5. SITE 441: JAPAN TRENCH LOWER SLOPE, LEG 57

Shipboard Scientific Party[1]

HOLE 441

Date Occupied: 21 November 1977

Date Departed: 22 November 1977

Time on Hole: 2 days

Position: 39°45.05′N; 144°04.59′E

Water Depth (sea level): 5655 corrected meters, echo sounding

Water Depth (rig floor): 5665 corrected meters, echo sounding

Bottom Felt: 5665 meters, drill pipe

Penetration: 273.0 meters

Number of Cores: 9

Total Length of Cored Section: 79.0 meters

Total Core Recovery: 16.6 meters

Core Recovery: 21 per cent

Oldest Sediment Cored:
Depth sub-bottom: 273.0 meters
Nature: Diatomaceous claystone
Age: Early Pliocene
Measured velocity: 1.6 km/s

HOLE 441A

Date Occupied: 23 November 1977

Date Departed: 27 November 1977

Time on Hole: 5 days

Position: 39°45.05′N; 143°04.59′E

Water Depth (sea level): 5644 corrected meters, echo sounding

Water Depth (rig floor): 5654 corrected meters, echo sounding

Bottom Felt: 5656 meters, drill pipe

Penetration: 662.0 meters

Number of Cores: 15

Total Length of Cored Section: 138.5 meters

Total Core Recovery: 19.7 meters

Core Recovery: 14 per cent

Oldest Sediment Cored:
Depth sub-bottom: 662.0 meters
Nature: Claystone
Age: Late Miocene
Measured velocity: 2.3 km/s

HOLE 441B

Date Occupied: 30 November 1977

Date Departed: 2 December 1977

Time on Hole: 3 days

Position: 39°45.08′N; 144°04.60′E

Water Depth (sea level): 5635 corrected meters, echo sounding

Water Depth (rig floor): 5645 corrected meters, echo sounding

Bottom Felt: 5650 meters, drill pipe

Penetration: 687.0 meters

Number of Cores: 2

Total Length of Cored Section: 18.0 meters

Total Core Recovery: 5.5 meters

Core Recovery: 30 per cent

Oldest Sediment Cored:
Depth sub-bottom: 687.0 meters
Nature: Vitric silty claystone
Age: Late Miocene
Measured velocity: Unable to measure

Principal results:

Site 441 was selected to sample the accretionary zone associated with the Japan Trench. It is 15 km landward of the trench axis, near Site 434, where the seismic data record a thin sequence of reflections subparallel to the slope, overlying a landward-dipping sequence of presumed accreted sediment. The accretionary wedge seaward of Site 440 is 30 km wide and is floored by igneous oceanic crust. Three holes were attempted, but periods of weather calm enough for drilling were too short to allow drilling to the depths of the dipping reflections. The lithology sampled is claystone and diatomaceous claystone of a hemipelagic slope sequence ranging in age from late Miocene to Pleistocene, much the same as at the other site on this transect, but the rock is highly fragmented. Rare pieces of coherent core consisted of

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highly fractured rock, tectonic breccia, or resedimented breccia. The Pliocene interval is about 25 per cent thicker than the Pliocene at Sites 438, 439, and 440. The lack of repeated paleontological zones and unfaulted material from the oceanic plate seems to rule out thickening of the section through imbrication. A more likely cause is combined small-scale slumping, as shown by redeposited microfossils, and tectonic thickening along pervasive microfractures. The volume increase by slumping or by tectonic thickening cannot be estimated from the cores, because they are mainly fine cuttings, derived from either intensely fractured rock, tectonic breccia, or redeposited breccia.

There is no evidence that a section from the oceanic plate was drilled. However, the hemipelagic section is more intensely fractured than any other section sampled on the Japan Trench transect except at Site 434. Therefore this section is thought to be overstressed by tectonism associated with plate convergence.

BACKGROUND AND OBJECTIVES

A unique feature of convergent margins is the disturbed sedimentary prism at the leading edge of the upper plate. Usually the prism is in very deep water or is covered by thick sedimentary layers parallel with the slope. This makes it difficult to study with conventional seismic reflection techniques, because even some gently dipping beds are not resolved, and the resolution degrades steadily below shelf depths. Therefore drilling is an important field method in the study of tectonic processes at convergent margins.

One of the main study objectives along the Japan Trench transect was the disturbed prism, but the depth of the trench and of its lower slope is greater than the length of the drill string aboard the *Glomar Challenger*. Three prospective sites on the upper part of the prism were recommended for drilling by the Active Margins Panel and the Japan IPOD Committee. During Leg 56 a large effort went into drilling near the deepest site recommended (Site 434), but the results were rather disappointing. Core recovery was poor, and the drill string stuck at 638 meters, terminating the third sampling attempt at that site.

At Site 440, penetration into a peripheral part of the disturbed prism was expected, but drilling and restudy of the reflection records showed that the continental slope section extends to the middle of the trench slope there. Site 441 was chosen at the point where the seismic record indicates the shallowest cover of slope material over the presumed accreted material at depths still within reach of the drill string. The site is 13 km downslope from Site 440 and 3 km upslope from Site 434 (Figure 1). The specific objective was to penetrate to about 800 meters and reach the first distinct reflection that has a pronounced landward dip (Figure 2). The landward-dipping sequence is thought to be an imbricated stack of uptilted oceanic and continental slope deposits. Above this reflection the record is obscured by diffractions that extend to the sea floor, indicating a rough lower-slope topography.

Some specific objectives we hoped to study in the disturbed prism were the structure in the initial stages of accretion and the diagenetic and early metamorphic changes. Samples obtained previously from similar environments indicate that highly compacted sediment and evidence of very rapid expulsion of interstitial fluids might occur in this zone. The structure has been largely inferred from theoretical models and from ancient analogs on land.

In two earlier legs, 18 and 31, in sampling lower-trench slopes a primary objective had been to obtain sediment from the oceanic plate in a zone of accretion on the continental plate (von Huene, Kulm, et al., 1973; Ingle, Karig, et al., 1975). On both legs it turned out that oceanic and continental sediment differed little in lithology, and this holds true for Leg 56 also. After initial compaction and diagenesis, Neogene sediment on the oceanic and continental plates is so similar as to be indistinguishable. Siliceous microfossils are usually absent or poorly preserved, and calcareous microfossils are dissolved. Thus the chance of demonstrating accretion along the Japan Trench, by positively identifying oceanic sediment on the continental plate from its lithology or paleontology, is small. In this situation the physical properties measurements and geophysical logging have greater than usual significance, because overconsolidation, anomalous water content, and other quantitative measurements are good indications of a high-stress environment.

OPERATIONS

Site 441 is about 12.7 km east of Site 440 (Figure 3). The *Glomar Challenger* was navigated by dead reckoning from the sonic beacon at Site 440, with a strong wind and current on the stern quarter. The airgun seismic reflection and 3.5-kHz systems were inoperative, so the new beacon was dropped on the basis of a poor 12-kHz bottom-sounding trace. Although checkpoints along the way to the site seemed good, several satellite navigation fixes had been received as the drillers prepared to lower the drill string and the beacon position was found to be about 2 km south of the desired location. Therefore a second beacon was positioned by offsetting to the proper position, using the first beacon as a navigational aid.

On the bottom-sounding record, the sea floor below the ship was indistinguishable from several side echos. The bottom measured with the drill string was about 40 meters below the highest reflection, which resulted in three false spud-in attempts. A total of 9 cores were recovered from Hole 441 (Table 1).

After about 2 days of drilling on the site, the first hole was abandoned because of a storm. After a day, Hole 441A was spudded in, and about three days later a strong storm was forecast. Assuming the approaching storm system would force abandonment, we decided to log the drilled interval. Only one logging run was completed before abandonment became necessary. The sea had already become rough enough to degrade the log with strong vertical motion of the ship, but nonetheless

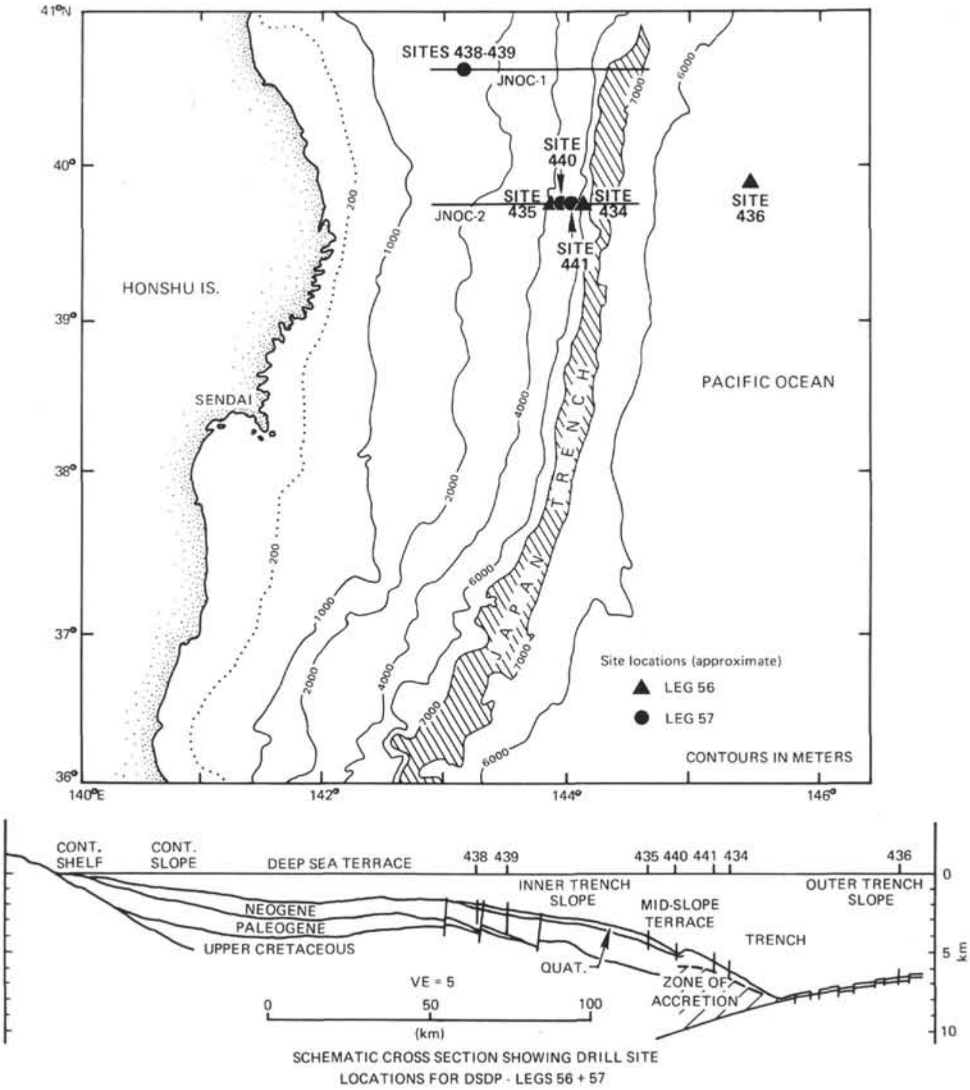

Figure 1. *Location map showing position of sites drilled on Legs 56 and 57 and of JNOC multichannel seismic reflection profiles. Diagrammatic cross section of continental margin shown below (based largely on Ishiwada and Ogawa, 1976).*

the logging information proved to be highly significant. The drill string was brought aboard during strong winds, high seas, and driving rain.

With less than four days of time remaining, we began Hole 441B in a final attempt to reach the disturbed prism. Drilling proceeded to the depth of Hole 441A, but almost immediately plugging of the bit and sticking of the core barrel became chronic. After 25 meters of penetration beyond the previous attempt, the core barrel became firmly stuck in the drill collar, and the drilling on Leg 57 was concluded.

LITHOSTRATIGRAPHY

The holes at Site 441, which were drilled on the lower trench slope, lie 15 km from the axis of the Japan Trench and about 3 km upslope from Site 434 (Figure 3). The sequence recovered at Site 441 is similar to but not identical with that encountered at Site 434. Both sites were plagued by poor recovery, apparently owing to highly fractured rock. A major conclusion from examination of the cores recovered at Site 441 is that the extensive breaking up of the material during drilling is due to a pervasive fracturing developed in place by tectonic stress. Important in this process are dewatering and the development of fracture porosity.

About 43 per cent of the core material obtained at Site 441 consists of material recovered in wash cores that were drilled at high pump pressure through relatively long depth intervals. This method reduced the choking of the core barrel with slumped fragmental material and was particularly effective in recovering the more coherent layers in this highly fractured section. Wash cores are designated by the prefix *H*.

The limited core recovery from the site as a whole allows only a general definition of lithostratigraphic units (Figure 4 and Table 1; Site Summary Chart 434/441, back pocket), but information obtained from downhole gamma-ray and formation density logs aids in iden-

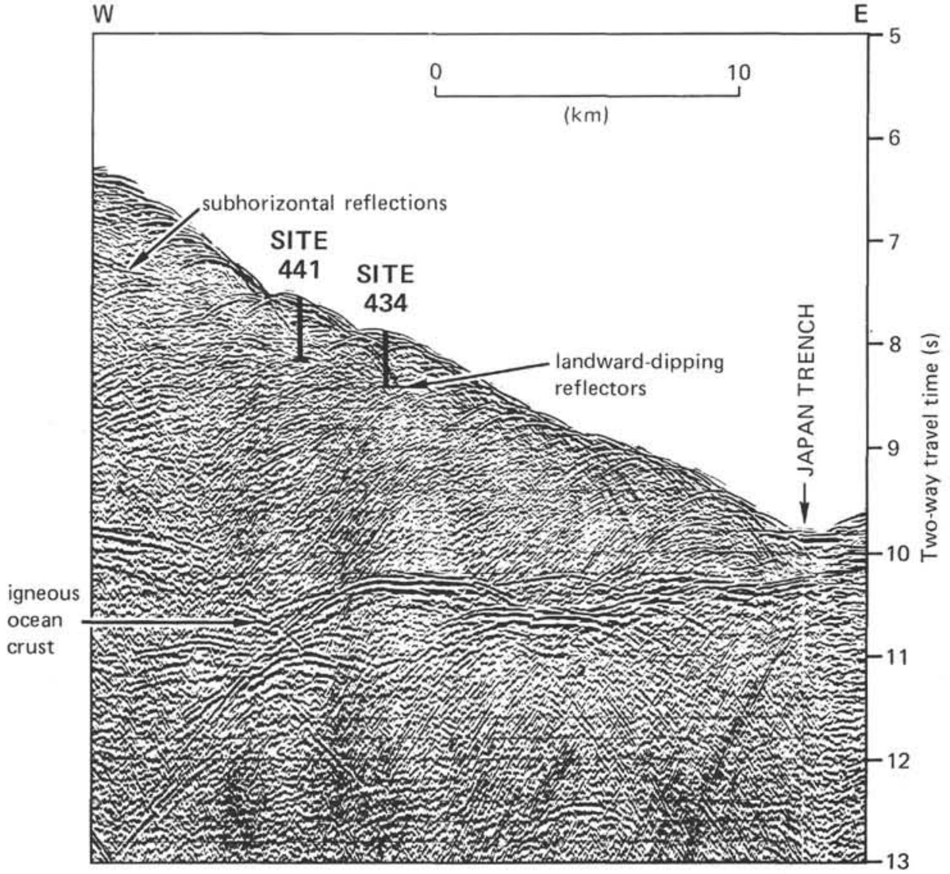

Figure 2. *Section of JNOC-2 multichannel seismic reflection record showing lower trench inner slope and reflective sequence penetrated at Sites 441 and 434. Note discontinuity between subhorizontal slope sequence and landward-dipping reflective sequence.*

tifying the boundaries. The five defined units are as follows: Unit 1, diatomaceous clay (0–132 m sub-bottom); Unit 2, diatomaceous claystone (132–380 m); Unit 3, siltstone breccia (380–410 m); Unit 4, diatomaceous claystone (410–504 m); Unit 5, claystone (504–671 m).

Lithostratigraphic Unit 1 (Cores 441-1–441-6 and 441A-1–441A-2, 0–132 m sub-bottom, upper Pleistocene and upper Pliocene)

Only the uppermost portion (0–16.5) of this unit was recovered sufficiently to characterize it with confidence. The remaining recovery consisted almost entirely of core-catcher samples. The upper 16.5 meters is composed mostly of dark greenish gray (5GY 4/1) silty diatomaceous clay, which is slightly mottled and sandy in part. Thin intervals of clayey sand and silt as well as diatomaceous clay also occur. Several rounded pebbles of basalt and dacite or andesite porphyry up to 2 cm in diameter were recovered in Core 441-1. Pumice granules (2–3 mm) occur at a few levels. Rare olive gray to light olive gray (5Y 5/4–7/1) mottles have a grain size from clay to silt.

The poorly sampled interval from 16.5 meters to the base of Unit 1 seems to be primarily olive gray to grayish olive green (5Y 4/2–5GY 3/2) diatomaceous clay. Clay content in the sediment is typically more than 40 per cent with up to 20 per cent quartz plus feldspar. Diatom content averages about 28 per cent; sponge spicules compose between 5 and 10 per cent of the rock, and carbonate, pyrite, glauconite, volcanic glass, and heavy minerals are more minor components. Calcareous concretions or pebbles occur in Samples 441-5,CC and 441-6,CC. These rocks are composed almost entirely of calcite. One of them shows possible concretionary growth lines; the surface of each specimen is covered by closely packed 1- 2-mm elongate rods, possibly cemented fecal pellets. A similar specimen was recovered at Site 434 nearby (see Site 434 this volume). A calcite-cemented sandy claystone pebble was found in Sample 441-6,CC. Sample 441-4,CC recovered a thin, graded, very fine-grained sand interbedded with diatomaceous clay. Core 441A-2, at the base of Unit 1, recovered a graded silty tuff bed as well as diatomaceous clay.

Unit 2 (Cores 441-7–441-9, 441A-2–441A-4, 441A-H1–441A-H2, and 441B-1; 132–380 m sub-bottom; upper Pliocene and lower Pliocene)

The major difference between Unit 2 and Unit 1 is the greater degree of lithification of Unit 2. Because coring and recovery were sparse, the downhole density log was

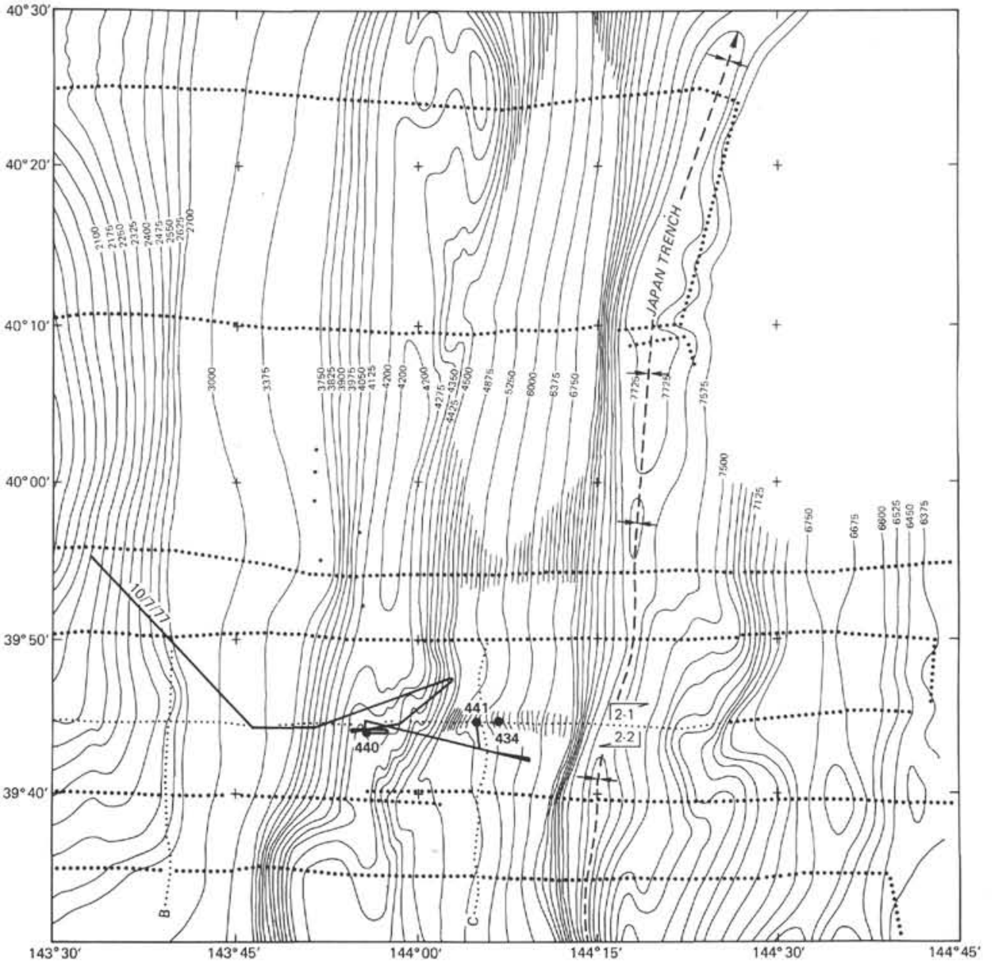

Figure 3. *Bathymetric map of lower part of Japan Trench inner slope (note trench axis), showing location of Sites 441, 440, and 434; tracklines of* Glomar Challenger*; and traces of other available seismic lines in area. Contours based on network of geophysical data as shown.*

used to place the diatomaceous clay/claystone boundary at 132 meters. Below this depth, recovery was usually limited to chips or cuttings of the rock, with rare intact pieces of the highly fractured material. Dark greenish gray (5GY 4/1) to olive gray (5Y 3/2) diatomaceous claystone predominates, along with minor olive gray (5Y 4/2) clayey diatomite and vitric diatomaceous claystone. Slight to intense mottling characterizes the diatomaceous claystone intervals; some mottling consists of pale yellow (5Y 3/1–N2) and less abundant white (N8) mottles of tuff. The composition of Unit 2 sediment is similar to that of Unit 1.

