3. SITE 291

The Shipboard Scientific Party[1]

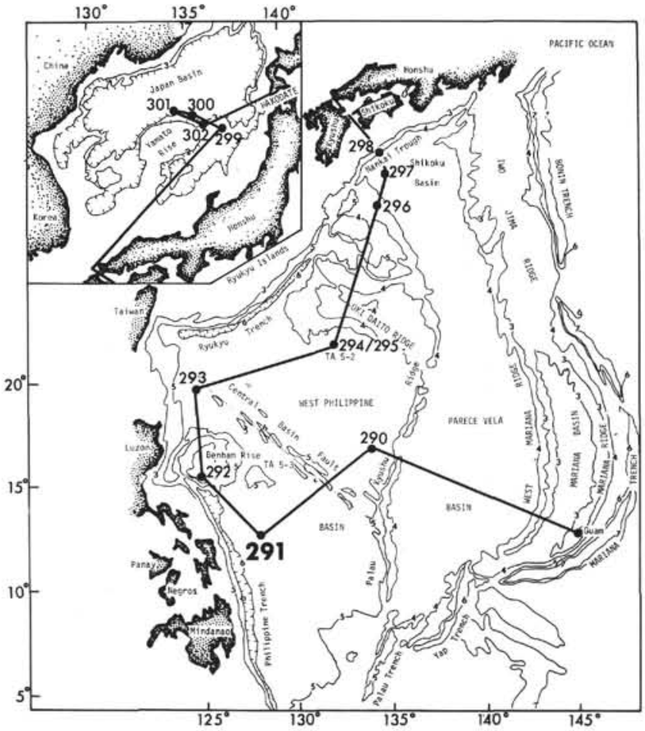

Figure 1. *Location map and* Glomar Challenger *Leg 31 track for region around Site 291. From map: "Topography of North Pacific," T. E. Chase, H. W. Menard, and J. Mammerickx, Institute Marine Resources, Geol. Data Center, Scripps Institution of Oceanography, 1971. Contour depths in kilometers; scale 1:6,500,000.*

SITE DATA

Position:
Hole 291: 12°48.43'N; 127°49.85'E
Hole 291A: 12°48.45'N; 127°49.98'E

Water Depth (from sea level): 5217 corrected meters (echo sounding)

Bottom Felt At: 5237.5 meters (drill pipe)

Penetration:
Hole 291: 126.5 meters
Hole 291A: 114.5 meters

Number of Holes: 2

Number of Cores:
Hole 291: 5
Hole 291A: 2

Total Length of Cored Section:
Hole 291: 41.0 meters
Hole 291A: 16.5 meters

Total Core Recovered:
Hole 291: 10.0 meters
Hole 291A: 1.4 meters

Percentage of Core Recovered:
Hole 291: 24.4%
Hole 291A: 8.5%

Oldest Sediment Cored:
Depth below sea floor: 120.9 meters
Nature: Compact brown clay
Age: Late Eocene

Basement:
Depth below sea floor: 121 meters (drilled)
Nature: Basalt

Principal Results: Site 291 was located on a N20-30W trending bench near the crest of the outer swell of the Philippine Trench. The stratigraphic section encountered consists of brown clay with increasingly frequent nannofossil and radiolarian interbeds below 50 meters based on seismic records, or 69 meters where first cored. This section is Recent to late Eocene age with the nannofossil beds ending in early late Oligocene or later. From 101 to 118 meters is a dark brown ferruginous, and zeolite clay with nannofossil- and radiolarian-rich beds of probable late Eocene age. Both Holes 291 and 291A bottomed in extrusive basalt with a glassy to very fine-grained surface, in which high torques limited penetration to 5.5 meters. Major questions arise concerning the interpretation of the late Eocene to late Oligocene calcareous section, and the noncalcareous, nonvolcanic section immediately above basalt.

BACKGROUND AND OBJECTIVES

Background

Site 291 was located on the outer arch of the Philippine Trench, as far from the Central Basin Fault as was feasible (Figure 1). Prior investigations outlined a region with basement relief of a few hundred meters covered by a regular pelagic blanket 100-150 meters (0.125-0.175 sec) thick. Analyses of data subsequent to Leg 31 indicate that Site 291 lay near the transition

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between quite smooth, undulating basement to the west and a much rougher basement tract to the east. To the north is an area of much greater basement relief showing a north-south trend.

Objectives

The two major objectives of Site 291 were: to obtain a basement age, as part of the Leg 31 drill-hole pattern designed to test the basin origin; and to penetrate the basement as deep as possible in order to investigate the nature of the basaltic crust in marginal basins. The first objective was satisfactorily accomplished, but caving hole conditions prevented attainment of the second.

OPERATIONS

Presite Survey

The original location for proposed Site 291 was based on limited seismic profiles (Alpine Geophysical and Lamont) made about 16 km (10 miles) from the proposed site. The area of Site 291 was approached along 231°T on 23 June 1973. The ship was slowed to 5 knots, and a search commenced along course 075°T for an area displaying a suitable sediment cover and acoustic basement configuration (Figure 2). It was desired to locate Site 291 on the flank of a local high so that an initial hole could be drilled through a reasonably complete, but relatively thin stratigraphic section in order to reach basalt. In this manner, another hole could then be drilled high on the flank of the same feature to obtain quick and maximum penetration into basalt. Both holes were to be offset from the beacon.

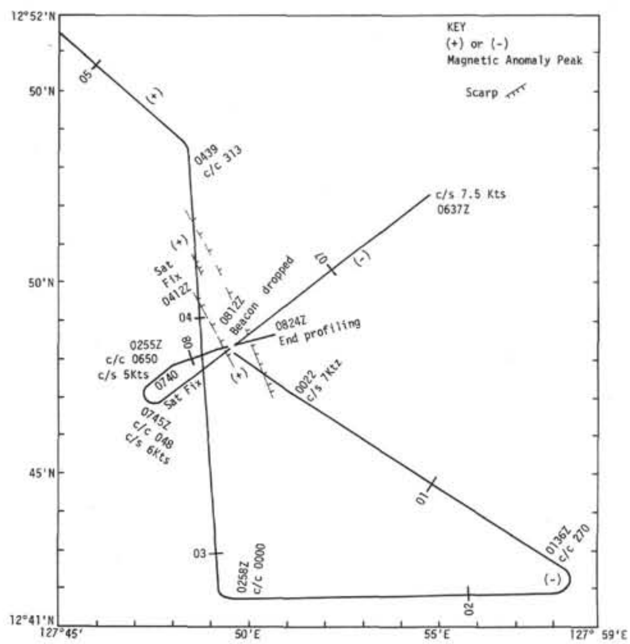

Figure 2. *Track of* Glomar Challenger *in the vicinity of Site 291. This short survey indicates that both the topography and magnetic field are lineated in an approximate N30°W direction.*

An area was located which displayed about 0.14 sec of attenuated transparent sediment over a diffuse acoustic basement hill (Figure 3). After one pass across this area the ship was brought about, and a 16-kHz beacon released in a water depth of 5217 meters (PDR). The vessel was stabilized over the site after offsetting 610 meters (2000 ft) east-northeast from the beacon to 12°48.43'N, 127°49.85'E.

Drilling Program

Hole 291 was spudded at 0230, 25 June in a depth of 5237.5 meters (drill pipe). A total of five cores was taken with a total penetration of 126.5 meters. The coring summary is found in Table 1. At 121 meters an abrupt change in drilling rate occurred (Figure 4), and was interpreted as the top of the basalt. Unusual torque and bit binding increased as the basalt was penetrated, ultimately causing drilling to be halted with Core 5. The drill string was pulled above the mudline, and the ship moved to Hole 291A.

The ship was stabilized over Hole 291A, 762 meters (2500 ft) northeast of the beacon (500 ft northeast of Hole 291) at 12°48.45'N, 127°48.99'E (Figure 2). It was proposed to penetrate to just above the basalt and drill until the bit was worn out to recover a lengthy section of basalt. Hole 291A was spudded in a water depth of 5217 meters (PDR) and washed down to 98 meters. Core 1 was cut at 98-107.5 meters recovering Eocene brown clay. Core 2 was cut at 107.5 meters to 114 meters with a change in drilling rate indicating basalt was hit at 112 meters (Figure 4). Increasing torque and binding of the bit again occurred within the basalt. After an interval of no progress, drilling was terminated and the hole abandoned. Upon retrieval, the bit was found to be worn on its upper shoulders, but the cones were in good operating condition, suggesting that loose, hard fragments had caught behind the bit. Hole 291A was departed at 0900, 25 June, and a postsite survey was begun.

