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SUBMERSIBLE OBSERVATIONS OF POTENTIAL GEOLOGIC HAZARDS ALONG THE MID-ATLANTIC OUTER CONTINENTAL SHELF AND UPPERMOST SLOPE

by

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ABSTRACT

Observations and photographs from the submersible DIAPHUS and seismic profiles were used to investigate potential geologic hazards along the uppermost Continental Slope off the Baltimore Canyon Trough lease area. The sea floor between submarine canyons was characterized by sparse fauna, few changes in the monotonous relief, and little or no evidence of potential geologic hazards such as slumps. Submarine canyons which cut into the upper slope and outer Continental Shelf were found to be biologically and sedimentologically active and small-scale slumps are common along their walls. These submarine canyons may be conduits for pollutants from drilling sites on the shelf to deeper water.

INTRODUCTION

During the summer of 1978, personnel from the U.S. Geological Survey (USGS), using the M/V STATE ARROW and the submersible DSRV DIAPHUS (fig. 1) made detailed observations of potential geologic hazards, especially slumping, along the uppermost Continental Slope off the Baltimore Canyon Trough area from $38^{\circ}00'$N. to $39^{\circ}39'$N. latitude, and $72^{\circ}30'$W. to $74^{\circ}00'$W. longitude (fig. 2, table 1). A number of features identified as sediment slumps have been mapped recently along the eastern Continental Slope of North America (Bennett and others, 1977; Embley and Jacobi, 1977; Knebel and Carson, 1977; McGregor and Bennett, 1977; Slater and others, 1979a). Leasing of deepwater (>200 m) tracts has been delayed because of potential hazards from this slumping

Figure 1

DSRV DIAPHUS–2 MAN SUBMERSIBLE WITH 365M DIVING CAPABILITY.

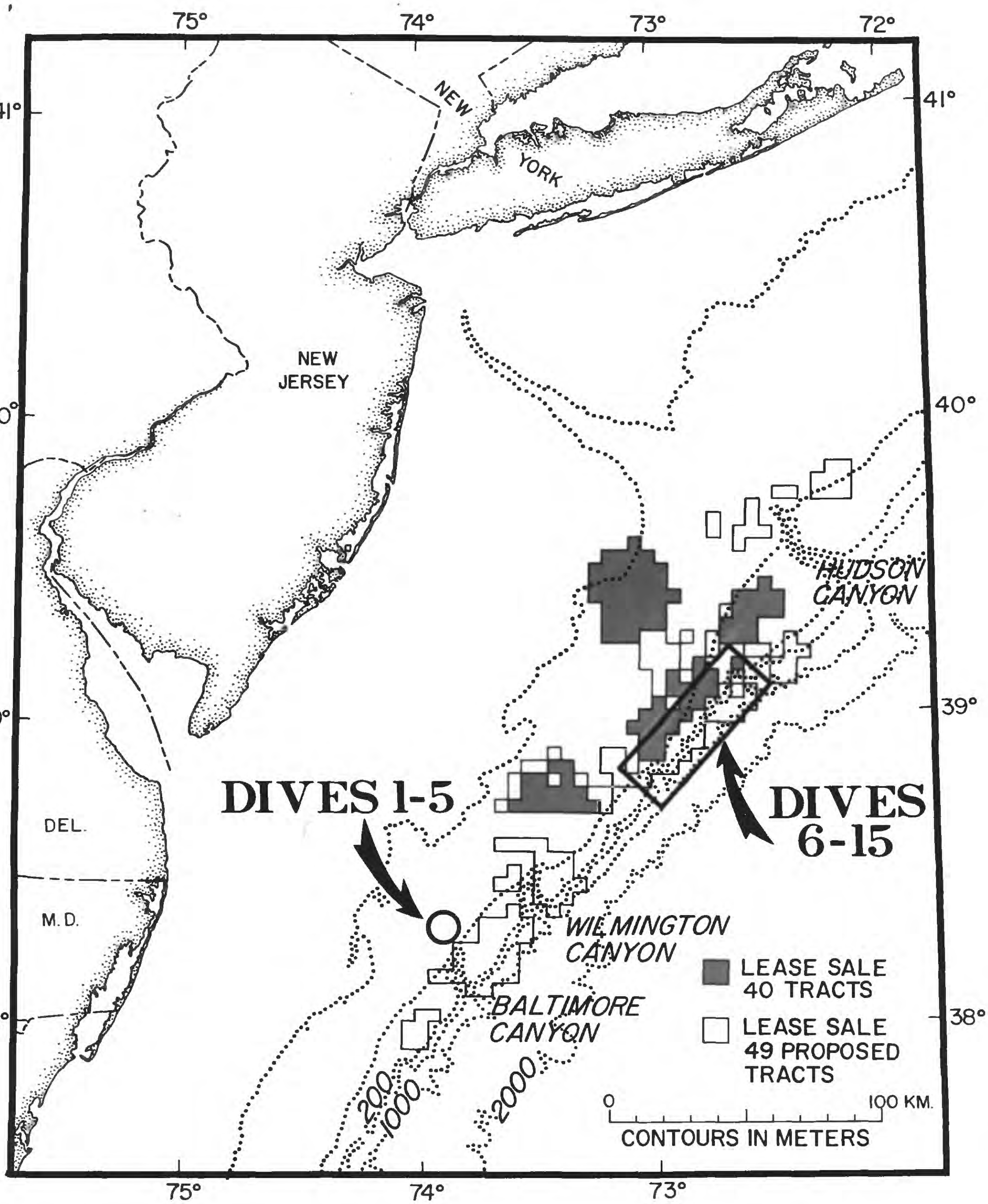

Figure 2. Locations of dive areas on the Continental Shelf and on the uppermost Continental Slope in the mid-Atlantic area.

Table 1. M/V STATE ARROW ship's log.

Date	Time		Weather	Problems
30 July	0000-0700	Transit (Cape May to Baltimore Canyon)	Seas calm, 2-3 foot swells	Ship's steering broke down.
	0700-2000	Diving (Baltimore Canyon)		
	2000-2400	Transit and adjusting sparker (Baltimore Canyon to South Toms Canyon)		
31 July	0000-0630	Transit (Baltimore Canyon to South Toms Canyon)	20-25 knot southeast wind 6-8 foot swells 1-2 foot chop	One engine down. Trouble with location of submersible.
	0630-1100	Fixing ship's engine		
	1100-1400	Diving (South Toms Canyon)		
	1400-1930	Standing by (weather)		
	1930-2400	Sparker survey		
1 Aug.	2400-0600	Sparker survey	2-3 foot swells	
	0600-0800	Transit	Sunny	
	0800-1900	Diving (South Toms Canyon)		
	1900-2100	Sparker survey		
	2100-2400	Sparker survey		
2 Aug.	0000-0730	Sparker survey	2-3 foot swells	
	0730-0800	Transit	Sunny	
	0800-1700	Diving (Carteret Canyon)		
	1700-2000	Sampling (three samples)		
	2000-2400	Sparker survey		
3 Aug.	0000-0730	Sparker survey	2-3 foot swells	Zodiac broke down.
	0730-0800	Transit	Calm, sunny	
	0800-1630	Diving (Carteret Canyon)		
	1630-2400	Transit (Carteret Canyon to Veatch Canyon)		

(Hall and Ensminger, 1979). Most slump features have been discovered and described from seismic profiles with few, if any, direct observations. A seismic profile provides only a two-dimensional section and will not resolve small-scale features or document features on slopes over 15-20^{o}. In order to ascertain whether direct observations of the sea floor could identify such features and aid in the assessment of potential geologic hazards, visual comparisons were made between presumed slump and interslump areas along the uppermost Continental Slope in proposed lease areas of the Baltimore Canyon Trough.

Slumping is the movement *en masse* of sedimentary deposits by gravity and has been considered the major known potential geologic hazard in this area. The form and initiation of a slump are closely dependent on such diverse factors as lithology, geotechnical properties, slope, sediment supply, and seismicity. Slumping occurs in sediments on submarine slopes when shear stresses acting downslope exceed the shear strength of the sediment along any potential surface of failure. A continuous shear stress is exerted by the downslope component of the weight of overlying sediment. The magnitude of the shear stress increases with the slope angle and with the density and thickness of overlying sediment. Slumping can occur on submarine slopes whose declivity is as little as 1^{o} (the upper Continental Slope off New Jersey averages 5-8^{o} with steeper slopes along submarine canyon walls). The shear strength of the sediment is a complex function of many parameters, including grain size, grain packing, mineralogy, depth of burial, rate of deposition, degree of consolidation, and conditions affecting the escape of pore water at failure. Sediments rich in coarse silt and very fine sand similar to those in the study area frequently have low shear strengths. During slumping, there may be compression at the toe of a slump and tension at its head. Compression raises the seabed by thrusting or folding (hummocky sea floor); tension lowers the seabed, often by faulting which exposes part of the slide plane at the sea-floor surface (slump scars). Hummocky sea floor and slump scars should be identifiable from submersibles.

Other possible hazards to petroleum exploration and production that could be observed *in situ* from a submersible include gas seeps, sand waves, collapse craters, and evidence of strong currents. None of these were observed during this project.

METHODS

Direct observations from small submersibles of the Continental Shelf and upper Continental Slope, including submarine canyons that cut the slope off the northeastern United States, have been made since 1973 (Uzmann and others, 1977; Stanley and Freeland, 1978; Warme and others, 1978; Folger and others, 1979; Slater and others, 1979b). Dive sites for this study (table 2) were selected from these reports, from previously run seismic-reflection lines, from a bathymetric map constructed for this project (fig. 3) using bathymetric data recently acquired by the USGS (Hall and Ensminger, 1979), and from 18 seismic-reflection (mini-sparker) lines run during the cruise (fig. 3). Many of the possible slump features that have been observed were in water depths too deep for the submersible DIAPHUS (maximum diving depth 365 m), but some were within the submersible's range. Fifteen dives made in the study area between July 30 and August 3, 1978 (table 2) produced more than 1,100 35-mm photographs and nearly 2 hours of videotape to document the present sea floor. These photos and tapes are on permanent file at the U.S. Geological Survey, Quissett Campus,