Core 441B-1 recovered greenish gray (5GY 5/1) diatomaceous claystone, vitric calcareous claystone, and dark greenish gray (5GY 4/1) diatomaceous claystone. Over 50 cm of light gray (N7) tuff is also present.

Parting, fractures, and black anastomosing veins are typical of this unit. Measured open fracture orientations range from horizontal to nearly vertical, but several orientations seem to predominate: relatively low-angle (30–35°) and two sets of intermediate-angle (40–50°and about 65°], for example, in Cores 441A-H1 and 441A-H2. Offset is difficult to demonstrate on the open fractures, and few of them seem to be related to the systems of black veins observed in cores from this and previous holes. No black material typical of basalt faults and fractures in Sites 438, 439, and 440 was noted along open fracture plane surfaces.

The base of Unit 2 is defined as a pronounced change in lithology and geophysical log character at about 380 meters.

Unit 3 (Cores 441A and 441B-H1, 380–410 m subbottom, lower Pliocene)

Only one core was taken in this interval, but the relatively good recovery consisted of a brecciated dark gray (N3) siltstone and clayey siltstone interbedded with thin graded and nongraded tectonically undisturbed siltstone to coarse-grained sandstone layers and light olive (5Y 6/1) claystone. The bulk density of the breccia unit is high, and this character was used in determining the total thickness of the unit on the downhole density log. Below 410 meters, the lithology again is a more monotonous diatomaceous claystone and claystone.

TABLE 1
Lithologic Units, Sub-bottom Depths, Ages, and Description of Sequence at Site 441

Unit	Sub-bottom Depth (m)	Thickness (m)	Core	Age	Lithology
1	0-132	132	1-6 A1-A2	Late Pleistocene and late Pliocene	Dark greenish gray (5GY 4/1) silty diatomaceous clay at top; predominantly olive gray (5Y 4/2) diatomaceous clay with minor ash layers; rounded pebbles up to 2 cm in diameter consisting of basalt, dacite, pumice, and some calcareous concretions. Minor clayey silt or sand layers. Slightly mottled throughout. One graded silty tuff noted at base.
2	132-380	248	7-9 A3-A4[a]	Late Pliocene and early Pliocene	Dark greenish gray (5GY 4/1), dark olive gray (5Y 3/2), and olive gray (5Y 4/1) diatomaceous claystone; minor clayey diatomite, vitric diatomaceous claystone, and a few thin tuff beds. Some calcareous mottles and concretions. Entire unit is characterized by fractures, partings, and some black veins (rehealed). Recovery is mostly in the form of less than 1-cm chips and is very poor.
3	380-410	30	A5	Early Pliocene	Breccia of dark gray (N3) siltstone consisting of rounded to angular siltstone fragments in a more clay-rich matrix. Dewatering veins at top of recovery. Several graded and nongraded very fine-grained to coarse-grained sandstone beds interbedded with claystone (5Y 6/1). Bottom of unit chosen on the basis of signature on downhole density log. Fair recovery.
4	410-504	94	A6-A7	Early Pliocene	Mostly dark olive gray (5Y 3/2) claystone and diatomaceous claystone; some siltstone, possible redeposited claystone, minor tuff layers, and calcareous concretions; highly fractured and poor recovery.
5	504-671	167	A8-A15[a]	Early Pliocene and late Miocene	Heterogeneous lithology consisting of olive gray (5Y 3/2) claystone, greenish black to greenish gray (5G 2/1-5/1) silty claystone, calcareous claystone, carbonate-cemented claystone breccia, and dark greenish gray (5GY 4/1) resedimented claystone. Lower part of unit composed of greenish black (5G 2/1-3/1) claystone and olive gray (5Y 4/1) silty claystone, with some light olive gray (5Y 5/1) silty tuff and dark olive gray (5Y 3/1) vitric silty claystone. Entire unit intensely fractured; dip to 45°.

[a] Includes adjacent wash cores drilled through an interval longer than a core barrel and archived with the prefix *H*.

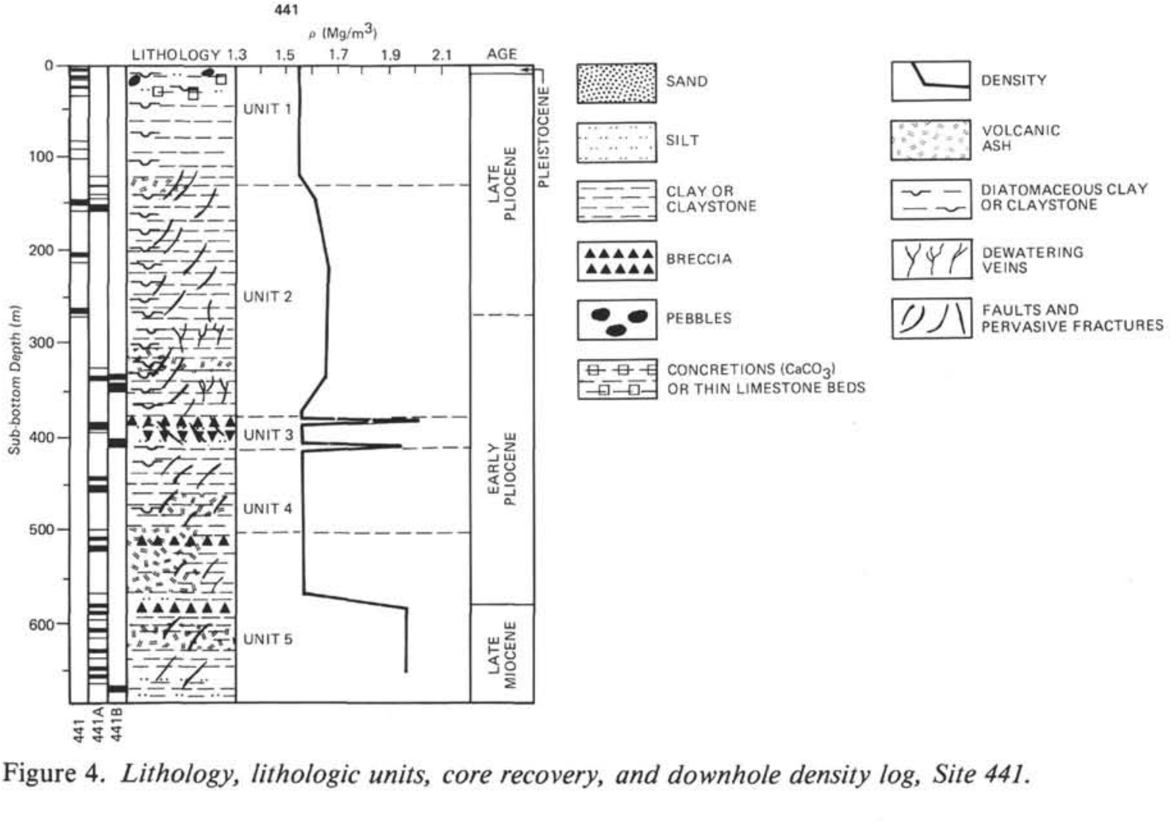

Figure 4. *Lithology, lithologic units, core recovery, and downhole density log, Site 441.*

The breccia is composed of angular to subrounded blocks of dark gray siltstone set in a matrix of softer and slightly lighter colored (N4) clayey silt. The top of the unit in Core 441A-5 shows thick dewatering conduits. The siltstone blocks consist mostly of quartz, feldspar, and heavy minerals, with more clay and no volcanic component. The recovered portion of the breccia unit is over 3 meters thick, and in its lowest part it is interbedded with disturbed siltstone and sandstone beds of from 3- to 20-cm thickness. A problem in interpretation involves whether this breccia originated as a sedimentary unit or as a result of tectonic faulting. The interbedded nondisturbed sandstone and siltstone layers seem to mitigate against the fault-zone–breccia hypothesis. The matrix of the breccia is similar in composition to the breccia blocks but finer grained. This relationship might be expected if the breccia originated as a mass-movement deposit.

Unit 4 (Cores 441A-6–441A-7 and 441A-H3, 410–504 m sub-bottom, lower Pliocene)

This unit is lithologically similar to Unit 2 and consists primarily of highly fractured olive gray (5Y 3/2) claystone and diatomaceous claystone. Recovery is limited to cuttings or chips of the rock which, because of its closely spaced fracture system, crumbles easily during drilling. Core 441A-H3 contains some interesting lithologic variations, including what might be a resedimented shale (fissile chips) in a grayish black (N2) soft siltstone. Whether this interval is due to compaction of cuttings during drilling or was an original sedimentary unit is difficult to determine. A 1.5-cm wood fragment and a 1-cm-diameter calcareous concretion also occur among the drill cuttings of claystone, as does a light olive gray (5Y 5/1) silt-sized tuff bed. Overall, the lithology of Unit 4 is poorly documented. However, the character on the gamma-gamma and gamma-ray logs is uniform in this interval and suggests a fairly homogeneous lithology.

Unit 5 (Cores 441A-8–441A-15, 441A-H4, 441B-2, and 441B-H2; 504–662 m sub-bottom; lower Pliocene to upper Miocene)

This lithologic unit seems rather heterogeneous partly because of spotty coring and poor recovery. The top of the unit is marked by olive gray (5Y 4/2) diatomaceous claystone and vitric claystone (441A-8 and 441A-H4, with persistent 32°-45° open fractures. Core 441A-H4, in which recovery was obtained from a 48.5-meter interval, contains a conglomerate breccia interval consisting of grayish black (N2) to greenish gray (5G 6/1) subangular pebbles suspended in a clay-sized matrix. The interval recovered amounts to only 14 cm. Breccia was also recovered in Cores 441A-10 and 441A-11 (Figure 5). These breccia units are clast-supported rocks consisting of angular 3- 15-mm fragments of greenish gray (5GY 5/1) and olive gray (5Y 4/2-5/2) claystone, with dark olive gray (5Y 4/1) claystone, yellow-gray (5Y 8/1) limestone, some dark greenish gray (5GY 2/1) glauconitic claystone, and white (N8) tuff fragments. Many but not all of the fragments seem to have at least partially lithified prior to resedimentation. Some more-rounded clasts are sutured together and have shapes conforming to the outlines of apparently more indurated adjacent clasts, suggesting an initially nonlithified state. A crude stratification indicates a 35°-45° dip for the breccia unit. Joints or partings with orientations of about 3°, 30°, 45°-60° and 85° are common. In Core 441A-10 the breccia unit at the base of the core is calcite-cemented,, whereas in 441A-11 it is not.

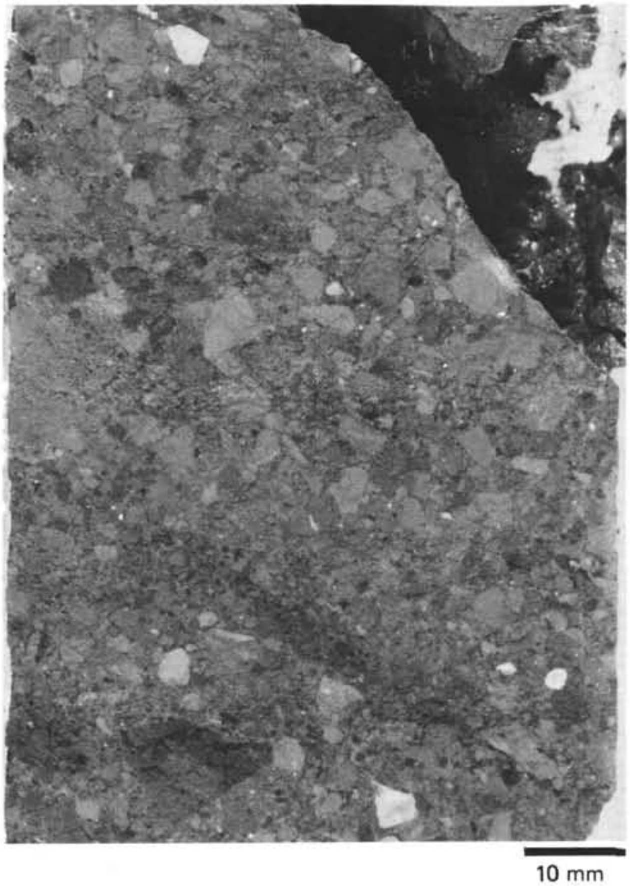

Figure 5. *Clast-supported breccia of late Miocene age, Site 441. Specimen 441A-11-1, 63–71 cm (sub-bottom depth 587 m).*

Cored intervals between the breccia units consist mainly of fissile olive gray (5Y 3/2) claystone and greenish black (5G 2/1) silty claystone. Limestone or calcareous claystone concretions or pebbles up to 5 cm in diameter are commonly recovered. Below the breccia intervals to the bottom of the hole (Cores 441A-12 through 441A-15), only greenish black (5G 2/1) to olive gray (5Y 4/1-3/1) claystone, silty claystone, and minor silty tuff (5Y 5/1) was encountered. This rock is highly fractured (open 65° fracture inclinations common), and black veins are present. Faint lamination in Core 441A-14 suggests a dip of 40°-42°. Unfortunately the bottom part of the section could not be logged because of a stuck pipe in Hole 441B.

Core 441B-2 from the bottom of the hole consists primarily of cuttings of dark olive gray to dark greenish gray (5Y 3/1-5GY 4/1) vitric silty claystone. Section 2 of this core contains larger pieces of the claystone, which are pervasively fractured; these open fractures dip 75°.

The wash core, 441B-H2, obtained from a large interval (402.0–668.01 m), although less stratigraphically useful, contributes good structural information on the dips of fractures and partings.

The sequence recovered at Site 441 is similar overall but differs in some aspects from that at Site 434, Leg 56. Because drilling at both sites was plagued by poor recovery, some of the apparent differences may be due to the lack of overlap of cored intervals. Though only 2 km apart, the two sites could conceivably have had a slightly different sedimentary history in this area of intense tectonism. The main differences are the following: Breccia units encountered at Site 441 (Units 3 and 5) are not noted at Site 434; Site 441 has a thicker upper Pliocene interval, thereby displacing biostratigraphic boundaries downward at Site 441 by 80 to 90 meters relative to Site 434; because of submarine sliding the 140-meter-thick silty and clayey tuff interval at Site 434 (Unit 4, 460–610 m sub-bottom) does not seem to be present.

Structural Geology

Despite the relatively homogeneous nature of the strata and the poor recovery caused by extensive fracturing, about a dozen bedding inclinations were recorded at Site 441 (Figure 6). These show a rather systematic increase in the dip with depth. Dips of 15° are recorded at about 300 meters in the middle of the Pliocene, 20° at 500 meters in the lower Pliocene, and as great as 45° at 600 meters in the upper Miocene.

The seismic reflection record across the drill sites, although partly obscured by diffractions, verifies the regional nature of the tilting seen in the cores. The seismic section shows a gradually increasing landward tilt of the reflections with depth. Below the gently dipping layers near the sea floor, rocks with disturbed bedding extend to a sub-bottom depth of about 5 km, where strong reflections indicate they are underlain by igneous crust (Figure 2). The generally continuous stratigraphic sequence down to the upper Miocene at Site 441 places a younger limit on the age of the more deformed rocks below and consequently indicates that the present cycle of subduction began during or before the Miocene.

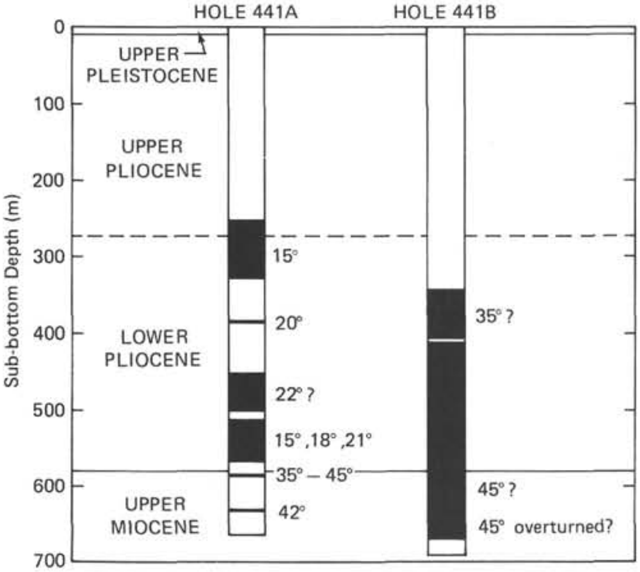

Figure 6. *Bedding inclination measurements at Site 441. The longer depth intervals indicate depth ranges of wash cores (H).*

Site 441 revealed no section of overturned strata in the upper levels such as was found during Leg 31 at the toe of the trench slope of the Shikoku subduction zone off southern Japan (Ingle, Karig, et al., 1975; Moore and Karig, 1976). A minor overturned fold does occur in Miocene rocks near the base of Hole 441B in Core 441B-H2. We are not certain whether this fold is syndepositional; or developed shortly after deposition, when the rock was nearer to the zone of maximum shear; or whether it is a drag fold associated with faulting that has affected the hemipelagic cover during more recent tectonism of the underlying prism of disturbed rocks.

In previous holes drilled on Leg 57, even the most structurally deformed sections yielded generally good recovery consisting of material that was well consolidated, though often coursed through by veins and rehealed fractures. Deformation resulting from drilling was limited to widely spaced fractures with various dips and to the typical drilling biscuits or "challengerites" found in somewhat less well consolidated sediment. Site 441 cores, on the contrary, do not hold together during drilling. This results in a low recovery of a drilling wash consisting of chips of indurated claystone less than 1 cm in diameter (Figure 7). Few larger pieces were obtained, and these are almost always cut by a series of closely spaced fractures which are open, not rehealed. Parallel fractures are common in individual core pieces, and several conjugate sets usually occur (Figure 8). Therefore we believe that much of the fracturing is part of the initial rock fabric that broke up during drilling. A full range of fracture inclinations was measured at the site as a whole (Figure 9).

Some fracture surfaces below about 175 meters commonly are marked by small grooves and steps. The steps on a given surface have a consistent sense of offset, and this fact, combined with the fact that fractures of several orientations in individual cores each show different sets of grooves, suggests that this type of fracture is not a cleavage. The displacement on the fractures probably is not large, but most of the edges of the steps are smoothed by slip, suggesting that the bulk of them are not simply joints. Indistinct slickensides suggest reverse, normal, and horizontal displacement (Moore, this volume).

Fracturing may originate from tectonic consolidation of the trench lower slope caused by horizontal compression, from faulting associated with uplift and deformation of the lower trench inner slope in response to plate convergence, or from downslope sliding of the larger slope sediment mass during a period of uplift and steepening of the slope. There is evidence of slumping or sliding in the missing Pleistocene section at Sites 441 and

Figure 7. *Drill cuttings typical of material most often recovered at Site 441. Sediment is fragmented into <1-cm chips. Specimen 441-8-1, 31–43 cm (sub-bottom depth 206 m).*

434, in older reflectors cropping out on the slope, and in apparent slump masses at the base of the trench inner slope seen on JNOC-1 (see back pocket).

There is a possibility that the missing Pleistocene section is due to erosion in a canyon. Inspection of JNOC Crossline C (see Geophysics) indicates that Sites 434 and 441 were drilled in a topographic depression which may be an incised canyon. Some reflectors in the seismic record appear to crop out on the slope. As much as 0.6 s two-way time (ca. 450 m) of Pleistocene section may exist under the hill to the southeast of Site 441 at a level above that at which we spudded in at the site.

At any rate the deformation is less one of thrusting or folding at the leading edge of the upper plate of the convergent margin than one of pervasive brecciation of a volume of material deposited atop older material that may be accreted from the oceanic plate. The stress apparently caused abnormal dewatering of the hemipelagic section and has resulted in development of the intense closely spaced fracturing of the claystone that is so characteristic of this site.

