, *Amaurolithus primus*, and *A. delicatus*, indicating the upper Miocene *D. quinqueramus* Zone (CN9). Samples from the interval between 538A-1-1, 28 cm and 538A-1-2, 63 cm contain *D. hamatus*, *Catisaster calyculus*, and *D. neohamatus*. This interval is assigned to the *C. calyculus* Subzone (CN7b) of late Miocene age. The core catcher of Core 1 contains *C. coali tus* but lacks both *D. hamatus* and *C. calyculus*, indicating the *C. coali tus* Zone (CN6) of middle Miocene age. The interval from 538A-2-2, 11 cm through 538A-2-3 contains *Cyclicargolithus floridanus*, *D. deflandrei*, and *T. carinatus*, but lacks both *S. belemnos* and *S. ciperoensis*. This indicates that this interval is in the *T. carinatus* Zone (CN1).

The interval from 538A-2, CC through 538A-9 contains an upper Oligocene assemblage that includes *S. ciperoensis*, *C. abisectus*, and *C. floridanus*. This interval is assigned to the *S. ciperoensis* Zone (CP19). The interval between the top of Core 538A-10 and 538A-10-5, 3-4 cm contains *S. distentus* and *S. predistentus* but lacks *S. ciperoensis*. This interval is assigned to the *S. distentus* Zone (CP18) of late Oligocene age. The interval from 538A-10-5, 22-23 cm through 538A-13-3 contains *S. predistentus* but lacks *S. distentus*, *R. umbilica*, and *R. hilaee*, indicating the *S. predistentus* Zone (CP17) of early Oligocene age. Both 538A-13, CC and 538A-14-1 contain *S. predistentus*, *R. umbilica*, and *R. hilaee*, indicating the *Helicopontosphaera reticulata* Zone (CP16) of early Oligocene age. Some Eocene species, such as *D. barbadiensis* and *D. saipanensis*, occur as very rare, badly dissolved, or overgrown elements of these assemblages.

The core catcher of 538A-14 contains a well-preserved assemblage that includes *D. barbadiensis* and *D. saipanensis* but lacks *Chiasmolithus grandis*, indicating the *D. barbadiensis* Zone (CP15) of late Eocene age. The interval from 538A-15 through 538A-17-5 contains *C. grandis* and *R. umbilica*; this association indicates the *R. umbilica* Zone (CP14) of middle Eocene age. The interval from 538A-17-6 through 538A-20-2, 75 cm contains *Nannotetraquadra quadrata* and *Rhabdosphaera inflate*, indicating the *R. inflate* Subzone (CP12b) of early middle Eocene age. A beautifully expressed hardground at 538A-20-2, 75 cm separates the overlying lower middle Eocene sediments from the underlying strata.

The interval from 538A-20-2, 75 cm through 538A-21-1, 57 cm contains a biostratigraphic succession of nannofossil assemblages that reveals structural complications in what appears to be a lithologically simple sequence. The interval from 538A-20-2, 75 cm through 538A-20-4, 111 cm contains assemblages typical of the *D. multiradiatus* Zone (CP8) of late Paleocene age. A hardground at 538A-20-4, 111 cm separates this upper Paleocene strata from the underlying sequence. The interval from 538A-20-4, 114 cm through 538A-21-1, 31 cm contains nannofossils of the lower Paleocene (Danian) *Crichtosphalolithus tenuis* Subzone (CP1b). A sharp lithologic boundary at 538A-21-1, 32 cm separates this Danian interval from the underlying strata. The structural complica-
tions are evident if the sediments immediately below this boundary are considered. The nannofossils in this sediment include *D. barbadiensis* and *D. lodoensis* but lack *D. sublodoensis*, *Nannotetraena quadrata*, and *Reticulofenestra umbilica*, indicating the *D. lodoensis* Zone (CPU) of early Eocene age. Thus, the Paleocene block lies between two interval of Eocene sediments. Slumping of the Paleocene block is a probable explanation for this situation. Slumping would have taken place during the early Eocene to early middle Eocene.

The lower Eocene sediments (538A-21-1, 32-57 cm) lie on a prominent hardground. The sediments below this hardground are Cretaceous. The interval from 538A-21-1, 60 cm through 538A-21-3, 123 cm contains a rich assemblage that includes *Tetrarhithus gothicus*, *T. trifi-
dus*, and *T. aculeus*, indicating a late Campanian to early Maestrichtian age. The interval from 538A-21-3, 127 cm through 538A-21-4, 78 cm contains *T. gothicus* and *T. aculeus* without *T. trifidus*; this indicates a middle to late Campanian age. The interval 538A-21-4, 80-110 cm contains nannofossils of the *Marthasterites furcatus* Zone of Coniacian to early Santonian age. A high angle fault (extending from 538A-21-4, 105-114 cm) is present in the core. Sediments containing nannofossils of the *Eif-
fellithus turrisiefelli* Zone (late Albian to early Cenoma-
nian) occur on both sides of the fault. In the hanging wall, upper Albian to lower Cenomanian sediments occur at 538A-21-4, 112-114 cm. In the footwall, sediments of late Albian to early Cenomanian age occur at 538A-21-4, 105-114 cm (the entire length of the footwall). These ages suggest that the fault is a minor one; it may have little displacement and resulted in little or no loss of section. Sediments of the *E. turrisiefelli* Zone occur from 538A-21-4, 105 cm through 538A-23-1, 40 cm (in the footwall of the fault). Sediments within this interval include hard limestones, softer marls, and calcareous clays, and (from 538A-23-1, 33-40 cm) a nannofossil ooze. The occurrence of nannofossil ooze underlying hard nannofossil limestone in this short sequence is somewhat curious. Preservation of nannofossils throughout this interval is excellent.

The sediments between 538A-23-1, 41 cm and 538A-
30-1, 6 cm are limestones with no significant nannofossil assemblages. No age can be assigned to this interval using nannofossils. A thin layer of nannofossil lime-
stone occurs at 538A-30-1, 6-7 cm, lying directly on metamorphic rock. The sparse, moderately preserved as-
semblage of nannofossils recovered from this sediment indicates an early Berriasian through Valanginian age. Species present include *Retecapsa angustiforata*, *Ruci-
nolitithus wisi*, *Parhambololithus asper*, and *Lithraphidi-
tes carniolensis*.

**SEDIMENTATION RATES**

Thirty-three cores were recovered from Hole 538A. The majority of the sedimentary record is punctuated by hiatuses, which make it difficult to compute accurate sedimentation rates. However, two intervals, middle Eocene and Oligocene, are relatively complete. These two intervals have been chosen for the calculation of sedimentation rates.

Core 538A-2 through 538A-13-3 contain an Oligocene section (Fig. 7), which is apparently continuous. The lowermost Oligocene and the Eocene/Oligocene boundary were not recovered. Cores 14 through 17 of Hole 538A apparently contain a continuous sequence of the middle Eocene. A list of the biostratigraphic data employed to define each of the sediment accumulation boxes is given below.

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**Figure 7**

<table>
<thead>
<tr>
<th>Box</th>
<th>Biozone</th>
<th>Sedimentation rate (m/Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>lower <em>Globigerina ciperoensis</em> Zone, P22</td>
<td>36</td>
</tr>
<tr>
<td>2</td>
<td>upper <em>Globorotalia opima</em> Zone, P21a</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>middle <em>G. opima</em> Zone, upper P21a; base of box defined by the bottom of <em>Sphenolithus ciperoensis</em> Zone (CP19)</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>lower <em>G. opima</em> Zone, lower P21a</td>
<td>19</td>
</tr>
<tr>
<td>5</td>
<td>lowest <em>G. opima</em> Zone and <em>Globigerina ampliaperta</em> Zone, P20</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td><em>Caesigerinella chipolensis</em> Zone, upper P19; base of box defined by bottom of <em>S. predistentus</em> Zone (CP17)</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>Hiatus</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td><em>Oribulinoides beckmannii</em> Zone, P13</td>
<td>5</td>
</tr>
</tbody>
</table>

**Figure 7.** Oligocene and middle Eocene sedimentation rate curves for Site 538. Data from Hole 538A. Numbered boxes give the depth and age ranges of zones described in the text. Wavy lines indicate hiatuses.
The sedimentation rate is low for the middle Eocene and early Oligocene intervals (Cores 16 through 12). The rate increases three-fold for the early late Oligocene (Fig. 7). This increase is even more marked in the later portion of the late Oligocene (Cores 2 through 5). The sedimentation rate increases markedly after 30 Ma and this age corresponds with a significant global sea level lowstand (Vail et al., 1977). The increased rates for the section younger than 30 Ma could reflect the subsequent sea level rise and establishment of a suitable pelagic depositional environment, one perhaps favored by a combination of increased productivity and sediment preservation.

**IGNEOUS AND METAMORPHIC PETROLOGY**

The igneous and metamorphic rocks underlying the sedimentary sequence in Hole 538A include gneiss and amphibolite intruded by diabase dikes. The diabase dikes allow convenient separation of this complex into four lithologic units. These are illustrated in Figure 8 and discussed below.

**Unit I: Cores 30 to 31**

Gneiss and amphibolite are the principal rock types of Unit I. A distinct interval of altered diabase within this sequence permits further separation into three subunits.