Table 2. DIAPHUS dive data

Dive	Date	Time down	Time up	Total time (min)	Position start	Position finish	Depth (m)	Visibility (m)	Pilot observer	Film
1	30 July	1004	1059	55	38°05´N.	38°04´W.	125-130	5	Hickey	35 mm (74)
					73°54´N.	73°54´W.			Aaron	video (2 min)
2	30 July	1142	1250	68	38°03´N.	38°03.43´W.	189-216	5	Barksdale	35 mm (0)
					73°51´N.	73°51.88´W.			Twichell	video (2 min)
3	30 July	1354	1510	76	38°06.3´N.	38°06.35´W.	125	5	Hickey	35 mm (109)
					73°53.4´N.	73°53.45´W.			Bryden	video (5 min)
4	30 July	1554	1741	107	38°07.1´N.	38°06.80´W.	213-365	4	Barksdale	35 mm (20)
					73°52´N.	73°51.67´W.			Phipps	video (20 min)
5	30 July	1835	1928	53	38°05.38´N.	38°05.06´W.	131	6	Hickey	35 mm (0)
					73°53.34´N.	73°53.22´W.			Butler	video (0 min)
6	31 July	1059	1357	178	39°03.75´N.	39°02.7´W.	131-365	4	Barksdale	35 mm (56)
					72°46.40´N.	76°46.3´W.			Slater	video (15 min)
7	1 Aug.	0806	1040	156	39°02.89´N.	39°02.58´W.	195-365	7	Hickey	35 mm (120)
					72°45.13´N.	72°45.81´W.			Twichell	video (3 min)
8	1 Aug.	1127	1341	134	39°02.33´N.	39°02.09´W.	200-314	6	Barksdale	35 mm (120)
					72°46.64´N.	72°46.62´W.			Bryden	video (9 min)
9	1 Aug.	1455	1638	104	39°01.87´N.	39°01.80´W.	186-299	7	Hickey	35 mm (200)
					72°47.55´N.	72°47.56´W.			Hampson	video (5 min)
10	1 Aug.	1730	1858	88	39°02.52´N.	39°02.32´W.	305-320	6	Barksdale	35 mm (11)
					72°45.10´N.	72°44.91´W.			Aaron	video (0 min)
11	2 Aug.	0816	1142	206	38°54.04´N.	38°53.31´W.	210-365	7	Hickey	35 mm (200)
					78°54.24´N.	72°52.87´W.			Phipps	video (30 min)
12	2 Aug.	1403	1645	162	38°55.27´N.	38°54.4´W.	150-327	8	Barksdale	35 mm (47)
					72°54.82´N.	72°54.8´W.			Slater	video (5 min)
13	3 Aug.	0816	1045	149	38°54.67´N.	38°54.24´W.	260-365	10	Hickey	35 mm (60)
					72°53.12´N.	72°53.31´W.			Twichell	video (5 min)
14	3 Aug.	1145	1415	150	38°56.93´N.	38°56.34´W.	210-345	7	Barksdale	35 mm (115)
					72°50.76´N.	72°51.35´W.			Aaron	video (6 min)
15	3 Aug.	1502	1618	76	38°59.96´N.	38°58.91´W.	210-300	8	Hickey	35 mm (26)
					72°49.32´N.	72°49.78´W.			Hampson	video (3 min)

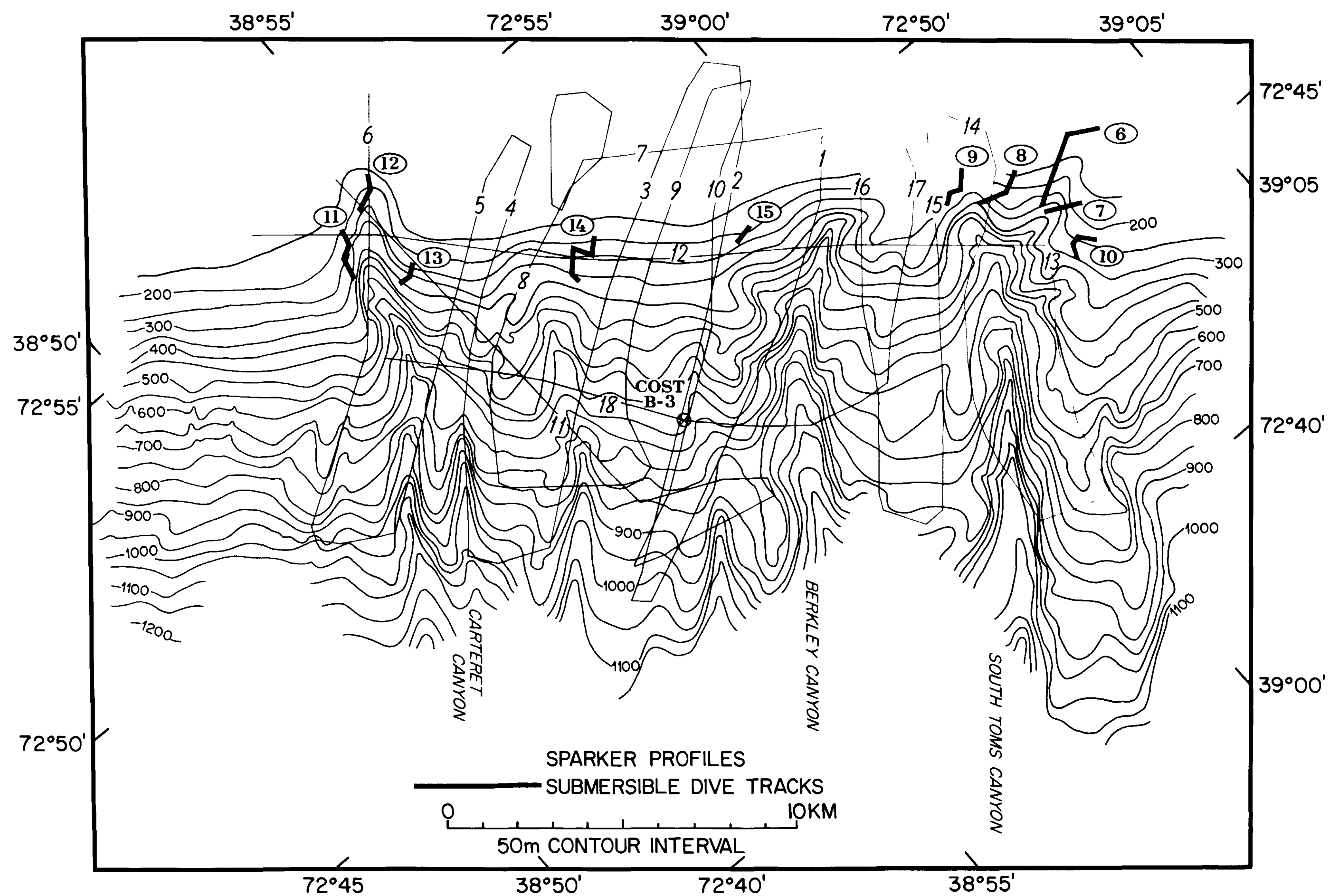

Figure 3. Bathymetry locations of dives 6-15 and minisparker profile locations in the study area on the mid-Atlantic upper Continental Slope. See figure 2 for study area locations.

Woods Hole, Mass., 02543. This report's written descriptions of observations made on each dive were compiled from these pictures, as well as from audiotapes made by the seven different observers during the nearly 30 hours underwater.

Three sediment samples were obtained from the STATE ARROW with a Van Veen grab to identify the sediment composition, and approximately 250 km of seismic-reflection (sparker) profiles (fig. 3) were gathered in the study area to define the subsurface. The seismic-reflection lines were run at night while the submersible batteries were being recharged. The thickness of the Pleistocene cover on the upper slope (Robb and others, 1981) and the limited depth range of the DSRV DIAPHUS indicate that the submersible observations were all made on Pleistocene aged material.

Navigation of the STATE ARROW used continuous Loran-C autotracking which is generally accurate to within 200 m. DIAPHUS's position relative to STATE ARROW was determined from the submersible's depth and its slant range and bearing from STATE ARROW. An acoustic pulse emitted every 2 seconds from DIAPHUS was received on STATE ARROW via a hand-held directional hydrophone. With relation to STATE ARROW, the navigation system is generally accurate to about 100 m.

DIVE DESCRIPTIONS

Dives one, two, and three

Dives one, two, and three were made near the edge of the Continental Shelf north of Baltimore Canyon near 38°06'N., 73°53'W. on 30 July 1978 (fig. 2) to find and describe large depressions detected in this area by sidescan sonar (Hall and Ensminger, 1979). Although visibility was very good (commonly 5-8 m) only one saucerlike depression

2 m in diameter and about 30 cm deep was observed. From comparison with similar depressions seen in previous dives associated with other studies, (R. A. Cooper, personal communication, 1980) such depressions are probably biologic in origin, most likely lobster or tilefish burrows. All three of these dives were in water depths between 120-130 m (figs. 4, 5, 6). The sea-floor sediment appeared to be silty sand containing many mollusc fragments. However, grain-size analyses from grab samples revealed the sediment to be moderately well sorted, slightly gravelly sand with a mean size between medium and coarse sand (R. A. Cooper, personal communication, 1980). The sea-floor color underwater is tan to greenish tan. A considerable amount of shell fragments, crab carapace fragments, and bivalve shells, mainly concave upward were visible on the sea floor. There was also coral debris from the small solitary cup coral *Desmosmilia*.

The sea floor has a lumpy appearance with numerous small conical mounds 5-15 cm high (polychaete worms?) and small depressions 15-30 cm across covering the surface. Animal tracks and trails are extremely common and are proof of considerable ongoing biological activity in the area. There was little evidence of any current activity except for occasional faint symmetrical ripple marks with crestlines parallel to the shelf break. They were probably formed by storm waves and subsequently smoothed by biological activity.

Dive four

Dive four, on the upper slope near Baltimore Canyon (fig. 2), started at 213 m and continued downslope to 365 m (fig. 7). The Benthos 35-mm camera failed after 20 pictures but approximately 20 minutes of videotape were taken to document the sea floor.

The 4-5° sloping sea floor at 213 m was well packed, highly

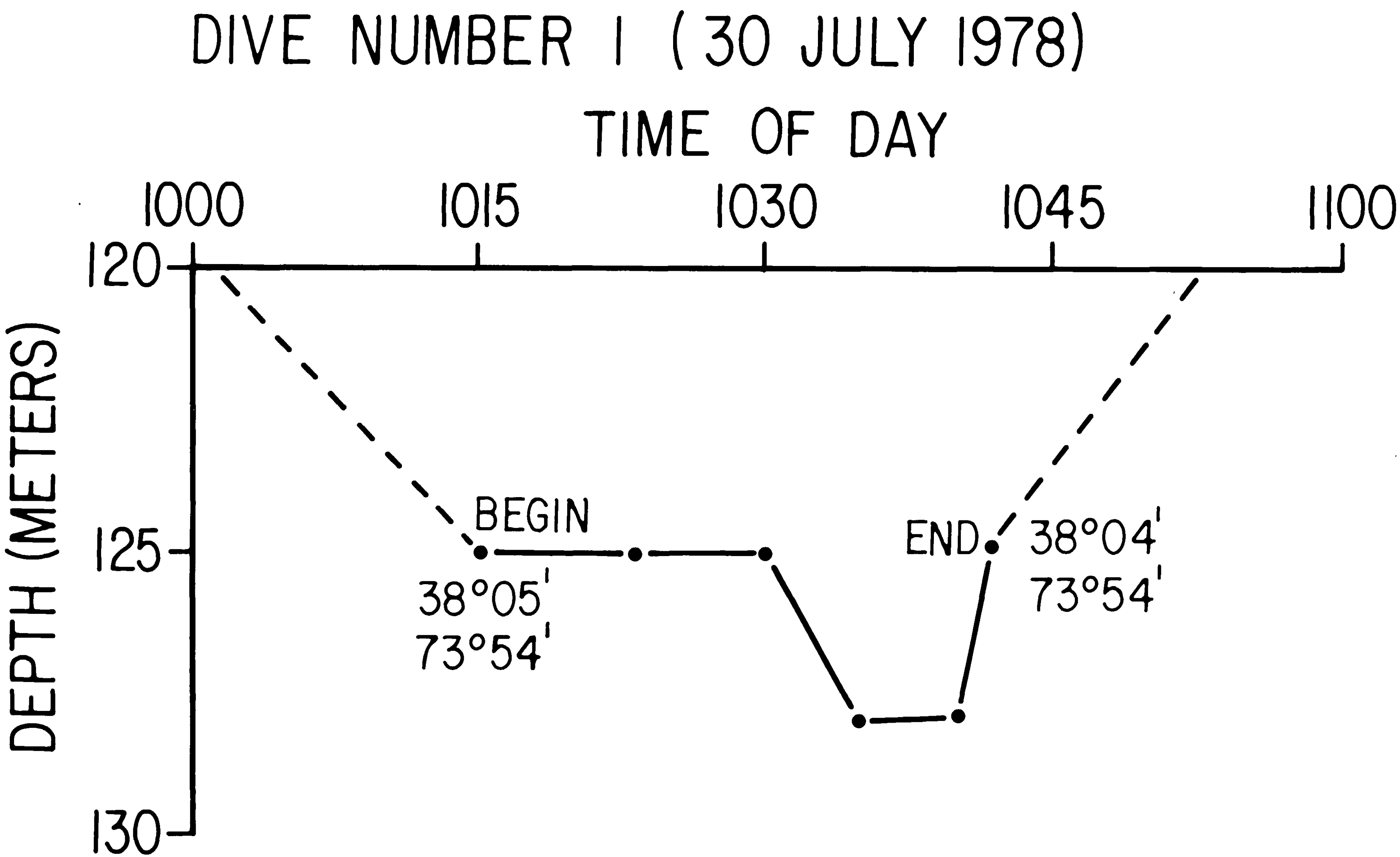

Figure 4. Dive 1 - Time vs. depth.