Figure 8. *Typical fractures at Site 441. A tuff bed dipping 15° occurs near the top. Specimen 441A-H1-3, 100 -111 cm (sub-bottom depth between 256 and 328 m).*

BIOSTRATIGRAPHY

Introduction

The water depth of Site 441 is below the carbonate compensation depth (CCD) (about 3500 m), therefore foraminifers and nannofossils are extremely rare. Biostratigraphically useful nannofossils were restricted to Cores 441-7, 441A-6, 441A-13, and 441A-14. The lack of foraminifera throughout the section suggests that the site has remained below the CCD since at least the late Miocene.

Upper Miocene through Pleistocene sediments are present in Holes 441, 441A, and 441B. Diatoms are the most abundant microfossil, followed by radiolarians. Both, however, become rare below 500 meters, where poor preservation begins.

Figure 10 shows the stratigraphic occurrence of microfossil zones in Holes 441, 441A, and 441B. The Pliocene/Pleistocene boundary is placed within Core 441-2 based on radiolarian and diatom evidence. In

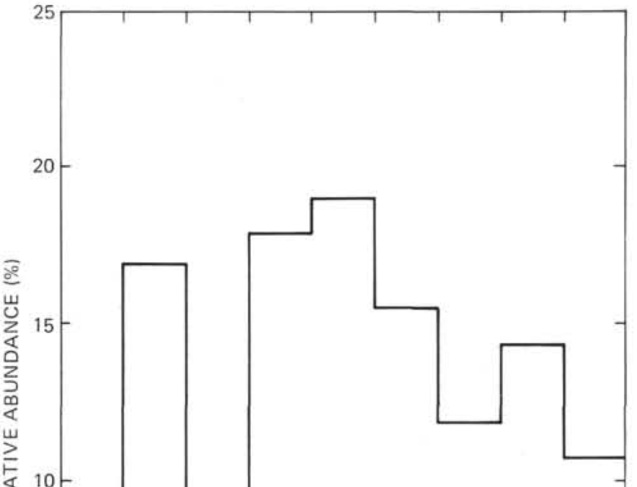

Figure 9. *Fracture inclinations at Site 441, based on 119 measurements.*

Figure 11 microfossil data are used to construct a sediment accumulation rate curve. The Miocene/Pliocene boundary (5.2 Ma) is estimated at about 600 meters. A sediment accumulation rate of 175 m/m.y. is implied from this curve for Holes 441, 441A, and 441B.

Diatoms

At Site 441, a thin cover (3–7 m) of uppermost Pleistocene to Recent sediment uncomformably overlies a thick sequence (660 m) of uppermost Pliocene to upper Miocene sediments. Although recovery in the composite section cored in Holes 441, 441A, and 441B is spotty, the Miocene–Pliocene diatom assemblages occur in the same sequence encountered at Sites 438 and 440; no evidence for repetition of diatom zones was found.

The *Denticula seminae* var. *fossilis* Zone (~1.7 to 2.43 m.y.B.P.) is present from Sample 441-2-1, 30–32 cm (7.3 m), to Sample 441A-2,CC (130.5 m). *D. seminae* var. *fossilis* is common to abundant throughout this interval, and *D. kamtschatica* is present as reworked speciments as in Hole 440B.

The *D. seminae* var. *fossilis*–*D. kamtschatica* Zone is recognized from Sample 441-7-1, 65–67 cm (150.1 m), to approximately Sample 441-9,CC (26.7 m). Here, the top of this zone is approximated by the last common *D. kamtschatica* and the last *Nitzschia jouseae* and the base by the first *Actinocyclus oculatus* (Barron, this volume). The first common *Denticula seminae* var. *fossilis* lies near the top of this zone at 441A-2,CC (130.5 m) just above the last *Nitzschia jouseae*. Occurrences of *Denticula seminae* var. *fossilis* below that level are rare and spotty, as they were in Holes 438A and 440B.

The interval from Sample 441A-9,CC (568 m) to the lowest sample cored, 441B-2,CC (670.5 m), is assigned to the *D. kamtschatica* Zone. The last occurrence of *Rouxia californica* in Sample 441-11-1, 50–52 cm (586.5 m), approximates the Miocene/Pliocene boundary (5.1–5.2 m.y.B.P.).

Reworking of middle Miocene diatoms such as *Coscinodiscus endoi, C. lewisianus, Denticula lauta,* and *Mediaria splendida* is especially prevalent in Cores 10 and 11 of Hole 441A (577–587 m). In fact, *Denticula kamtschatica* is missing from this interval. Preservation, however, is very poor, and the straightforward sequence of lower Pliocene and upper Miocene diatom assemblages above and below this interval argues against repetition. These middle Miocene diatoms occur in extremely well brecciated sediment that may have been slumped into place.

Sediments in the lowest part of the section cored contain fragments of *D. kamtschatica, Nitzschia reinholdii,* and *Rouxia californica* and are correlated with Subzone *b* of the *Denticula kamtschatica* Zone (uppermost Miocene). Wash core Sample 441B-H2-4, 130–150 cm, contains *Nitzschia miocenica* and *Thalassiosira miocenica* along with *Denticula kamtschatica* and is very similar to the uppermost Miocene recovered from Hole 438A.

Preservation is good to moderate down to Sample 441-4,CC (26.0 m); generally moderate through Sample 441-9,CC (267.2 m); moderate to poor from 441B-1-2, 62–64 cm (337.6 m), through 441A-8,CC (511.6 m); and poor below that level. Diatoms are common to abundant down to Core 9 of Hole 441 (264 m); few in the interval from Sample 441B-1-2, 62–64 cm (337.6 m), to Sample 441A-8,CC (511.6 m); and rare below that level.

Radiolaria

Radiolarian abundance at Site 441 ranges from common to rare with poor to good preservation. Radiolarians are common in Sections 441-1-2 to 441-8-1, few in 441-8,CC to 441A-8,CC, and rare in 441-9,CC to 441B-2,CC. Section 441A-5-1 is barren of radiolarians. Radiolarian preservation is good from Section 441-1-2 to 441-6,CC, moderate from 441A-8-1 to 441B-2-1, and poor in 441B-2,CC.

Pleistocene to Recent radiolarian assemblages may be found in the following intervals: Sections 441-1-2 to 441-1,CC (*Botryostrobus aquilonaris* Zone), 441-2-1 (*Axoprunum angelinum* Zone), and 441-2-3 to 441-2,CC (*Eucyrtidium matuyamai* Zone). Pliocene radiolarians are observed in Sections 441-3,CC to 441-7,CC (*Lamprocyrtis heteroporos* Zone) and 441-7,CC to 441A-8-1 (*Sphaeropyle langii* Zone). Sections 441A-8,CC to 441B-2,CC (*Stichocorys peregrina* Zone) represent an interval of upper Miocene strata.

Reworking of Miocene radiolarians such as *Cyrtocapsella tetrapera, C. cornuta,* and *C. japonica* into Pliocene sediments of Site 441 was found at depths between 300 and 450 meters. These forms were also found

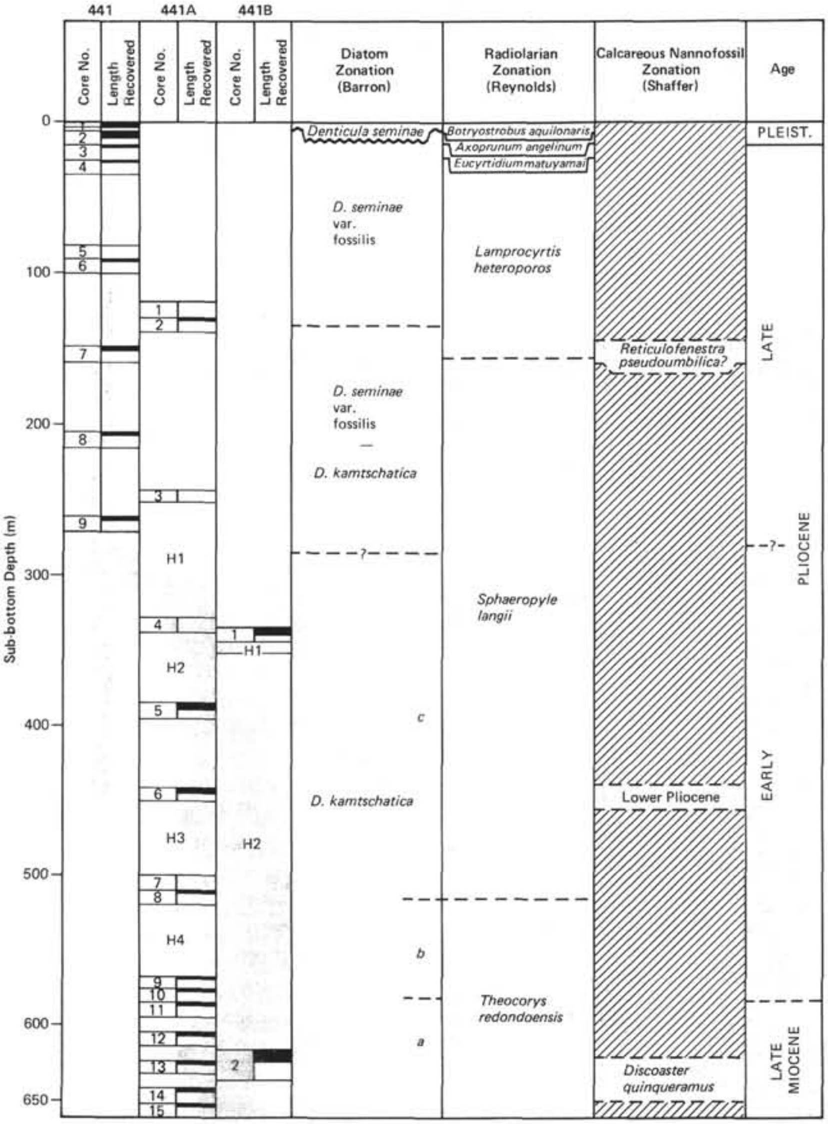

Figure 10. *Planktic biostratigraphy at Site 441.*

at depths of about 600 meters in the *Stichocorys peregrina* Zone and are considered to be reworked.

Nannofossils

Of the 61 samples studied from Site 441, only three intervals, Section 7-2 of Hole 441, and Cores 6, 13, and 14 of Hole 441A, contained age-diagnostic nannofossils. Most other samples were barren; a few yielded very rare, diminutive, nondiagnostic coccoliths. This site is presently below the calcite compensation depth and apparently has been throughout the depositional history of the cored interval, with the possible exception of brief episodes in the upper Miocene and middle portion of the Pliocene.

A calcareous mottle within Section 7-2 of Hole 441 contained a common but poorly preserved, almost monospecific, nannoflora. Because of dissolution around shield peripheries and overgrowth in central areas, precise identification of the coccoliths was difficult. The dominant forms are probably referrable to *Coccolithus doronicoides*. They may also be small to intermediate forms of *Reticulofenestra pseudoumbilica* and may represent populations occurring near the extinction level of that species. Larger forms more typical of *R. pseudoumbilica* were extremely rare. Equally rare components included *Discoaster* cf. *brouweri* and *Coccolithus pelagicus*. This sample is tentatively placed within the upper part of the *Reticulofenestra pseudoumbilica* Zone (Pliocene).

Rare and poorly preserved nannofossils in Sample 6,CC of Hole 441A include *Reticulofenestra pseudoumbilica*. A lower Pliocene age for this sample agrees with age determinations based on diatoms and radiolarians. Rare and moderate to poorly preserved nannofloras in Sections 13-1 and 14-1 are assigned to the upper Miocene *Discoaster quinqueramus* Zone, based on the presence of the nominate species.

Sections 1,CC, 2-2, and 2,CC of Hole 441B contain rare, poorly preserved occurrences of small coccoliths (*Coccolithus doronicoides* and/or small *Reticulofen-*

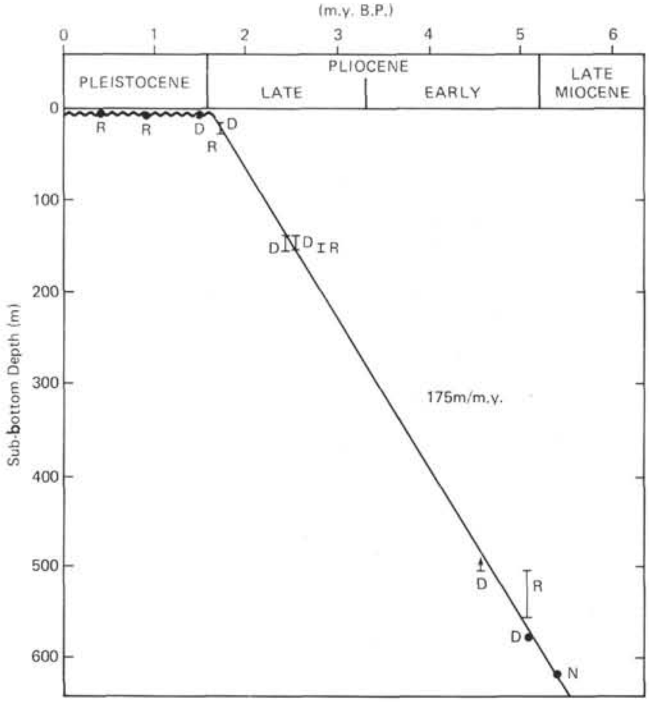

Figure 11. *Sedimentation rate curve for Site 441, uncorrected for compaction. Based on diatom* (D), *nannofossil* (N), *and radiolarian* (R) *datum levels.*

estra pseudoumbilica) and Discoaster fragments. No definite ages can be determined for Hole 441B on the basis of nannofossils.

In general, nannofossil evidence for Site 441 was insufficient to determine repeated zones or other indications of imbrication.

GEOCHEMISTRY

Shipboard geochemical studies at Site 441 consisted of analysis of interstitial water and characterization of hydrocarbon gases in the cores. The holes were drilled to a total depth of 687 meters on the lower part of the inner trench slope of the Japan Trench. The sea floor is rough in this area, and seismic reflection profiles indicate that deformed strata underlie the drilled section down to the igneous oceanic crust at a sub-bottom depth of about 5 km. The cores were highly fractured, and core recovery was very poor.

The strata consist of diatomaceous clay and claystone in the upper half of the drilled section and claystone in the lower half. The geologic age ranges from late Miocene to Holocene.

Cores 441-1 through 441-4 (0–26 m) had a strong hydrogen sulfide odor. The lower extent of the H_2S zone is not certain, however, because the next few cores had little recovery. Core 441-7 at 150 meters did not contain noticeable H_2S.

Interstitial Water Analysis

Because of the short length of most regular cores at this site, only three samples from them could be spared for inerstitial water study. These samples were supplemented by two from wash cores, which have a large depth uncertainty and which had been in contact with the sea water drilling fluid for some hours before recovery. For each sample, core fragments were scraped free of drilling mud, packed in a stainless steel press, and the water was squeezed out through filters into a sealed syringe.

The available analyses characterize the interstitial water chemistry only discontinuously (Table 2). As far as they go, the analyses are similar to the much more complete column analyzed at Site 440 but lack the extremely high alkalinity values that were found there. Analyses from Site 434, which is 3 km to the east, provide additional detail in the depth range from 0 to 300 meters.

Gas Analysis

Only a few regular cores longer than 2 meters were available for reporting core gas analyses, but by supplementing them with wash cores a reasonably systematic spacing was acheived, and we believe that a fair representation of the gas content was obtained (Table 2).

The methane content varies considerably throughout the holes, as it does at Site 434, probably because both sites contain highly fractured cores.

The ethane content at Site 441, as inversely marked by the methane/ethane ratio (Table 2), increases normally with depth. Anomlously high values of ethane (and low values of the ratio) were measured in two samples between 337 and 385 meters. On the basis of the methane/ethane curve established by the remaining samples, these gases could have migrated upward from a depth of about 800 meters, where such ethane values might be expected.

All the gas at this site is believed to be diagenetically generated for the following reasons: (1) the methane/ethane ratio, despite some fluctuations between individual samples, changes with depth in a normal log-linear fashion; (2) the two methane/ethane ratios less than 1000 are compatible with depths only a little below the drilled depths; (3) the general behavior of the propane through pentane curves (Sato and Whelan, this volume) is similar to that at other Deep Sea Drilling Project sites where the gas was demonstrated to be generated diagenetically; (4) spot analyses suggest that the organic carbon content of the rock is too low both in quantity and in hydrocarbon richness to consider it as a potential source for petroleum.

The ethane analyses at Site 441 are generally higher than at Site 438, which is less tectonically stressed despite its much higher geothermal gradient. This suggests that most of the samples at Site 441 have been enriched with diagenetic ethane that has migrated upward through fractures from deeper levels.

Extrapolating from the measured geothermal gradients at Sites 438 and 440, respectively, of 3.6°C and 1.6°C per 100 meters suggests that the gradient in the drill holes at Site 441 is about 1.1°C/100 m. Ignoring the probability that the gradient becomes less as the under-

TABLE 2
Shipboard Geochemical Analyses at Site 441

Core Section	Depth (m)	Salinity (‰)	Cl^- (mM/l)	Ca^{2+} (mM/l)	Mg^{2+} (mM/l)	*p*H	Alkalinity (meq/l)	Methane (%)	Methane/Ethane Ratio
1-1	1	35.8	542	10.6	52.7	7.49	2.85	–	–
Wash core	102–149	–	–	–	–	–	–	91.1	10,200
7-1	150	–	–	–	–	–	–	55.5	21,900
Wash core	159–206	–	–	–	–	–	–	68.4	12,300
8-1	207	–	–	–	–	–	–	26.2	15,400
9-3	267	–	–	–	–	–	–	79.9	14,700
H1A-2	255–326	–	–	–	–	–	–	97.0	3,810
1B-2	337	–	–	–	–	–	–	90.9	639
H2A-1	339–385	–	–	–	–	–	–	64.6	938
H1B-3, 4	348–401	32.0	530	12.5	12.0	7.89.	8.74	74.2	3,480
5A-3	390	33.3	556	14.4	13.3	–	–	93.0	2,860
H3A-2	454–498	–	–	–	–	–	–	85.1	2,800
H2B-3, 4	406–666	31.9	525	11.5	12.5	8.25	7.30	98.2	2,250
Wash core	520–567	–	–	–	–	–	–	84.9	3,660
10A-1	577	–	–	–	–	–	–	27.1	3,140
14A-2	645	32.9	547	13.9	20.4	–	–	–	–
2B-2	670	–	–	–	–	–	–	73.4	3,750

thrusting plate is approached below, the temperature at the level of the igneous oceanic crust is calculated to be only about 50°C.

PHYSICAL PROPERTIES

Recovery at Site 441 was sparse, owing both to the highly fractured nature of the sediments over most of the column and the preponderance of drilled section over cored interval. As a result, the physical properties determined by shipboard analyses (water content, porosity, bulk density, thermal conductivity, and sonic velocity; see Site Summary Chart, back pocket) do not define vertical distributions nearly as completely as they did at other sites. The data serve, rather, as points of comparison with the previous holes and with the density log run in this hole (105–555 m). The log is the only complete vertical section available at this site.

Bulk Density, Water Content, and Porosity

The density in the upper 120 meters of the hole (Lithologic Unit 1) is apparently uniform at about 1.55 Mg/m^3, although control is very poor.

Below 120 meters, the density increases rapidly to 1.65 Mg/m^3 at 135 meters and then fluctuates between 1.52 Mg/m^3 (276 m) and 1.80 Mg/m^3 (220 m), to a depth of 340 meters. This section represents the major portion of Lithologic Unit 2. The well-defined density deviations (from a mean value of ~1.65 Mg/m^3) in this interval probably reflect variations in texture, composition, or degree of fracturing.

The lowermost part of Unit 2 (34]–380 m) is a transition zone (characterized by rapid variations from 1.51–1.67 Mg/m^3) to the lower densities (~1.54 Mg/m^3), which persist to about 560.

Densities below Unit 2 (380–560 m, Lithologic Units 3, 4, and upper Unit 5) are both low (1.54 Mg/m^3) and uniform. Two major density excursions occur in Unit 3 (381, >2.0 Mg/m^3; 405 m, 1.93 Mg/m^3), and smaller deviations are common below 455 meters (lower Unit 4–upper Unit 5).

At some point between 560 meters (bottom of density log) and 575 meters, the density increases rapidly to 1.83–2.10 Mg/m^3. These higher values apparently continue to the base of the hole and may reflect fracture closure or lithologic control (e.g., conglomerates, breccias, Unit 5) or both. It was suggested in the 440 site chapter that the increased densities near the base of the hole might be the result of annealing of fractures under lithostatic pressure. Observation of a similar depth–density pattern at Site 441 also suggests lithostatically induced closure of the fractures, although the fissile nature of the recovered sediment (and the poor rate of recovery) indicates that annealing may not be occurring.