*Subunit Ia (538A-30-1, 5 cm to base of core).* Dark gray, variably mylonitic, felsic gneiss with a steeply dipping fabric composes this subunit. The contact of this gneiss with the overlying limestone was apparently recovered in 538A-30-1 (piece 2), where several fragments of fractured, partly brecciated, and calcite-cemented gneiss are coated with a thin veneer of white, chalky nanofossil limestone. The uppermost piece is coated on two sides with this limestone; the underlying fragment has only a thin coating at its top surface. The gneiss is fine-grained to coarse-grained with a porphyritic texture. Protomylonitic textures are locally developed. Quartz is the most abundant mineral (about 50%), forming irregular and elongate crystals up to 2 mm long with sutured contacts. Feldspars (about 20%) occur as large (up to 3 mm) porphyroblasts of orthoclase, as smaller interstitial groups of perthitic orthoclase-albite, and as granular crystals (0.1-0.05 mm) of albite. Some orthoclase is zoned. Greenish brown pleochroic biotite is common (about 5%) in the gneiss as small (0.1-0.05 mm), platy crystals aligned parallel to apparent shear zones. Locally, biotite is completely replaced by chlorite. Sphene occurs as small (0.1-0.3 mm, but can be up to 1 mm), idiomorphic grains, some with opaque minerals in their cores. Opaque minerals are cubic or subhedral (about 0.1-0.5 mm) and randomly distributed. A large pink calcite vein cuts this gneiss in 538A-30-1.

*Subunit Ib (538A-31-1, 0-105 cm).* This lower subunit is a complex association of gneiss and amphibolite. At the top a calcite-cemented gneiss breccia occurs. Below this is dark gray green amphibolite interlayered in the middle of Section 538A-31-2 by several pieces of gneiss with a steeply dipping fabric. The gneiss is texturally and compositionally identical to that in Subunit Ia. The amphibolite has an ophitic to subophitic texture and consists of about equal proportions of idiomorphic green hornblende and xenoblastic plagioclase with minor sphene (less than 1%) and no opaque minerals. The hornblende is strongly pleochroic and has good cleavage and an extinction angle of about 16°. Plagio-

![Figure 8. Summary of igneous and metamorphic rocks at Hole 538A.](image-url)
class crystals (about AN_{40}) are slightly larger than the hornblende and partly sericitized. Sphene occurs as small (about 0.2 mm) xenoblastic crystals associated with the hornblende. We observed only a faint lineation in thin sections of this amphibolite. However, some fragments at the base of Core 31 have a strong steeply dipping fabric, parallel to the gneiss.

**Unit II: Top of Core 538A-32 to 538A-33-1, 120 cm**

Medium gray to dark gray, fine-grained to medium-grained diabase with abundant carbonate vein makes up Unit II. It has an ophiitic to subophitic texture and consists of plagioclase (55%), pyroxene (40%), interstitial glass (about 5%; completely altered to green clay), minor biotite (less than 1%), and opaque minerals (about 5%). Plagioclases (about An_{30-60}) are zoned, lath-shaped crystals (1-2 mm long) with common Carlsbad and albite twins. Pyroxene is mostly normal euhedral augite (0.2-1.2 mm) with ZAC ~ 40°, 2V ~ 60° and a positive optical sign. One hundred twins occur in the larger euhedral crystals. Green clay, probably a replacement of glass, occurs in interstices between plagioclase and augite crystals. Small, platy, green brown, pleochroic biotite crystals are associated with this clay. Opaques (magnetite?) form skeletal and interstitial, granular crystals up to 0.5 mm across. The upper contact of this diabase with Unit I is a drilling break. The lower contact with amphibolite of Unit III is a wide alteration zone of 538A-33-1, 10-110 cm. Abundant calcite veins cut this zone. A diabase sample from the middle of this zone shows relic biotite, plagioclase laths, and augite crystals, the latter apparently pseudomorphed by calcite. The lowest piece (538A-33-1, 110 cm) has a relic metamorphic fabric.

**Unit III: 538A-33-1, 120 cm through Base of Core 538A-34**

Green to medium gray and dark gray, fine-grained, variably altered amphibolite forms the bulk of Unit III. It is texturally and compositionally similar to amphibolite described in Subunit Ic except that it contains up to 5% opaque minerals and the hornblendes are more altered. The hornblende is green, strongly pleochroic with ragged terminations. It occurs as ophitic to subophitic intergrowths with plagioclase and as inclusions in some large plagioclase crystals. Plagioclase crystals (about AN_{30-45}) are about 0.2-0.4 mm across and twinned (albite mostly, but Carlsbad for larger crystals). Opaque minerals are irregular or subhedral (0.1-0.2 mm) occurring mostly in the centers of hornblende crystals. A well-developed linear fabric is evident in thin section.

Enclaves of felsic gneiss occur locally in Unit III. The best examples are in 538A-32 and 538A-34-3, where complete gradations from gneiss to amphibolite can be seen. Relatively unaltered gneiss is similar to that in Unit I. Several pieces (e.g., piece 6 in 538A-34-3) have protomylonite to mylonite textures, with large 1-2 mm porphyroblasts of fractured feldspar (orthoclase and perthitic orthoclase-albite) and an interstitial “fluxion” foliation defined by ribbons of recrystallized quartz and biotite. Epidote (less than 1%) is present as small (0.1-mm) broken grains along the fluxion surface. Soft, dark green severely altered amphibolite and/or diabase (?) is common in 538A-34-2.

**Unit IV: Top of Core 35 through Core 36**

Fine-grained to medium-grained diabase forms most of Unit IV. It is texturally and compositionally similar to that of Unit II. The occurrence of variably altered amphibolite and gneiss breccia in the top of Core 36 permit a threefold division of this unit.

**Subunit IVa: Core 35.** This subunit consists of fine-grained to medium-grained, calcite-veined diabase and a thin interval of amphibolite and common calcite veins. The diabase is composed of plagioclase, augite, biotite, opaque minerals, and green clay (altered interstitial glass). It is texturally and mineralogically similar to that of Unit II. A 2-cm thick “lens” of pink feldspar (and quartz?) occurs in this diabase at 538A-35-1, 45 cm.

The amphibolite is dark gray and medium-grained to coarse-grained. It is highly altered green clay, particularly near its lower contact with the diabase. The contacts between these rocks are steep, complex, and extensively veined with calcite.

**Subunit IVb (top of Core 538A-36 to 538A-36-2, 55 cm).** Amphibolite, diabase, and gneiss breccia make up this subunit. The amphibolite occurring at the top of Section 538A-36-1 is dark gray and macroscopically similar to the amphibolite of Unit III. No thin sections were taken, so it is not possible to compare it further with those Unit III rocks. The contact with the underlying diabase is a drilling break. This diabase is dark gray and very fine-grained with abundant calcite veins. It contains plagioclase, augite, biotite, opaques, and green clay. It is similar in mineralogy and texture to the diabase of Unit II and Subunit IVa. The basal contact of this diabase with the underlying gneiss breccia is obscured by drilling breaks but appears to be gradational; the last few pieces of diabase in 538A-36-1 have a faint gneissose fabric. In addition, fragments of diabase occur in the gneiss breccia. The lowest member of Subunit IVb is a gneiss breccia consisting of gneiss and some diabase fragments (up to 3 cm across) in a calcite cement. Severely altered amphibolite and/or diabase forms the base of this member and the transition to the underlying diabase.

**Subunit IVc (538A-36-2, 55 cm to base of core).** The dark gray, medium-grained diabase of this subunit is similar to but slightly coarser-grained than the diabase of Subunits IVa and IVb and of Unit II. A zone of alteration containing large (0.5-1 mm) white crystals of mica occurs in 538A-36-3. This mineral is probably muscovite despite the low 2V (~15°); it is too hard for talc and the wrong paragenesis for phlogopite(?). Calcite veins are also common in this diabase.

**Interpretation**

The igneous and metamorphic suite penetrated at Ca-toche Knoll records a complex history of metamorphism and igneous intrusion. The gneiss and amphibolite of this sequence are, in part, interlayered. Mineral assemblages within both the gneiss and amphibolite are char-
characteristic of middle to upper amphibolite grades of metamorphism. The high grade minerals are aligned into well-defined foliations suggesting that growth occurred during a regional, deep-seated metamorphic event. Later mylonitic fabrics are locally superimposed on the gneiss-amphibolite sequence but are not developed on the diabase dikes. The dikes also show no evidence of metamorphism and are not foliated. Both the metamorphic suite and the dikes are variably affected by low-temperature hydrothermal and/or deuteric alteration. Alteration products occur as unfoliated, pseudomorphic replacements.