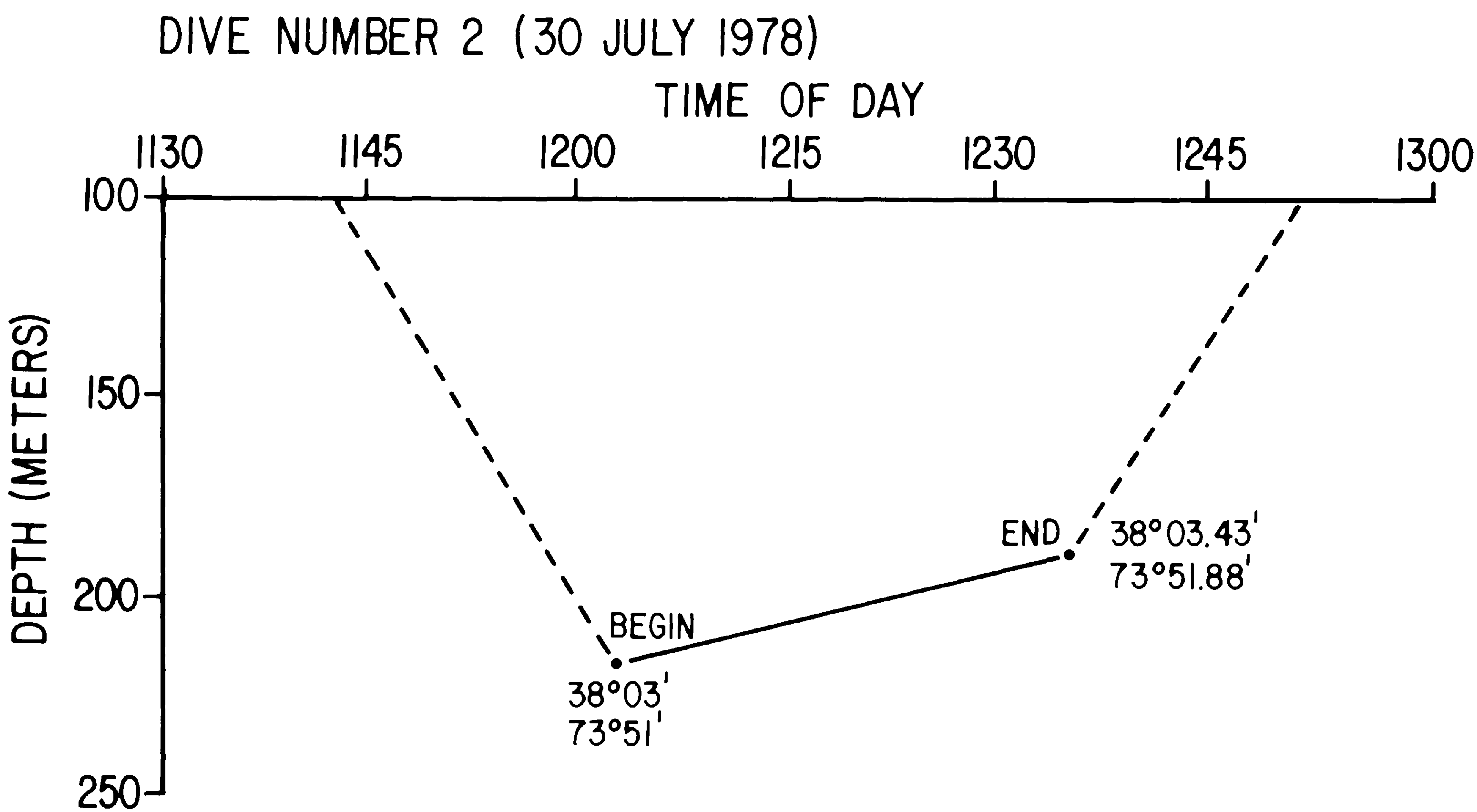

Figure 5. Dive 2 - Time vs. depth.

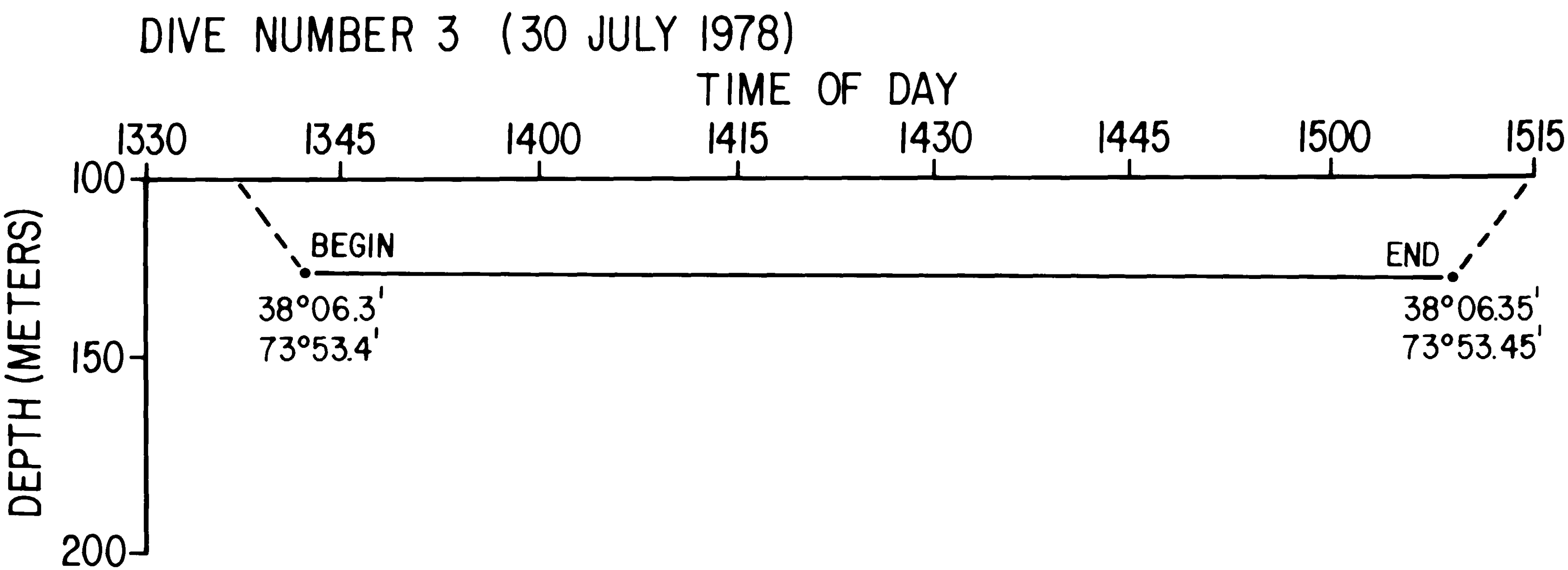

Figure 6. Dive 3 - Time vs. depth.

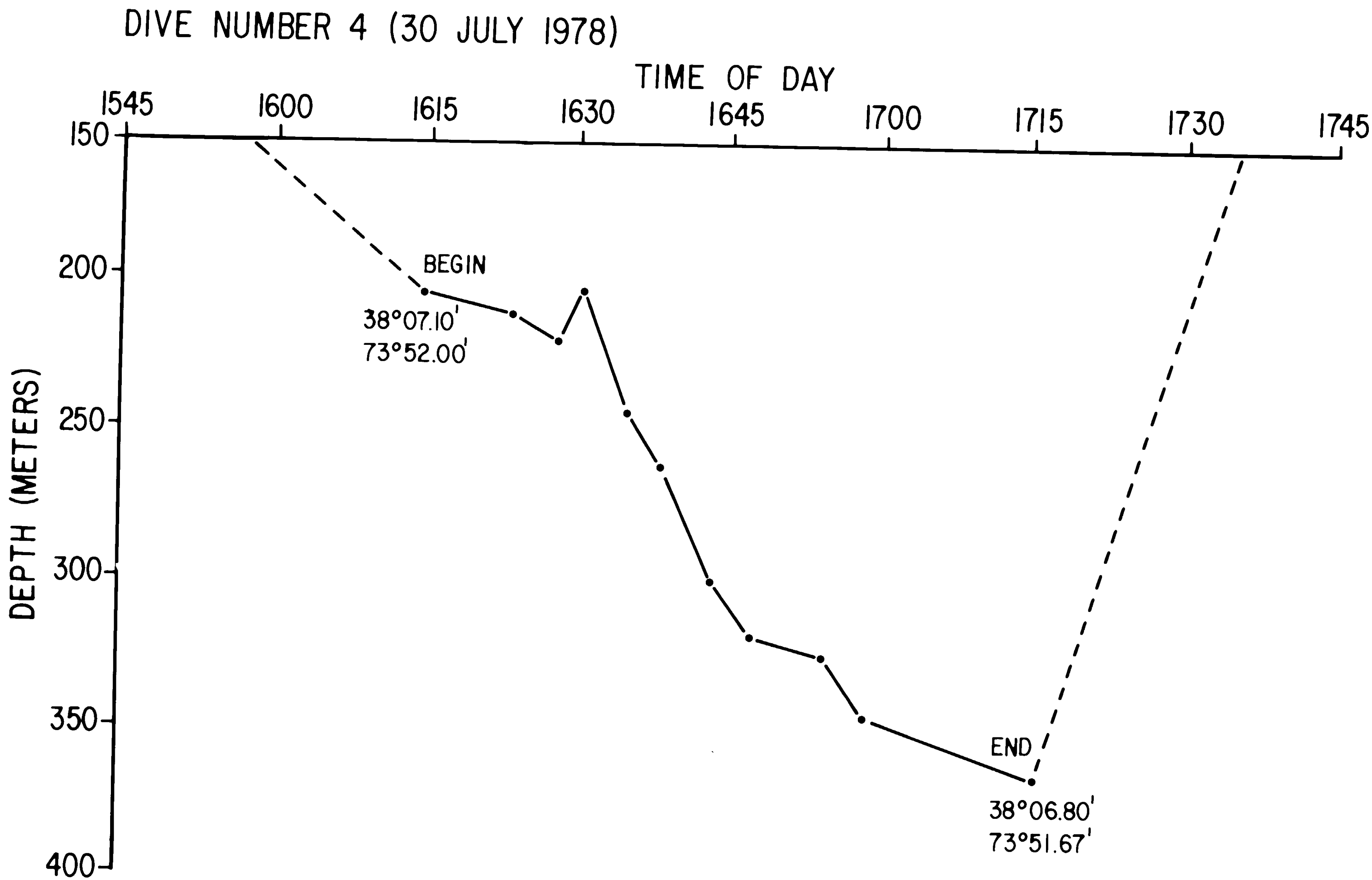

Figure 7. Dive 4 - Time vs. depth.

burrowed olive-green silty sand formed into mounds and burrows with abundant mollusc and crab skeletal debris on the surface. Some small areas (approximately 3 cm in diameter) had coarser material that probably was brought up from the subsurface by burrowing organisms. Some of the mounds were formed by polychaetes, but others were crab burrows as evidenced by tracks around the openings.