The distribution of porosity is analogous to the density distribution, from which it is derived (Boyce, 1976) in large part. The low-density zone (380–560 m) defined previously is apparent as a zone of high (69 per cent) porosity. Conversely, the high-density sediment below 570 meters constitutes a low-porosity (20–43 per cent) section.

Water contents range from about 45 per cent (wet weight) at the surface to 20 per cent at the base of the hole. Control is very poor.

Sonic Velocity

Sonic velocity increases from ~1.5 km/s at the surface to ~2.7 km/s at depths greater than 570 meters.

The values are similar to velocities obtained at Site 440, with the exception of anomalously high values at 380–390 meters (brecciated siltstone) and below 560 meters (calcareous claystone–claystone–tuffite). The latter velocities are higher (>2.38 km/s) than any recorded at Site 440 and are encountered only at depths greater than 910 meters at Site 441. The elevated velocities presumably reflect the overconsolidated nature of these (lower Unit 5) deposits.

GEOPHYSICS

Seismic Reflection

The Japan National Oil Corporation multichannel seismic reflection JNOC-2 (Figure 1), which was used to locate Site 440, was also used to locate Site 441, which is located about 13 km farther east. Another record, Line C, was made across the site but normal to Line 2 (Figure 12).

Reflections in the disturbed sediment prism are characteristically of moderate to low amplitude, discontinuous, and obscured by diffractions (Figure 2), and therefore reflections cannot be traced from one site to the other. Only the acoustic basement reflection has high amplitude and is continuous enough to be traced across the margin. The basement reflection extends from the deep ocean basin and is interpreted to be igneous oceanic crust. This reflector contains side reflections as well as diffractions indicating a rough surface; under Site 441, the reflection breaks into vertically offset segments. The basement surface is also seen in Line C, the short reflection record crossing the site and parallel to the strike of the slope (Figure 12). Here ocean crust is also broken into segments under Site 441 with about the same amount of vertical displacement. Therefore whatever is causing the vertical offset of segments of the ocean crust reflection may strike transverse to the trend of the trench. However, whether segmentation of the oceanic crust reflection is caused by faulting, by sea floor irregularity developed prior to subduction, or by effects not removed from the reflection record (migration, depth) is indeterminate without much more study. The correspondence between the sea floor and the breaks in the oceanic crust suggests a velocity or wavefront effect, but on the other hand, the same configuration would result from near vertical faulting with sea floor expression.

A small canyon that could mark a transverse fault near the site is observed in Line C. Thus the fracturing at Sites 441 and 434 (Leg 56) could be influenced by transverse faulting. In addition, much of the missing Pleistocene section may have been removed by canyon erosion.

Above the basement, short reflections can be seen among the diffractions that suggest a sequence of landward-dipping beds or possibly low-angle faults. However, faults are not expressed by scarps on the sea floor, although it is rough. Instead the uppermost part

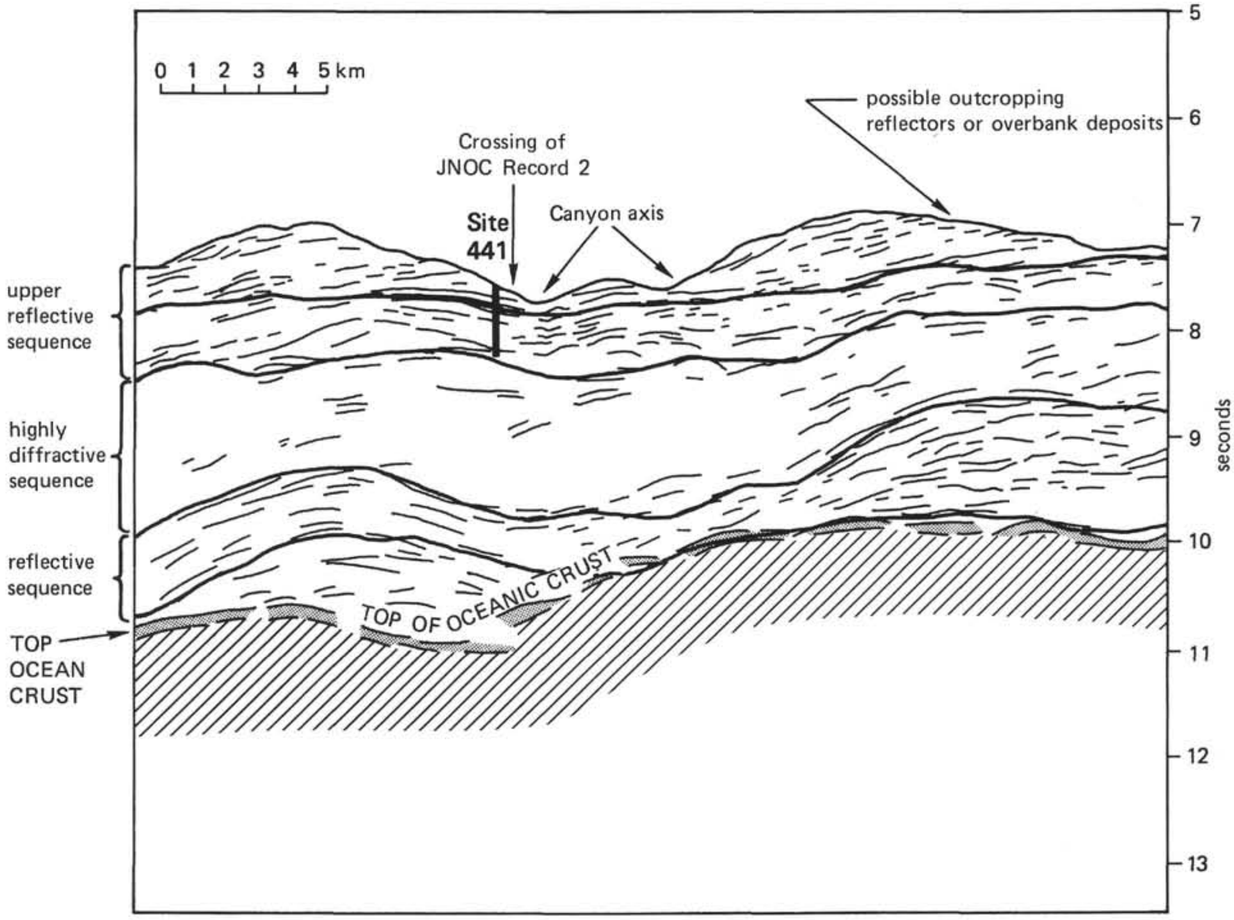

Figure 12. *JNOC multichannel seismic record, Crossline C (after Matsuzawa et al., 1980). Line crosses just south of Site 441 (see Figure 3). Note reflections from oceanic basement with large fault offset near center and coherent reflections from sediment above.*

of the record has rare reflections subparallel to the slope that can be traced through an almost continuous sequence of diffractions from the sea floor. The uppermost reflections are interpreted to be beds in the downslope apron of terrigenous debris, and some of the roughness of the sea floor may be caused by slumping.

Beneath Site 441 a reflector can be correlated with the lithologic boundary between Units 2 and 3, and also corresponds with a sharply bounded high-density layer on the downhole log. Another reflector is correlated with the lithologic boundary between Units 4 and 5. These reflections are traceable for 1 or 2 km; they appear near horizontal in seismic record JNOC-2 down the slope and dip gently south in seismic record JNOC-C parallel to the slope.

The upper reflections suggest deposition on the present slope near the site. They contrast in attitude with beds that dip steeply landward below 800 meters. The latter are considered part of the uptilted subduction-deformed sediment prism, based on their structure in relation to the trench and the oceanic crust. The former are structurally in the position of the downslope apron of terrigenous material. The drilling in Holes 441 and 441A did not penetrate into the reflective sequence presumed to be partly accretionary (see interpretive sketch, Figure 13).

Logging

Rapidly deteriorating weather allowed only one log to be run before the hole was abandoned. A formation density log and a natural gamma-ray log were made, despite very poor sea conditions during which the vessel heave was about 2 meters.

The gamma-ray trace is periodically variable, particularly below 300 meters, and it shows breaks in the lithology that were used to define the lithologic boundaries. Generally, its small range in value reflects the monolithologic character of the section, with sharp spikes that usually but not always correspond to similar spikes in the density log.

The formation density log is unusual in showing low density between 380 and 560 meters, below a higher density sequence. This log is discussed more fully in the Physical Properties section.

SUMMARY AND CONCLUSIONS

Summary

A main objective in sampling on the Japan Trench transect at the leading edge of the upper plate in a convergent margin was to study products of tectonic accretion. The products of accretion unique to convergent margins are difficult to study with sea surface geophysical techniques because of their resolution in relation to the scale of the accretionary structure. Thus the study of samples from well below the sea floor can contribute significantly to understanding the processes involved.

The term "tectonic accretion" is sometimes used in a restricted sense to refer to oceanic material that has been plastered against the continent during subduction. Broader usage defines it as ancient deformed sediment in land outcrops, where much of the material is trench inner slope deposits. In the latter sense the term includes slope sediment involved in the tectonism at the leading edge of the continental plate.

At Site 440, it was expected that penetration would reach at least the peripheral part of the accretionary zone, but the samples indicate that the nonfolded section equivalent to that of the deep sea terrace extends to the middle of the trench inner slope. However, the presence of a pervasive fracturing and microbrecciation suggests a strongly stressed environment. Similar conditions might explain the poor drilling conditions and low core recovery at Site 434, drilled on Leg 56.

Site 441 was where the seismic reflection record indicates the shallowest downslope apron of terrigenous cover over steeply tilted reflections — presumed to be from subduction-deformed sediment — within reach of the drill string. The site is within 0.5 km of proposed Site J-1a, approximately 3 km upslope from Site 434 and 15 km from the Japan Trench axis. In order to avoid penetration of a thick slope sequence, a site was selected on the wall of a canyon (see Figure 12) where up to 450 meters of the upper part of the slope sequence is missing.

Drilling was greatly hampered by stormy weather, which is usual off northern Japan in late November and early December. Storms caused all the holes at Site 441 to be abandoned; once the ship was driven completely off site, and part of the drilling was done in gale-force winds. Because of the proximity of Site 441 to 434 and the availability of downhole logs, interval coring was permitted in the upper 600 meters of the section. Core recovery problems at this site were experienced during both Leg 56 and 57.

Seismic records at the site include a short north-trending reflection record (Figure 12) crossing the main east-trending multichannel reflection record 0.5 km from the site (Figure 3). The records show reflections from igneous oceanic crust as acoustic basement. These are overlain by a series of reflections dipping steeply landward, which possibly include deep ocean basin deposits accreted from the downgoing slab. These strata are covered in turn by reflections subparallel to the slope which are inferred to represent terrigenous material deposited on the trench slope. The target reflection at this site was at about 800 meters in the landward-dipping zone of reflections.

Late Miocene through Pleistocene sediment was sampled at Site 441. The time span is determined by 10 microfossils, of which diatoms and then radiolarians are the most abundant. The site is presently below the calcite compensation depth, and the lack of benthic foraminifers throughout the section suggests that it has been below the CCD since at least the late Miocene. However, two stratigraphically useful calcareous nannofossil assemblages were recovered.

A rather uniform sediment accumulation rate of 175 m/m.y. is defined by the datum levels. In five cores reworked upper lower and lower middle Miocene diatoms are present in clasts from lower Pliocene and

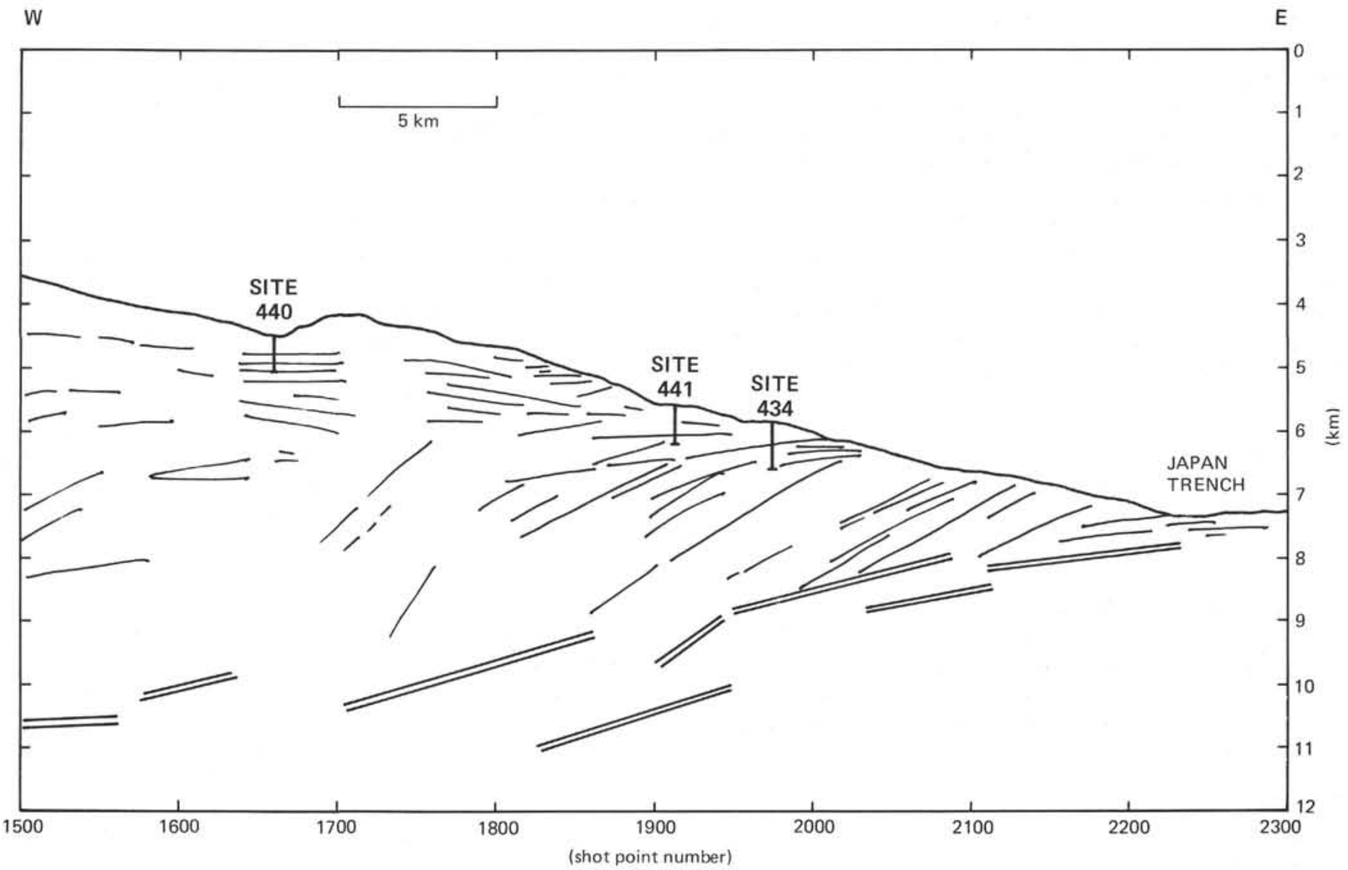

Figure 13. *Interpretive sketch of JNOC Line 2 across Sites 440, 441, and 434, computed as depth section at 2:1 vertical exaggeration. Velocities from well logs and unpublished refraction data (Murauchi, personal communication). Reflections from oceanic basement indicated by double line; Miocene/Pliocene boundaries in drill core indicated by short crosslines on drill holes.*

upper Miocene claystone breccias. Reworked radiolarians of that age are also common.

The thickness of lithologic intervals of Miocene age at Site 441 are about equivalent to coeval intervals at Site 434, a short distance downslope, and they are thicker than those at Site 440, a short distance upslope. No paleontologic evidence exists for repeated sections or for major hiatuses below a late Pliocene through Pleistocene hiatus. Only 7 meters of Pleistocene was recovered. This may be due to the location of the site in a canyon as previously mentioned. The Pleistocene sequence at Site 434, drilled in the same canyon, is also largely missing.

The lithology of cores from Site 441 is similar to that at Sites 434 and 440. The composition of sediment at all these sites is hemipleagic clay and some silt with variable siliceous-biogenic and volcanic ash components. Most apparent are differences in the degree of consolidation and fracturing. It is the physical character of the rock and the ease with which the section at Sites 434 and 441 fragmented during drilling that prevented penetration and logging beyond the depths achieved during the brief periods of operable weather.

The upper lithologic unit in Site 441 is a 132-meter-thick silty diatomaceous clay with minor clayey silt and sand layers and pebbles of presumed ice-rafted origin. The underlying unit, 248 meters thick, is defined principally by its increased lithification and the first appearance of partings, fractures, and black veins. The third unit, only 30 meters thick, contains a dense brecciated siltstone. Angular to subrounded siltstone blocks are set in a matrix of softer material. This unit gives a distinctive spike on the density log trace, and it could correspond to a strong horizontal reflection in the seismic record. But it was only encountered in Hole 441A, despite an attempt to recover it in Hole 441B, so it may be of local extent. It is interbedded with thin undisturbed claystone, siltstone, and sandstone layers.

The two lower units, from 410 to 687 meters, are similar in composition to the clay in the top of the hole, with the addition of minor siltstone and several redeposited claystone-breccia intervals. The transported lithic claystone clasts are middle Miocene and occur in an early Pliocene and late Miocene matrix. The lowest unit is more ash-rich, although the material is not as vitric as the equivalent interval at Site 434.

A most distinctive feature of the section is its highly fractured nature. At 130 meters, black anastomosing veins presumed to be associated with dewatering and fracturing begin to appear, and the section is highly fractured on a micro-to-macro scale throughout the rest of the interval drilled. The high degree of fracturing produces brecciation. There are similar conditions at sites farther from the trench, but they are less intensely developed, not as shallow, and show some rehealing. Persistent drill cuttings of less than 1-cm-sized lithic chips that readily break down further characterize cores from Sites 441 and 434. On a larger scale, fractures cut across all cores in a variety of orientations and divide the coherent material into blocks. Some fractures are healed and show small offset, but other, open fractures seem to be partings or joints. From the study of weakly developed slickensides we conclude that movement has occurred along some fractures. The effects of pervasive brittle fracturing, brecciation, and redeposition of breccia clasts are clearly seen in the physical character of this section.

Physical properties measurements are relatively sparse as a result of the core condition and recovery; the downhole formation density log provides the only continuous record of any kind at this site. Bulk density is generally uniform in the upper 120-meter zone of relatively unlithified sediment; it increases in value and fluctuates as brittle fracture becomes more prevalent. Below about 400 meters a curious zone of uniform lower density occurs, much as at Site 440 but more pronounced, followed at 570 meters by a very rapid jump to high density values equivalent to those from below 900 meters in Hole 439. This suggests the beginning of closure and possible healing of fractures. The porosity values are inverse to density as is water content; sparse laboratory sonic velocity measurements follow a pattern similar to those at Site 440.

Hydrocarbon gas analyses give a scattered distribution of values, much as at Site 434. The genetic significance of this scatter may be lost in the effects of sparse sampling; only biogenic gas was detected. If any migration has occurred, it is minor and its effect is hidden in the scatter.

Conclusions

The general structure indicated by the seismic reflection records consists of a lower sequence of beds tilted from a near-horizontal attitude at the trench to dips of greater than 45°, 15 km landward, as noted on many other trench slopes (Seely, Vail, and Walton, 1974) and an upper sequence of discontinuous subhorizontal beds in an apron of terrigenous material, some of which may have been displaced downslope by mass movement. Sampling at Site 441 was probably limited to the trench slope apron; the 800-meter-deep target reflection, not reached here, appears to be near the top of the tilted sequence.

The paleontologic evidence for displaced and reworked material is consistent with this interpretation, although this evidence derives from a limited section of the hole. The uniform rate of sedimentation and lack of repeated paleontologic zones argue against thick repeated imbricated sections. Small periodic slumps are one likely explanation for at least the interval with known reworked and transported clasts containing microfossil assemblages older than the matrix. According to seismic records, Site 434, which is 3 km downslope from Site 441, may have penetrated the landward-tilted sequence. Since Site 434 is lower on the slope and since seismic records indicate erosion or slumping has cut out the upper part of the sequence drilled at Site 441, much of the Pleistocene and upper Pliocene should be missing. This appears to be borne out by the drilling. Thus the biostratigraphy and other evidence at Site 434 that suggest series of repeated sections, possibly due to tectonic "imbrication" (see chapter on Site 434), may occur in a section below that encountered at 441.