Together, textural and mineralogy characteristics of the basement terrain suggest the following history.
1. regional middle to upper amphibolite grade metamorphism (protoliths uncertain) concomitant with penetrative deformation
2. uplift and cooling of the metamorphic terrain
3. local development of high-strain ductile fabrics
4. intrusion of diabase dikes
5. low-temperature alteration

GEOCHEMISTRY

Organic Geochemistry

The techniques used to analyze the organic geochemistry of rocks and sediments on Leg 77 are described in the introductory chapter of this volume. Eleven rock samples were taken from Cores 16 through 22 at Hole 538A for Rock-Eval analysis. From the Rock-Eval data, two CHN and carbonate bomb samples were selected. Unit I, upper Pliocene to upper Oligocene foraminiferal-nannofossil ooze, was not sampled because it was much too light-colored to contain any organic material. Three samples were taken from Unit II, upper Oligocene to middle Eocene nannofossil ooze and chalk, as there were several dark gray intervals in Section 538A-16-5. Seven samples were analyzed from Unit III, a series of different lithologies of middle Eocene to latest Albian age. Unit IV, late Albian nannofossil chalk, was sampled once. Unit V and basement were not sampled because the lithologies were not suitable; the former unit is a skeletal-oolitic limestone and the latter unit is composed of igneous and metamorphic rocks.

Except for the first two samples from Unit II, all other samples give no indication of volatile (S1) or pyrolyzable (S2) hydrocarbons (Fig. 9 and Table 3). The two samples from 538A-16-5 (25-26 cm and 60-61 cm) are dark gray nannofossil ooze with S2 values of 4.5 and 2.1 mg HC/g rock, respectively. The S2 peak temperature of the two samples is below 435°C, and thus they are immature. The production index is below the minimum value for generated hydrocarbons or for "live" oil shows. Organic and carbonate carbon analyses were carried out on the first two samples to determine the type of kerogen in these rocks. The organic carbon values are 3 and 2 wt.%, respectively. The hydrogen index is low (150 and 105), and the oxygen index is high (80 and 96). Type III kerogens, when they are this low in hydrogen content (0.75 H/C), are generally gas "prone." However, these rocks contain 2-3 wt.% organic carbon so they may yield some oil as well as gas at maturity. Car-

![Figure 9. Organic geochemistry summary, Hole 538A (after Clementz et al., 1979). TD = total depth. * denotes asphalt.](image)
bon in carbonate for Sample 538A-16-5, 25-26 is 52 wt.%, a marl, whereas that for Sample 538A-16-5, 60-61 is 12 wt.%, a shale (Table 3).

Asphalt was disseminated throughout Core 16 (135.5–141.5 m) as small particles or, in a few cases, as small blebs (1–3 mm). The asphalt did not fluoresce under the fluoroscope but did fluoresce when cut with 1,12,2-tetrachloroethane. There was no oil stain in the host nanofossil chalk, and the dark intervals sampled for the Rock-Eval were not involved.

An explanation for the asphalt in Core 16 may be that in the late Oligocene to middle Eocene, oil or asphalt from a seep near Site 538 settled out of the water column and became incorporated into the sediment on the seafloor. An alternative explanation might be a large oil spill from an Eocene supertanker.

Inorganic Geochemistry

Six samples for carbonate bomb analyses were taken from Hole 538 and 25 samples were taken from Hole 538A. The results are tabulated in Table 4 and are shown on the summary figure (Fig. 2). The analyses generally confirm the petrographic evidence. No interstitial water samples were taken at Hole 538, but four samples were taken at 538A. The results are tabulated on Table 5. The results are typical of many deep-sea sections. Salinity, pH, alkalinity, and chlorinity do not vary significantly with depth. Calcium increases slightly and magnesium decreases somewhat with depth, a pattern common to many deep-sea sites.

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PALEOMAGNETISM

Danian

At Hole 538A, a 2.1-m section of Danian chalk was recovered from 538A-20-4 through 538A-20-6. It is sandwiched between Eocene rocks and topped by a hardground, implying that it was lithified at the time of slumping. There was apparently little tilting during slumping, because the bedding is nearly horizontal and the foraminiferal zones are in correct stratigraphic sequence. Magnetic polarity determinations should, therefore, be correct, although there may be a slight inclination error. Eleven oriented minicores were taken at 15–25 cm intervals within the Danian section in order to magnetically correlate this sequence with Site 536, where a complete section through the Cretaceous/Tertiary boundary was sampled.

Low intensities made it necessary to measure the samples with a cryogenic magnetometer at the University of Texas, Galveston Geophysical Laboratory. All samples were demagnetized at 50, 100, and 200 Oe, followed by thermal demagnetization at 220, 300, 400, 500, and 550°C. Two samples had a single component of magnetization, and in all other samples two components could be clearly identified from orthogonal vector diagrams. In the latter case, the less stable component was always of normal polarity.

The reversal stratigraphy, derived from the more stable component cannot be unequivocally correlated with the Danian reversal pattern until more detailed paleon-
tologic data are available. The occurrence of two foraminiferal zones ("Subbotina" pseudobulloides and Globorotalia trinidadensis) in the sample interval necessitates that the reversal pattern includes Anomaly 28. Two possible correlations are shown in Figure 10. One makes use of the observation that Anomaly 27 may consist of a triplet (Gubbio section, Roggenthen and Napoleone, 1977). Additional sampling may help determine the correct correlation. Magnetically this section cannot be correlated with an equivalent section at Site 536.

**Basement**

The basement complex at Hole 538A (Cores 30 through 36) consists of gneiss and amphibolite intruded by diabase dikes. Low-temperature hydrothermal and/or deuteric alteration locally affects rocks of the basement complex, so sampling was concentrated in unaltered intervals. Twenty-one oriented minicores were taken from the diabase, and five were collected from the amphibolite. Shipboard measurements included initial susceptibility and natural remanent magnetization (NRM). To avoid the effect of the ship’s 1-Oe field on any viscous component in the samples, demagnetization was not conducted onboard. Further work was done in the magnetically shielded room at the Galveston Geophysics Laboratory.

Shore-based NRM measurements agreed well with shipboard measurements. After pilot studies, all samples were demagnetized at four or five levels between 50 and 400 Oe, and further demagnetization at 100-Oe intervals was performed on selected samples to a maximum of 700 Oe. The samples behaved very systematically upon demagnetization. Component #1, which is normal in all but two cases, is usually removed by demagnetization to 100 to 200 Oe. Component #2 is a stable component evident at higher demagnetization steps. The stable inclination and other measured parameters are listed in Table 6 and plotted in Figure 11. The magnetic mineralogy of the basement complex is discussed in a separate paper in this volume.

The five amphibolite samples are readily distinguished from the diabase by their low NRM intensities and low susceptibilities. Four of the five samples have a low positive inclination. The negative inclination of the one sample (538A-33-2, 81 cm) may be due to remagnetization during the intrusion of the overlying diabase. A thermoremanent magnetization (TRM) acquired in this manner would also explain the extremely high mean demagnetizing field (MDF) of that sample.

The magnetic parameters provide constraints on any model of diabase intrusion. The diabase from Core 32 differs significantly from that of Core 35 in its polarity, average inclination, Qn, and NRM intensity. The Qn and intensity differences can be explained by a different cooling rate, which would result in a different grain-size distribution. The opposite polarities suggest that the intrusions occurred after the end of the Permian Kiaman Interval, which was a period of constant reverse polarity lasting most of the Permian. The difference in inclinations (23.5 versus 37.5°) would suggest north-south block tilting or latitudinal motion between the time of the two intrusions.

The polarities of the diabase in Core 36 present a confusing picture. Each sample was from a different piece and could, therefore, represent a separate diabase dike whose contacts were not recovered. Alternatively, one could call upon a reversely magnetized intrusion adjacent to the drill hole to remagnetize the two middle samples, 538A-36-1, 89 cm and 538A-36-2, 86 cm.

The paleolatitude (σ) of a site is related to magnetic inclination (I) by:

\[
\tan \sigma = \frac{1}{2} \tan I.
\]

The average inclination of the basement rocks at Hole 538A (20.6°) is significantly different from that of the sedimentary rocks of Leg 77 (about 40°). It is tempting to interpret this as evidence of "plate motion." Alternatively, one could assume Catoche Knoll was part of the North American Plate and use the paleolatitude to determine the age of the intrusions. Unfortunately, neither of these approaches can be employed without first cor-

![Figure 10. Paleomagnetic results for Hole 538A showing several possible correlations with the Gubbio section (Roggenthen and Napoleone, 1977) and related foraminiferal zones. Circled numbers are marine magnetic anomalies. T = Tertiary; K = Cretaceous.](image)
recting for any tilting that has occurred since the time of the intrusions. Seismic sections from the southeastern Gulf of Mexico indicate that during rifting, tilting of basement blocks was a widespread phenomenon. Indeed, the inclination difference between the diabase in Core 32 and that in Core 35 suggests that Catoche Knoll did tilt. Unfortunately, the seismic lines do not provide sufficient information to correct the inclination data from Hole 538A for possible tilting.

**PHYSICAL PROPERTIES**

Sonic velocity, density, porosity, thermal conductivity and Torvane shear strength measurements were conducted at Site 538. Continuous GRAPE was run for sediment cores only. The results are listed in Table 7 and are shown graphically in Figure 12. Five groups of samples, each with a significantly different physical property and lithologies can be distinguished (Table 8). A discussion of these groupings and of vertical trends of these properties follow.