Postsite Survey

The short postsite survey was run to determine the orientation of local highs and magnetic anomalies (Figure 2). Departing Site 291 on a course of 120° (gyro), a triangular pattern was traced with a course change to 270° (gyro), then north across the beacon for 16 km (10 miles).

LITHOLOGY

Two holes, 291 and 291A, were drilled at Site 291. The sediments and basalt cored at Site 291 are divided into five lithologic units (Table 2 and Figure 4).

Unit 1

A dark yellowish-brown, moderately to strongly deformed, silt-rich clay (silty clay) was found in Hole 291, Core 1, Section 1, and the top 1.5 meters of Hole 291, Core 2, Section 1. The unit consists dominantly of clay-sized particles (65%-75%) which are a mixture of clay minerals (50%-75%) with zeolites (5%-10%) and palagonite (10%). Feldspar, heavy minerals, and micronodules are also present. Volcanic components are

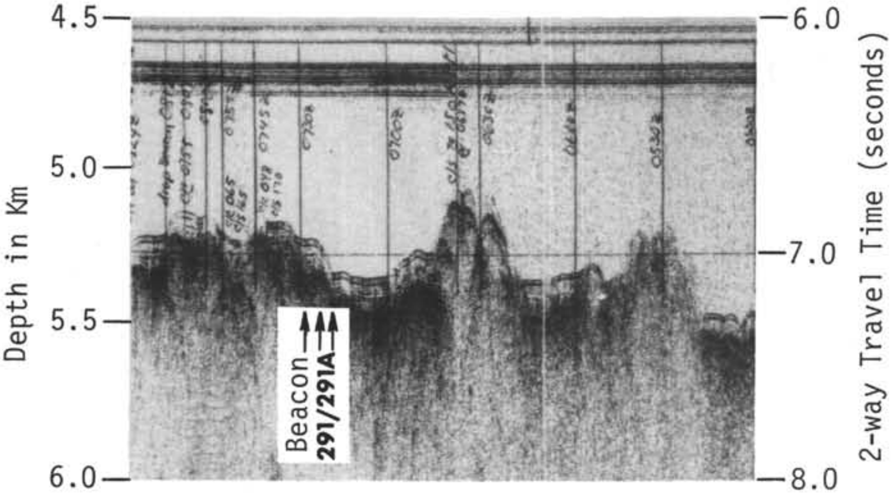

Figure 3. *Seismic reflection profile approaching Site 291 showing relatively uniform pelagic sediment cover and apparent topographic benches.*

TABLE 1
Coring Summary, Site 291

Core	Cored Interval Below Bottom (m)	Cored (m)	Recovered (m)	Recovered (%)	Remarks[a]
Hole 291					
1	0.0-3.0	3.0	0.3	10.0	Punch Core
Wash	3.0-60.0				
2	60.0-69.5	9.5	2.1	22.1	
Wash	69.5-79.0				
3	79.0-88.5	9.5	0.6	6.0	
Wash	88.5-98.0				
4	98.0-107.5	9.5	5.2	55.0	
Wash	107.5-117.0				
5	117.0-126.5	9.5	1.8	19.0	Abrupt change in drilling rate at 121 meters
Total	126.5	41.0	10.0	24.4	
Hole 291A					
Wash	0.0-98.0				
1	98.0-107.5	9.5	1.4	15.0	
2	107.5-114.5	7.0	0.0	0.0	Drilling rate change at 112 meters
Total	114.5	16.5	1.4	8.5	

[a]See Figure 4 for graph of drilling rates and lithology.

present primarily in the silt fraction and are predominantly amphibole and pyroxene with minor amounts of feldspar.

The biogenic content is low; however, nannofossils and foraminifera indicate an age at the top of the unit of at least late Pliocene.

Unit 2

A very pale brown, moderately mottled, intensely deformed clay-rich (locally clayey) nannofossil ooze, composed of nannofossils (70%-80%), with 12% to 30% clay minerals. The upper and lower contacts of this unit found in Cores 2 and 3, respectively, indicate a thickness of 15.6 meters. Nannofossils indicate an early to late Oligocene age.

Unit 3

Unit 3 may be subdivided into two subunits: an upper (80.1-98.5 m) dark reddish-brown radiolarian ooze with abundant clay minerals (40%); silt-size quartz and feldspar fragments (5%); and traces of zeolites, sponge spicules, and nannofossils. This subunit occurs in the bottom 7.5 meters of Core 3, and the top 0.5 meter of Core 4, suggesting a thickness of 8 meters. Nannofossils and Radiolaria indicate a late Eocene/early Oligocene age; the lower subunit occurs as a well-defined layer in Core 4 and consists of dark yellowish-brown clayey radiolarian-rich nannofossil ooze with abundant clay minerals (30%). The boundaries with the upper subunit and the underlying Unit 4 are vague. The lower

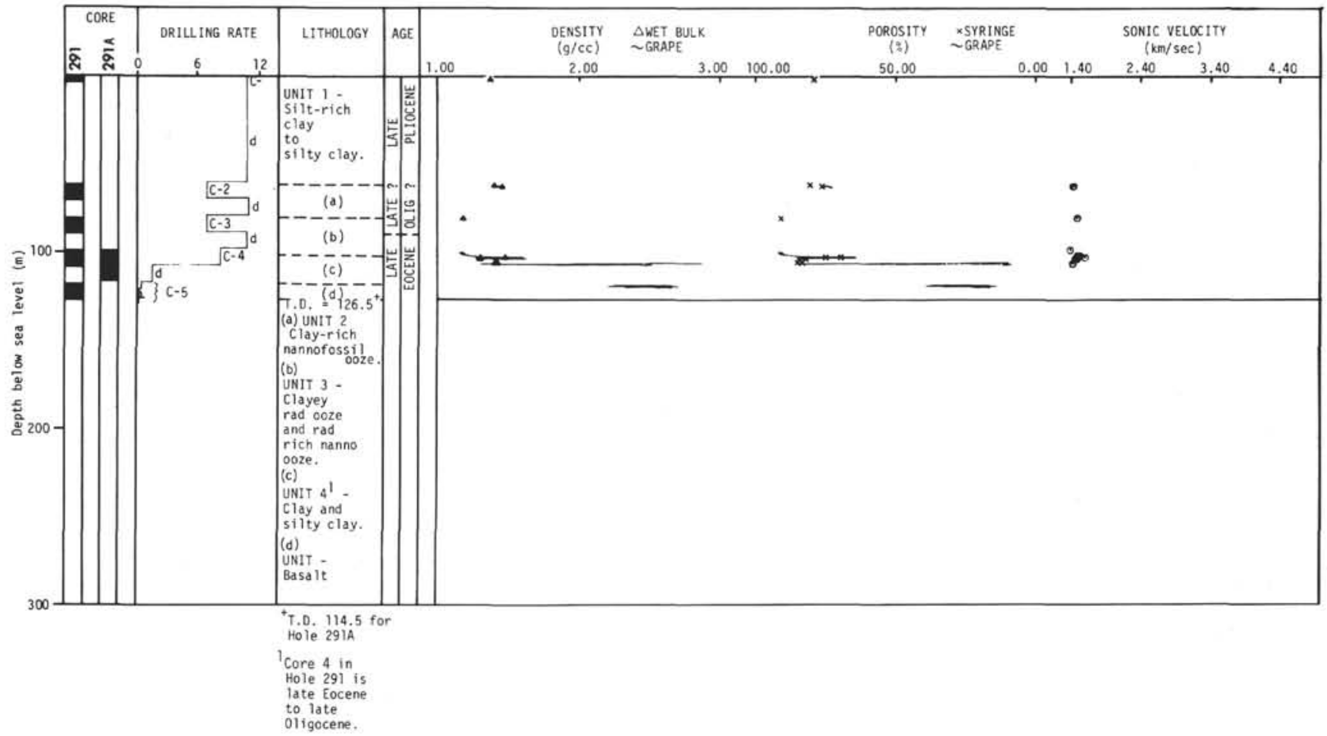

Figure 4. *Hole summary diagram, Site 291.*

TABLE 2
Unit Descriptions, Depths, Thicknesses, and Ages, Site 291

	Unit and Descriptions	Depth (m)	Thickness (m)	Age
1	Silt-rich clay	0.0–61.5 (291)	≅61.5	Late Oligocene–late Pliocene
2	Clay-rich to clayey nannofossil ooze	61.5–80.1 (291)	≅15.6	Early to late Oligocene
3	Clayey radiolarian ooze to clayey radiolarian-rich nannofossil ooze	80.1–101.8 (291)	≅21.7	Late Eocene–early Oligocene
4	Nannofossil/radiolarian-bearing silty clay to ferruginous zeolite-rich clay	101.8–118.2 (291) 98.0–114.5 (?) (291A)	≅16.4 ≅16.5 (?)	Eocene (late) Late Eocene, mid early Eocene
5	Basalt, fine-grained tholeiitic	118.2–119.8 (?) (291)	+1.6 (?)	?

boundary was established at 101.8 meters (Core 4), indicating an estimated thickness of 3.3 meters. The age is late Eocene.