The sea floor at 244 m, resembled that at 213 m, but the slope had increased to 7-8°. Crabs, polychaetes, and fish with occasional squid, hermit crabs, black-bellied rose fish, and sea pens dominated the epifauna. At 274 m, the sea floor was smoother with less bioturbation than in shallower depths, but the sediment remained unchanged. At 290 m, the slope increased to more than 10°.

The sea floor leveled out at 305 m. There was no indication of slumping or any abrupt changes in slope during this segment of the dive. Here the bottom was firm, silty, and bioturbated with no signs of current activity. Crab tracks were clearly visible. Hake were lying in depressions of 10 cm diameter and 3 cm depth. A few shrimp were observed at 305 m.

At 359 m, the slope again steepened to more than 15°, in an 080° direction, and the sediment became siltier and softer. The submersible's skids dug into the sediment about 8 cm. Red crabs were common at this depth and an occasional octopus was observed. Lighter gray mud seen in burrows had a different texture and seemed firmer than the surface sediment which was fine greenish silt with some flaky material that might have been mica. The submersible and animals easily stirred up this surface sediment causing clouds of sediment to rise up into the water column. When the submersible backed off or ran downslope, small slumps approximately 30 cm across and a few centimeters deep appeared in the surface sediment. The sea floor was pocked with burrows and 15-30 cm deep depressions of probable biological origin. Dive four ended at 365 m, the submersible's maximum safe depth.

Dive five

Dive five was a test dive for the submersible and no scientific observations were made.

Dive six

This was the first of six planned dives in the head of South Toms Canyon (fig. 3). Detailed observations and documentation of the sea floor in this area were considered important because this canyon is one of the major distributaries from lease blocks of the Baltimore Canyon Trough area into deep water. This documented record of the area could prove valuable for comparison with conditions after oil drilling starts.

Dive six was along the northern flank of the head of South Toms Canyon ($39^{o}03'$N., $72^{o}46'$W.)(fig. 3) and covered a depth range of 131-365 m (fig. 8). The submersible landed at a depth of 131 m on a gray-green, silty sand surface covered with iron-stained shells and pebbles which may have been subaerially exposed during the Pleistocene lower stands of sea level (fig. 9A). The submersible was maneuvered along a course of 180^{o} with a slight current from astern. Very little burrowing of the surface sediment was observed in this area except for occasional polychaete holes. Many crab tracks were observed. Apparently there was slight current action in this area because consistent faint ripple mark patterns (with crestlines consistently oriented northeast-southwest) were noted on the sea floor to a depth of 170 m but were observed only intermittently at deeper depths. The ripples were about 2-3 cm high and 5-8 cm in wave length with only occasional tracks and trails on them (fig. 9B). The few pebbles and

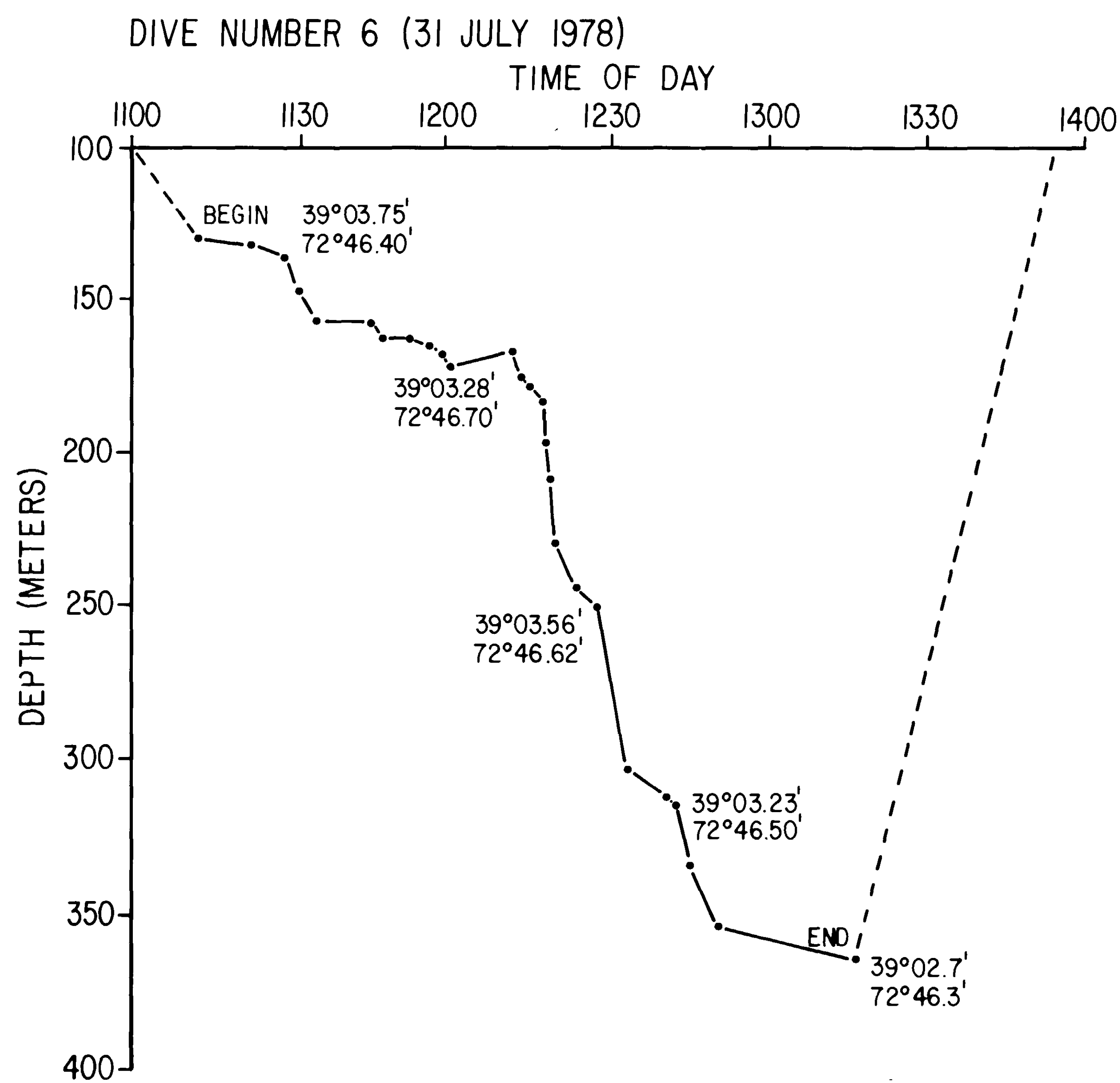

Figure 8. Dive 6 - Time vs. depth.

A 125M–OUTER CONTINENTAL SHELF. SLIGHTLY GRAVELLY SANDY SEDIMENTS WITH MOLLUSCAN DEBRIS AND GALATHEID CRABS (MUNDIA SP) BOTTOM OF PHOTOGRAPHS APPROXIMATELY 1.75M ACROSS

B 150M–GRAY-GREEN SILTY-SAND. 3CM HIGH RIPPLES WITH 5-7CM WAVELENGTHS

C 221M–TYPICAL BIOTURBATED OLIVE-GREEN SILTY SEA FLOOR OF THE UPPER CONTINENTAL SLOPE. SLOPE LESS THAN 5°

D 159M–25CM SCARP TRENDING PERPENDICULAR TO SLOPE. ONE OF SEVERAL SCARPS SPACED 6-7M APART

Figure 9. Bottom photographs of the outer Continental Shelf and upper Continental Slope near South Toms Canyon.

cobbles observed on the sediment surface were completely ringed by scour marks. These scours are of probable biological origin as lobster and hake are commonly seen lying in these depressions. A gray-green clay substrate was observed about 3 cm below the surface in many of these scour marks.

At a water depth of 159 m, the submersible crossed over a series of small (25-cm high), downslope-facing scarps about 4-7 m apart, trending perpendicular to the slope (fig. 9D). Ripple marks with crestlines parallel to the scarps were superimposed on the scarp surfaces. Very little animal life or evidence of biological activity was observed in this area. Below the scarps it leveled off for a short distance before it dropped at a 2 m scarp down to another level plateau at 162 m which was covered with silty sand. This plateau had numerous sea pens but none of the coarse sand and shell hash common in shallower depths. Man-made debris was common, including bottles, wire, gloves, a book, nets, cans, and wood. Some of the debris possibly was transported from the shelf but most of it was probably thrown overboard by fishermen who heavily fish this canyon area. Currents appear to concentrate the debris in depressions. Because of the limited visibility from the submersible (less than 8 m) it was not possible to determine whether the apparent depressions were channel crossings or truly holes. The observer dug into the surface sediment on this plateau with the submersible's hydraulic arm, but could not find the clay substrate commonly seen elsewhere. The sediment here was mainly greenish silt intermixed with some sand. The surface shell hash reappeared near the top of a 10^{o} slope at a water depth of 168 m. It covered the slightly rippled silty sand sediment to a water depth of 220 m.

Below 220 m, the sediment had little shell debris on its surface and was siltier. As the submersible descended below 275 m, the slope was still about 10° and the sediment became still siltier.

At a water depth of 335 m, the sea floor leveled off again and the very silty sediment was formed into mounds, depressions, and burrows. A very large amount of man-made debris was observed here including dozens of cans, bottles, wires, nets, and wood. Hake commonly were curled up in small sea-floor depressions. There was a definite increase in infauna activity below the 310 m contour where the surface sediment was obviously silt and not sand. The dive ended at 365 m, the submersible's maximum depth. Fifty-six 35-mm photos and 15 minutes of videotape document this dive.

Dive seven

Dive seven investigated the north wall of South Toms Canyon (fig. 3) in water depths from 195-366 m (fig. 10). At 195 m the sea floor was tan sand with abundant coarse mullusc debris. There was a slight current from 320° when the submersible started moving over the bottom on course 165°. Digging into the sea floor with the submersible's hydraulic arm revealed that a thin layer of silt covered the sand. This silty layer is constantly resuspended in the water column by crabs, fish, and other vagrant benthic animals but it quickly resettles. Many small sea-floor depressions, 3-4 cm across, probably were formed by crabs and hake. There were occasional pebbles and large clam shells lying concave upward upon the surface of the 3-4° slope. Normally, currents would flip these shells over; hence, their concave upward position suggests that there must be little current activity or that biological activity turns them up again. An abandoned lobster trap with lobster and fish around it was observed at 213 m. As the submersible continued downslope there was less shell hash but still many