The sonic velocity of unconsolidated nannofossil ooze of Group A reflects only the horizontal component. The sonic velocity values of this group are distributed mostly between 1.5 and 1.7 km/s and they show little change with depth. At the bottom of Group B, where sediments consist of homogenous nannofossil chalcedony, the velocity value shows a small but rapid increase by about 0.3 km/s (Fig. 13). This small velocity increase correlates with the boundary of Lithologic Units II and III. Therefore, the section can be divided at this boundary into A (Lithologic Units I and II) and B (Unit III). Below Unit B, there is a sharp change in the acoustic values associated with the change in the lithofacies from Unit III to Unit IV (Fig. 13). An additional acoustic boundary correlates with the lithologic boundary between Units IV and V (base of Group C) (Fig. 13).

Most of the limestones of Group D are highly fragmented and, hence, their orientations could not be determined. The velocity values along vertical and horizontal directions are not differentiated for these samples and they are treated as identical. A low velocity layer is clearly observed in this portion.

The basement rocks have markedly higher velocities than any of the overlying sedimentary units and are easily distinguished (Fig. 13).

The density and porosity distribution showed an abrupt change at around 190 m sub-bottom depth in Hole 538A (Fig. 12). Density increases sharply and porosity decreases at this position. These changes correspond to the boundary between Lithologic Units III and IV. The density and porosity principally reflect increasing lithification and diagenesis of the carbonate section.

The Torvane shear strength and the thermal conductivity data show considerable scatter and general increases with depth. Scattering of the Torvane data is probably caused by the disturbance of cores due to drilling. Scattering of the thermal conductivity might reflect poor contacts between sample surface and the flat probe face. The effect is evidently more pronounced as the sample becomes harder (refer to 270-326 m sub-bottom depth in Fig. 12).

**SEISMIC STRATIGRAPHY**

Site 538 was drilled on the top of Catoche Knoll, which is located about 25 km northeast of the Campeche Escarpment (Fig. 1). The knoll is a large topographic feature that rises over 750 m above the surrounding abyssal seafloor. The seismic data suggest that the knoll is an uplifted and tilted basement block, based on the apparent asymmetry of the block and the possible synrift sediments filling basins between the blocks. This relationship can be seen on regional seismic Line SF-2 (Fig. 3).
Single-channel seismic profiles published by Bryant and others (1969) clearly showed the relationship atop Catoche Knoll i.e., an acoustic basement block overlain by a relatively thin sediment cover. More recent multi-channel seismic lines shot across the knoll by the University of Texas (SF-2 and GT3-63, Figs. 3 and 14), also show the same relationships.

Line GT3-63 cuts across the western flank of the knoll and shows only a thin sediment cover (Fig. 14), whereas Line SF-2 cuts across the top of the knoll and shows a more complete sedimentary section (Fig. 3). Figure 3 shows the regional setting of the knoll along Line SF-2, whereas Figure 15 shows a more detailed blowup of the site.

The sedimentary section overlying the knoll consists of two main seismic sequences. This subdivision is quite obvious on the earlier single-channel lines of Bryant and others (1969), as well as on the multichannel Line SF-2 (Fig. 15). The two sequences are separated by a strong prominent reflector. Prior to drilling, the upper relatively
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<td>Chalk</td>
</tr>
<tr>
<td>1-2, 120-122</td>
<td>4</td>
<td>1.544</td>
<td>1.57</td>
<td>2.41</td>
<td>21.77</td>
<td>2.70</td>
<td></td>
<td>Limestone</td>
</tr>
<tr>
<td>1-4, 25-27</td>
<td>6</td>
<td>1.532</td>
<td>1.57</td>
<td>2.41</td>
<td>21.77</td>
<td>2.70</td>
<td></td>
<td>Chalk</td>
</tr>
</tbody>
</table>

Note: H = horizontal; V = vertical; φ = porosity.
transparent sequence was thought to represent mainly Tertiary pelagic sediments, whereas the lower sequence was thought to represent older Mesozoic rocks. The acoustic basement reflector was interpreted to be the top of the crystalline basement and was the main objective of the site.

The final drill site for Hole 538A was located almost exactly along SF-2 at the crest of the knoll (Fig. 15). Drilling at the site penetrated three major lithologic groups as follows: (1) 189 m of ooze and chalk of Miocene through Late Cretaceous age (Lithologic Units I–III); (2) 79 m of deep-water limestone underlain by skeletaloolitic limestone, both of Early Cretaceous age (Lithologic Units IV–V); and (3) 64 m of igneous-metamorphic basement. Average sonic velocities and calculated acoustic impedances show marked increases at the boundaries between Lithologic Units III and IV (chalk to limestone) and also at the basement (Fig. 16). These changes should produce strong reflectors. These boundaries were converted to two-way traveltime using the measured average velocities (Table 8 and Fig. 16) and were plotted on the seismic section beginning at a water depth of 2801 m (based on 1500 m/s) (Fig. 15). There is a good correspondence between the boundaries and the two strong reflectors on the section. The upper reflection, therefore, is correlated with the major change from Upper Cretaceous-Tertiary ooze and chalk to Lower Cretaceous limestones, whereas the lower reflectors or acoustic basement is correlated with the igneous-metamorphic basement.
Figure 12. (Continued).

Table 8. Groupings of physical properties, Hole 538A.

<table>
<thead>
<tr>
<th>Group</th>
<th>Sub-bottom depth (m)</th>
<th>Number of samples</th>
<th>Wet-bulk density (g/cm$^3$)</th>
<th>Porosity (%)</th>
<th>Acoustic velocity$^a$ (km/s)</th>
<th>Sonic impedance$^a$ ($\times 10^6$ g cm$^{-2}$ s$^{-1}$)</th>
<th>Thermal conductivity ($\times 10^{-3}$ cal deg$^{-1}$ s$^{-1}$ cm$^{-1}$)</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0-171</td>
<td>43</td>
<td>1.62</td>
<td>62</td>
<td>1.74</td>
<td>1.76</td>
<td>2.85</td>
<td>Units I and II; carbonate ooze and chalk</td>
</tr>
<tr>
<td>B</td>
<td>172-189</td>
<td>6</td>
<td>1.63</td>
<td>56</td>
<td>2.00</td>
<td>2.01</td>
<td>3.50</td>
<td>Unit III; chalk</td>
</tr>
<tr>
<td>C</td>
<td>190-211</td>
<td>6</td>
<td>2.43</td>
<td>15</td>
<td>4.99</td>
<td>5.08</td>
<td>12.22</td>
<td>Unit IV; chalk, limestone</td>
</tr>
<tr>
<td>D</td>
<td>212-269</td>
<td>5</td>
<td>2.28</td>
<td>18</td>
<td>3.69</td>
<td>8.83</td>
<td></td>
<td>Unit V; limestone</td>
</tr>
<tr>
<td>E</td>
<td>270-326</td>
<td>16</td>
<td>2.67</td>
<td>12</td>
<td>5.03</td>
<td>5.09</td>
<td>13.63</td>
<td>Basement: gneiss, amphibolite, and diabase</td>
</tr>
</tbody>
</table>

$^a$ Correction applied according to Boyce (1976).
Figure 13. Vertical velocity groupings and corresponding lithologic units, Hole 538A.

The seismic unit in between the two reflectors is tentatively correlated with the skeletal-oolitic limestone (Unit V). A cross section across the knoll using the average velocities from the cores shows that the top of the seismic unit is relatively flat, but the unit thickens considerably along both flanks of the knoll. This supports the hypothesis that this unit was deposited in situ as a shallow-water carbonate platform on top of a raised basement block.

CONCLUSIONS

The conclusions concerning this site are given in the Summary section earlier in this chapter.

REFERENCES


Date of Initial Receipt: July 22, 1983
Date of Acceptance: July 22, 1983
Figure 14. Northwest-southeast seismic Line GT3-63 across the western flank of Catoche Knoll showing sedimentary cover over acoustic basement (see Fig. 1 for location).
Figure 15. A. Enlarged portion of seismic Line SF-2 (Fig. 2) showing correlation of seismic stratigraphic units with lithologic units drilled at Hole 538A. WD = water depth; TD = terminal depth. B. Depth section showing major seismic units, lithologic units, and average velocity from cores used for depth conversion. VE = vertical exaggeration.
<table>
<thead>
<tr>
<th>Vertical sonic velocity (km/s)</th>
<th>Acoustic impedance (x 10^5 g cm^-2 s^-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>2.55</td>
</tr>
<tr>
<td>0.4</td>
<td>3.50</td>
</tr>
<tr>
<td>0.6</td>
<td>4.99</td>
</tr>
<tr>
<td>0.8</td>
<td>7.37</td>
</tr>
<tr>
<td>1.0</td>
<td>10.97</td>
</tr>
<tr>
<td>1.2</td>
<td>15.22</td>
</tr>
</tbody>
</table>

**Unit**

**Lithology**

- **Ia**: Foraminiferal-nannofossil ooze, nannofossil ooze, and clay
- **Ib**: Foraminiferal-nannofossil and nannofossil-foraminiferal ooze
- **IIa**: Nannofossil ooze, nannofossil chalk, and rare volcanic ash
- **IIb**: Nannofossil chalk, nannofossil marls, nannofossil-radiolarian mudstones, radiolarian-nannofossil chalks, and occasional volcanic ash
- **IIia**: Foraminiferal-nannofossil and nannofossil-foraminiferal chalks with manganese-rich emission surfaces
- **IV**: Foraminiferal-nannofossil and nannofossil-foraminiferal chalks with minor claystones and nannofossil claystones; some Mn
- **V**: Nannofossil chalk, nannofossil marly limestone, limestone, and chert
- **V**: Skeletal grainstones and minor packstones and wackestones
- **V**: Igneous-metamorphic basement complex

Figure 16. Relation between velocity, acoustic impedance, and lithologic boundaries at Site 538.
LITHOLOGIC DESCRIPTION

NAOMIFEROUS Ooze, variable colors with generally deep changes — 1) light gray (2.5Y 7/1) to brown (2Y 7/2) at 52 cm, Section 1; 2) white to light gray (2.5Y 7/1) at 130 cm, Section 2; 3) white to light gray with a thin green zone (2.5Y 4/2) at 145 cm, Section 3; 4) light gray (2.5Y 7/1) to brown (2Y 7/2) at 150 cm, Section 4; 5) brown to light gray (2.5Y 7/1) at 130 cm, Section 4. Sediments are slightly disturbed by drilling. No significant changes in color or texture were observed beyond 1 m from the core.