Unit 4

A dusky red to dark reddish-brown clay and silty clay varies continuously in lithology from the top to the bottom of the unit. The top portion at 101.8 meters (Hole 291) is characterized by nannofossils (10%), Radiolaria (15%), and clay minerals (58%-87%). The fossil content decreases in Core 4, while the abundance of zeolite increases. Similarly the abundance of iron oxides (goethite, hematite) increases downwards, particularly near the base of the unit. The abundance of clay minerals fluctuates from 60% to 80%, and the detrital components increase from trace amounts to 2% at the base of the unit. Interruptions in the systematic variations are noted by a few thin clayey nannofossil ooze layers not more than a few centimeters in thickness and silicified zones (Core 4, Section 4) characterized by cristobalite and tridymite. Unit 4 extends from a depth of 101.8 meters in Core 4 (Hole 291) to the top 1.2 meters of Core 5, indicating a thickness of 16.4 meters. Both cores in Hole 291A were recovered from this unit. Nannofossils and radiolarians indicate an Eocene age (late Eocene) at the basalt/sediment interface. The unit in Hole 291A is late Eocene to late Oligocene in age.

Unit 5

Basalt was recovered (1.6 m) in Hole 291, and fragments were recovered in Sample 291A-2, CC. In Hole 291 the sediment basalt boundary was recovered. The basalt varies systematically in grain size from a very fine-grained (2μ) felted mass of quench crystals and altered glass at the top; a medium-grained (8-40μ) ophitic textured crystal basalt in the middle; to a very fine-grained (2-5μ) felted, quench-crystal basalt at the base. The grain-size variations suggest that the core intersected a single unit.

Basalt Petrography

The basalt is composed of plagioclase (60%), clinopyroxene (36%), and opaques (4%). There is proportionately more altered glass (up to 40%) in the upper few centimeters and a slight increase in the plagioclase to pyroxene ratio in the chilled margins, where feldspar microphenocrysts have been concentrated and trapped during flowage and cooling. Small glass fragments recovered in Hole 291A probably represent the thin carapace of a pillow. The glass is fresh at the margin and changes inwards to a fine altered matte of fibrous quench crystals. The plagioclase crystals consist predominantly of lath-like or acicular crystals, often with central canals of microcrystalline material. Feldspars (An_{70}) are present both as microphenocrysts and as microlites in the groundmass. Pyroxenes occur as granular to subhedral crystals, or in quench fibrous masses near the margins of the unit. The opaque phases are euhedral throughout and are scattered throughout the thin sections. The unit is composed of a tholeiitic basalt. The basalt shows slight degrees of alterations to a brownish-red serpentineous material.

Lithologic Interpretations

The alternate interpretations leading to an understanding of the history of the sediments recovered at Site 291 involve the mechanisms of depositing and preserving biogenic pelagic sediments. The sedimentary record recovered indicates a continuous rain of inorganic debris interrupted by periods of biogenic sedimentation.

The base of the stratigraphic section is characterized by the pelagic accumulation of inorganic debris. Locally high concentrations of iron oxide may reflect proximity of the sediment to the basalt and chemical interaction between the basalt and basal sediment unit. Upwards, in Unit 4, there is evidence of an onset of a progressively greater contribution from siliceous and calcareous organic remains extending into Unit 3, which is a calcareous ooze with a rich radiolarian fauna. Units 3 and 4 indicate a progressive change in which either the silica and carbonate compensation depths are increasing in depth, or the sea floor is shoaling to intersect these boundaries. At the top of Unit 3 the absence of calcareous fossils, but abundance of Radiolaria, indicate sedimentation beneath the carbonate, but above the silica compensation depth.

The overlying nannofossil ooze of Unit 2 indicates the onset of early Oligocene calcareous biogenic accumulation, resulting either from further changes in the carbonate compensation depth (CCD) relative to the sea floor, or from slumping of calcareous debris from adjacent topographic highs. Unit 1 represents predominantly inorganic pelagic sedimentation, with the additional contribution (30%) of volcanic debris.

If the cored basalt section can be assumed to represent the local oceanic basement, it appears that new oceanic crust in this region has formed beneath the CCD. The subsequent sediment record of calcareous and siliceous sediments requires mechanisms for changing sea-floor depths relative to the organic compensation depths, or the sudden introduction of organic debris by gravity flows from adjacent topographic highs which were above the local organic compensation depths.

Possible mechanisms for varying the compensation depths relative to the ocean floor are as follows and are discussed further in the Summary and Interpretations section of this chapter: (1) variation in the depth of the sea floor; (2) changes in sea level; (3) regional variation of climate with time; (4) regional variation in the compensation depths; (5) variation in rates of supply, such as the increased supply resulting from the increased biogenic activity in regions where cold nutrient-rich waters upwell to the surface along equatorial divergences, and the relationship of plate motions to the regions of anomalously high supply; (6) a combination of the above.

PHYSICAL PROPERTIES

Generally, the cores of Holes 291 and 291A were disturbed by coring and mixed with drill fluid, which reduced the number of measurements that could be carried out. All physical property results are given graphically in Figure 4. Although some variations were recognized in physical properties in Cores 1 through 4 of Hole 291, they should be regarded as random fluctuations. However, the differences in physical properties between the upper four cores and Core 5 of Hole 291 are striking. The measurements on cores from Hole 291A are nearly similar to those of Hole 291 at similar depths.

Bulk Density, Porosity, and Water Content

In most cases it was possible to average the analog record for each core section. Only when consistent offsets were recognized, was the bulk density measured over smaller intervals. The bulk densities thus obtained for Core 5 (Hole 291) were very unreliable in spite of corrections made for the smaller diameter. This must be attributed to the fragmentation of the material. For this reason, a selected number of pieces, having a uniform diameter and a fairly smooth surface, was subjected to the count method. A difference of about 0.1 to 0.2 g/cc was obtained between analog reading and count computation. This seems to be almost within the order of magnitude for technical errors.

A minor, but rather consistent increase in bulk density from 1.28 to 1.42 g/cc can be observed in the upper four cores of Hole 291. The basaltic material from Core 5 reveals a much higher bulk density: 2.82-2.87 g/cc on the analog recording and 2.96-3.04 g/cc via the direct-count method.

The water-content values varied from 46.28% to 76.02% for the upper four cores of Hole 291, with no uniform decrease with depth observed. The values for bulk density and porosity derived range from 1.19 to 1.49 g/cc and from 68.8% to 90.2%, respectively. The water-content value for Core 3 seems too high as it falls out of line with the water contents for the rest of the cores. However, GRAPE measurements could not be carried out on this core for comparison.

Sonic Velocity

The sonic velocity was generally measured in a section perpendicular to the stratigraphic direction (Table 3 and Figure 4). For the rock fragments from Core 5, a 6.7-mm-thick slab, sliced from a pebble, was measured.

The values ranged from 1.48 to 1.55 km/sec in the clays and oozes, and a velocity as high as 5.07 km/sec for the pebble in Core 5, Section 2. The lowest velocities occurred in Core 2 (measured only in one direction), which is a value smaller than the sound velocity in seawater at room temperature.