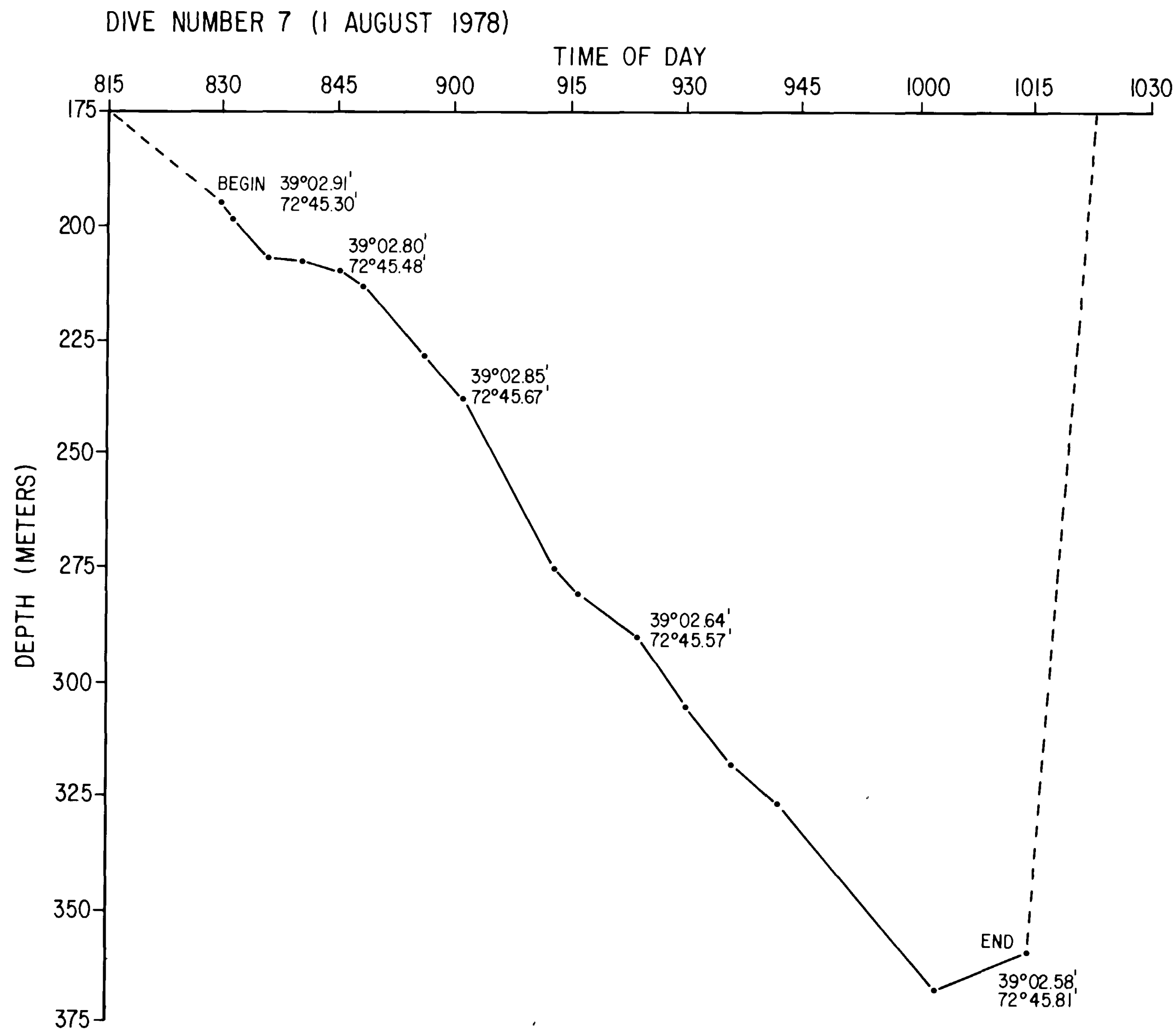

Figure 10. Dive 7 - Time vs. depth.

sea pens, crabs, and small pebbles in the surface sediment.

At 238 m, the slope was a little steeper and the sediment was siltier with very little shell hash. Basket starfish, fish, sea anemones, and crabs were common. Between 200 and 249 m many crabs and fish were seen lying in shallow depressions on the sea floor. At 275 m, there were more mounds and depressions than observed in shallower depths with tracks and trails crisscrossing them and many crab carapaces lying on the sediment. From 250-280 m there were no current-indicating bed forms on the sea floor. Most of the bottom irregularities were due to biological activities. In general, the epifaunal density at this location was somewhat lower than at the comparable depths of dive six even though the sediment was similar. The dive was terminated at 365 m after 125 35-mm photographs and 3 minutes of videotape were shot along this traverse.

Dive eight

Dive eight at 39°02.46′N., 72°46.65′W. covered the depth interval from 200-314 m (fig. 11) down the axis of South Toms Canyon (fig. 3). Sea-floor sediments were uniformly silt or silty sand throughout the dive and no mollusc shell debris or ripple marks were seen. Small polychaete(?) mounds, many with fecal matter deposited around the tops, and hake depressions were common. Some hake were observed resting on their sides covered with sediment except for their heads which protruded through the sea-floor surface. Several large shallow depressions, 50-75 cm across, were observed on the sea-floor surface. These depressions were probably scoured out by lobsters for their protection as many similar depressions with lobsters in them have been observed on other submersible dives. Digging into the surface sediment with the submersible′s hydraulic arm revealed a hard substratum underlying about

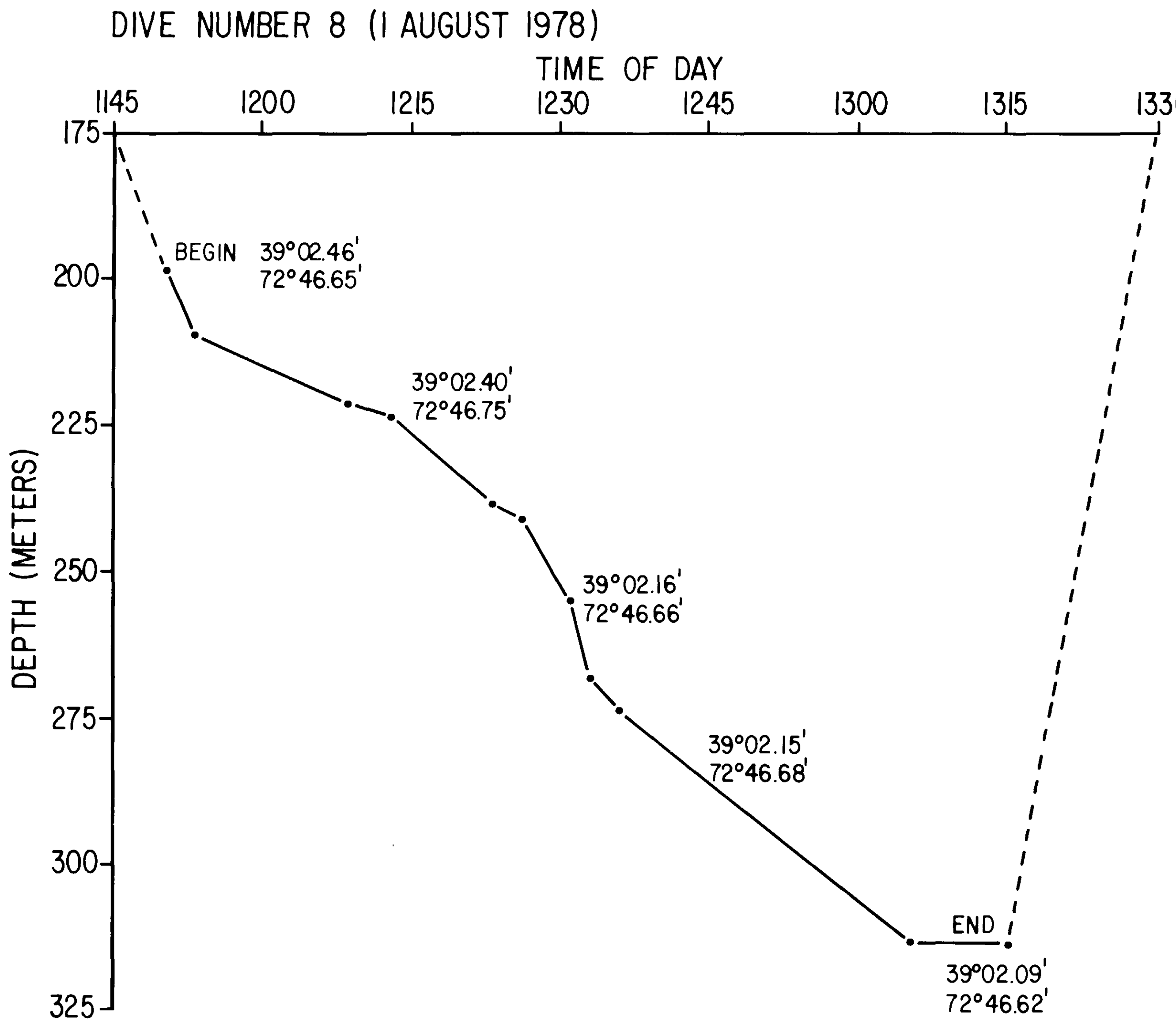

Figure 11. Dive 8 - Time vs. depth.

3-4 cm of silty sand. This gray clayey material was difficult to sample with the hydraulic arm so no specimens were obtained during this series of dives. The observer reported that the submersible crossed over a series of large deep depressions in this area between 200 and 249 m. These may have been steps in the topography as the large plexiglass bubble nose of the submersible distorts the observer's view into a fisheyelike picture. Bottles and other man-made debris were concentrated in this area. Burrows are fairly common in the depth range from 250-299 m. The dive ended at a water depth of 314 m. The observer on this dive was a biologist, and the geological information was obtained from 125 35-mm photographs and nine minutes of videotape.

Dive nine

Dive nine took place at 30°02'N., 72°47.5'W. on the southern flank of the head of South Toms Canyon (fig. 3) and traversed the bottom between depth of 186-299 m (fig. 12). The sea-floor sediments were mostly silt or silty sand with some mollusc debris, particularly between 240-265 m depth. Tracks and trails were numerous on the sediment surface below 265 m.

The submersible started its traverse at a depth of 186 m on course 135°, where there was no perceptible slope even though the submersible descended about 2 m/min. The sea floor between 200-249 m in depth was very bumpy and burrowed.

A course change to 100° at 200 m water depth headed the submersible straight down a slope of about 5°. There was no current during the dive, but a faint sediment ripple pattern oriented north-south was observed on the sea-floor surface.

At water depths greater than 274 m, there were a few mounds on the relatively smooth sea floor which continued to slope about 5° throughout