SMEAR SLIDE SUMMARY (%):

Texture: Sand 10 5 5 1
Silt 35 35 75 10
Clay 35 35 10 10
Composition: Mica 3
Carbonate unspec. 5 5 5 5
Foraminifers 6 2 2 7
Calc. nannofossils 96 89 59
Dolomite 1

ORGANIC CARBON AND CARBONATE (%):

Organic carbon 2.61 2.13 3.83
Carbonate 63 78 78

NAOMIFEROUS Ooze and FORAMINIFERAL-NANNOFOSSIL Ooze. Foraminiferal-nannofossil ooze is yellowish gray (5Y 7/2) to light greenish gray (5G 6/1 and 5GY 6/1) and is greenish gray (5GY 6/1) changing to very light gray (N8), light greenish gray (5G 8/1) with light to medium gray (N7—N6) streaks. Light—dark ooze contacts light gray (2.5Y 7/1) to brown (2Y 7/2) with some medium gray pyrite streaks. Contact with nannofossil ooze at top Section 2 is mixed by drilling.

SMEAR SLIDE SUMMARY (%):

Texture: Sand 15 20 10 4
Silt 75 70 85 89
 Clay 15 10 10 11
Composition: Mica 3
Carbonate unspec. 5 5 5 5
Foraminifers 6 2 2 7
Calc. nannofossils 96 89 59
Dolomite Tr

ORGANIC CARBON AND CARBONATE (%):

Organic carbon 2.61 2.13 3.83
Carbonate 63 78 78

NAOMIFEROUS Ooze and FORAMINIFERAL-NANNOFOSSIL Ooze. Foraminiferal-nannofossil ooze is yellowish gray (5Y 7/2) to brown (2Y 7/2) with some medium gray pyrite streaks. No significant changes in color or texture were observed beyond 1 m from the core.
### SITE 538 HOLE A CORE 7 CORED INTERVAL 50.0–59.5 m

**LITHOLOGIC DESCRIPTION**

<table>
<thead>
<tr>
<th>Section</th>
<th>Text</th>
<th>Source</th>
<th>Clay</th>
<th>Composition</th>
<th>Fossil</th>
<th>Radiolarites</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1.0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SHEAR SLIDE SUMMARY (%)**

- Organic carbon: 2.61%
- Carbonate: 96%

### SITE 538 HOLE A CORE 8 CORED INTERVAL 59.5–69.0 m

**LITHOLOGIC DESCRIPTION**

<table>
<thead>
<tr>
<th>Section</th>
<th>Text</th>
<th>Source</th>
<th>Clay</th>
<th>Composition</th>
<th>Fossil</th>
<th>Radiolarites</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1</td>
<td>0.5</td>
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<td></td>
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<tr>
<td>1</td>
<td>1</td>
<td>1.0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SHEAR SLIDE SUMMARY (%)**

- Organic carbon: 2.61%
- Carbonate: 96%

### SITE 538 HOLE A CORE 9 CORED INTERVAL 69.0–78.5 m

**LITHOLOGIC DESCRIPTION**

<table>
<thead>
<tr>
<th>Section</th>
<th>Text</th>
<th>Source</th>
<th>Clay</th>
<th>Composition</th>
<th>Fossil</th>
<th>Radiolarites</th>
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<tr>
<td>1</td>
<td>1</td>
<td>1.0</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SHEAR SLIDE SUMMARY (%)**

- Organic carbon: 2.61%
- Carbonate: 96%
NANNOFOSIL CHALK, white (N9) to bluish white (5B 9/1) with some light greenish gray (5G 8/1) laminations. Section 4 had several medium gray (N5) layers of ash. Upper ash layer is mixed with chalk, lower ash layer has a sharp base and gradational, burrowed top. Chalk is homogeneous.

SMEAR SLIDE SUMMARY (%):

1,103 2.69

Composition:

Volcanic glass
Carbonate
Diatoms
Sponge spicules
Radiolarian spines
Holothurian spines
—

ORGANIC CARBON AND CARBONATE (%):

Organic carbon
Carbonate
### Lithologic Description

**Site 538 Hole A Core 12 Cored Interval 97.5-107.0 m**

**Nannofossil Chalk**, bluish white (5B 9/11) to very light gray (N8) with scattered light greenish gray (5G 8/1) intervals. Thin medium gray (N5) Volcanic Ash with sharp base and gradational, burrowed top in Section 1. Ash also fills burrows in Section 1 and perhaps in Section 2.

**Smear Slide Summary (%)**

<table>
<thead>
<tr>
<th>Sponge spicules</th>
<th>2,50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic Carbon</td>
<td>5,12</td>
</tr>
</tbody>
</table>

**Organic Carbon and Carbonate (%)**

<table>
<thead>
<tr>
<th>Organic Carbon</th>
<th>2,60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonate</td>
<td>86</td>
</tr>
</tbody>
</table>

### Lithologic Description

**Site 538 Hole A Core 13 Cored Interval 107.0-116.5 m**

**Nannofossil Chalk**, white (N9) to very light gray (N8), fractured by drilling. Small patch of medium gray (N5) Volcanic Ash at 42 cm, Section 3.

**Smear Slide Summary (%)**

<table>
<thead>
<tr>
<th>Calc. nannofossils</th>
<th>2,119</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiolarians</td>
<td>2,122</td>
</tr>
<tr>
<td>Sponge spicules</td>
<td>3,42</td>
</tr>
</tbody>
</table>

**Organic Carbon and Carbonate (%)**

<table>
<thead>
<tr>
<th>Organic Carbon</th>
<th>2,40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonate</td>
<td>86</td>
</tr>
</tbody>
</table>

### Lithologic Description

**Site 538 Hole A Core 14 Cored Interval 116.5-126.0 m**

**Nannofossil Chalk**, very light gray (N8) to indistinctly or faintly laminated in upper 35 cm, homogeneous. Core-Catcher is Radiolarian Nannofossil Limestone with irregular Chert lenses or nodules ~1 cm across. Core fractured by drilling.

**Smear Slide Summary (%)**

<table>
<thead>
<tr>
<th>Calc. nannofossils</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiolarians</td>
<td>45</td>
</tr>
<tr>
<td>Sponge spicules</td>
<td>27</td>
</tr>
</tbody>
</table>

**Organic Carbon and Carbonate (%)**

<table>
<thead>
<tr>
<th>Organic Carbon</th>
<th>2,60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonate</td>
<td>86</td>
</tr>
</tbody>
</table>
LITHOLOGIC DESCRIPTION

NANNOFOSIL Ooze/Chalk, bluish white (5B 9/1), homogeneous.

SMEAR SLIDE SUMMARY (%):

Texture:
- Sand: 5
- Silt: 95

Composition:
- Volcanic glass: 5
- Carbonate: 44
- Foraminifers: 5
- Calc. nannofossils: 45
- Radiolarians: 2
- Sponge spicules: 3

ORGANIC CARBON AND CARBONATE (%):
- Organic carbon: 4-17
- Carbonate: 30-53
LITHOLOGIC DESCRIPTION

SITE 538 HOLE A CORE 17 CORED INTERVAL 145.0–154.5 m

NANOFOSIL CHALK with thin layers of VOLCANIC ASH. Chalk is light greenish gray (5G 8/1) to white (N9) with sparse very pale green (10G 6/2) veining or lamina-
tions; these dip 25° in top Section 4. Otherwise chalk is homogeneous with no obvious burrowing. Ash is medium-
gray (5G 6/2) and soft. Several layers have sharp bases and burrowed tops. Core fairly intact but broken by solution.

SMEAR SLIDE SUMMARY (%):

<table>
<thead>
<tr>
<th>Composition</th>
<th>5.6</th>
<th>5.9</th>
<th>6.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Silt</td>
<td>96</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>Clay</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Volcanic Glass</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Palagonite</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Calc. nannofossils</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Calc. nannofossils</td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Foraminifers</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Radiolarians</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sponge spicules</td>
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</tr>
<tr>
<td>Turritospirulina</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

SITE 538 HOLE A CORE 18 CORED INTERVAL 154.5–164.0 m

RADIOLARIAN/NANOFOSIL CHALK, light greenish gray (5G 8/1) and white (N9) to yellowish gray (5Y 8/1). Sections 3–5 contain occasional olive-green layers of algae. Core fairly intact but broken by solution.