One sonic-velocity measurement was attempted in a slab cut in the stratigraphic direction from Core 4, Section 4. The value was about 8% higher than the value obtained from a horizontally cut section.

GEOCHEMICAL MEASUREMENTS

Alkalinity, *p*H, and salinity measurements are summarized in Table 4.

Alkalinity

The average alkalinity of the four samples examined is 2.35 meq/kg. The highest values (2.74 for Hole 291, Core 4, Section 4 and 2.64 for Hole 291A, Core 1, Section 6) occur in Units 3 and 4, respectively. Unit 3 is a clayey radiolarian ooze to clayey radiolarian-rich nannofossil ooze. Unit 4 is a nannofossil/radiolarian-bearing silty clay to ferruginous zeolite-rich clay.

TABLE 3
Sonic-Velocity Measurements, Site 291

Sample (Interval in cm)	Hole Depth (m)	Sonic Velocity (km/sec)
Hole 291		
2-2, 73	62.2	1.47[a]
2-2, 73	62.2	1.48
3-1, 143	80.4	1.53[a]
3-1, 143	80.4	1.53[a]
4-3, 104	102.0	1.57[a]
4-3, 104	102.0	1.54[a]
4-3, 104	102.0	1.53[a]
4-4, 106	103.6	1.53
4-4, 107	103.6	1.50
4-4, 106	103.6	1.53[a]
5-2, 59	119.1	5.15[b]
5-2, 59	119.1	5.16[b]
5-2, 59	119.1	4.93[b]
5-2, 59	119.1	5.10[b]
5-2, 59	119.1	5.02[b]
Hole 291A		
1-1, 53	98.5	1.43
1-1, 84	106.3	1.46
1-1, 84	106.3	1.47

[a]Measured in horizontal direction.
[b]Pebble slab.

pH

*p*H values were all below that of the seawater reference value at the site (8.27 and 8.18). The punch-in *p*H averages 7.51, while the flow-through values averaged 7.46.

Salinity

Four salinity measurements from Site 291 averaged 35.5‰. The one measurement in Hole 291A was 35.2‰. All values were higher than the overlying seawater reference value of 34.6‰. One sample of hard sediment in Hole 291 (Core 2, Section 1), had a salinity of 36.2‰. This sediment was a clay-rich to clayey nannofossil ooze.

PALEONTOLOGIC SUMMARY

Introduction

Cores taken at Site 291 contain late Pliocene and late Oligocene calcareous nannofossils and foraminifera, as well as late Eocene radiolarians and calcareous nannofossils. No diatoms or silicoflagellates were recovered at this site.

Samples of a silt-rich zeolitic clay recovered in Core 1 (0-3 m) contain a few poorly preserved late Pliocene nannofossils and several dwarfed planktonic foraminifera of probable late Pliocene age. Core 2 (60-69.5 m) is within the same clay; however, calcareous nannofossils and planktonic foraminifera indicate a late Oligocene age for this portion of the unit. Late Oligocene nannofossils, and possible early Oligocene radiolarians were also found in Core 3, Section 1 (80 m) with late Eocene nannofossils and radiolarians identified in Sample 3, CC (88.5 m) emphasizing the telescoped nature of this section. Both radiolarians and nannofossils recovered from Core 4 (98-107.5 m) are of late Eocene age.

Calcareous nannofossils recovered from fragments of red clay, immediately overlying basalt encountered in Core 5, Section 1 (118 m) indicate this sediment can be no older than mid early Eocene and could be as young as late Eocene.

All radiolarians and calcareous nannofossils identified in the core catchers of cores taken in Hole 291A are of late Eocene age.

Calcareous Nannofossils

A sample from 291-1 was found to contain rare specimens of the late Pliocene species *Discoaster brouweri* and *D. asymmetricus* which can be used to identify the *Cyclococcolithina macintyrei* Subzone of Bukry (1973). Preservation is very poor; consequently, these specimens could possibly represent reworking of late Pliocene fossils into younger sediments.

The presence of the species *Sphenolithus distentus* and *Discoaster tani* and the absence of *S. ciperoensis* in

TABLE 4
Summary of Shipboard Geochemical Data, Site 291

Hole	Sample (Interval in cm)	Depth Below Sea Floor (m)	pH		Alkalinity (meq/kg)	Salinity (°/oo)	Lithologic Unit
			Punch-in	Flow-through			
Surface seawater reference			8.27	8.18	2.10	34.6	
							Unit 2
291	2-1, 144-150	61.5	7.43	7.47	2.05	35.2	Soft sediment
			–	7.33	1.96	36.3	Hard sediment
291	4-4, 0-6	102.5	7.48	7.45	2.74	35.2	Unit 3
291A	1-6, 0-6	107.0	7.62	7.58	2.64	35.2	Unit 4
Average			7.51	7.46	2.35	35.5	

samples from Core 2 and Sample 3-1, 110-111 cm provide evidence for assigning this assemblage to the late Oligocene *Sphenolithus distentus* Zone of Bukry (1973).

Samples 3-1, 124-125 cm through 4, CC contain an assemblage typical of the late Eocene *Discoaster barbadiensis* Zone of Bukry (1973).

Sample 5-1, 115-116 cm immediately overlies basalt. Only two specimens of *Cyclococcolithina formosa* were observed. This species ranges from the middle of the early Eocene to the middle of the early Oligocene. The presence of this species dictates that the age of the sediment above basalt can be no older than mid early Eocene.

The sample from 291A-1 contains a typical, abundant, and moderately preserved late Eocene nannofossil assemblage belonging to the *Discoaster barbadiensis* Zone. The nannofossil assemblage recovered from Core 2 contains considerably fewer species in much reduced abundance, but it also belongs to the *Discoaster barbadiensis* Zone.

Several pebbles were recovered from the drill bit upon completion of Hole 291A. One of these pebbles proved to be an up-hole contaminant of nannofossil ooze assigned to the late Oligocene *Sphenolithus distentus* Zone and containing the index species *S. distentus* in association with *Discoaster tani*. Red mud recovered from the bit was found to contain a late Eocene nannofossil assemblage.

Foraminifera

Four core-catcher samples were found to contain planktonic foraminifera in varying abundances.

A sample from 291-1 contains many tiny planktonic foraminifera, which suggest dwarfing of the fauna because of unfavorable environmental conditions. Almost 78% of the total assemblage is composed of *Globigerinita uvula* and *"Globigerina" quinqueloba*. Normal-sized individuals of these two species are considered to represent subboreal to cool-temperate biofacies in the Recent ocean. However, specimens as small as those found in the Core 1 assemblage are not normally retained on plankton nets.

Several specimens of a single planktonic species, *Globorotaloides suteri*, were found to occur with numerous benthonic foraminifera in the sample from 291-2. Although *G. suteri* ranges in age from middle Eocene through the Oligocene, its lone occurrence here in association with a well-developed benthonic fauna suggests an Oligocene age. The benthonic assemblage also indicates an abyssal to bathyal environment above the calcium carbonate compensation depth.

The foraminifera recovered from Core 291A-1 are similar to those observed in Core 291-2, but are present in much lower abundances. These faunas are interpreted as representing up-hole contamination.

Several pebbles retained by the drill bit were found to contain a rather large benthonic fauna in addition to three planktonic species. These three species and their respective ranges are: *Globorotaloides suteri*, late middle Eocene to Oligocene; *Globigerina venezuelana*, middle Eocene to Miocene; and *G. linaperta*, late Paleocene to late Eocene. The ranges of these three species suggest a late Eocene age for this sample.

Radiolaria and Silicoflagellates

Radiolaria were rare to absent in the sediments of Hole 291, Cores 1 and 2. A possible faunal boundary between the *Theocyrtis tuberosa* Zone of the Oligocene, and *Thyrsocyrtis bromia* Zone of the late Eocene is drawn between Samples 3-1, 100-102 and 115-117 cm. The remaining sections of Core 3 and sediments of Core 4 also belong to the *Thyrsocyrtis bromia* Zone. No radiolarians were recognized from Core 5 to the base of Hole 291.

Common, but poorly preserved radiolarians were found in 291A-1 whereas they are few with moderate preservation in Cores 2 and 3. Judging from the faunal composition, this assemblage also belongs to late Eocene *Thyrsocyrtis bromia* Zone.