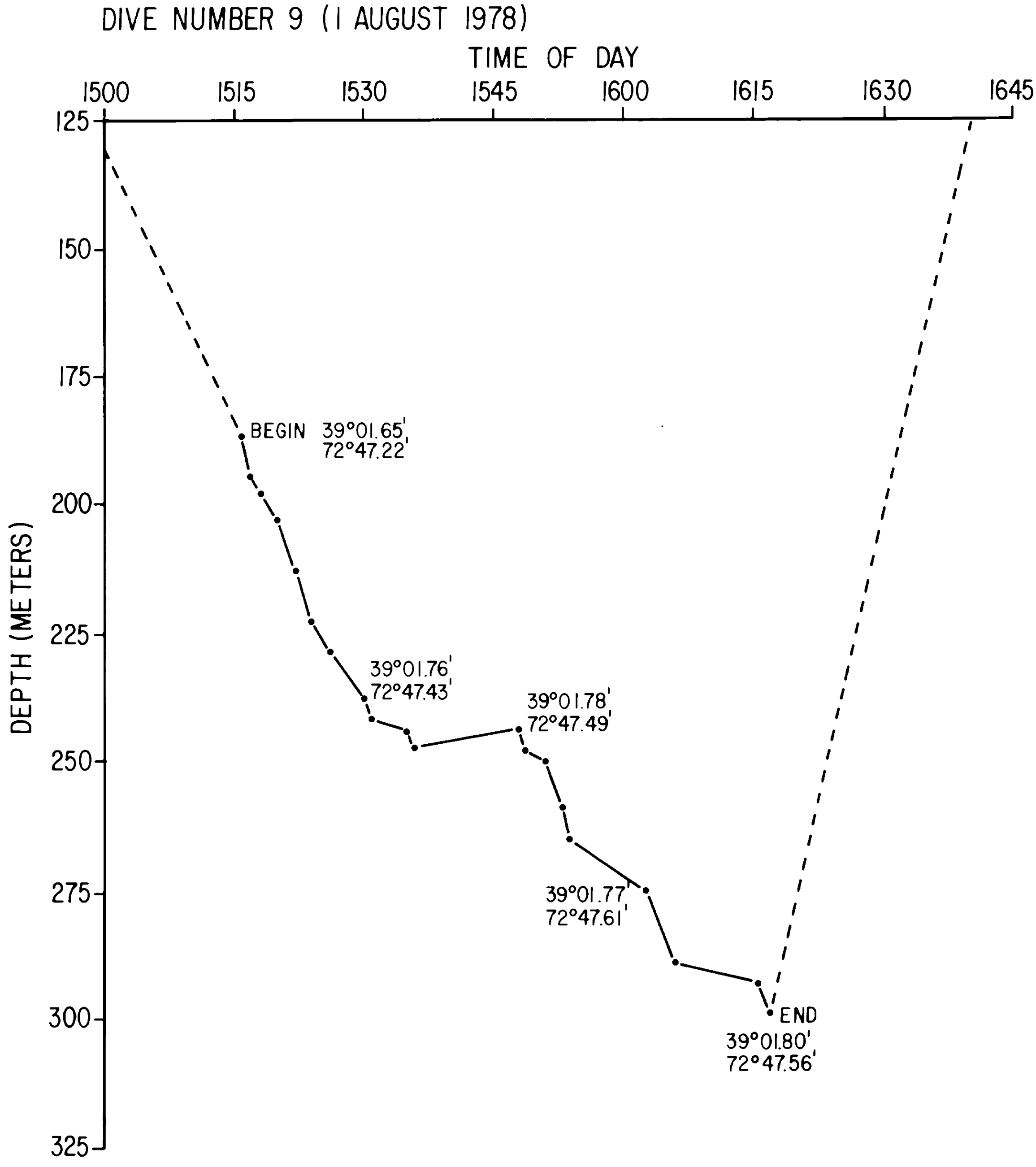

Figure 12. Dive 9 - Time vs. depth.

the dive.

The pilot had to gradually adjust the submersible's course to the east during this dive in order to stay perpendicular to the slope. The sea-floor sediment was mainly silt over the entire traverse; local zones of concentrated fauna were observed along with other zones where no life was apparent. The dive was terminated at 299 m. Two hundred 35-mm photographs and 5 minutes of videotape were taken of the sea floor to document this area.

Dive ten

This late afternoon dive investigated the northern side (39°02.52'N., 72°45.10'W.) of the head of South Toms Canyon (fig. 3). The submersible landed on the sea floor at a depth of 305 m (fig. 13) on light-colored silty sediment which was extensively burrowed. Surface relief was about 15 cm with numerous mounds and depressions. The bottom was covered with tracks and trails. Probing the sediment with the hydraulic arm revealed that only the top few centimeters of the sediment were unconsolidated and that the sediment a few centimeters below the surface was much firmer. There was no evidence of bottom currents. At a heading of 180° the submersible ran over the same type of sea-floor surface for an hour with no perceptible changes. The dive had to be terminated at 320 m because of low battery voltage. No videotape and only 11 35-mm pictures were recovered from this dive.

Dive eleven

Dives 11, 12, and 13 took place in the head of Carteret Canyon to compare the biota and geology of the of the area with observations in South Toms Canyon from dives 6, 7, 8, 9, and 10. Carteret Canyon is another possible major conduit for drilling mud, oil, and other substances which might escape from drilling operations on the outer

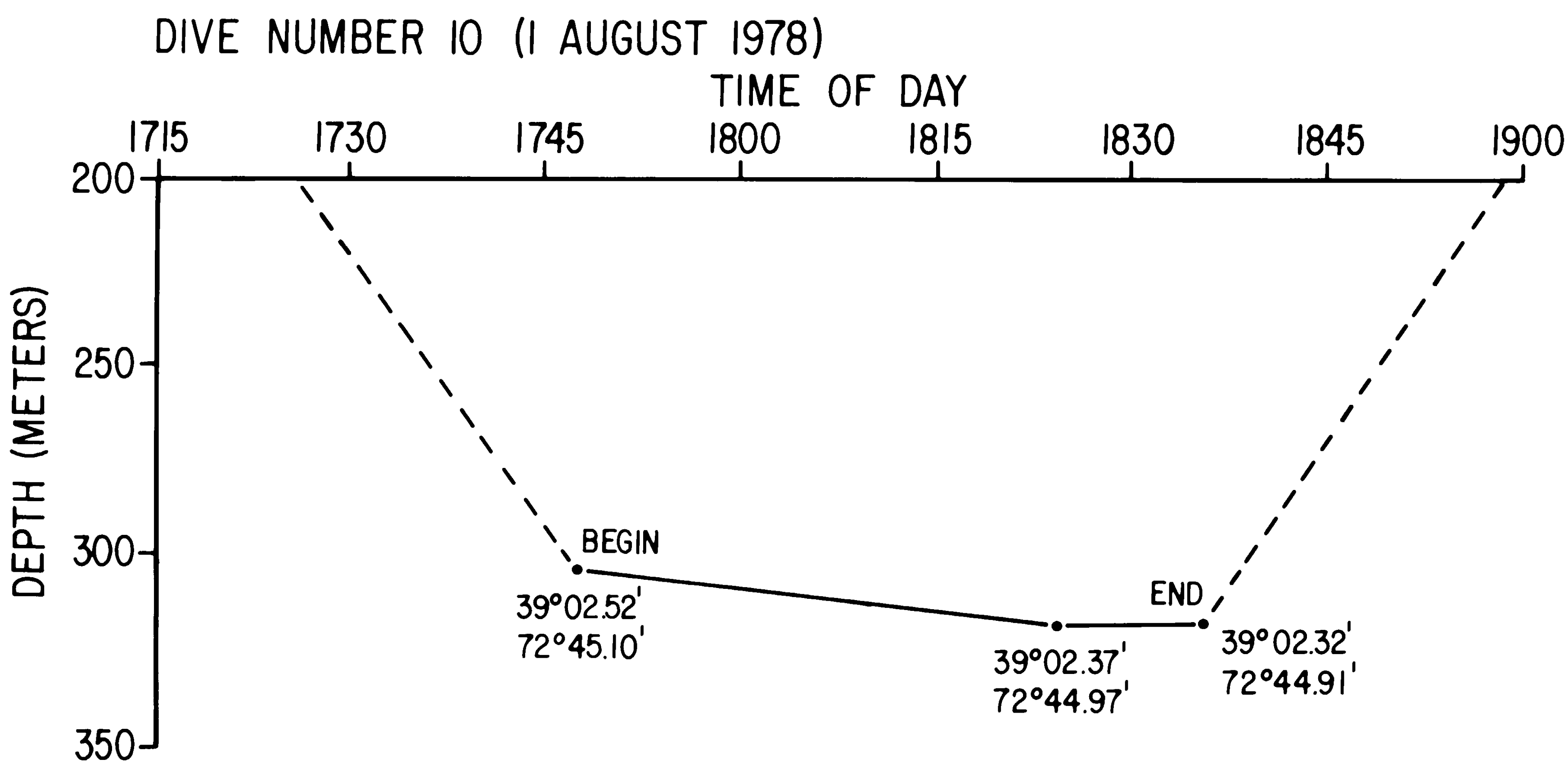

Figure 13. Dive 10 - Time vs. depth.

Continental Shelf in the proposed Baltimore Canyon Trough lease area.

Dive 11 (38°54.04′N., 78°54.24′W.) was on the south flank of Carteret Canyon (fig. 3) from water depths of 210-365 m (fig. 14). The sea floor down to a water depth of about 290 m was silt or silty sand with numerous tracks and trails on its surface. Below a water depth of 290 m, there were clay outcrops having only a thin covering of surficial sediment. The dive started at a water depth of 210 m where the sea floor was covered with symmetrical ripples (10 cm wave length, 1 cm high) and shelly sand covered with numerous tracks. The submersible′s skids penetrated only about 1 cm into the thin surface sediment. The current during the dive was approximately 10 cm/s in a direction of 180°, even though the sediment ripple marks indicated a former current direction of about 090°. There were many fishing trawl marks in this area (fig. 15A) cutting through the ripple marks which were only local, not continuous. The sea floor sloped only slightly along the submersible′s course of 100°. As the water depths increased, the mottled, grayish-brown sediment became finer grained and some bioturbation of the surface sediment became evident (fig. 15C). The submersible stayed at a depth of 213 m for over 30 minutes on the course 100°. Most of the sea-floor features had been obscured or completely destroyed by trawl marks in the interval between 210 and 249 m.

Lighter colored sand underlay a thin surface coating of brown silt giving a mottled look to the sea floor in the 250-290 m depth interval. Occasional 1- to 2-m-diameter depressions about 30 cm deep were observed (lobster shelters?).

At a depth of approximately 290 m, the surface sediment became finer. The sea floor steepened (fig. 15B) and dropped away at an angle of approximately 45° for about 12 m, then leveled out to a flat surface

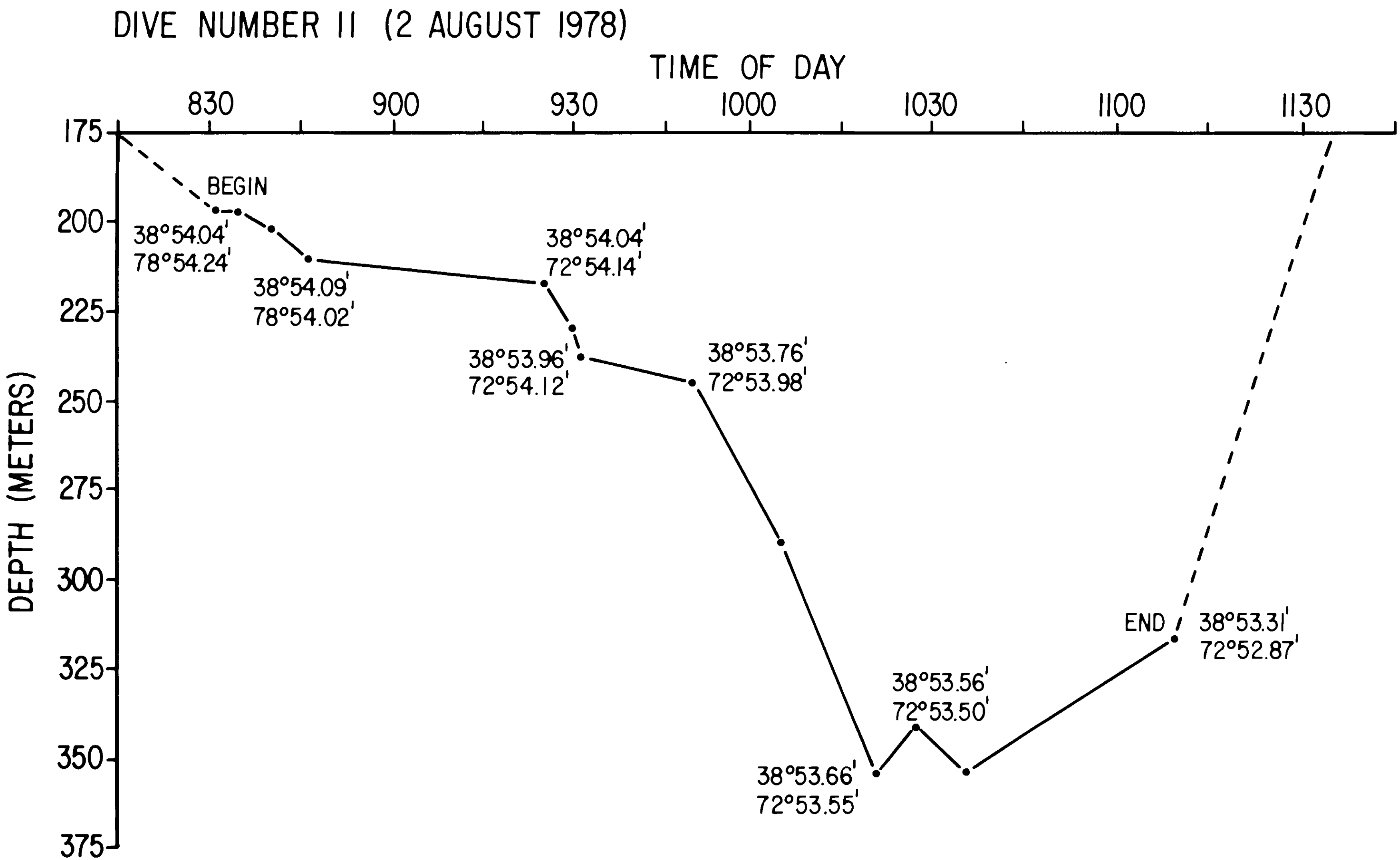

Figure 14. Dive 11 - Time vs. depth.