SMEAR SLIDE SUMMARY (%):

<table>
<thead>
<tr>
<th>Composition</th>
<th>5.6</th>
<th>5.9</th>
<th>6.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>1.3</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td>Silt</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Clay</td>
<td>96</td>
<td>96</td>
<td>96</td>
</tr>
<tr>
<td>Volcanic Glass</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Palagonite</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Calc. nannofossils</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Calc. nannofossils</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Foraminifers</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Radiolarians</td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Sponge spicules</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Turritospirulina</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
SITE 538 HOLE A CORE 19 CORED INTERVAL 164.0-173.5 m

LITHOLOGIC DESCRIPTION

RADIOLARIAN-NANOFOSIL CHALK, yellowish gray (5Y 8/1) with common patches of medium gray (N5V) with volcanic ash scattered throughout. An asphalt-filled fracture ~1 mm across occurs at 14 cm. Section 2, dark gray with thin bedding, is scattered through core at 36-40 cm. Sections 3 and below 47 cm in Section 4. Core/Catcher contains several pieces of yellowish gray to light grayish gray limestone with a prominent light gray (5G 6/1) patch. Lithology is homogeneous. No tectonic notes in the middle of the chalk in Core/Catcher.

SMEAR SLIDE SUMMARY (%):

Clay
Compositon
Quartz
Calcite
Radiolaria

ORGANIC CARBON AND CARBONATE (%):

Organic carbon
Sulfate

SITE 538 HOLE A CORE 20 CORED INTERVAL 173.5-183.0 m

LITHOLOGIC DESCRIPTION

NANOFOSIL-FORAMINIFERAL and FORAMINIFERAL NANOFOSIL CHALK, variable colors ranging from yellowish gray (5Y 8/1), very pale orange (5Y 8/1), and light gray (5Y 6/1) at 111 cm. Sections 4 below, chalk is mottled pinkish gray (5YR 7/2) and light gray (5Y 6/1). Black manganese oxide pockets and spots scattered throughout. At least two sharp boundaries occur:

1) Surface at 78 cm. Section 2 is highly irregular and bored, borings filled with light foraminiferal ooze. Several large (1 cm) burrows shaped, light burrows (cylindrical) and small faults occur below this surface.

2) Irregular surface at 111 cm. Section 4 coated with ~0.5 cm of black manganese oxide crust and brown iron-oxides. Burrows common below crust and sand-size Mn fragments present in abundance dominate below the crust. Pinkish gray chalk below the surface is mottled with faint suggestions of bedding. An unidentified zeolite (?) occurs in this chalk.

SMEAR SLIDE SUMMARY (%):

Clay
Compositon
Quartz
Calcite
Dolomite
Organic carbon
Sulfate
LITHOLOGIC DESCRIPTION

**SITE 538 HOLE A CORE 21 CORED INTERVAL** 183.0-192.5 m

- **0-18 cm**: Pale green CLAYSTONE as at base Section 4.
- **18-25 cm**: Light brownish gray (5YR 6/1) LIMESTONE, with abundant foraminifer and radiolarian fragments.
- **25-33 cm**: Light gray (5Y 6/1) FORAMINIFERAL-NANNOFOSSIL CHALK, with light gray (5Y 6/1) and medium light gray (5Y 6/6) nannofossil chalk, and coarse abundant arenaceous material (including foraminifer and calcareous nannofossil debris). A large breccia at 20 cm (Section 2).
- **33-57 cm**: Light gray to yellowish gray (5Y 6/3) LIMESTONE, with light gray (5Y 6/3) to yellowish gray (5Y 6/6) staining. Burrowed, with foraminifer and radiolarian fragments.
- **57-150 cm**: Light gray to yellowish gray FORAMINIFERAL CHALK with light gray (5Y 6/3) foraminiferans and radiolarian fragments. These are bored and borings filled with chalk.
- **150-180 cm**: Yellowish brown (10YR 6/6) and laminated grading downcore to less distinct layers. A large burrow at 160 cm (Section 2).
- **180-202 cm**: Complex LITHOLOGIC DESCRIPTION. Some brecciated thin layers within. Chalky intervals near base Section 3 and a brecciated section throughout. A large breccia at 190 cm (Section 4).
- **202-211 cm**: Foraminiferans and radiolarian fragments, broken pieces of foraminiferans, radiolarian molds, and foraminiferan crusts.

**SITE 538 HOLE A CORE 22 CORED INTERVAL** 192.5-202.0 m

- **0-18 cm**: Pale green CLAYSTONE as at base Section 4.
- **18-25 cm**: Light brownish gray (5YR 6/1) LIMESTONE, with abundant foraminifer and radiolarian fragments.
- **25-33 cm**: Light gray (5Y 6/1) FORAMINIFERAL-NANNOFOSSIL CHALK, with light gray (5Y 6/1) and medium light gray (5Y 6/6) nannofossil chalk, and coarse abundant arenaceous material (including foraminifer and calcareous nannofossil debris). A large breccia at 20 cm (Section 2).
- **33-57 cm**: Light gray to yellowish gray (5Y 6/3) LIMESTONE, with light gray (5Y 6/3) to yellowish gray (5Y 6/6) staining. Burrowed, with foraminifer and radiolarian fragments.
- **57-150 cm**: Light gray to yellowish gray FORAMINIFERAL CHALK with light gray (5Y 6/3) foraminiferans and radiolarian fragments. These are bored and borings filled with chalk.
- **150-180 cm**: Yellowish brown (10YR 6/6) and laminated grading downcore to less distinct layers. A large burrow at 160 cm (Section 2).
- **180-202 cm**: Complex LITHOLOGIC DESCRIPTION. Some brecciated thin layers within. Chalky intervals near base Section 3 and a brecciated section throughout. A large breccia at 190 cm (Section 4).
- **202-211 cm**: Foraminiferans and radiolarian fragments, broken pieces of foraminiferans, radiolarian molds, and foraminiferan crusts.

**SITE 538 HOLE A CORE 23 CORED INTERVAL** 202.0-211.5 m

- **0-18 cm**: Pale green CLAYSTONE as at base Section 4.
- **18-25 cm**: Light brownish gray (5YR 6/1) LIMESTONE, with abundant foraminifer and radiolarian fragments.
- **25-33 cm**: Light gray (5Y 6/1) FORAMINIFERAL-NANNOFOSSIL CHALK, with light gray (5Y 6/1) and medium light gray (5Y 6/6) nannofossil chalk, and coarse abundant arenaceous material (including foraminifer and calcareous nannofossil debris). A large breccia at 20 cm (Section 2).
- **33-57 cm**: Light gray to yellowish gray (5Y 6/3) LIMESTONE, with light gray (5Y 6/3) to yellowish gray (5Y 6/6) staining. Burrowed, with foraminifer and radiolarian fragments.
- **57-150 cm**: Light gray to yellowish gray FORAMINIFERAL CHALK with light gray (5Y 6/3) foraminiferans and radiolarian fragments. These are bored and borings filled with chalk.
- **150-180 cm**: Yellowish brown (10YR 6/6) and laminated grading downcore to less distinct layers. A large burrow at 160 cm (Section 2).
- **180-202 cm**: Complex LITHOLOGIC DESCRIPTION. Some brecciated thin layers within. Chalky intervals near base Section 3 and a brecciated section throughout. A large breccia at 190 cm (Section 4).
- **202-211 cm**: Foraminiferans and radiolarian fragments, broken pieces of foraminiferans, radiolarian molds, and foraminiferan crusts.
**SITE 538**

**HOLE A**

**CORE 24**

**CORED INTERVAL** 211.5-221.0 m

**LITHOLOGIC DESCRIPTION**

LIMESTONE: lenticular, greyish-white (10YR 7/4), well-sorted, fine to medium-grained, bioclastic packstone. Primary porosity 20-30%. Secondary moleculare porosity is well-developed. Gas: low hydrocarbons.

This Section:
1. Limestone (bioclastic packstone) — grains include molluscs, foraminifers, pellets, and echinoderms. Secondary moldic porosity is well-developed. Gas: low hydrocarbons.

**SITE 538**

**HOLE A**

**CORE 26**

**CORED INTERVAL** 230.5-240.0 m

**LITHOLOGIC DESCRIPTION**

LIMESTONE: oncoidal, dark grey (2.5Y 1/2), well-sorted, fine to medium-grained, bioclastic packstone. Primary porosity 10%. Secondary moldic porosity is well-developed. Gas: low hydrocarbons.

This Section:
1. Limestone (bioclastic packstone) — grains include molluscs, foraminifers, pellets, and echinoderms. Secondary moldic porosity is well-developed. Gas: low hydrocarbons.

---

**SITE 538**

**HOLE A**

**CORE 27**

**CORED INTERVAL** 240.0-249.5 m

**LITHOLOGIC DESCRIPTION**

LIMESTONE: oncoidal, dark grey (2.5Y 1/2), well-sorted, fine to medium-grained, bioclastic packstone. Primary porosity 10%. Secondary moldic porosity is well-developed. Gas: low hydrocarbons.