No silicoflagellates were observed at Site 291.

SUMMARY AND INTERPRETATIONS

Summary

The sedimentary section at Site 291 consisted entirely of pelagic deposits, but the widely spaced cores and very poor core recoveries led to ambiguity and lack of agreement as to the position of lithologic breaks. Nannofossil ooze was first recovered in Core 2 (60-69.5 m). The probability of additional layers above this level, as suggested by faint seismic reflectors near 50 meters, is high. Calculated sedimentation rates through the upper 65 meters are nearly identical to those of brown clays in Sites 290 and 53 (Figure 5) (Fischer et al., 1971). Because there is no evidence for breaks in sedimentation on

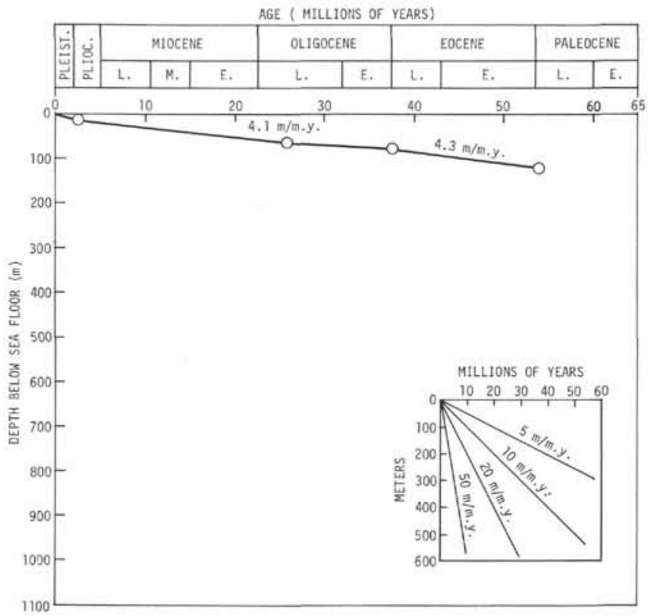

Figure 5. *Estimated rate of sedimentation at Site 291 based on calcareous nannoplankton zonation (Ellis, this volume) and time scale of Berggren (1972). Maximum possible mid-early Eocene age is assumed for sample in Core 3 immediately above basalt basement.*

seismic reflection records, this low rate suggests that there are no more than a few of the more rapidly deposited nannofossil ooze layers above Core 2. The zone of interbedded ooze and clay continues to 102 meters and rests on a thin basal section of dark brown clay, which in turn overlies basalt. The basalt-clay contact, placed at 118 meters on the lithologic log (Figure 4), probably occurs at 121 meters where a very sharp decrease in drilling rate occurred (Figure 4). The probable late Eocene age of the basal sediment is reasonably well bounded, and is assumed to represent the age of the underlying basaltic basement.

The extrusive nature of the tholeiitic basalt is indicated by its glassy surface. Fluctuating drill rates, plus the inflow of basalt pieces behind the bit in this cored section is suggestive of thin flows and rubbly interbeds. Seismic reflection profiles (Figure 3), and the results of *Glomar Challenger*'s brief site survey (Figure 2) delineate N20-30W trending basement benches, on one of which both holes were located. The 120-meter northeasterly offset to Hole 291A was perpendicular to the trend of this bench, and the intersection of basalt 9 meters shallower in Hole 291A indicates a shallow basement dip away from the bench edge. This is opposite to the expected dip of flows from a topographic high and suggests that the area consists of faulted and tilted basalt flows. With the available data, it cannot be ascertained whether faulting occurred at the time of basin formation and basalt extrusion or long afterwards. Perhaps the correlation of magnetic anomaly trends with the topographic lineations (Figure 2) would support an early period of faulting.

Interpretation

The interlayers of brown clay and nannofossil ooze and the lack of calcareous material in the basal dark brown clay unit require a much more complicated explanation for the history of the basin crust than simple creation at a shallow spreading center and subsequent subsidence, which sufficed at Site 290. Possible explanations of the interbedding at Site 291 include: (1) redeposition of calcareous material from nearby topographic highs; (2) alternating climatic conditions ultimately regulating low to high rates of planktonic productivity and/or a fluctuating carbonate compensation depth; (3) passage of the crust at Site 291 northward through an equatorial belt of high productivity; (4) vertical oscillations of the sea floor in response to tectonic activity.

Redeposition is suggested by common, well-preserved, calcareous benthonic foraminifera in the nannofossil ooze sections. Many of the species are indicative of lower bathyal or abyssal biofacies well above the CCD. Nannofossils, which might predominate on highs only slightly above the CCD, would presumably also participate in the downslope movement. Seismic reflection profiles do indicate thickened pelagic sections in the local lows, further suggesting redeposition. Topographic highs with sufficient relief lie several tens of kilometers to the north. Although the lack of sedimentological evidence for redeposition in the cores weakens these arguments, there was marked drilling disturbance and very little recovered core on which observations could be made.

Recent plots of the CCD with time (Berger, 1973) show that this level has dropped significantly since the late Eocene, but it is difficult to see how such a change could cause rapid fluctuations in lithology, particularly if there are more interbeds than actually recovered. Furthermore, the fluctuations are present in early to late Oligocene strata, after the postulated drop occurred.

Northward drifting on the Philippine plate, from beneath low productivity waters south of the equatorial belt of high productivity, and into areas beneath low productivity waters north of the equator is a possibility which requires more data. The present knowledge of the Tertiary tectonism in the Philippine Sea does not suggest the necessary 1200 km or greater northward shift. The northern boundary of the plate has been nearly fixed relative to Japan during most of this time, because there has been relatively little subduction along that boundary. Paleomagnetic data show no such northward shift for Japan but rather a southerly shift (McElhinny, 1973). Explanations calling for volcanic or tectonic events in the Site 291 area following creation of the basin are also without supporting evidence.

Another problem arising at Site 291 is the lack of calcareous material immediately overlying the basalt. Either the basalt does not represent true basement or conditions were such that the generative spreading zone lay beneath the local compensation depth. Arguments countering the probability of a masked sediment section are given in Karig (this volume), but this possibility cannot yet be dismissed. The possibility of crustal generation beneath the compensation depth is reasonable in this marginal basin setting. Both the spreading zones and older crust of given ages are deeper in the Philippine Sea than in most oceanic areas (Sclater, 1972). Coupled with only moderate to low biogenous productivity in surface waters, and a regionally shallower Eocene compensation depth, this tectonic character could easily result in the lack of a basal carbonate section. The lack of volcanic ash and mineral grains, as seen in deposits of a similar setting of the Mariana Basin (Karig, 1971), imply that the crust at Site 291 was created at a significant distance from the volcanic chain and frontal arc.

The most reasonable geologic history of Site 291 would have the early history occur as just proposed in the preceding paragraph. The overlying interbeds of calcareous and noncalcareous sediments would be attributed to a combination of downslope redistribution and a lowering of the regional CCD. Continued subsidence of the basin and of the carbonate-collecting topographic highs would end all carbonate deposition and produce the late Oligocene to Recent brown clays.