A 216M–TRAWL MARKS IN OLIVE-GREEN SILTY SAND. SLOPE DIPPING LESS THAN 5°. BOTTOM OF PHOTOGRAPHS APPROXIMATELY 1.75M ACROSS

B 305M–JONAH CRAB (CANCER BOREALIS) ON STEEP SLOPE ON THE CANYON WALL (40-50°); BLOCKS ARE PLEISTOCENE(?) CLAY

C 241M–BIOTURBATED RIPPLES IN OLIVE-GREEN SILT. 25CM HAG FISH (MYXINE GLATINOSA) FOR SCALE

D 320M–BIOEROSION INTO PLEISTOCENE(?) CLAY EXPOSED ON NEAR VERTICAL SCARP

Figure 15. Bottom photographs of the outer Continental Shelf and upper Continental Slope near Carteret Canyon.

of broken blocks of gray clay which formed small scarps about 1 m high and 1-2 m wide. These scarps were partly covered by fine sediment which had slid down the slope. The outcropping clay blocks were highly burrowed creating a spongy appearance.

At a water depth of 332 m, the submersible landed in a small steep-sided valley. In traversing to the other valley wall, a sea floor similar to the one just crossed was revealed. There appeared to be two slump structures on either side of a valley which feeds into Carteret Canyon. The slumps are multiple, having a number of slices forming a set of steps (fig. 16). The outer edges of the level areas appear to be broken up into a series of small scarps 1-2 m long and 7-30 cm high. Such intensively burrowed areas were called "pueblo villages" by Warme and others (1978) (fig. 15D); they are inhabited by numerous crabs, lobsters, and fish. Recent sediment has covered most of the "pueblo village" areas near the top of the slump but those near the bottom are still exposed. Some of the "pueblo village" caverns had collapsed and lumps of the clayey substrate had rolled or slid down to the next lower terrace. This dive was terminated after nearly 3-1/2 hours of observation, 200 35-mm photographs, and 30 minutes of videotape.

Dive twelve

Dive 12 ($38^{o}55.27'$N., $72^{o}54.82'$W.) was down the axis of Carteret Canyon's head (fig. 3) from 150 to 327 m water depths (fig. 17). The observer tried to use a penetrometer to test the shear strength of the surface sediment but was unsuccessful due to difficulties with the submersible's hydraulic arm. The submersible moved downslope from 150 m in a direction of 240^{o} over a sea floor that had been heavily trawled and was strewn with man-made debris (cans, bottles, etc.). The slope of 8^{o} to 10^{o} was covered with silty sand crisscrossed with numerous tracks

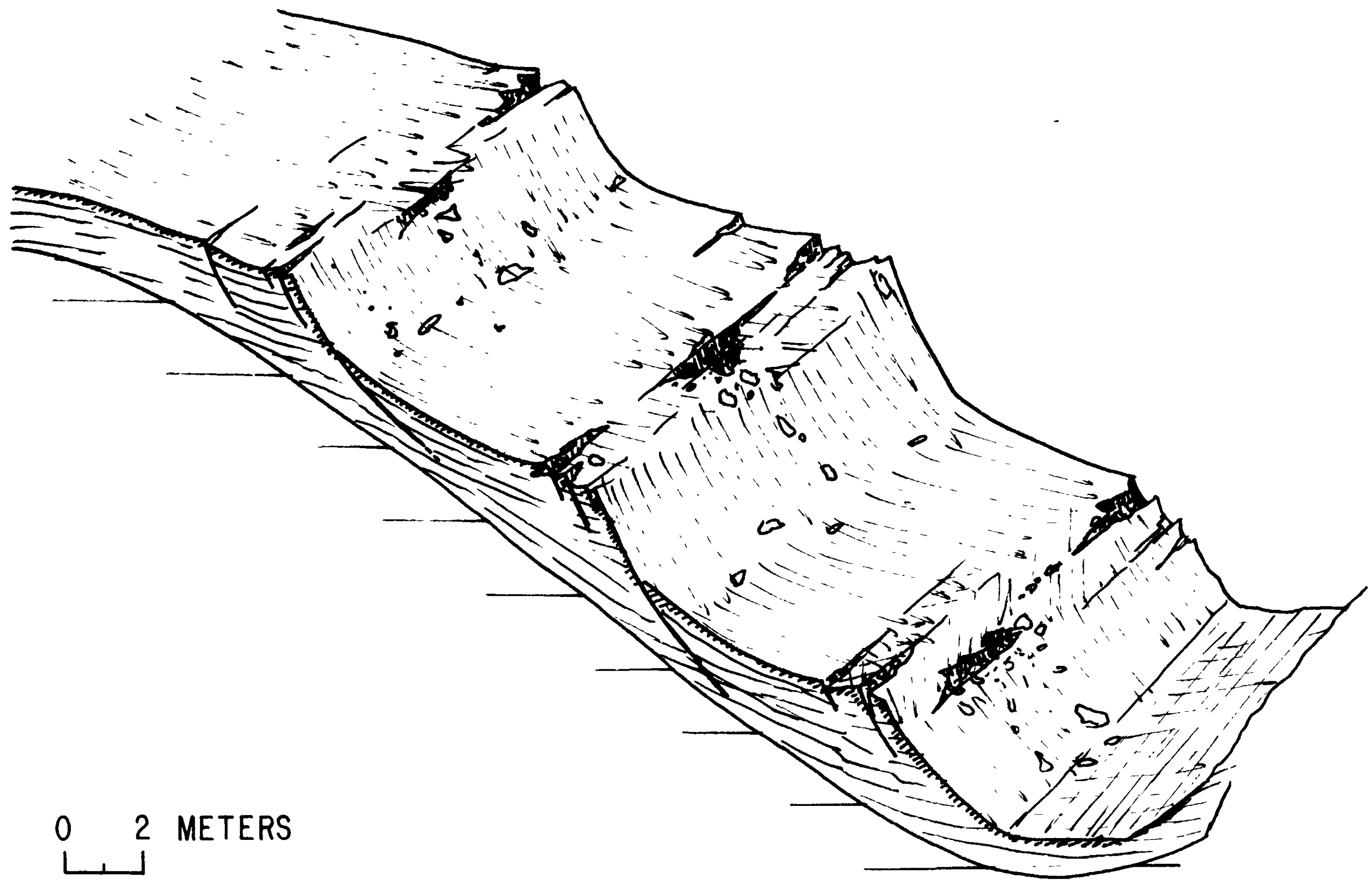

Figure 16. Diagrammatic section of Carteret Canyon wall showing inferred structural control of observed morphology.

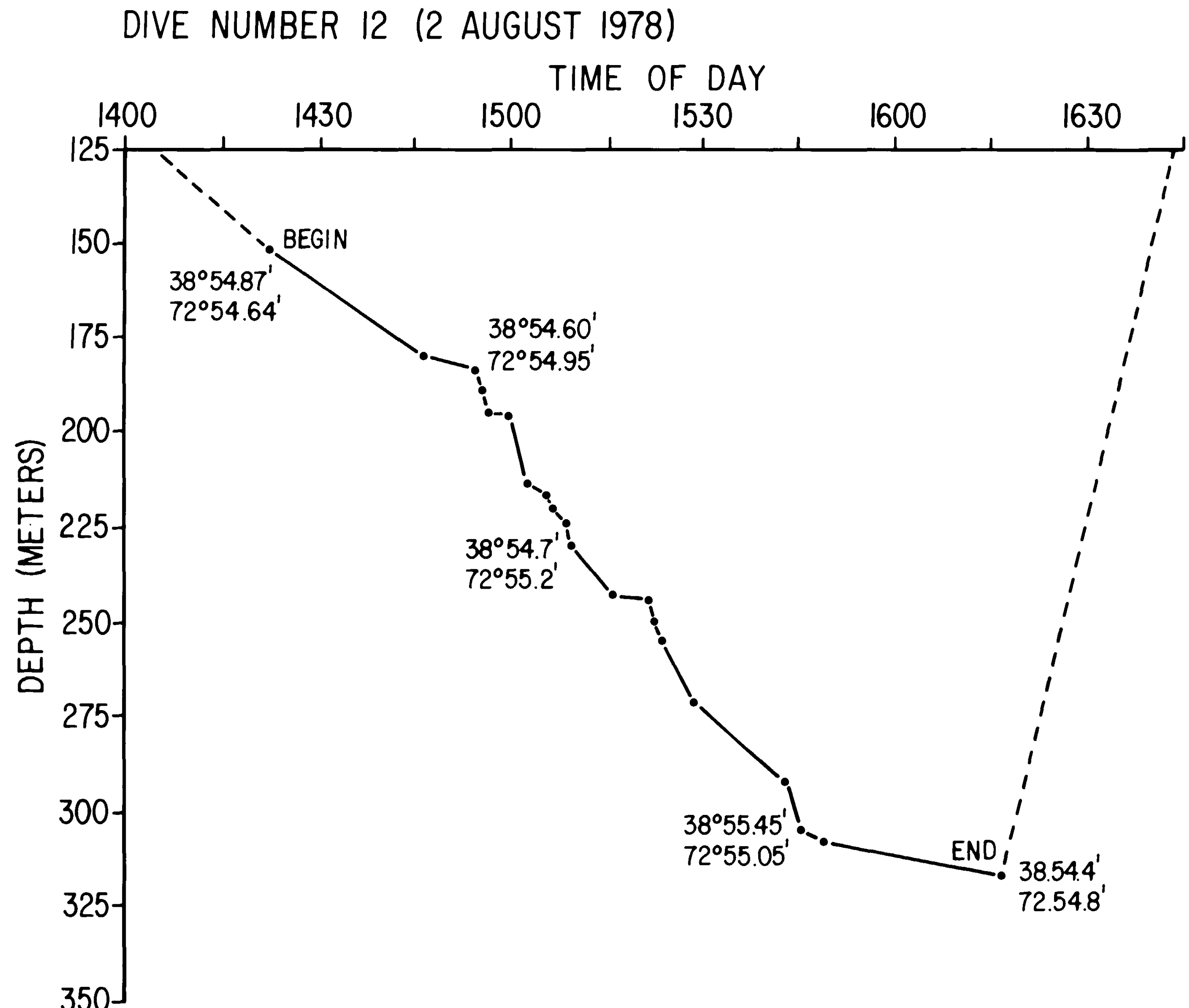

Figure 17. Dive 12 - Time vs. depth.

and trails. A series of 15- to 20-cm high scarps which could have been surface expressions of slumps were traversed between depths of 200-250 m. From 250 to 300 m, the sediment was more silty, but was still covered with tracks, trails, and man-made debris. The debris was observed to collect in low areas. As reported on previous dives it is uncertain whether these depressions are holes or the crossing of a small valley. At a depth of 300 m, there were scattered burrows in the sea floor with chunks of hard gray clay lying on the surface around them. The clays probably represented the substratum below the silty sediment. In general, faunal densities were quite low below depths of 250 m. This dive was terminated at 327 m due to the low voltage of the submersible's batteries. Forty-seven 35-mm photographs and 5 minutes of videotape were taken during dive 12.