The section penetrated at Site 441 has the same hemipelagic character as sections sampled farther upslope. There is no evidence of an older section from the oceanic plate, although the upper Neogene section at Site 436 on the oceanic plate is lithologically similar to the Neogene trench slope section, so distinction would be difficult. Despite its presumed origin from hemipelagic sedimentation and downslope movement, the section below 130 meters is far more intensely fractured than any equivalent section upslope. Therefore it is thought to be overstressed by tectonism associated with convergence near the trench and to be part of the accretionary zone in a dynamic sense. Despite being deposited on top of the tilted accretionary zone this body of sediment does show a pervasive parting along closely spaced fractures. But the evidence does not exclude the possibility that fracturing is due to more local causes such as proximity to a fault or break up because of downslope movement. Although the drilling at Sites 434 and 441 gives nearly the same results the evidence is not definitive, because these sites occupy similar positions relative to the axis of the canyon on JNOC Line C (Figure 12) and could be located along the same (hypothetical) fault which caused fracturing.

The sequence of fracture development is best indicated by the change in bulk density. It would be unusual in normally compacted sequences for a near-bottom high bulk density layer to be underlain by a consistent low density interval nearly 300 meters thick which in turn rests on a higher than normal density interval. This unusual consolidation pattern is most easily explained as a sequential reaction to combined lithostatic and tectonic stress. Near the sea floor, the sediment deforms plastically, consolidates, and dewaters. At greater depth, the now lithified sediment responds to stress by pervasive brittle fracture which imparts a secondary fracture porosity. If the fractures are open and filled with fluid from even higher stressed levels below, a low density zone could result. The underlying high density cores may indicate fracture closure as loading exceeds the pressure limit of the structural seal.

This type of response to overstress is a form of tectonic consolidation. One might speculate that the process at Site 441 begins with anastomosing dewatering veins that develop into an oriented fracture system. The claystone lacks sufficient biogenic silica and calcareous material to promote healing of fractures. Dewatering, fracturing, and microfaulting might be the principal mechanisms that accommodate volume reduction of a deformed sediment prism near the trench and aid in sediment diagenesis.

There is one implication in regard to the dynamics of convergence that can be derived from the age of the tilted sequence below this site. If the interpretation of the structural data is correct, the age of the tilted beds, presumed to have been derived partly from the oceanic plate, can be estimated. Extrapolating the rate of sedimentation linearly from 660 to 800 meters gives approximately 8 m.y. for the minimum age of the top of the consistently tilted sequence observed in the seismic records. Hence the youngest age for any material accreted from the oceanic plate at Site 441 would be late Miocene.

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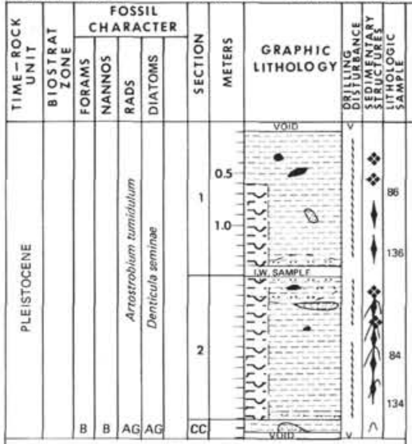
SITE 441 HOLE CORE 1 CORED INTERVAL: 0.0-3.0 m



LITHOLOGIC DESCRIPTION

Rounded 2 cm diameter black (N1) basalt pebbles

Pocket of fine-grained to medium-grained sandy silt (N4)
Dark olive gray (5Y 3/2)
Slightly silty grayish olive (10Y 4/2) interval

Diatomaceous silty clay

Clayey sand 2 cm thick
Slightly siltier
3 mm diameter black pumice fragment

Slightly mottled diatomaceous clay with silty spots: several dark greenish gray (5G 4/1) and medium bluish gray (5B 5/1) mottles.

Silty diatomaceous clay

Dark greenish gray clay (5GY 4/1) with deformed bed of olive gray (5Y 4/1) silty clay at base.

Mostly dark greenish gray (5GY 4/1) slightly sandy and silty clay and diatomaceous clay

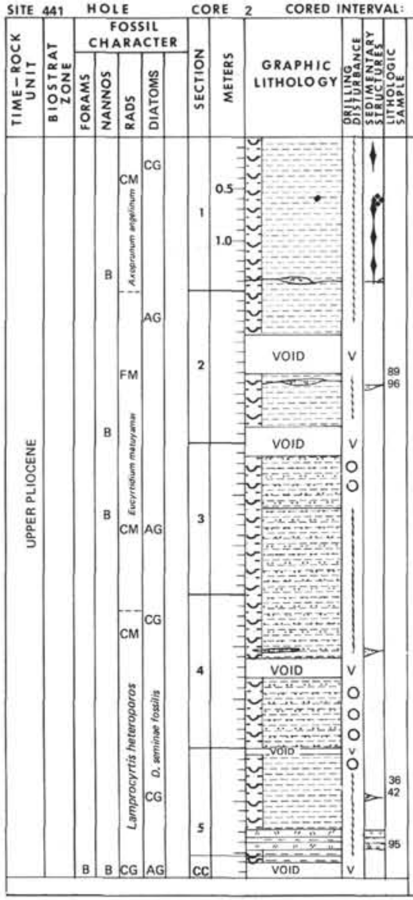
TOTAL C – ORGANIC C – CARBONATE (%)
1, 134 cm (1.1, 1.2, 0)
2, 82 cm (0.7, 0.7, 0)

CARBONATE BOMB
2, 65-67 cm = 1-2%

SMEAR SLIDE SUMMARY

	Sandy silt (M)	Diatomaceous clay (D)	Diatomaceous clay (D)	Diatomaceous clay (M)
	1-86	1-136	2-84	2-134
Sand	32	1	6	3
Silt	46	47	26	38
Clay	22	52	68	59
Quartz	16	8	7	10
Feldspar	27	12	6	13
Heavy minerals	9	2	2	2
Clay minerals	16	35	46	39
Volcanic glass	9	9	4	5
Glauconite	–	–	–	TR
Pyrite	3	–	2	TR
Foraminfiers	–	–	–	TR
Diatoms	7	26	24	23
Radiolarians	1	2	1	2
Sponge spicules	5	4	5	4
Lithic fragments	7	–	–	2
Other carbonate	–	2	3	–

SITE 441 HOLE CORE 2 CORED INTERVAL: 7.0-16.5 m



LITHOLOGIC DESCRIPTION

2 mm pumice clast mottling of 5Y 4/1 in 3-4 cm irregular patches

5Y 5/4 ash

olive (5Y 5/3) clayey ash

Dark greenish gray (5GY 4/1) plastic homogeneous diatomaceous silty clay (slightly sandy)

5Y 4/3 silt

Dark greenish gray (5GY 4/1) plastic diatomaceous clay

Olive gray (5Y 3/2) clayey ash

5Y 7/1 silt-sized ash layers (5 and 10 cm thick)
olive gray (5Y 4/2) firm diatomaceous clay

Dark greenish gray (5GY 4/1) diatomaceous silty clay and diatomaceous clay, plastic, mottled slightly or homogeneous. Several ash layers up to 10 cm thick.

TOTAL C – ORGANIC C – CARBONATE (%)
1, 98 cm (0.8, 0.7, 0)

CARBONATE BOMB
2, 120-122 cm = 0-1%

SMEAR SLIDE SUMMARY

	Diatomaceous clay (D)	Clayey ash (M)	Diatomaceous clay (D)	Clayey ash (M)	Ash (silt-sized) (M)	Diatomaceous clay (D)
	2-89	2-96	5-36	5-42	5-95	CC
Sand	2	4	–	14	–	1
Silt	27	44	37	54	61	45
Clay	71	52	63	32	39	54
Quartz	11	6	7	6	5	8
Feldspar	4	3	5	9	4	6
Heavy minerals	1	–	TR	–	TR	1
Clay minerals	44	42	46	26	13	44
Volcanic glass	6	33	5	44	75	2
Glauconite	–	–	1	–	–	–
Pyrite	2	2	1	2	1	2
Diatoms	26	22	28	10	2	27
Radiolarians	–	TR	1	–	–	2
Sponge spicules	6	3	6	3	–	7
Carbonate	–	–	–	–	–	1

SITE 441 HOLE CORE 3 CORED INTERVAL: 16.5-26.0 m

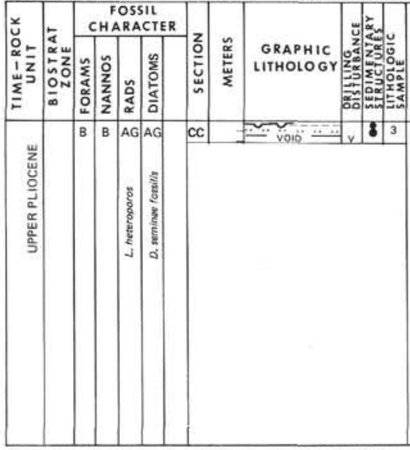
LITHOLOGIC DESCRIPTION

Firm, olive gray (5Y 4/2) diatomaceous clay with a 4 cm interval of dense, calcite-cemented, mottled, clayey sandstone (5Y 4/1), possibly a clast.

SMEAR SLIDE SUMMARY

	Diatomaceous clay (D)
	CC, 10
Sand	2
Silt	40
Clay	58
Quartz	12
Feldspar	7
Heavy minerals	1
Clay minerals	35
Volcanic glass	4
Palagonite	1
Glauconite	1
Pyrite	2
Foraminifers	1
Diatoms	29
Radiolarians	TR
Sponge spicules	7

SITE 441 HOLE CORE 4 CORED INTERVAL: 26.0-35.5 m



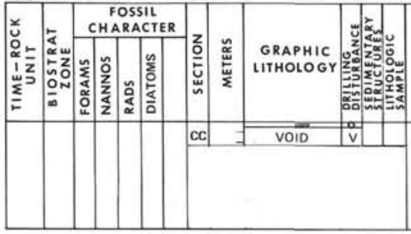
LITHOLOGIC DESCRIPTION

Olive gray (5Y 4/2) diatomaceous clay; one 2 cm thick graded very fine-grained sand layer.

SMEAR SLIDE SUMMARY

	Diatomaceous clay (D)
	CC, 3
Sand	–
Silt	42
Clay	58
Quartz	8
Feldspar	5
Heavy minerals	1
Clay minerals	39
Volcanic glass	7
Pyrite	1
Diatoms	28
Radiolarians	1
Sponge spicules	10

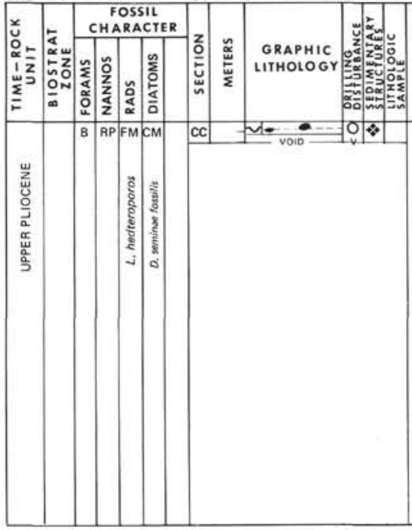
SITE 441 HOLE CORE 5 CORED INTERVAL: 83.0-92.5 m



LITHOLOGIC DESCRIPTION

Only recovery is from Core-Catcher; consists of elongate 4 cm pebbles, light olive gray (5Y 6/2), calcite-cemented; surface coating of elongate rods (possibly fecal pellets); faint interval laminae suggesting encrustation or concretionary growth.

SITE 441 HOLE CORE 6 CORED INTERVAL: 92.5-102.0 m



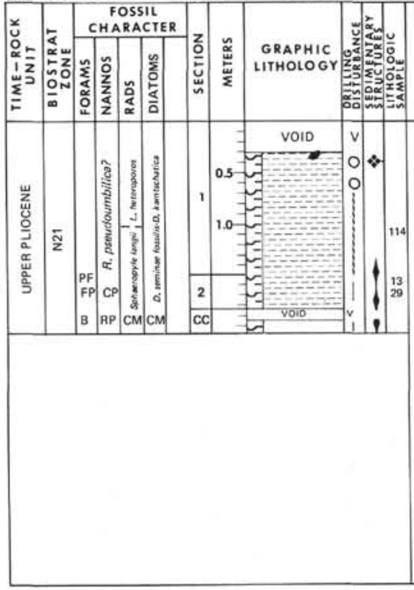
LITHOLOGIC DESCRIPTION

Grayish olive green (5GY 3/2) diatomaceous clay. At 7 cm, a subrounded calcite-cemented greenish gray (5GY 6/1) 25 x 50 mm sandy claystone clast containing pumice fragments. At 10 cm, a 20 x 30 mm nodule of chalk containing growth layers and 1-mm ovoid rods on the surface; perhaps it is an algal nodule.

SMEAR SLIDE SUMMARY

	Diatomaceous clay	Chalk
	CC, 5	CC, 10
Sand	2	–
Silt	30	4
Clay	68	96
Quartz	8	2
Feldspar	3	1
Heavy minerals	1	–
Clay minerals	68	–
Volcanic glass	3	3
Palagonite	TR	TR
Glauconite	TR	–
Diatoms	12	1
Sponge spicules	3	1
Carbonate	2	92

SITE 441 HOLE CORE 7 CORED INTERVAL: 149.5-159.0 m



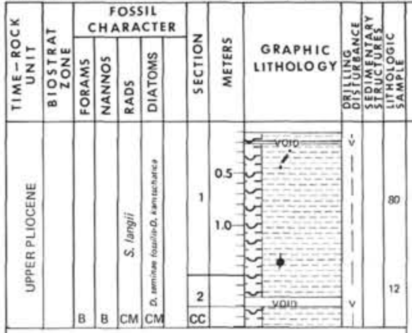
LITHOLOGIC DESCRIPTION

Calcite-cemented olive gray (5Y 5/1) 13 mm diameter concretionary warm burrow, dark greenish gray (5GY 4/1) diatomaceous claystone. Slightly fissile(?), highly deformed in drilling, breaks into chunks less than 1 cm in diameter. Better indurated at base. Mottles of pale yellow (5Y 7/4) chalk, Section 2, 7-16 cm; mottles of very light gray (N8) silty tuff, Core-Catcher, 20-22 cm.

SMEAR SLIDE SUMMARY

	Diatomaceous claystone	Chalk	Diatomaceous claystone
	1-114	2-13	2-29
Sand	16	6	8
Silt	26	13	33
Clay	58	81	59
Quartz	8	4	7
Feldspar	3	1	2
Heavy minerals	1	–	TR
Clay minerals	58	–	57
Volcanic glass	2	3	2
Palagonite	1	TR	TR
Glauconite	TR	TR	–
Pyrite	TR	–	1
Foraminifers	–	2	–
Diatoms	17	5	20
Radiolarians	TR	TR	TR
Sponge spicules	9	4	9
Silicoflagellates	–	TR	–
Other carbonate	1	81	2

SITE 441 HOLE CORE 8 CORED INTERVAL: 206.5-216.0 m



LITHOLOGIC DESCRIPTION

Drill cuttings

Possible fault surface, time inclination 45°, reverse slickensides, rake 80° clockwise from strike of surface. (Hole deviation at 149 m, 1.2°.)

Dark olive gray (5Y 3/2) homogeneous diatomaceous claystone. Hard layers, Section 1, 13-18 cm, 30-37 cm, Core-Catcher, 29-39 cm.

TOTAL C – ORGANIC C – CARBONATE (%)
1, 74 cm (0.9, 0.7, 1)

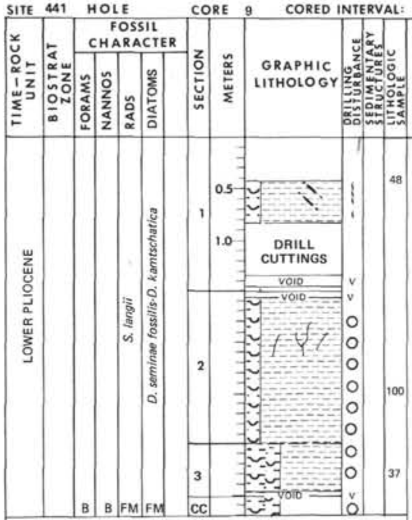
CARBONATE BOMB
1, 91-93 cm = 0-1%

SMEAR SLIDE SUMMARY

	Diatomaceous claystone	Diatomaceous claystone
	1-80	2-12
Sand	10	8
Silt	29	31
Clay	61	61
Quartz	7	9
Feldspar	3	4
Heavy minrals	1	1
Clay minerals	56	54
Volcanic glass	1	3
Pyrite	2	1
Diatoms	22	20
Radiolarians	1	1
Sponge spicules	7	6
Carbonate	TR	1

NOTE:
⧫ = sponge fragments

SITE 441 HOLE CORE 9 CORED INTERVAL: 263.5-273.0 m



LITHOLOGIC DESCRIPTION

Wash-resistent core fragments as below.

Possible fault, inclination 35°. Fault, inclination 35°, grooves rake 85° clockwise.

Dark olive gray (5Y 3/2) diatomaceous claystone.

Drill cuttings

This core was cut at core-cutting pump pressure from 263.5-273.0 m, but the core barrel had not been cleaned following washing at high pump pressure from 216.0 m. Some or all of the material described as core may have been cut about 263.5 m.

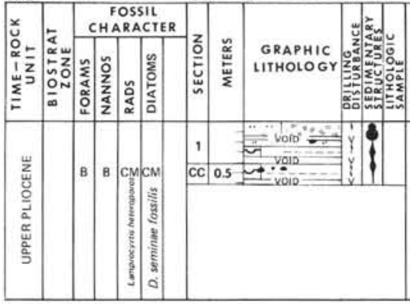
Fractured into 1-cm pieces.

Olive gray (5Y 4/2) clayey diatomite, homogeneous, less brittle than first two sections. Hackly fracture, Section 3, 0-25 cm.

SMEAR SLIDE SUMMARY

	Diatomaceous claystone	Diatomaceous claystone	Clayey diatomite
	1-48	2-100	3-37
Sand	8	7	5
Silt	26	25	45
Clay	66	68	50
Quartz	8	9	7
Feldspar	6	6	3
Heavy minerals	2	1	TR
Clay minerals	58	65	46
Volcanic glass	4	–	3
Glauconite	1	2	–
Pyrite	1	–	–
Foraminifers	1	–	–
Diatoms	13	11	31
Radiolarians	1	TR	1
Sponge spicules	5	4	8
Other carbonate	–	2	1

SITE 441 HOLE A CORE 2 CORED INTERVAL: 130.0-139.5 m



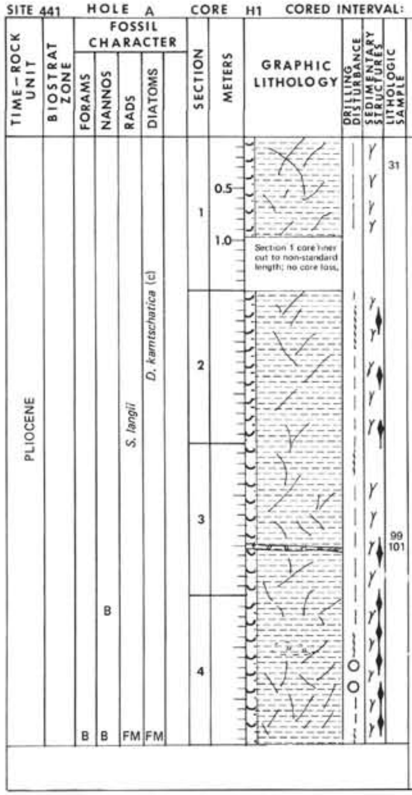
LITHOLOGIC DESCRIPTION

NOTE: Site 441A, Core 1, 120.5-130.0 m: NO RECOVERY.

Olive gray (5Y 4/1) silty tuff, graded, very fine-grained sand-size at base. Pumice clast, 3 mm, at base.

Olive gray (5Y 4/2) diatomaceous claystone. Contains calcitic concretions up to 30 mm at 45 cm.

SITE 441 HOLE A CORE H1 CORED INTERVAL: 252.5-329.5 m



LITHOLOGIC DESCRIPTION

Olive gray (5Y 4/2) homogeneous well-indurated diatomaceous claystone, intensely fractured throughout.