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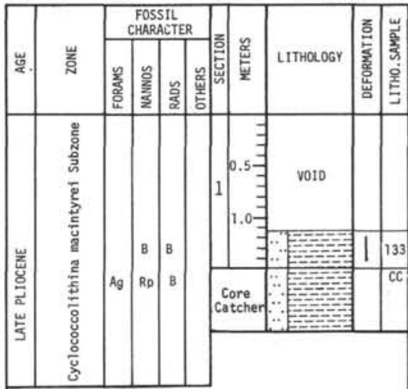
APPENDIX A
Summary of X-Ray, Grain Size, and Carbon-Carbonate Results, Site 291

Section	Sample Depth Below Sea Floor (m)	Lithology	Age	Bulk Sample Major Constituent			2-20μm Fraction Major Constituent			<2μm Fraction Major Constituent			Grain Size			Classification	Carbon Carbonate			Comments
				1	2	3	1	2	3	1	2	3	Sand (%)	Silt (%)	Clay (%)		Total (%)	Organic (%)	$CaCO_3$ (%)	
291-1-1	1.3	Unit 1	Late Oligo-	Plag.	Quar.	Mica	Plag.	Quar.	Mica	Mont.	Mica	Quar.	0.2	35.0	64.8	Silty Clay				Amph. in bulk, 2-20μm (1.5-3.3%)
291-2-1	60.5	Dark yellow-	cene to late	Plag.	Quar.	Mica	Plag.	Quar.	Mica	Mont.	Mica	Quar.	0.0	12.6	87.4	Clay				Clin. in bulk (1.8%); 2-20μm (1.7%)
291-2-1	61.4	brown silt-rich clay	Pliocene																	Amph. in bulk (1.5%); 2-20μm (2.8%)
291-2-2	62.2	Unit 2	Early to														8.5	0.0	70	
291-3-1	80.0	Pale brown clay-rich	late														9.9	0.0	82	
		nannofossil ooze	Oligocene																	
291-3-1	80.4	Unit 3	Late	Mont.	Plag.	Quar.	Plag.	Mont.	Quar.	Mont.	Plag.	Quar.								
291-4-1	98.7	Dark reddish-brown	Eocene										20.2	24.9	54.9	Sand-silt-clay	4.9	0.1	40	
291-4-2	100.5	clayey radiolarian	to early																	
		ooze and radiolarian-	Oligocene																	
		rich nannofossil ooze																		
291A-1-1	98.4-98.5	Unit 4	Mid early	Clin.	Mont.	Mica	Clin.	Mont.	Mica.	Mont.	Quar.	Goet.	0.5	21.1	78.4	Clay				Goet. present (5-25%) in bulk
291-4-4	102.7	Dusky red dark red-	Eocene	Cris.	Trid.	Quar.	No Residue Available			No Residue Available										2-20μm & Abund (25-65%) in <2μ.
291-4-4	103.4	brown nannofossil	to late	Cris.	Mont.	Clin.	Cris.	Clin.	Mont.	Mont.	Cris.	Trid.	9.8	18.6	71.6	Silty Clay				Trid. (1.5%) in 2-20μm
291A-1-6	106:6	radiolarian-bearing	Eocene	Clin.	Quar.	*	Clin.	Quar.	*	Mont.	Quar.	*	0.1	35.9	64.0	Silty Clay				Clin. (1.6%) in <2μm
		clay to zeolite-rich																		*Goet. major (<65%) in all fractions
		silty clay																		

Note: Complete results of X-ray, Site 291, will be found in Part V, Appendix I. X-ray minerological legend in Appendix A (Chapter 2).

Site 291 Hole Core 1 Cored Interval: 0.0-3.0 m



LITHOLOGIC DESCRIPTION

10YR 4/2

Unit 1. Dark yellowish brown (10YR 4/2); moderately deformed by drilling.

SILT-RICH CLAY
Smears: 1-133, CC

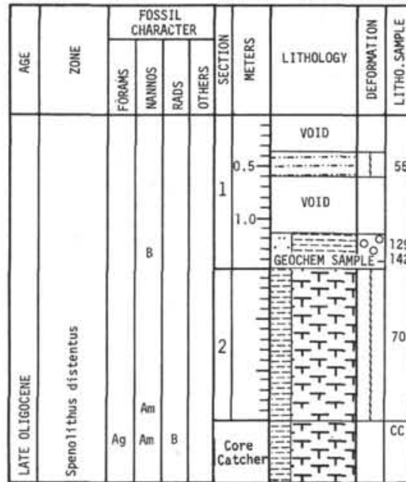
Texture	Composition
90% Clay	50-55% Clay minerals
10% Silt	10-20% Feldspar
	10% Quartz
	10% Palagonite (Fe-oxide?)
	5- 7% Zeolites
	5% Heavy minerals
	1% Micronodules
	Tr% Diatoms
	Tr% Volcanic glass
	Tr% Radiolaria
	Tr% Sponge spicules

Heavy minerals include amphiboles, pyroxenes; clay is very dark due to Fe-oxide platelets or aggregates. Zeolites are clinoptilolite.

X-ray 1-133 (Bulk)
26.1% Plag
23.0% Quar
20.9% Mica
17.6% Mont
5.8% K-Fe
5.1% Chlo
1.5% Amph

Explanatory notes in chapter 1

Site 291 Hole Core 2 Cored Interval: 60.0-69.5 m



LITHOLOGIC DESCRIPTION

10YR 4/2 (55)
10YR 4/2 (129)
10YR 4/2
5YR 5/2 (70)

Core initially dark yellow brown (10YR 4/2) clay with the nannofossil ooze being a pale brown (5YR 5/2); deformation intense with mottling noticeable in ooze.

SILTY CLAY (TO SILT-RICH CLAY)
Smears: 1-55, 1-129, 1-142

Texture	Composition
64.8-70 % Clay	65-72% Clay minerals
12.6-35 % Silt	15-20% Fe-oxides (and palagonite)
0- 0.2% Sand	5-10% Zeolite
	3-10% Heavy minerals
	2- 5% Feldspar
	1% Micronodules
	Tr% Radiolarians
	Tr% Volcanic glass
	Tr% Nannofossils

CLAY-RICH (to clayey) NANNOFOSSIL OOZE
Smears: 2-70, CC

Texture	Composition
100% Clay	70-88% Nannofossils
	12-30% Clay minerals
	1% Fe-oxides
	Tr- 1% Zeolites
	Tr% Volcanic glass

Heavy minerals include: pyroxenes, amphiboles. The Fe-oxides reported occur as irregular to round plate-lets. Brown coloring lightens down core.

Grain Size 1-52
0.2, 35.0, 64.8

Grain Size 1-139
0.0, 12.6, 87.4

Carbon Carbonate 2-70
8.5, 0.0, 70

X-ray 1-53 (Bulk)
30.4% Plag
24.3% Quar
19.0% Mica
17.8% Mont
5.1% Chlo
1.8% Clin
1.5% Amph

Explanatory notes in chapter 1

Site 291 Hole Core 3 Cored Interval: 79.0-88.5 m

AGE	ZONE	FORAMS	NANNOS	RADS	OTHERS	SECTION	METERS	LITHOLOGY	DEFORMATION	LITHO. SAMPLE	LITHOLOGIC DESCRIPTION
EARLY OLIGOCENE / LATE EOCENE	S. predistentus; Theocyrtis Tuberosa? (R); D. barbadiensis; Thyrsocyrtis bromia (R)	B	Am Ap Rm Am Rm Cm	Cg Ag Ag		1; Core Catcher	0.5, 1.0	VOID		103, 125, 137, CC	5YR 5/2 – 10R 3/4

Unit 2. Nannofossil ooze, very pale brown (5YR 5/2) to dark reddish brown (10R 3/4) in radiolarian ooze (Unit 3). Moderate drilling deformation.

CLAY-RICH NANNOFOSSIL OOZE
Smear: 1-103

Texture	Composition
100% Clay	80% Nannofossils
	20% Clay minerals

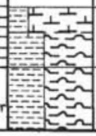
CLAYEY RADIOLARIAN OOZE
Smears: 1-137, CC

Texture	Composition
95% Clay	30-46% Clay minerals
5% Silt	25-45% Radiolarians
	10-19% Nannofossils
	1- 5% Quartz, Feldspar
	1- 5% Sponge spicules
	1- 3% Zeolites
	Tr- 1% Opaques

The nannofossils, in some cases may be contaminants in the radiolarian unit. The samples at 1-125 and CC were designated as nannofossil-rich.

Carbon Carbonate 1-103
9.9, 0.0, 82

X-ray 1-137 (Bulk)
47.8% Mont
36.8% Plag
8.5% Quar
6.8% Mica



Explanatory notes in chapter 1

Site 291 Hole Core 4 Cored Interval: 98.0-107.5 m

AGE	ZONE	FORAMS	NANNOS	RADS	OTHERS	SECTION	METERS	LITHOLOGY	DEFORMATION	LITHO. SAMPLE	LITHOLOGIC DESCRIPTION
LATE EOCENE	Discoaster barbadiensis; Thyrsocyrtis bromia (R)	B	Am Ap Cm Apm B Rm	Ag Ag Ag Fm Fm Rp		1, 2, 3, 4, Core Catcher	0.5, 1.0	VOID; MIX ZONE; GEOCHEM SAMPLE		65, 80, 65, TS, 91, CC	10R 3/4 – 10YR 4/2; 10R 2/2; 10R 2/2; 5YR 3/2; 5R 2/2; 5YR 3/2; 10R 2/2

Core soft, soupy, loose, and highly disturbed. Colors dark yellow brown (10YR 4/2) with very dusky reds (10R 2/2) in nannofossil and radiolarian-bearing clays; intense drilling deformation lower in core. Hard chert nodules in Section 4 (12 cm, 65 cm), are opal with zeolites (silicified mudstone), color reddish black (5R 2/2) to very dusky red (10R 2/2). Unit 4 boundary at 101.8 meters.