This Section:
1. Limestone (bioclastic packstone) — grains include molluscs, foraminifers, pellets, and echinoderms. Secondary moldic porosity is well-developed. Gas: low hydrocarbons.
<table>
<thead>
<tr>
<th>SITE 538</th>
<th>HOLE A</th>
<th>CORE 28</th>
<th>CORED INTERVAL</th>
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<tr>
<td>LIMESTONE (oolitic packstone), white (N9) to yellowish gray (5Y 8/1). Poorly sorted granoclastic packstones. Grain types include peloids/coated grains, foraminifers, gastropods, and echinoderms. Good second moldic porosity. Core is drilling breccia.</td>
<td></td>
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</tbody>
</table>

**Thin Section:**
1. 4. Limestone (oolitic grainstone) – oolite containing 80% ooids, 10% peloids, and rare molluscs, gastropods, and echinoderms. Some primary porosity. Porosity (15%) is mostly primary.
2. 1. Limestone (oolitic grainstone) – grain population includes 50% coated grains, 20% echinoid spines, 20% peloids, and 10% foraminifers. Some primary porosity.

<table>
<thead>
<tr>
<th>SITE 538</th>
<th>HOLE A</th>
<th>CORE 29</th>
<th>CORED INTERVAL</th>
<th>259.0–268.5 m</th>
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<tr>
<td>LIMESTONE (oolitic packstone), white (N9) to yellowish gray (5Y 8/1). Poorly sorted granoclastic packstones. Grain types include peloids/coated grains, foraminifers, gastropods, and echinoderms. Good second moldic porosity. Core is drilling breccia.</td>
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</table>

**Thin Section:**
1. 1. Limestone (oolitic grainstone) – grain population includes 50% coated grains, 20% echinoid spines, 20% peloids, and 10% foraminifers. Some primary porosity.
2. 2. Limestone (oolitic grainstone) – grain population includes coated grains, echinoid spines, foraminifers, gastropods, and echinoderms. Poorly sorted granoclastic packstones. Some primary porosity.

<table>
<thead>
<tr>
<th>SITE 538</th>
<th>HOLE A</th>
<th>CORE 30</th>
<th>CORED INTERVAL</th>
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<tr>
<td>LIMESTONE (oolitic packstone), white (N9) to yellowish gray (5Y 8/1). Poorly sorted granoclastic packstones. Grain types include peloids/coated grains, foraminifers, gastropods, and echinoderms. Good second moldic porosity. Core is drilling breccia.</td>
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</tr>
</tbody>
</table>

**Thin Section:**
1. 1. Limestone (oolitic grainstone) – grain population includes 50% coated grains, 20% echinoid spines, 20% peloids, and 10% foraminifers. Some primary porosity.
Core/Section 30/1

Macroscopic Description:
Green clay (30-120 cm. Section 1). The altered diabase amphibolite between 50-70 cm in Section 2; darker feldspar crystals up to 2 mm across and partly altered concentric alteration occurs between 15-30 cm. Calcite veins in Piece 6, Section 1, Piece 2 at 15 cm: fine-grained, altered diabase containing small (0.01-0.02 mm) Plagioclase laths in a matrix of green clay occur sporadically. Pieces 4-6 are highly fractured. White calcite veins occur in Piece 6, Section 2. Excellent transition from green clay to calcite veins in the matrix. Thin section (not shown).

Paleomagnetic/Physical Properties:
Sample: Section 1, Piece 6

<table>
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<th>Sample</th>
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<th>V(ii)</th>
<th>Ind.</th>
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<th>s.l.</th>
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<td>14</td>
<td>3.73</td>
<td>4.04</td>
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</table>

HOLE 538A, CORE 31, SECTIONS 1-2, 268.5-271.3 m

MAJOR ROCK TYPE - DIABASE

MINOR ROCK TYPE - LIMESTONE

MACROSCOPIC DESCRIPTION:
Diabase - Piece 1 and Piece 2 down to ~30 cm is dark green, very fine-grained to aphyric diabase. rusty brown, colorless alteration occurs between ~85-30 cm. Calcite veins are common. Diabase is altered to diabase in dark green grey (100-120 cm, Section 1). The altered diabase contains some calcite veins and is highly fractured. White talc and some vein-like white-detrital interbeds./

Gneiss and Gneiss Breccia - Piece 1 and Fractures 6 in Section 1 consists of aligned fragments of phyllitic gneiss (and perhaps some very fine-grained amphibolite) up to 2 cm across cemented together by calcite.

Amphibolite - Piece 1 and Piece 2 in Section 2 are dark gray to grayish green, fine-grained amphibolite with distinct amphibolite to slightly mylonitic texture and a steeply dipping schistosity. Green hornblende and minor biotite (up to 0.5 mm) are abundance.

MINOR ROCK TYPE - LIMESTONE

MACROSCOPIC DESCRIPTION:
Limestone - Piece 1, Section 1, consists of several fragments of white and pinkish yellow gray detrital limestone (see description on sample description form).

MACROSCOPIC DESCRIPTION:
Gneiss - Section 1, Piece 6 at 26 cm: both pieces are fine to coarse-grained gneiss with a porphyroblastic texture. Lenses are abundant mineral (10%) forming irregular and irregularly shaped crystals up to 2 mm long with elongated forms and moderate crystal orientation. Felspar (>50%) mostly large (up to 3 mm) porphyroblasts of orthoclase and potash feldspar; smaller (0.2-0.5 mm) plagioclase, amphibole and accessory minerals. Bioclasts (up to 3 cm) consist of pink feldspar, plagioclase, plagioclase, and quartz.

MACROSCOPIC DESCRIPTION:
Gneiss — dark gray, fine- to coarse-grained with a porphyroblastic to slightly mylonitic texture. Quartz is rhyolite, very fine-grained to aphyric diabase. Rusty brown, very fine-grained to aphyric diabase. Pink feldspar veins occur in Piece 6 and top of Piece 1, excellent transition from gneiss to diabase amphibolite has relic gneissose fabric in this interval. Post-abundant quartz is very fine-grained and parallel to shear zone that is up to 3 cm across cemented together by calcite. Quartz is brown to yellow color. Very fine-grained quartz is common, very fine-grained quartz is common, and parallel to shear zone that is up to 3 cm across cemented together by calcite.

MACROSCOPIC DESCRIPTION:
Limestone - Piece 1, Section 1, consists of several fragments of white and pinkish yellow gray detrital limestone (see description on sample description form).
HOLE 538A, CORE 32, SECTIONS 1-7, 287.5-296.5 m

MAJOR ROCK TYPE - DIABASE

Macroscopic Description:
Diabase - medium gray, medium grained and generally homogeneous. Piece 1A in Section 1 is slightly finer grained than rest of core; contains some phenocrysts, feldspar, calcite, and some vesicles. Pieces in Sections 1 and 2 are more vesicular. Most cores have a gray to light gray, generally homogenous color and moderate to high biotite content.

Thin Section Summary:
Section 3, Piece 4A - medium grained diabase with ophitic to subophitic texture composed of plagioclase (55%), pyroxene (40%), green clay (alteration of interstitial glass; 5%), and biotite (1%). Plagioclase is mainly normal euhedral augite (0.2-1.2 mm) with extinction angle ~4° and some (100) twins. Green clay is present between crystals and crystal fragments. Biotite is small, dark gray biotite with crystal fragments and interstitial green clay. Opaque minerals are absent or present in minor amounts.

Paleomagnetics/Physical Properties:
Sample | D | P | V(b) | V(i) | Int. | Incl. | S.I. | Q.
Section 1, Piece 2A, 21 cm | - | - | 733 | 3.3 | -23.0 | 5.60 |
Section 1, Piece 3 | - | - | 770 | -7.0 | -27.0 | 7.03 |
Section 1, Piece 5A, 85 cm | - | - | 783 | -10.9 | -19.9 | 6.10 |
Section 1, Piece 5F, 132 cm | - | - | 967 | -2.2 | -33.4 | 7.63 |
Section 2, Piece 1C, 30 cm | - | - | 672 | 11.2 | -10.4 | 5.19 |
Section 2, Piece 2A, 108 cm | - | - | (62) | -18.3 | -25.4 | 0.94 |
Section 3, Piece 3 | - | - | 560 | 5.5 | -25.3 | 5.15 |
Section 3, Piece 4B, 70 cm | - | - | 703 | 3.3 | -17.4 | 6.17 |
HOLE 538A, CORE 34, SECTIONS 1-3, 305.5-309.0 m

MAJOR ROCK TYPES - DIABASE, AMPHIBOLITE

Macroscopic Description:

- Diabase - Pieces 1-6F, Section 1 are dark gray to greenish gray, medium grained diabase. White plagioclase clusters give rock an apparent perphyrygous texture. Abundant white calcite veins throughout, many lined on outside with green clay. Modal part of Piece 6F below large calcite vein has thin feldspar needles and relic gneissic fabric. Dark green to dark oxide vein, brecciated altered amphibolite makes up Pieces 1 and 2 of Section 1, and the upper portions of Pieces 3, 4, and 5. Small blebs of altered feldspar and glassy matrix. Some pieces are partly serpentinized. Porphyroclasts in Piece 1, Section 1 appear to have a relic gneissic fabric.