TOTAL C – ORGANIC C – CARBONATE (%)
2, 68 cm (1.0, 0.9, 1)
4, 82 cm (0.9, 0.9, 0)

CARBONATE BOMB
3, 137-140 cm = 0-1%

Faint black anastomosing veins

5Y 4/2

FRACTURE INCLINATIONS

Section 1	Section 2	Section 3	Section 4
7 cm 50°	6 cm 50°	65 cm 0°	13 cm 35°
19 cm 2°	7 cm 50°	65 cm 80°	16 cm 15°
28 cm 90°	18 cm 26°	89 cm 13°	17 cm 80°
29 cm 10°	39 cm 47°	90 cm 55°	17 cm 45°
41 cm 28°	39 cm 33°	93 cm 45°	23 cm 50°
46 cm 2°	54 cm 45°	95 cm 32°	29 cm 35°
52 cm 52°	54 cm 43°	106 cm 55°	91 cm 10°
53 cm 45°	60 cm 2°	115 cm 15°	95 cm 76°
62 cm 40°	70 cm 15°	115 cm 68°	107 cm 53°
68 cm 35°	75 cm 55°	120 cm 35°	117 cm 15°
80 cm 22°	82 cm 68°	137 cm 20°	117 cm 68°
86 cm 37°	91 cm 36°		125 cm 78°
88 cm 60°	135 cm 45°		126 cm 37°
92 cm 30°	146 cm 15°		

5Y 4/2

Very light gray mottled tuff with dip 15°

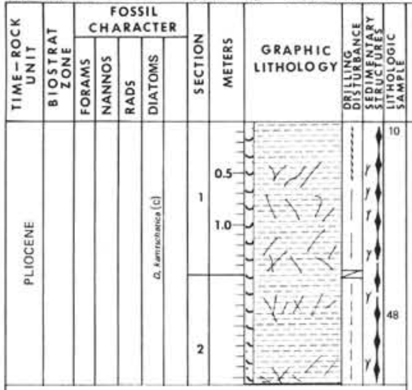
5Y 4/2

Very light gray ash slurry

SMEAR SLIDE SUMMARY

	Diatomaceous claystone (D)	Tuff (M)	Vitric diatomaceous claystone (D)
	1-31	3-99	3-101
Sand	8	36	12
Silt	26	56	29
Clay	66	8	59
Quartz	9	3	9
Feldspar	4	4	4
Mica	TR	–	–
Heavy minerals	1	–	TR
Clay minerals	66	8	59
Volcanic glass	5	83	10
Palagonite	TR	TR	TR
Glauconite	1	–	TR
Diatoms	10	2	12
Sponge spicules	3	–	6
Carbonate	1	–	–

SITE 441 HOLE A CORE H2 CORED INTERVAL: 338.0-386.5 m



LITHOLOGIC DESCRIPTION

Olive gray (5Y 4/2) diatomaceous claystone with many fractures. Intense mottling of 1-2 mm size, and faint black veins with offsets, through Section 1.

Olive gray (5Y 4/2) diatomaceous claystone with moderate mottling of small size.

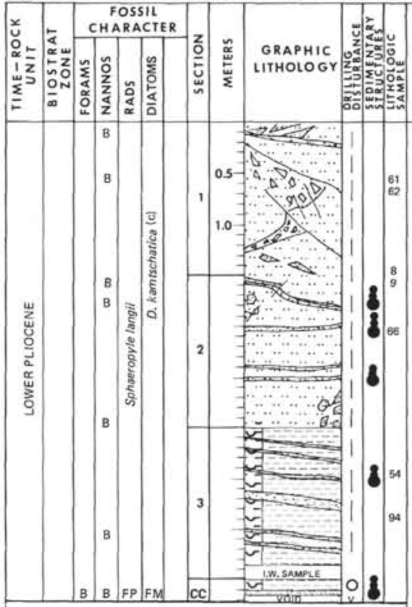
FRACTURE INCLINATIONS

Section 1	Section 2
70 cm 80°	26 cm 62°
80 cm 81°	46 cm 68°
85 cm 55°	96 cm 61°
88 cm 70°	
104 cm 29°	
138 cm 19°	

SMEAR SLIDE SUMMARY

	Vitric calcareous clayey siltstone (M)	Diatomaceous claystone (D)
	1-10	2-48
Sand	21	6
Silt	47	30
Clay	52	64
Quartz	12	5
Feldspar	26	3
Heavy minerals	4	1
Clay minerals	15	64
Volcanic glass	10	4
Palagonite	1	–
Glauconite	–	1
Pyrite	2	–
Diatoms	7	11
Radiolarains	TR	TR
Sponge spicules	6	4
Carbonate	17	7

SITE 441 HOLE A CORE 5 CORED INTERVAL: 386.5-396.0 m



LITHOLOGIC DESCRIPTION

Bedding, 20° inclination
clay-sized devitrified ash(?)

Siltstone (blocks)
silty claystone (matrix)

Calcareous claystone
Clayey siltstone

Very fine graded sandstone
graded sandstone
Siltstone

Dark gray (N3) sandy siltstone
Dark grav (N3) sandy siltstone

Graded medium sandstone;
7 cm clast at base.
Diatomaceous claystone

Coarse-grained; up to 2
mm grains; 60° and 75°
fractures, normal.
Diatomaceous claystone

Medium-grained sandstone

NOTE: Site 441A, Core 3, 244.0-252.5 m and Site 441A, Core 4, 329.5-338.0 m: NO RECOVERY.

Dark gray (N3) siltstone as "tectonic breccia". Blocks are dark gray (N3), and the softer interblock matrix is medium dark gray (N4). Matrix is more clay rich. Some graded sand layers.

Dark gray (N3) diatomaceous claystone.

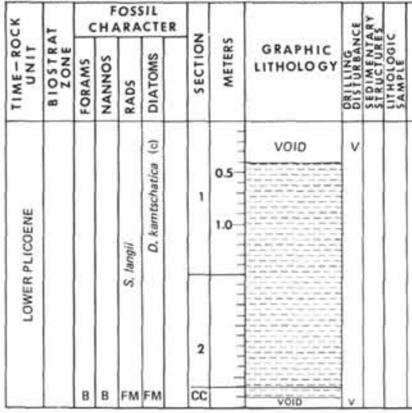
TOTAL C – ORGANIC C – CARBONATE (%)
2, 132 cm (0.7, 0.6, 1)

CARBONATE BOMB
3, 105-107 cm = 0-1%

SMEAR SLIDE SUMMARY

	Clayey siltstone (D)	Silty claystone (M)	Calcareous claystone (M)	Sandy clayey siltstone (M)	Clayey siltstone (D)	Diatomaceous claystone (M)	Diatomaceous claystone (D)
	1-61	1-62	2-8	2-9	2-66	3-54	3-94
Sand	20	15	8	27	21	7	7
Silt	50	30	17	41	48	41	32
Clay	30	55	75	32	31	52	61
Quartz	50	35	7	47	45	11	14
Feldspar	13	8	5	16	17	5	6
Heavy minerals	4	1	TR	4	3	2	1
Clay minerals	25	54	61	22	30	47	48
Volcanic glass	–	1	TR	3	2	6	8
Palagonite	–	–	–	–	–	–	TR
Glauconite	–	–	–	1	–	–	–
Pyrite	2	1	–	–	–	1	1
Diatoms	–	–	1	–	TR	16	12
Sponge spicules	–	–	–	–	–	2	1
Lithic fragments	4	–	–	5	–	6	5
Carbonate	2	TR	26	2	3	4	4

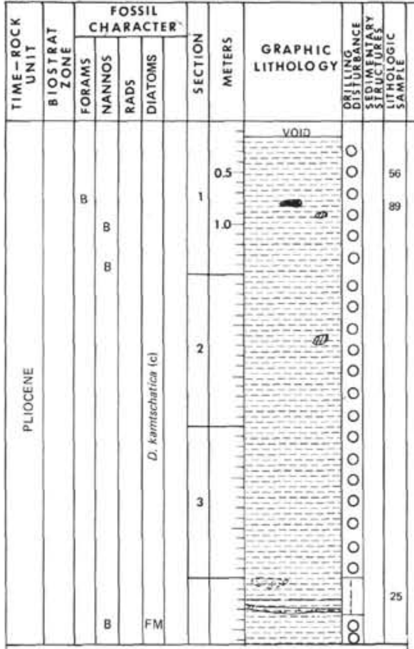
SITE 441 HOLE A CORE 6 CORED INTERVAL: 443.5-452.0 m



LITHOLOGIC DESCRIPTION

DRILL CUTTINGS THROUGHOUT

SITE 441 HOLE A CORE H3 CORED INTERVAL: 452.0-500.5 m



LITHOLOGIC DESCRIPTION

Olive gray (5Y 3/2) claystone

1-2 cm chips in drilling mud matrix

Wood fragment, 1.5 cm

Fine sand-sized 1 cm calcite-cemented concretion

Olive gray (5Y 3/2) claystone

Fine sand-sized 1 cm calcite-cemented concretion

Olive gray (5Y 3/2) claystone

Medium-grained sandstone chips

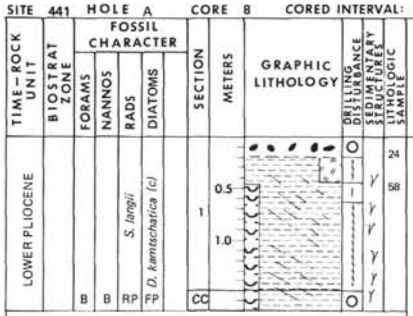
Medium olive gray (5Y 5/1) silt-sized tuff

Grayish black (N2) re-sedimented shale.

SMEAR SLIDE SUMMARY

	Claystone (D)	Marlstone (M)	Tuffite (M)
	1-56	1-89	4-25
Sand	6	6	12
Silt	18	11	53
Clay	76	83	35
Quartz	7	3	7
Feldspar	3	–	5
Clay minerals	70	59	13
Volcanic glass	6	–	72
Palagonite	–	3	–
Pyrite	–	–	3
Diatoms	7	–	TR
Sponge spicules	2	–	–
Carbonate	5	35	–

SITE 441 HOLE A CORE 8 CORED INTERVAL: 510.0-519.5 m



LITHOLOGIC DESCRIPTION

Vitric claystone olive gray

45° and 65° fractures, reverse

32°-35°

NOTE: Site 441A, Core 7, 500.5-510.0 m: NO RECOVERY

Pebbles, rounded to subrounded, possible from uphole:
- 5 cm phaneritic basalt;
- 2.5 cm medium dark gray (N4) siltstone;
- 4 and 3.5 cm olive (5Y 4/3) claystone.

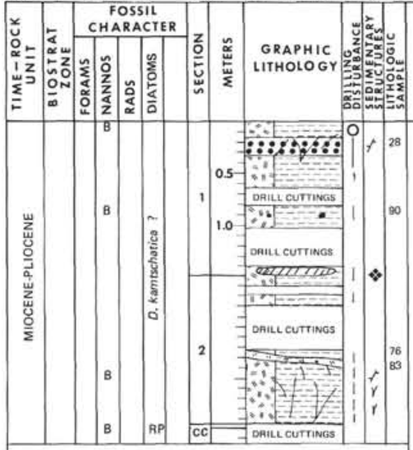
Dark olive gray (5Y 3/2) diatomaceous claystone, highly broken up during drilling into fissile chips with persistent fractures or partings (joints): 40°-45°.

TOTAL C – ORGANIC C – CARBONATE (%)
1, 60 cm (1.3, 0.9, 3)

SMEAR SLIDE SUMMARY

	Vitric claystone (D)	Diatomaceous claystone (D)
	1-24	1-58
Sand	7	6
Silt	36	20
Clay	57	74
Quartz	13	3
Feldspar	4	2
Heavy minerals	1	–
Clay minerals	57	74
Volanic glass	11	1
Palagonite	1	TR
Glauconite	TR	–
Diatoms	8	14
Sponge spicules	2	3
Other carbonate	2	2
Nannofossils	1	1

SITE 441 HOLE A CORE H4 CORED INTERVAL: 519.5-568.0 m



LITHOLOGIC DESCRIPTION

3 mm rounded clasts

10 cm calcite-concretion clast
DRILL CUTTINGS
Olive gray (5Y 4/2) vitric claystone

Tuff; bedding inclination 18°; reverse fault, 65°

Hackly cleavage 35°; bedding 21°

Olive gray (5Y 4/2) vitric claystone.

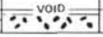
Grayish black (N2) to greenish gray (5G 6/1) conglomerate, with 1 cm subangular clasts of calcareous claystone; bedding dip 15°; fault 75°, slickensides approximately horizontal.

SMEAR SLIDE SUMMARY

	Calcareous diatomaceous claystone (M)	Vitric claystone (D)	Silty tuff (M)	Tuff (M)
	1-28	1-90	2-76	2-83
Sand	4	11	15	–
Silt	20	33	62	60
Clay	76	56	23	40
Quartz	6	7	13	5
Feldspar	3	5	9	–
Heavy minerals	–	2	4	–
Clay minerals	51	52	15	5
Volcanic glass	4	24	51	90
Palagonite	–	TR	3	–
Pyrite	–	–	–	TR
Foraminifers	1	–	–	–
Diatoms	11	5	1	–
Radiolarians	TR	–	–	–
Sponge spicules	3	2	1	–
Other carbonate	21	2	1	–
Zeolite	–	1	2	–

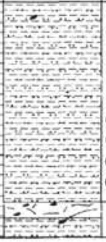
SITE 441 HOLE A CORE 9 CORED INTERVAL: 568.0-576.5 m

TIME–ROCK UNIT	BIOSTRAT ZONE	FOSSIL CHARACTER FORAMS	NANNOS	RADS	DIATOMS	SECTION	METERS	GRAPHIC LITHOLOGY	DRILLING DISTURBANCE	SEDIMENTARY STRUCTURES	LITHOLOGIC SAMPLE	LITHOLOGIC DESCRIPTION
LOWER PLIOCENE	*D. kamtschatica* (b)	B	B	RM	FP	1		VOID	○			5Y 3/2 claystone Five calcitic concretionary pebbles or concretions ranging from claystone to fine sandstone; one is microbrecciated and contains pyrite veins. All are different. No Core-Catcher sample.



SITE 441 HOLE A CORE 10 CORED INTERVAL: 576.5-586.0 m

TIME–ROCK UNIT	BIOSTRAT ZONE	FOSSIL CHARACTER FORAMS	NANNOS	RADS	DIATOMS	SECTION	METERS	DRILLING DISTURBANCE	LITHOLOGIC SAMPLE
LOWER PLIOCENE	*D. kamtschatica?* (b)	B	B B B B B	RP	RP	1 2 CC	0.5 1.0	○ ○ ○ ○ ○ ○ ○ ○ ○	48 51 52 7



LITHOLOGIC DESCRIPTION

Greenish black (5G 2/1).
Drill cuttings (small chips) of silty claystone.

Less than 5 mm breccia pieces; (51) is green, (52) is N4-N6. Calcite-cemented breccia; thin veinlets of calcite separating clots of dark greenish gray (5G 4/1) claystone (does not effervesce) and gray (N4-N6) calcareous chalk(?), silt-sized with dark angular sand-silt grains tightly cemented.

Dark greenish gray (5G 6/1) calcareous claystone mottled very slightly with N5, streaked.

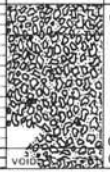
TOTAL C – ORGANIC C – CARBONATE (%)
2, 50 cm (6.1, 0.3, 48)

SMEAR SLIDE SUMMARY

	Silty claystone (D)	Muddy limestone (pebble) (M)	Limestone (pebble) (M)	Limestone (M)
	1-48	2-51	2-52	CC-7
Sand	11	–	2	–
Silt	30	85	68	65
Clay	59	15	30	35
Quartz	24	5	1	1
Feldspar	5	4	1	TR
Clay minerals	59	15	–	–
Volcanic glass	8	6	3	3
Palagonite	–	TR	–	–
Diatoms	1	–	1	–
Sponge spicules	1	–	–	–
Carbonate	2	70	94	96

SITE 441 HOLE A CORE 11 CORED INTERVAL: 586.0-595.5 m

TIME–ROCK UNIT	BIOSTRAT ZONE	FOSSIL CHARACTER FORAMS	NANNOS	RADS	DIATOMS	SECTION	METERS	DRILLING DISTURBANCE	LITHOLOGIC SAMPLE
UPPER MIOCENE	*D. kamtschatica?* (a)	B	B B B	RP	RP	1 CC	0.5 1.0	○ ○ ○	49 70 126



LITHOLOGIC DESCRIPTION

Cuttings of dark greenish gray (5GY 3/1) claystone.

Re-sedimented breccia, clast-supported, dark greenish gray (5GY 4/1) overall, typically 5 mm or smaller angular clasts, some to 1.5 cm; crude stratification indicates possible 35°-45° dip. Clasts, mostly 5GY 5/1 claystone (see smear 49 cm), some yellowish gray (5Y 8/1) calcareous marlstone, minor olive gray (5Y 4/1) claystone, and 5GY 2/1 glauconitic claystone, silty claystone, and white (N8) tuff. Entire unit indurated; many clasts appear to have been lithified upon sedimentation, while some are rounded and sutured together, conforming to adjacent clast shapes, as though soft when transported.

Cuttings of breccia unit 5Y 3/1; minor ash mottles, white (N8) in chips.

TOTAL C – ORGANIC C – CARBONATE (%)
1, 46 cm (0.9, 0.4, 5)

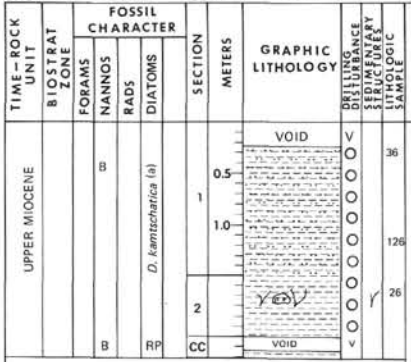
SMEAR SLIDE SUMMARY

	Claystone (pebble) (M)	Tuff (M)	Tuff (M)
	1-49	1-70	1-126
Sand	–	–	12
Silt	33	35	58
Clay	67	65	30
Quartz	11	2	4
Feldspar	5	1	2
Clay minerals	67	–	–
Volcanic glass	5	97	94
Palagonite	1	–	–
Diatoms	4	–	TR
Sponge spicules	3	–	–
Carbonate	4	–	–

FRACTURE INCLINATIONS
Section 1

38 cm 70°, normal	87 cm 3°
38 cm 40°, reverse	89 cm 45°
53 cm 32°, reverse	90 cm 85°
53 cm 65°, reverse	93 cm 28°
63 cm 51°, reverse	96 cm 29°
72 cm 59°	

SITE 441 **HOLE** A **CORE** 12 **CORED INTERVAL:** 605.0-614.5 m



LITHOLOGIC DESCRIPTION

Drill cuttings throughout, greenish black (5G 2/1-3/1) and olive gray (5Y 5/1); see smear slide summary. Chiefly clayey siltstone and claystone.

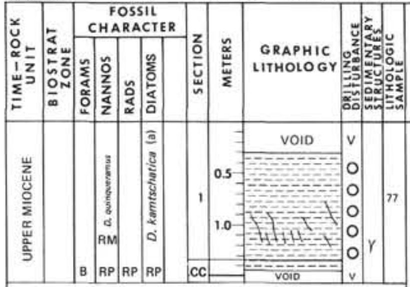
Fragment of silty tuff, light olive gray, containing numerous aligned somewhat branching non-calcareous light veins that lack offset.

TOTAL C – ORGANIC C – CARBONATE (%)
1, 96 cm (0.5, 0.0, 0)

SMEAR SLIDE SUMMARY

	Clayey siltstone	Claystone	Silty tuff
	1-36	1-126	2-26
Sand	6	–	15
Silt	54	26	46
Clay	40	74	39
Quartz	42	11	22
Feldspar	8	3	5
Heavy minerals	1	–	–
Clay minerals	40	74	39
Voclanic glass	3	5	33
Palagonite	–	–	TR
Diatoms	2	2	TR
Sponge spicules	4	3	TR
Carbonate	–	2	1

SITE 441 **HOLE** A **CORE** 13 **CORED INTERVAL:** 624.0-633.5 m



LITHOLOGIC DESCRIPTION

Greenish black (5G 2/1) claystone, mainly drill cuttings.

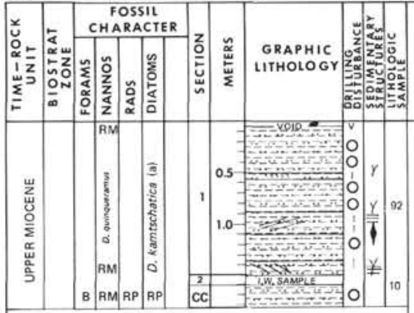
Clasytone, fissile, breaks easily along partings all of several orientations. Fracture surfaces have slickensides or grooves.
Fractures dipping 65°, closely-spaced partings

TOTAL C – ORGANIC C – CARBONATE (%)
1, 70 cm (0.9, 0.8, 1)

SMEAR SLIDE SUMMARY

	Claystone (D)
	1-77
Sand	–
Silt	22
Clay	78
Quartz	8
Feldspar	3
Clay minerals	78
Volcanic glass	2
Diatoms	4
Sponge spicules	2
Carbonate	3

SITE 441 **HOLE** A **CORE** 14 **CORED INTERVAL:** 643.0-652.5 m



LITHOLOGIC DESCRIPTION

Pebble, N3 silt-sized sanstone, 3 cm in diameter, subrounded.

Parallel fractures, 65° inclination

A few mottles, small 5Y 4/1 silty claystone

Silty claystone with probable dewatering veins (blocks, 1 mm black streaks), very fine laminations showing at 42° inclination.

5Y 4/1 silty claystone strongly disturbed by drilling. Apparent dip, 40°.

Very fine laminations or cleavage N4-N5 show an apparent dip of about 40°.