NANNOFOSSIL-BEARING/RADIOLARIAN-RICH (SILTY CLAY)
Smear: 2-80

Texture	Composition
60% Clay	74% Clay minerals
30% Silt	15% Radiolarians
10% Sand	10% Nannofossils
	1% Sponge spicules
	Tr% Zeolite

RADIOLARIAN/ZEOLITE-BEARING CLAY
Smear: 3-65

Texture	Composition
100% Clay	70% Clay minerals
	8-10% Radiolarians
	5-10% Zeolite
	5% Nannofossils
	3% Fe-oxides
	2% Micronodules

FERRUGINEOUS/ZEOLITE-RICH CLAY
Smears: 4-91, CC

Texture	Composition
71.6% Clay	58-80% Clay minerals
18.6% Silt	5-25% Fe-oxides
9.8% Sand	15% Zeolite (clinoptilolite)
	1% Feldspar
	Tr- 5% Radiolarians
	Tr% Nannofossils

CLAYEY/RAD-RICH NANNOFOSSIL OOZE (Minor Lith)
Smear: 1-65

Texture	Composition
100% Clay	43% Nannofossils
	30% Clay minerals
	20% Radiolarians
	5% Fe-oxides
	2% Sponge spicules

Grain Size 2-100
20.2, 24.9, 54.9

Grain Size 4-85
9.8, 18.6, 71.6

Carbon Carbonate 1-65
4.9, 0.1, 40

X-ray 4-16 (Bulk)
77.0% Cris
17.2% Trid
5.8% Quar

X-ray 4-88 (Bulk)
42.2% Cris
36.4% Mont
8.5% Clin
5.7% Trid
3.2% Mica
2.3% Plag
1.8% Quar

Explanatory notes in chapter 1

Site 291 Hole Core 5 Cored Interval: 117.0-126.5 m

AGE	ZONE	FOSSIL CHARACTER: FORAMS	NANNOS	RADS	OTHERS	SECTION	METERS	LITHOLOGY	DEFORMATION	LITHO. SAMPLE	LITHOLOGIC DESCRIPTION
EOCENE			Rm			1	0.5, 1.0	VOID		115	5YR 4/4
		B		B		2		VOID		TS, TS, TS	

Unit 5. Core is basalt with two small fragments of mildly-indurated ferruginous/zeolite-bearing clays at 113-121 cm; moderate brown (5YR 4/4) color.

BASALT: Tabular to acicular plagioclase in fine-grained groundmass of pyroxene; calcite veinlets.

Composition (Ranges) from thin sections
60-65% Groundmass
23-60% Plagioclase
35-56% Pyroxene
2- 8% Opaques
5-40% Glass
35-40% Phenocrysts
35-40% Plagioclase

FERRUGINEOUS/ZEOLITE-BEARING CLAY (MINOR LITH)
Smear: 1-115

Texture	Composition
95% Clay	87% Clay minerals
5% Silt	5% Fe-oxides
	5% Zeolite
	1% Heavy minerals
	1% Micronodules
	1% Feldspar

*After Core 5 had been taken a quantity of material was recovered from the core barrel after pipe had been pulled, and even though a new coring interval had not occurred. The sample designated Sample 5A contained four pieces of basalt and some moderate brown (5YR 4/4) nannofossil-rich ferrugineous clay.

NANNOFOSSIL-RICH FERRUGINEOUS SILTY CLAY
Smear: 5A

Texture	Composition
60% Clay	45% Clay minerals
40% Silt	25% Fe-oxides
	20% Nannofossils
	5% Zeolites
	4% Feldspar
	2% Heavies
	Tr% Volcanic glass

Explanatory notes in chapter 1

Site 291 Hole A Core 1 Cored Interval: 98.0-107.5 m

AGE	ZONE	FOSSIL CHARACTER: FORAMS	NANNOS	RADS	OTHERS	SECTION	METERS	LITHOLOGY	DEFORMATION	LITHO. SAMPLE	LITHOLOGIC DESCRIPTION
			B			1	0.5, 1.0	VOID; Z Z; VOID		45	5YR 3/4
						2					
						3		VOID			
						4					
						5		Z Z Fe			10R 2/2-5YR 3/4 (mottled)
LATE OLIGOCENE	Sphenolithus distentus; Thyrsocyrtis bromia (R)		B			6		VOID; MIX ZONE; Z Fe; GEOCHEM SAMPLE		110	10R 2/2; Mixture (soupy) of clay-rich nannofossil ooze and Fe-rich zeolitic silty clay.; 10R 2/2
		Fm	Am	Cp		Core Catcher				CC	5YR 3/4

Core very irregularly disturbed in Sections 1, 5 and 6 generally moderate drilling deformation; some color mottling of moderate brown (5YR 3/4) and very dusky red (10R 2/2); Unit is similar to that recovered in Core 4 Hole 291 (Unit 4).

FERRUGINEOUS-RICH ZEOLITIC SILTY CLAY
Smears: 1-45, 6-110

Texture	Composition
64.0-78.4% Clay	80% Clay minerals
21.1-35.9% Silt	17-20% Fe-oxides
0.1- 0.5% Sand	20% Zeolites
	2% Nannofossils
	1% Heavy minerals
	Tr% Radiolarians
	Tr% Sponge spicules

ZEOLITE-BEARING/CLAY-RICH NANNOFOSSIL OOZE
Smear: CC

Texture	Composition
97% Clay	30-57% Nannofossils
3% Silt	20-24% Clay minerals
	15-35% Fe-oxides
	10% Zeolite
	Tr- 5% Radiolarians
	Tr% Sponge spicules