- Amphibolite - part of Piece 2, Sections 1-3, and all of Section 3 are dark gray, medium grained amphibolite. Texture varies from fine-grained chlorite to coarse-grained average with very implied gneissic fabric. Some pieces are partly serpentinized. Porphyroclasts in Piece 1, Section 1, have a large "lense" of pink feldspar. Piece 3, Section 3 has a high angle shear zone where gneissic fabric is well-preserved.

Thin Section Summary:

- Section 1, Piece 6C - altered diabase containing relic plagioclase laths and patches of glomerocrystalline material and biotite. Most of the rock is calcite, possibly pseudomorphed after pyroxene, and fine and altered amphibolite.

- Section 2, Piece 5, 81 cm - - 1.37 4.2 -11.6 0.32

- Section 3, Piece 5A, 75 cm - - 13.7 25.9 3.0 2.65

HOLE 538A, CORE 33, SECTIONS 1-3, 296.5-300.4 m

MAJOR ROCK TYPES - DIABASE, AMPHIBOLITE

Macroscopic Description:

- Diabase - Pieces 1-6F, Section 1 are dark gray to greenish gray, medium grained diabase. White plagioclase clusters give rock an apparent perphyrygous texture. Abundant white calcite veins throughout, many lined on outside with green clay. Modal part of Piece 6F below large calcite vein has thin feldspar needles and relic gneissic fabric. Dark green to dark oxide vein, brecciated altered amphibolite makes up Pieces 1 and 2 of Section 1, and the upper portions of Pieces 3, 4, and 5. Small blebs of altered feldspar and glassy matrix. Some pieces are partly serpentinized. Porphyroclasts in Piece 1, Section 1 appear to have a relic gneissic fabric.

- Amphibolite - part of Piece 2, Sections 1-3, and all of Section 3 are dark gray, medium grained amphibolite. Texture varies from fine-grained chlorite to coarse-grained average with very implied gneissic fabric. Some pieces are partly serpentinized. Porphyroclasts in Piece 1, Section 1, have a large "lense" of pink feldspar. Piece 3, Section 3 has a high angle shear zone where gneissic fabric is well-preserved.

Thin Section Summary:

- Section 1, Piece 6C - altered diabase containing relic plagioclase laths and patches of glomerocrystalline material and biotite. Most of the rock is calcite, possibly pseudomorphed after pyroxene, and fine and altered amphibolite.

- Section 2, Piece 5, 81 cm - - 1.37 4.2 -11.6 0.32

- Section 3, Piece 5A, 75 cm - - 13.7 25.9 3.0 2.65

MAJOR ROCK TYPES - GNEISS, AMPHIBOLITE, ALTERED AMPHIBOLITE, and GNEISS

Macroscopic Description:

- Diabase - Pieces 1-6F, Section 1 are dark gray to greenish gray, medium grained diabase. White plagioclase clusters give rock an apparent perphyrygous texture. Abundant white calcite veins throughout, many lined on outside with green clay. Modal part of Piece 6F below large calcite vein has thin feldspar needles and relic gneissic fabric. Dark green to dark oxide vein, brecciated altered amphibolite makes up Pieces 1 and 2 of Section 1, and the upper portions of Pieces 3, 4, and 5. Small blebs of altered feldspar and glassy matrix. Some pieces are partly serpentinized. Porphyroclasts in Piece 1, Section 1 appear to have a relic gneissic fabric.

- Amphibolite - part of Piece 2, Sections 1-3, and all of Section 3 are dark gray, medium grained amphibolite. Texture varies from fine-grained chlorite to coarse-grained average with very implied gneissic fabric. Some pieces are partly serpentinized. Porphyroclasts in Piece 1, Section 1, have a large "lense" of pink feldspar. Piece 3, Section 3 has a high angle shear zone where gneissic fabric is well-preserved.

Thin Section Summary:

- Section 1, Piece 6C - altered diabase containing relic plagioclase laths and patches of glomerocrystalline material and biotite. Most of the rock is calcite, possibly pseudomorphed after pyroxene, and fine and altered amphibolite.

- Section 2, Piece 5, 81 cm - - 1.37 4.2 -11.6 0.32

- Section 3, Piece 5A, 75 cm - - 13.7 25.9 3.0 2.65

PALEOMAGNETICS/PHYSICAL PROPERTIES:

<table>
<thead>
<tr>
<th>Sample</th>
<th>P</th>
<th>V(i)</th>
<th>V(n)</th>
<th>Int.</th>
<th>Incl.</th>
<th>S.I.</th>
<th>Q.</th>
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<td>Section 2, Piece 5, 81 cm</td>
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<td>-</td>
<td>1.37</td>
<td>4.2</td>
<td>-11.6</td>
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<tr>
<td>Section 3, Piece 5A, 75 cm</td>
<td>-</td>
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<td>-</td>
<td>13.7</td>
<td>25.9</td>
<td>3.0</td>
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</tbody>
</table>
HOLE 538A, CORE 35, SECTIONS 1-4, 314.5-320.3 m
MAJOR ROCK TYPES - DIABASE AND AMPHIBOLITE

Macroscopic Description:
Diabase - all of Section 1 and from Piece 6A. Basaltic, with medium-grained, greenish gray, abundant large calcite veins and yellow-orange alteration patches. Groundmass too altered for recognition, and the greenish gray color in the amphibolites. Pieces 6A-6E, Section 2, shows gradational change from calcite altered contact between "overlying" amphibolite and fine-grained diabase. Piece 8 in Section 2 has a thin quartz vein and Dealers overprint. Large calcite veins in Piece 1H, Section 3, have birefringent fragments of diabase.
Amphibolite - dark greenish gray, highly altered with some rare medium to coarse-grained habit and a hint of interlayered layers from top Section 3 through Piece 8A. Sections 3 and 4 contain diabase xenoliths and extensively veined with calcite.

Thin Section Summaries:
Section 1, Piece 1F - altered medium-grained diabase with intersertal to subophitic texture. Plagioclase (~An33-45) makes up about 30% of rock, mostly laths up to 0.4 mm long. Pyroxenes (~10%) are subhedral, normal augite with 2V = 60° and an extinction angle of ~50°. Most of sample (~20%) is black brown augite in clay (±) and matrix. Green clay (~1%) is interstitial between plagioclase laths. Opal flow (~1%) are cubic and skeletal intergrowth with quartz crystals, 0.1-0.3 mm across.
Section 1, Piece 1H - diabase, intersertal to subophitic texture with ~40% plagioclase, 15% augite, 20% green clay, rare biotite (1%) and opaques (5%). Pyroxene (~15%) in zoned laths ~0.2-0.4 mm long. Green clay is interstitial in calcite. Opal is cubic and skeletal (~2%) and several chlorite plagioclase.

Paleomagnetics/Physical Properties:
Sample D P V (l) V III) Int. Incl. S. I. Q.
Section 1, Piece 1B, 14 cm - 388 18.8 11.8 6.91
Section 1, Piece 1N 2.70 13 4.80 4.72 -
Section 2, Piece 1A 2.65 16 4.95 5.00 -
Section 3, Piece 1C, 146 cm - - 2110 53.6 37.2 14.11
Section 4, Piece 1C, 18 cm - - 1790 45.3 37.2 12.42
Section 4, Piece 1H, 94 cm - 3100 46.1 38.1 21.31

HOLE 538A, CORE 36, SECTIONS 1-3, 323.5-327.8 m
MAJOR ROCK TYPES - DIABASE, AMPHIBOLITE, GNEISS, and GNEISS BRECCIA

Macroscopic Description:
Diabase - fine grained in Section 1, coarsening to medium grained in Sections 2 and 3. Calcite veins common throughout,Westinghouse white quartz vein mineralization in Pieces 10 and 10 in Section 3.
Amphibolite - dark greenish gray, fine-grained with relic feldspar porphyroblasts and faint gneissose texture. Only Pieces 1 and 2 in Section 1 are amphibolites; contact with underlying diabase is a drilling break.
Gneiss, Gneiss-Diabase Breccia - These rock types occur between Pieces 7B and Piece 7C, Section 3, with diabase xenoliths and biotite. Pieces 9 and 10 in Section 3 are altered diabase with intersertal to subophitic texture. Consists of plagioclase laths (~50%), ~An33-45, up to 0.5 mm long, mostly 0.1-0.2 mm long, and a few mm-long crystals of white mica and interstitial green clay. Opal is cubic and skeletal (~15%) and scattered skeletal and cubic opaques (0.2 mm) mostly around plagioclase.

Paleomagnetics/Physical Properties:
Sample D P V (l) V III) Int. Incl. S. I. Q.
Section 1, Piece 5B 2.83 9 5.21 5.08 -
Section 1, Piece 5C, 57 cm - - 2110 24.8 15.5 14.00
Section 1, Piece 7C, 89 cm - - 221 46.7 18 14.92
Section 2, Piece 5D, 86 cm - - 686 - 1.2 -20.8 4.58
Section 2, Piece 5E 2.69 14 4.84 4.42 -
Section 3, Piece 1A, 21 cm - - 221 46.7 18 14.92