All other parts are drill cuttings (chips).

Core-Catcher: Drill cuttings; some slickensides visible on small blocks.

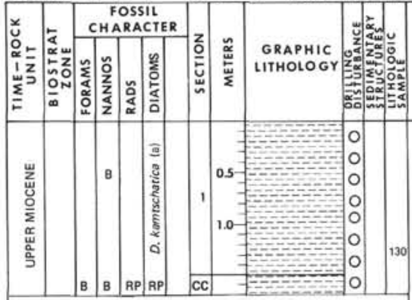
TOTAL C – ORGANIC C – CARBONATE (%)
1, 122 cm (0.6, 0.6, 1)

CARBONATE BOMB
1, 114-116 cm = 0-1%

SMEAR SLIDE SUMMARY

	Silty claystone (D)	Silty claystone (D)
	1-92	CC-10
Sand	2	2
Silt	25	38
Clay	73	60
Quartz	25	25
Feldspar	2	5
Heavy minerals	–	TR
Clay minerals	64	58
Voclanic glass	8	8
Palagonite	–	1
Glauconite	TR	TR
Pyrite	TR	1
Diatoms	1	2

SITE 441 **HOLE** A **CORE** 15 **CORED INTERVAL:** 652.5-662.0 m



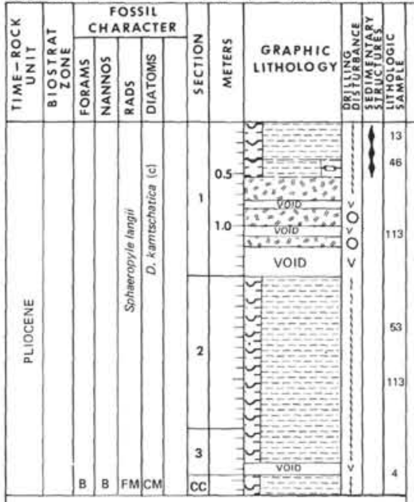
LITHOLOGIC DESCRIPTION

Drill cuttings, throughout, 5Y 3/1 claystone, with pumice pebbles (2-3 mm diameter), and black rounded basalt(?) pebbles scattered throughout. Possible caving from uphole.

SMEAR SLIDE SUMMARY

	Claystone (D)
	1-130
Sand	–
Silt	10
Clay	90
Quartz	6
Feldspar	2
Clay minerals	85
Volcanic glass	5
Diatoms	2

SITE 441 HOLE B CORE 1 CORED INTERVAL: 335.5-344.0 m



LITHOLOGIC DESCRIPTION

Greenish gray (5GY 5/1) vitric diatomaceous claystone with medium dark to dark gray (N3 & 4) 1-2 mm mottles. Breaks into small soft chips. Olive gray (5Y 5/1) diatomaceous calcareous claystone. Light olive gray to light gray (5Y 6/1-N7) tuff. Contains some olive gray (5Y 5/1) chips, 62-65 cm. A soft drilling wash with a high water content; structureless.

Dark greenish gray (5GY 4/1) diatomaceous claystone. Compressed drilling chips less than 1-2 mm in diameter in most part; a few drilling biscuits that crumble into chips.

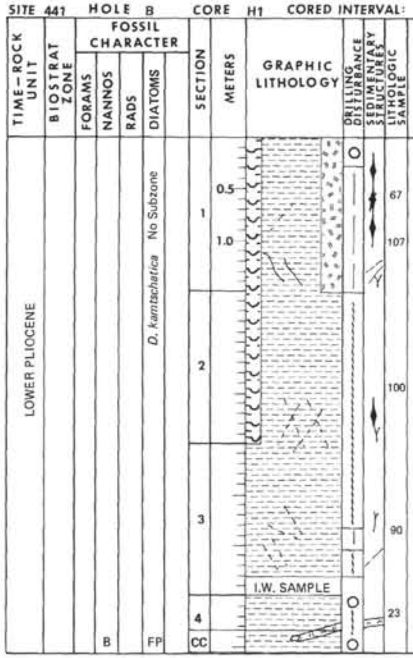
5Y 4/1

TOTAL C – ORGANIC C – CARBONATE (%)
2, 68 cm (1.0, 0.9, 1)
2, 124 cm (1.2, 1.0, 1)

SMEAR SLIDE SUMMARY

	Vitric diatomaceous claystone	Diatomaceous calcareous claystone	Tuff	Diatomaceous claystone	Diatomaceous claystone	Diatomaceous claystone
	1-13	1-46	1-113	2-53	2-113	CC, 4
Sand	10	6	50	8	5	12
Silt	48	16	28	38	35	32
Clay	42	78	22	54	60	56
Quartz	12	4	9	14	9	8
Feldspar	6	3	8	4	3	3
Mica	–	–	–	–	–	–
Heavy minerals	1	TR	1	1	–	1
Clay minerals	42	42	–	54	60	56
Volcanic glass	10	6	75	5	3	3
Palagonite	1	1	4	1	–	TR
Glauconite	1	–	2	TR	–	1
Pyrite	–	–	–	–	–	–
Foraminifers	–	–	–	–	–	–
Diatoms	18	12	1	11	16	14
Radiolarians	–	–	–	–	TR	–
Sponge spicules	8	4	–	3	6	5
Carbonate	1	28	–	8	3	9

SITE 441 HOLE B CORE H1 CORED INTERVAL: 344.0-402.0 m



LITHOLOGIC DESCRIPTION

67	Very faint 2 mm mottles throughout
	Vitric diatomaceous claystone fractured into 2-3 cm blocks
107	Calcareous claystone (olive calcitic mottles)
	Black dewatering vein
	Fractured into 1 cm blocks. Desoriented when drilling; deformation is intense
100	Diatomaceous claystone
	Gravish green (5G 5/1) mottles inclined 35° (bedding)
	Fractured in 1 cm blocks
90	Claystone fault 55°
23	Light gray clayey tuff bed with 35° dip, uncertain (drilling disturbance)

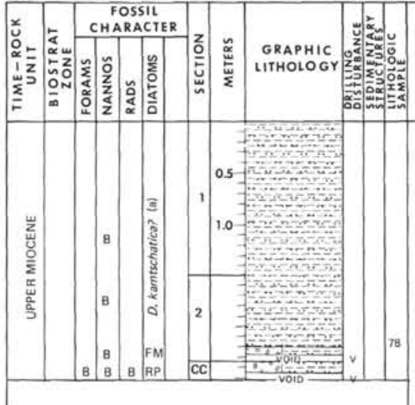
Olive gray (5Y 4/2) diatomaceous claystone and claystone, faintly fractured.

FAULTS:
55°, 80° clockwise, normal
8° reverse, rake 80°
80°, normal, slickensides, rake 80°
18°, slickensides, 90°, normal
20°, slickensides, rake 80°, clockwise

SMEAR SLIDE SUMMARY

	1-67	1-104	2-100	3-90	4-23
Sand	3	0	2	–	2
Silt	30	18	28	23	60
Clay	67	82	70	77	38
Quartz	6	3	8	7	8
Feldspar	4	1	3	4	3
Mica	–	–	–	–	–
Heavy minerals	1	TR	1	1	–
Clay minerals	62	50	68	75	30
Volcanic glass	10	–	2	2	50
Palagonite	–	–	–	–	–
Glauconite	–	–	–	–	–
Pyrite	–	–	–	–	1
Foraminiers	–	–	–	–	–
Diatoms	11	7	11	6	2
Radiolarians	TR	–	1	–	–
Sponge spicules	3	2	3	2	–
Carbonate	3	37	3	3	–

SITE 441 HOLE B CORE 2 CORED INTERVAL: 668.0-687.0 m



LITHOLOGIC DESCRIPTION

Drill cuttings throughout; chips approximately 3 mm in diamter, 5Y 3/1, vitric silty claystone.

Vitric silty claystone (5GY 4/1) highly fractured, most persistently at about 75°.

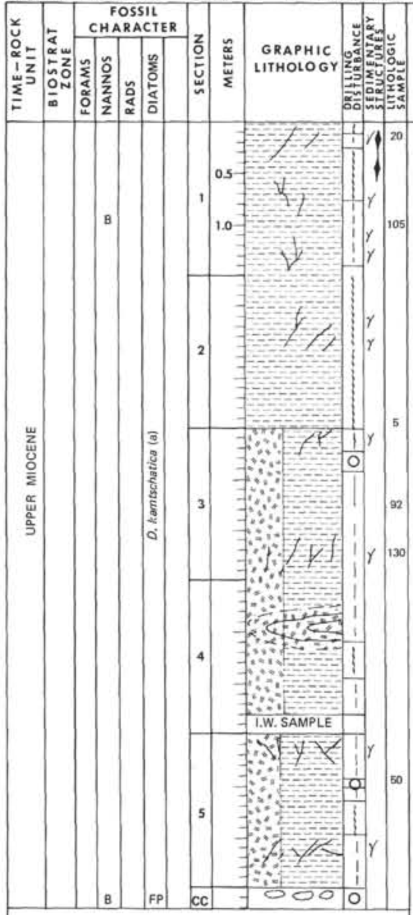
5GY 4/1 vitric silty claystone and claystone; hackly somewhat braided fractures, predominantly 75°.

TOTAL C – ORGANIC C – CARBONATE (%)
1, 44 cm (0.7, 0.7, 0)

SMEAR SLIDE SUMMARY

	Vitric silty claystone (D)
	2-78
Sand	11
Silt	51
Clay	38
Quartz	22
Feldspar	8
Mica	
Heavy minerals	2
Clay minrals	34
Volcanic glass	26
Pyrite	2
Diatoms	4
Radiolarians	
Sponge spicules	1
Zeolite	2

SITE 441 HOLE B CORE H2 CORED INTERVAL: 402.0-668.0 m



LITHOLOGIC DESCRIPTION

Dark greenish gray to olive gray (5GY-5Y 4/1) claystone.

Olive gray (5Y 4/1) claystone, relatively homogeneous; disturbed by drilling.

Olive gray to medium dark gray (5Y 4/1-N4) claystone.

SMEAR SLIDE SUMMARY

Axis of fold; plane dips 0°, the folded surfaces are made up of 1-3 mm mullions parallel with the fold axis (N4-5Y 4/1).

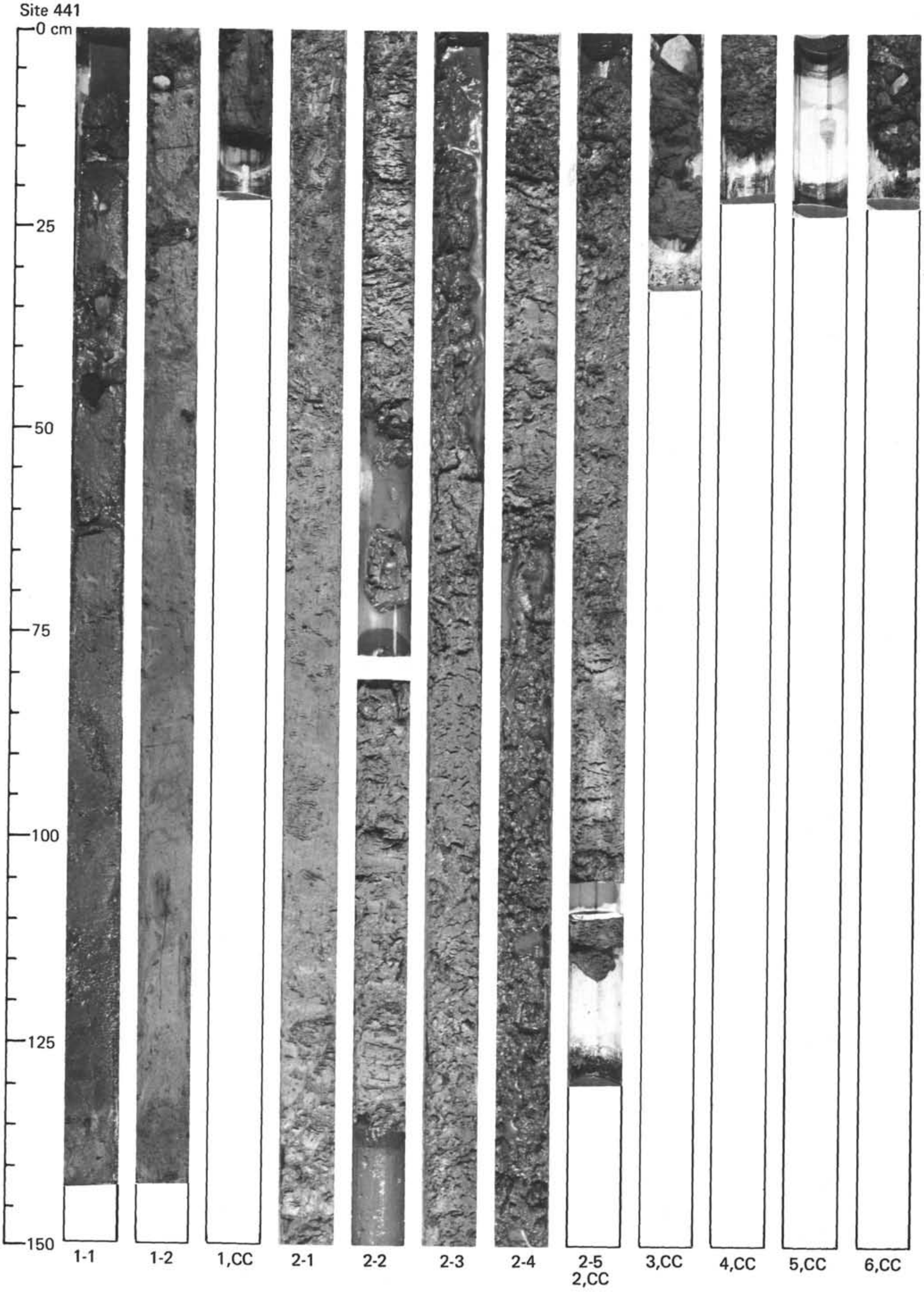
Olive gray (5Y 4/1) diatomaceous silty claystone.

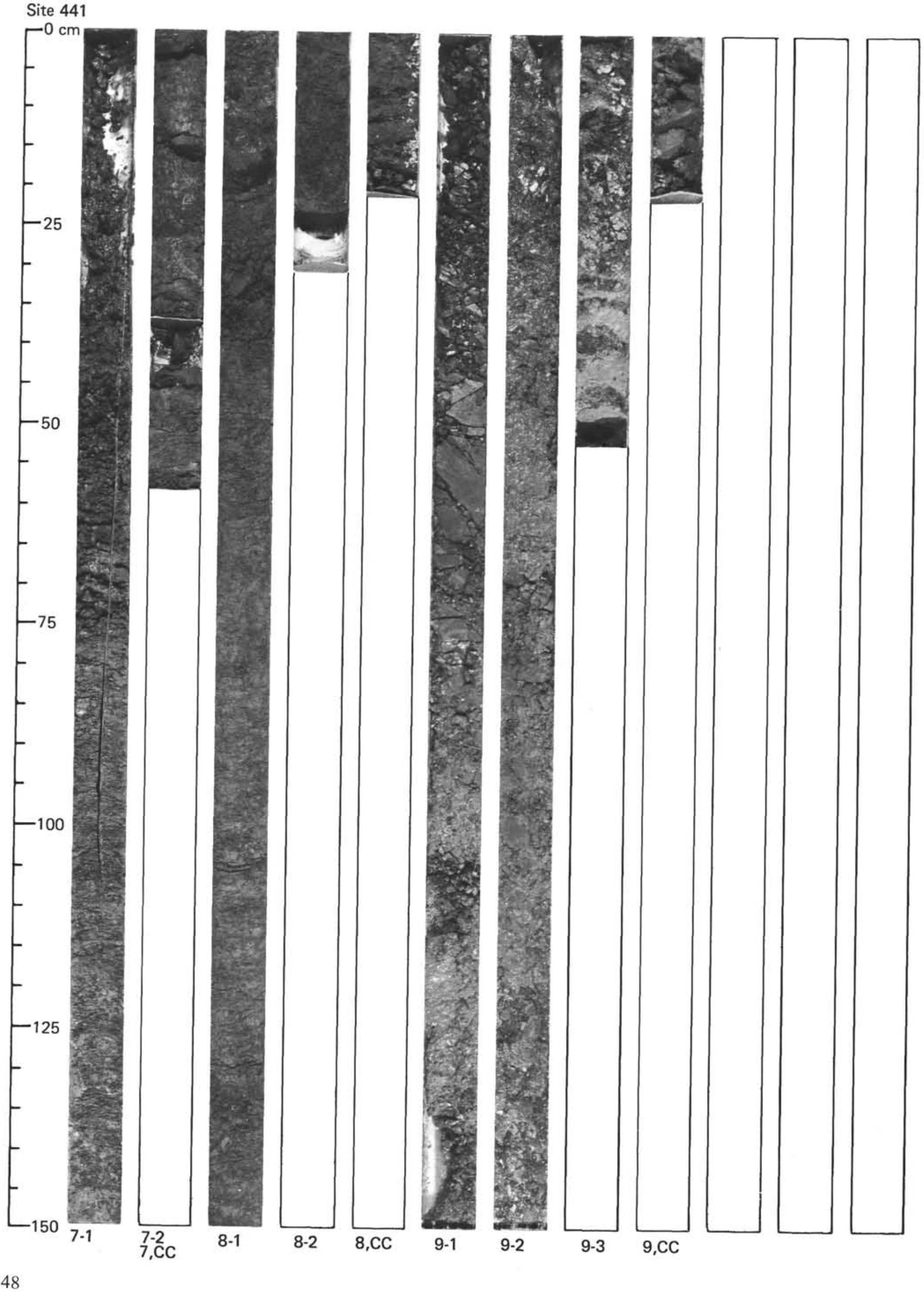
	Claystone (D)	Claystone (D)	Silty claystone (D)	Silty claystone (D)	Silty claystone (D)	Diatomaceous silty claystone (D)
	1-20	1-105	3-5	3-92	3-130	5-50
Sand	1	2	7	5	15	8
Silt	30	25	38	45	40	36
Clay	69	73	55	50	45	56
Quartz	6	9	14	31	21	17
Feldspar	3	4	6	12	12	7
Mica	TR	–	–	–	–	–
Heavy minerals	TR	TR	1	TR	1	2
Clay minerals	69	73	55	37	45	50
Volcanic glass	5	4	8	1	TR	6
Palagonite	1	TR	1	1	1	–
Glauconite	–	1	1	–	1	–
Hematite	–	–	–	TR	–	–
Pyrite	–	–	–	–	–	1
Diatoms	7	3	7	3	3	11
Radiolarians	–	–	TR	TR	–	TR
Sponge spicules	4	3	4	4	3	4
Other carbonate	2	3	3	4	3	2
Nannofossils	3	–	–	–	TR	–
Lithic fragments	–	–	–	7	10	–

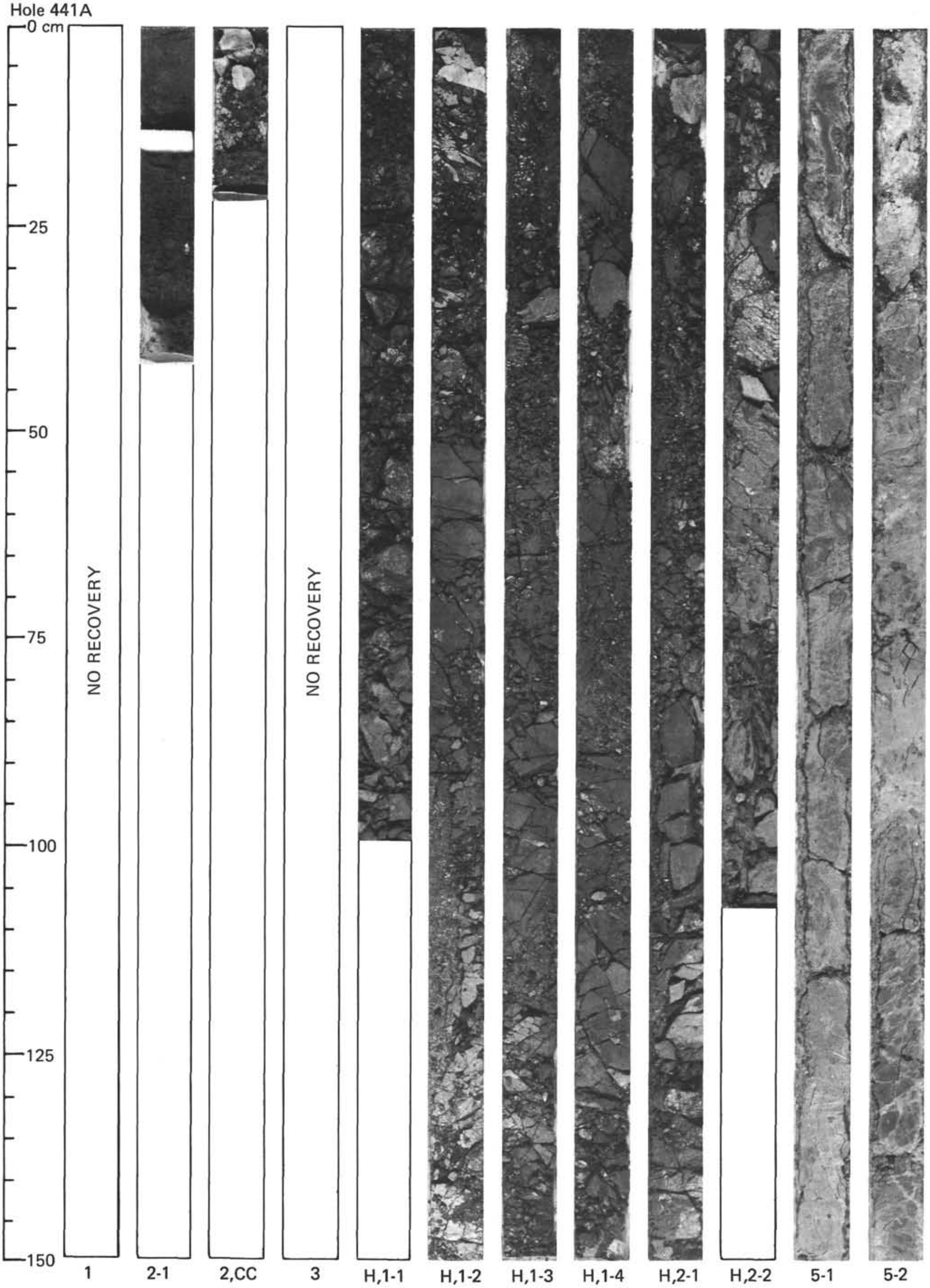
Several concretions of calcite-cemented tuff and claystone.
Cuttings