Grain Size 1-45	Grain Size 6-110
0.5, 21.1, 78.4	0.1, 35.9, 64.0

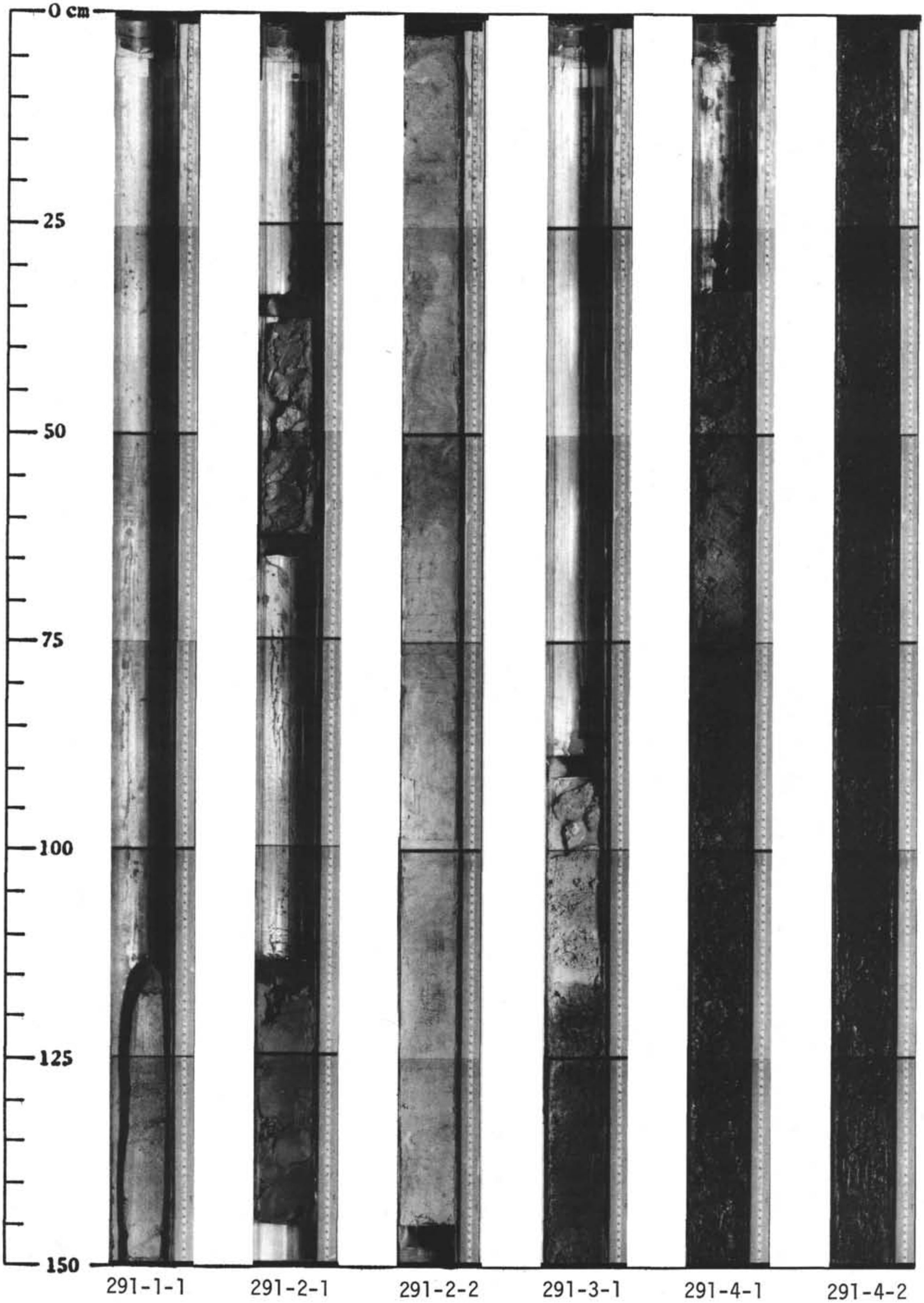
X-ray 1-43 (Bulk)	X-ray 6-108 (Bulk)
50.5% Clin	91.2% Clin
31.7% Mont	8.8% Quar
9.5% Mica	M Goet
8.4% Quar	
P Goet	

Explanatory notes in chapter 1

Site 291 Hole A Core 2 Cored Interval: 107.5-114.5 m

AGE	ZONE	FOSSIL CHARACTER: FORAMS	NANNOS	RADS	OTHERS	SECTION	METERS	LITHOLOGY	DEFORMATION	LITHO. SAMPLE	LITHOLOGIC DESCRIPTION	
LATE EOCENE	D. barbadiensis Thyrsocyrtis bromia (R)	Fg	Rm	Rp		Core Catcher					10R 2/2 and 5YR 4/4	Core catcher sample contained mixture of clay = (Fe-rich), clay-rich nannofossil oozes, and basalt fragments. *After drill pipe was brought on deck upon hole termination the core barrel contained basalt fragments, with minor amounts of moderate brown (5YR 4/4) clay-rich nannofossil ooze. Sample was designated as Sample 2A for Hole 291A.

Explanatory notes in chapter 1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125
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291-3-1
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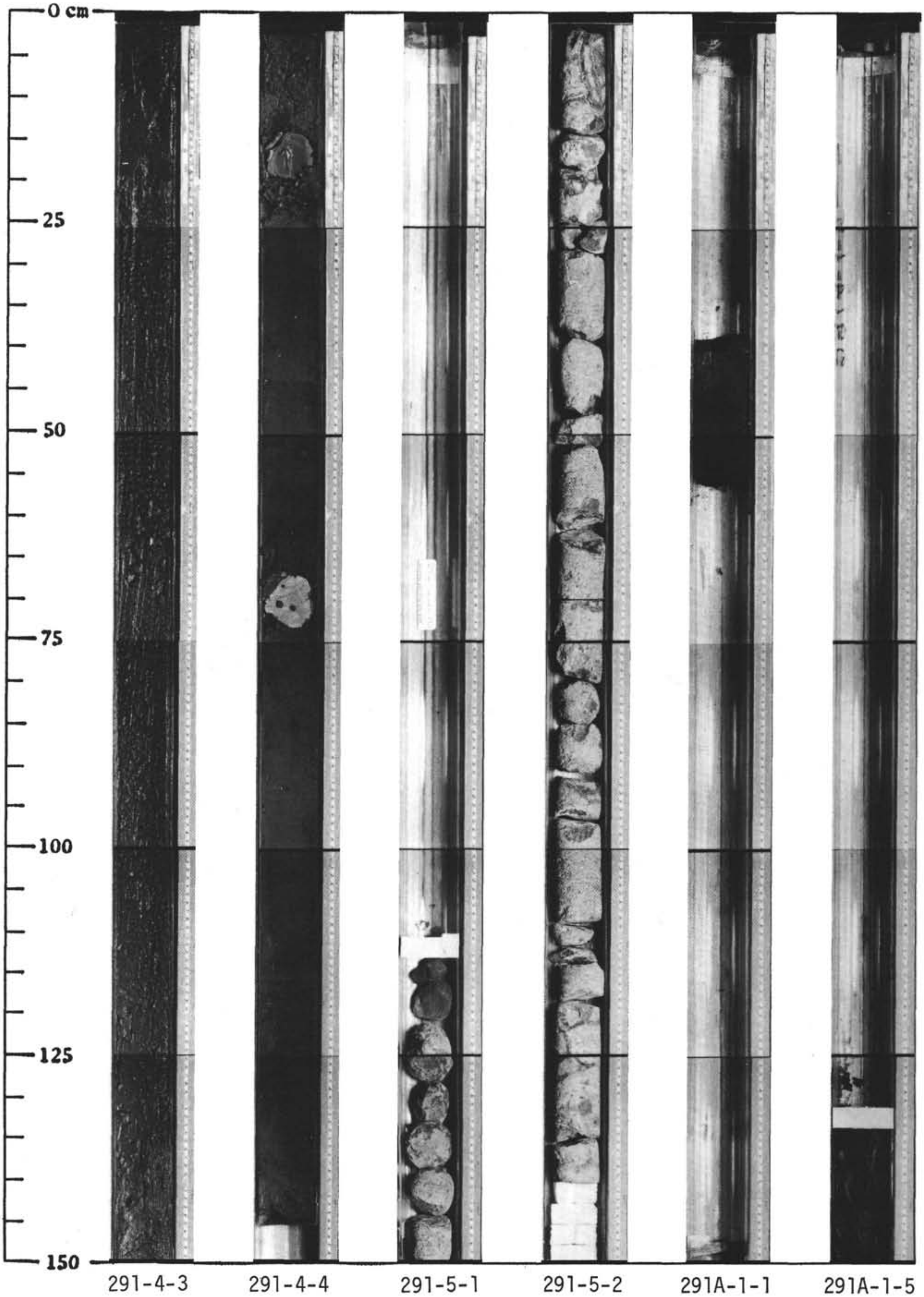
291-4-2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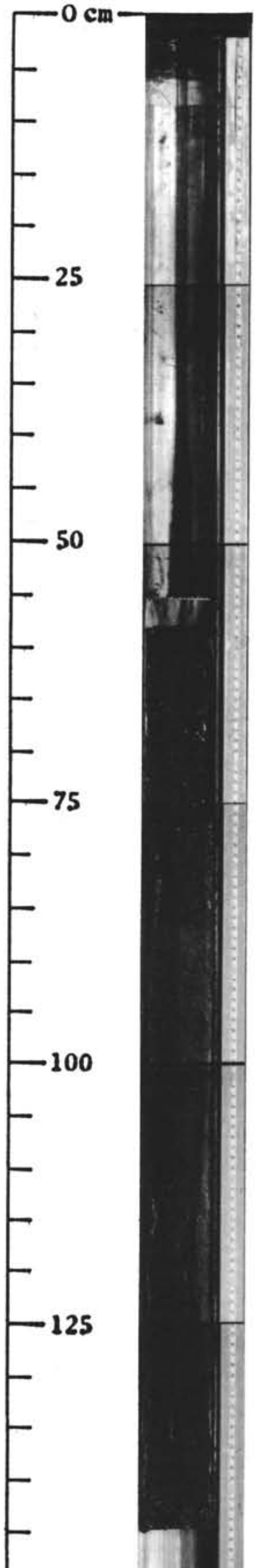

291A-1-6