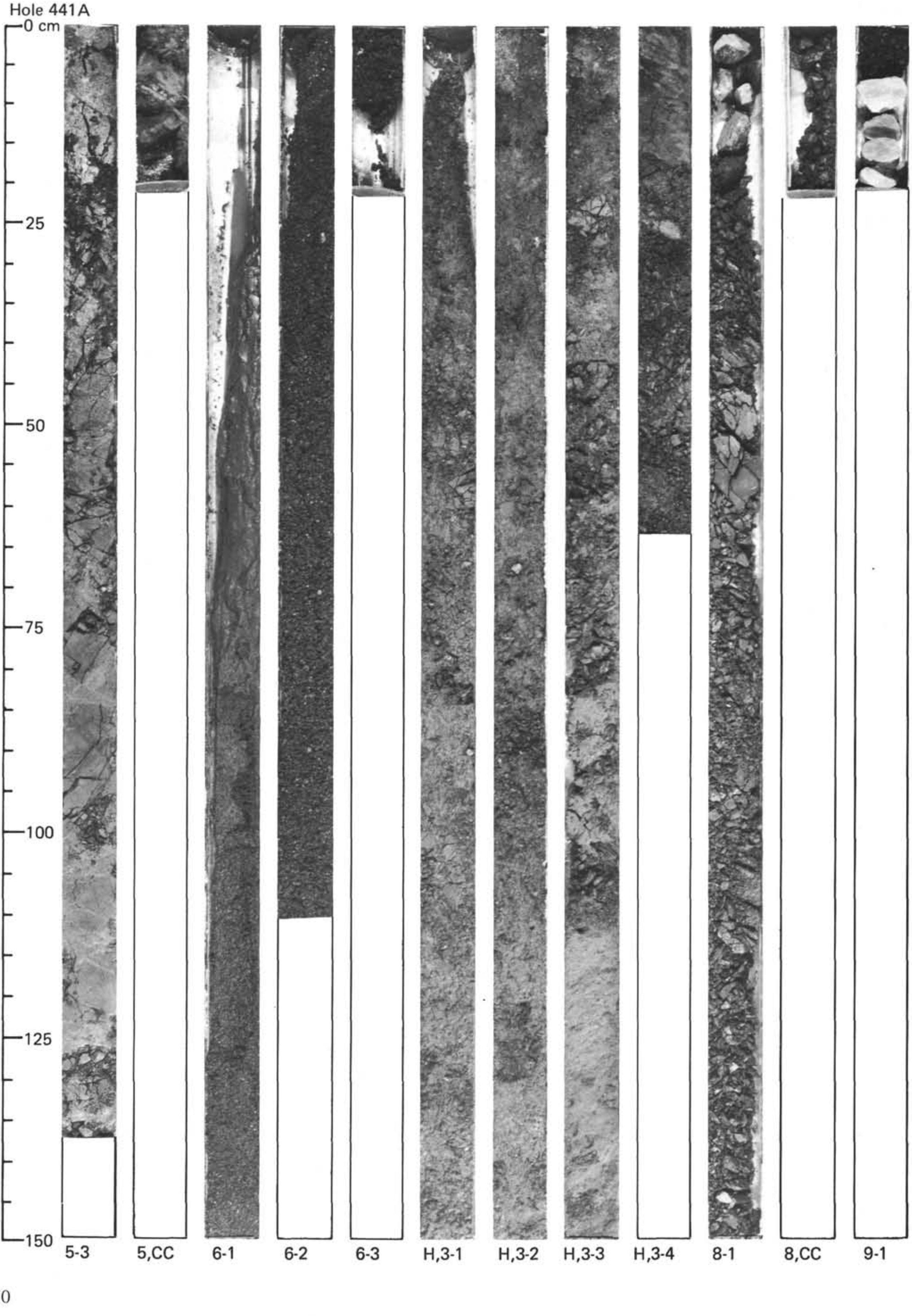
Fracture Orientations:

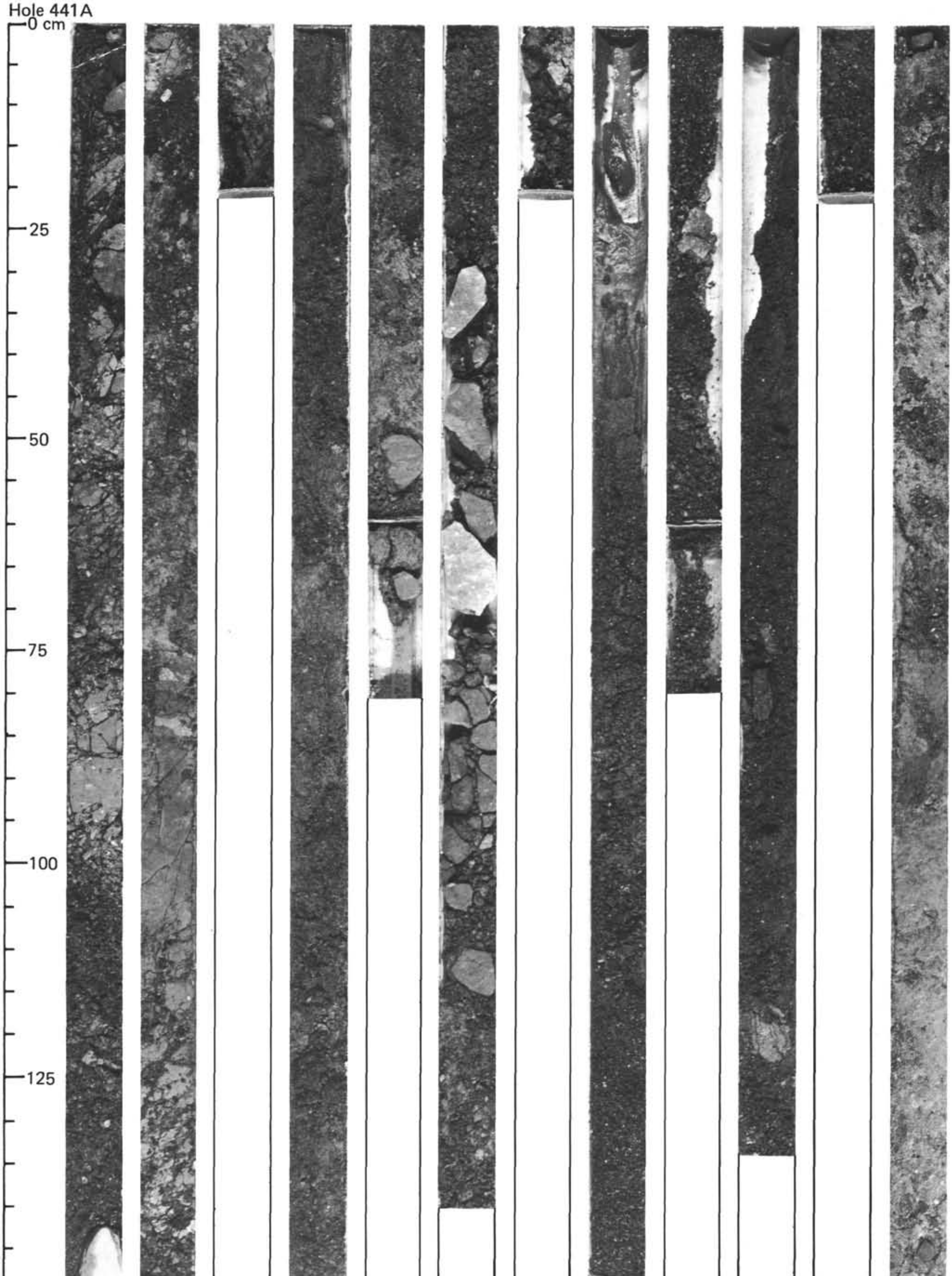
Section 1	Section 2	Section 3	Section 4	Section 5
17 cm 40°	55 cm 65°	10 cm 15°	10 cm 1°	3 cm 11°
21 cm 45°		10 cm 75°	15 cm 2°	10 cm 82°
77 cm 11°		10 cm 35°	17 cm 15°	10 cm 12°
105 cm 75°		135 cm 70°	20 cm 18°	14 cm 11°
		135 cm 11°	101 cm 72°	14 cm 27°
		135 cm 45°	104 cm 12°	18 cm 8°
				22 cm 2°
				24 cm 15°
				24 cm 82°

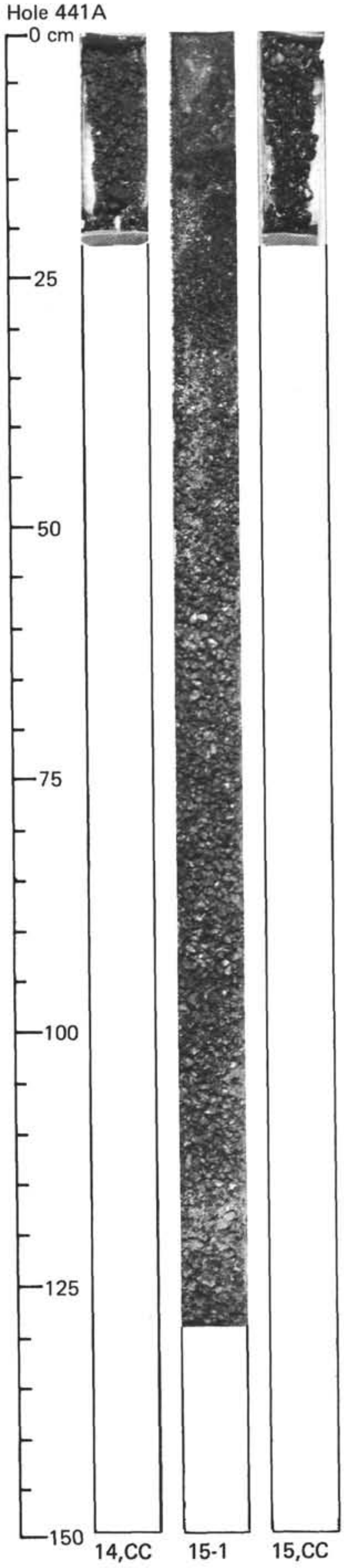

Site 441
0 cm
25
50
75
100
125
150
1-1
1-2
1,CC
2-1
2-2
2-3
2-4
2-5
2,CC
3,CC
4,CC
5,CC
6,CC

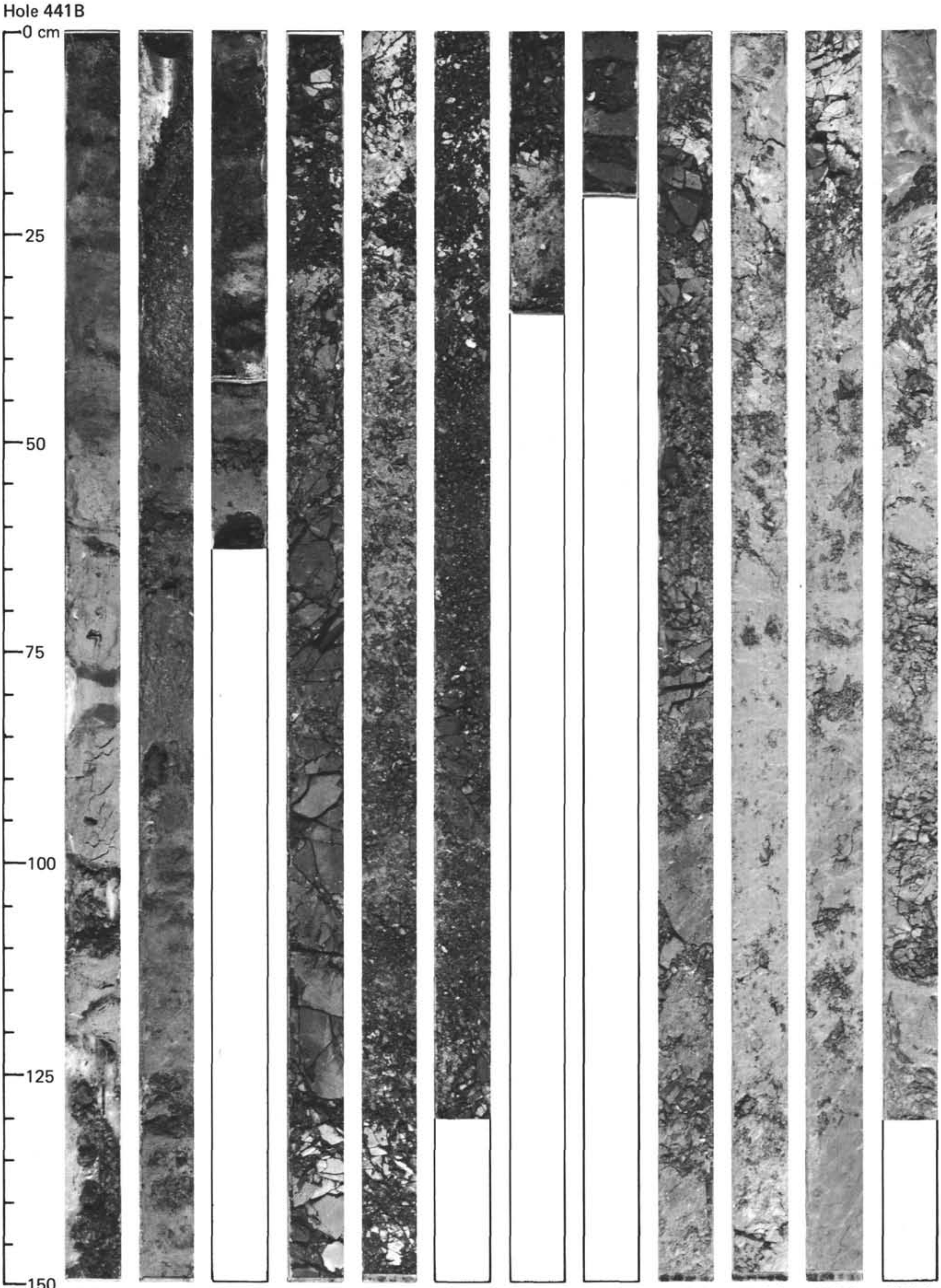

Site 441
0 cm
25
50
75
100
125
150
7-1
7-2
7,CC
8-1
8-2
8,CC
9-1
9-2
9-3
9,CC

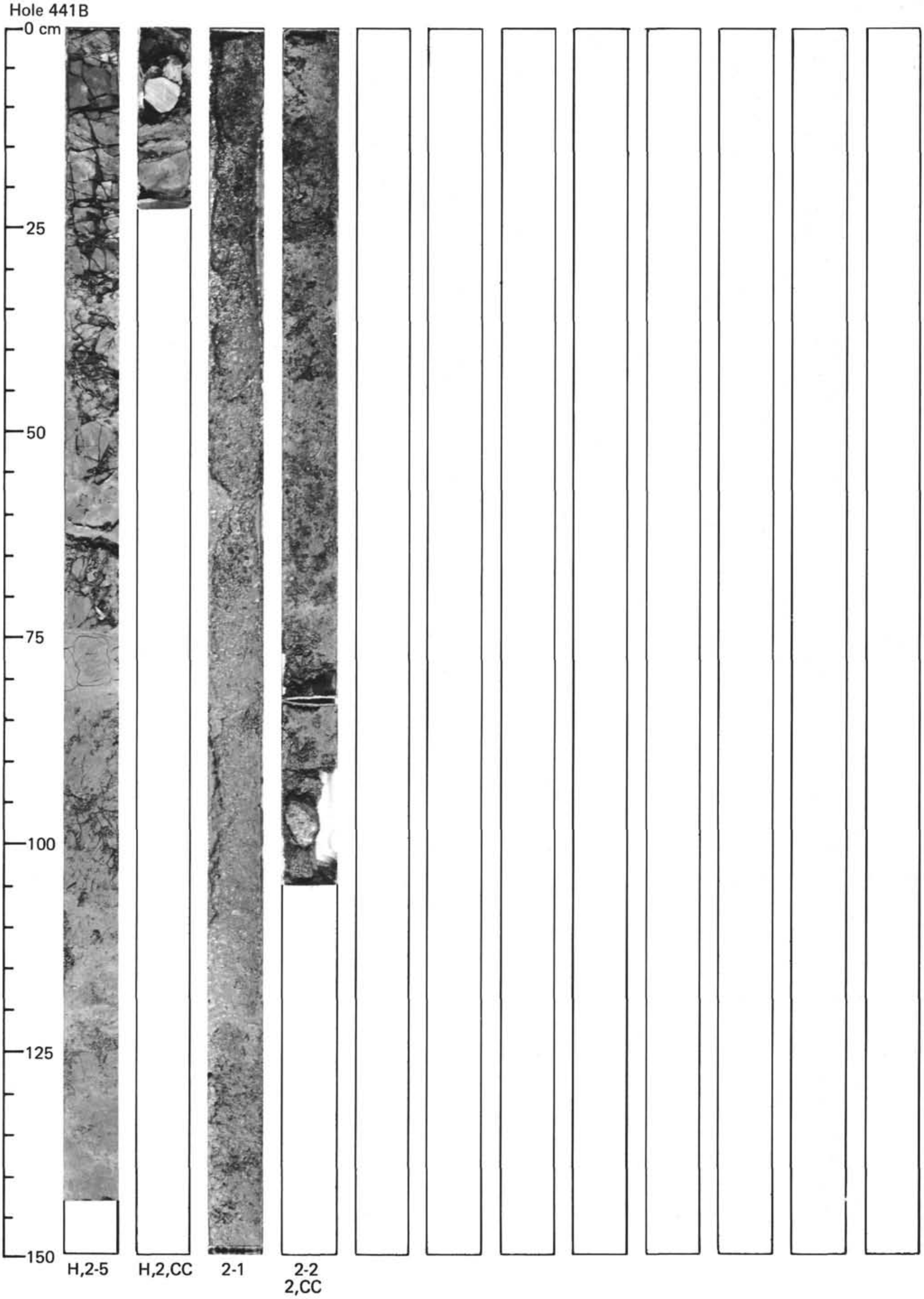

Hole 441A
0 cm
25
50
75
100
125
150
NO RECOVERY
NO RECOVERY
1
2-1
2,CC
3
H,1-1
H,1-2
H,1-3
H,1-4
H,2-1
H,2-2
5-1
5-2


Hole 441A
0 cm
25
50
75
100
125
150
5-3
5,CC
6-1
6-2
6-3
H,3-1
H,3-2
H,3-3
H,3-4
8-1
8,CC
9-1


Hole 441A
0 cm
25
50
75
100
125
150
H,4-1
H,4-2
H,4,CC
10-1
10-2
10,CC
11-1
11,CC
12-1
12-2
12,CC
13-1
13-2
13,CC
14-1


Hole 441A
0 cm
25
50
75
100
125
150
14,CC
15-1
15,CC


Hole 441B
0 cm
25
50
75
100
125
150
1-1
1-2
1-3
1,CC
H,1-1
H,1-2
H,1-3
H,1-4
H,1,CC
H,2-1
H,2-2
H,2-3
H,2-4


Hole 441B
0 cm
25
50
75
100
125
150
H,2-5
H,2,CC
2-1
2-2
2,CC