Dive thirteen

Dive 13 ($38^{\circ}54.67'$N., $72^{\circ}53.12'$W.) was down the north flank of Carteret Canyon (fig. 3) in water depths from 260 m to 365 m (fig. 18). The submersible landed on a 40° slope in a water depth of 260 m where fine sand and silt with abundant shell debris covered a smooth sea floor except for a few small burrows and mounds. The submersible's downslope course was 170°. Many cans, rags, and bottles littered the sea floor. Occasional fish, crabs, and sea anemones were the only epifauna observed. A fairly strong current from the east pushed the submersible westerly as it traversed down the slope. At a depth of 300 m, the hydraulic arm was used to investigate the sediment which was found to be unconsolidated silt and fine sand.

The submersible continued on its course of 090° past the 300 m depth over a sea floor which was flat and featureless except for occasional burrows and human trash. A change of the submersible's

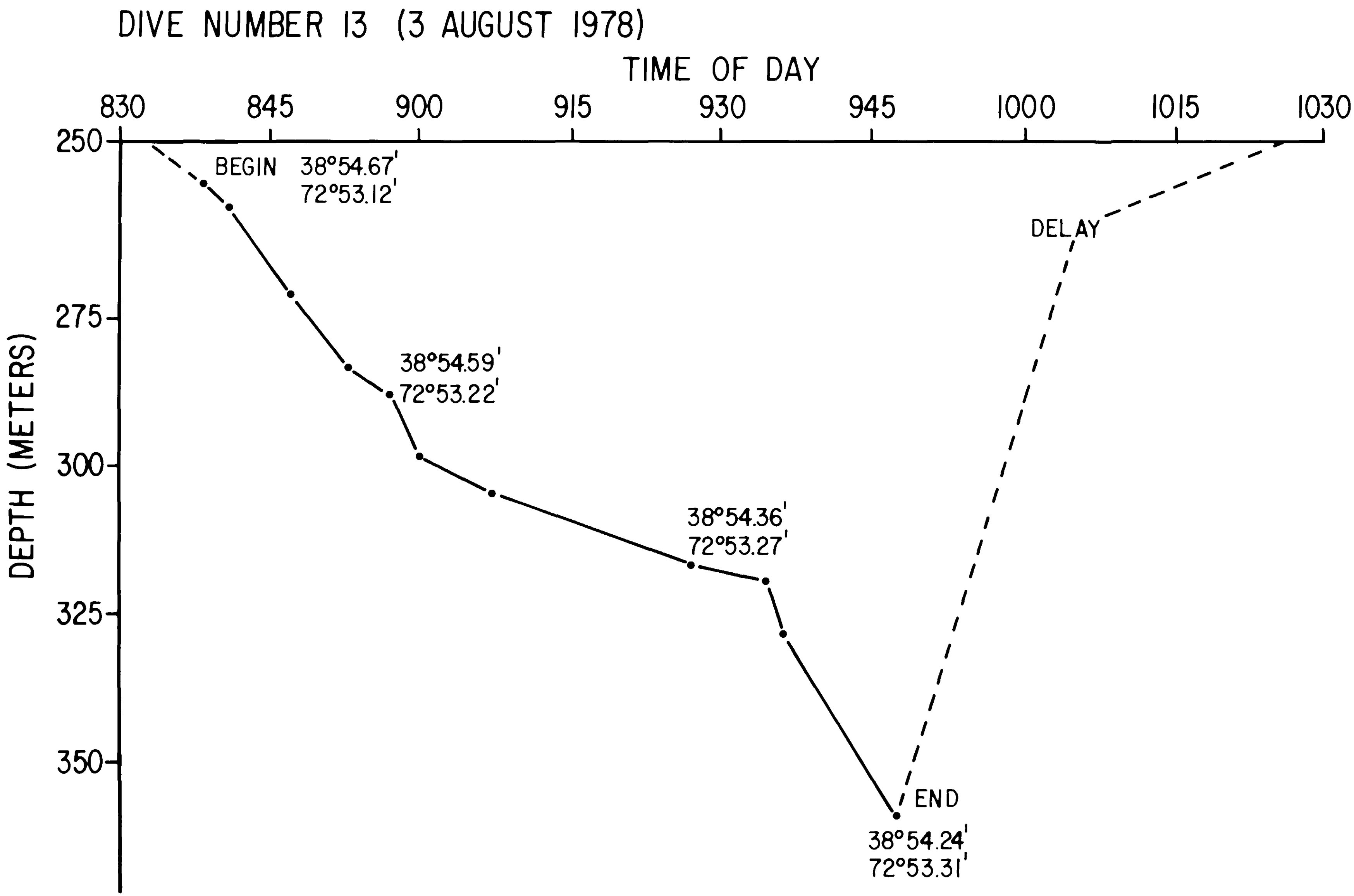

Figure 18. Dive 13 - Time vs. depth.

course to 130^{o} took the submersible down a fairly steep slope with faint steplike features, then across a flat area, features similar to those crossed during dive 12. The dive was terminated at a depth of 365 m after 60 35-mm photographs and 5 minutes of videotape were taken.

Dive fourteen

After the biology and geology of the two submarine canyon heads had been photographed and documented, it was decided to make two dives (14 and 15) down the slope between the canyons for comparison purposes. Dive 14 was on the Continental Slope between South Toms and Carteret Canyons (38^{o}56.93′N., 72^{o}50.76′W.) (fig. 3) in water depths from 210 m to 345 m (fig. 19). The sea floor at 210 m was covered with a greenish-brown silty sand containing many molluscan shell fragments. A few polychaete mounds were the only features observed on the otherwise flat surface. The submersible traveled downslope on a course of 150^{o} across a gently dipping sea floor. A slight current was also moving in a downslope direction, but no current features were observed on the sea floor. At a depth of 220 m, the sediment was finer, tracks and trails on the sea-floor surface were more evident, and numerous small clay balls were observed, probably brought to the surface by burrowing organisms. A large depression having slopes of 30^{o} was noted but the depth change was minimal as the submersible traversed it. Slight asymmetrical ripples were oriented so that the current that formed them was heading downslope between water depths of 270 and 290 m. Considerable man-made debris was scattered over the sea floor. The stalked anemone, *Cerianthus borealis*, dominated the hummocky seascape of polychaete mounds. Below 300 m, the sediment became finer with depth until at 330 m it was silty. Dive 14 was terminated at 345 m because the slope was not steepening and the dive had lasted nearly 2-1/2 hours.

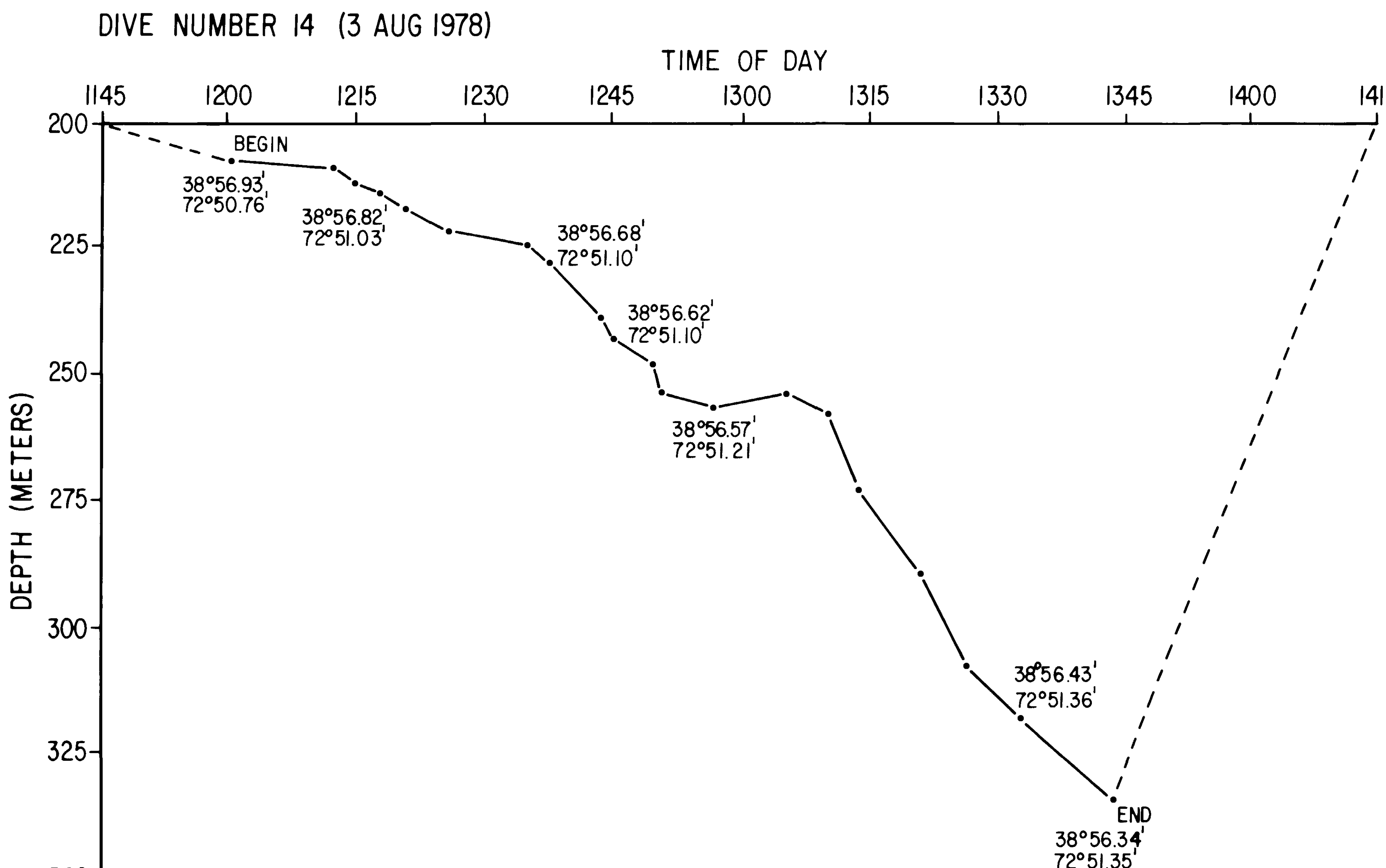

Figure 19. Dive 14 - Time vs. depth.

One hundred fifteen 35-mm photographs and 6 minutes of videotape were recorded.

Dive fifteen

Dive 15 (38°59.96′N., 72°49.32′W.) passed down the Continental Slope between Carteret and South Toms Canyons (fig. 3) from water depths of 210-300 m (fig. 20). This dive was north of dive 14 and near the site of AMCOR well 6021 (Hathaway, 1976, 1979). The dominant sediment was a grayish-green silty sand mixed with considerable shell debris. The percentage of shell debris decreased in deeper water. There were a few polychaete burrows on an otherwise flat, gently dipping sea floor along the submersible′s traverse along a 110° heading. Several pieces of man-made debris were also noted. The dive had to be aborted after 1 hour due to low battery voltage. Twenty-six 35-mm photographs and 3 minutes of videotape were taken during this dive.

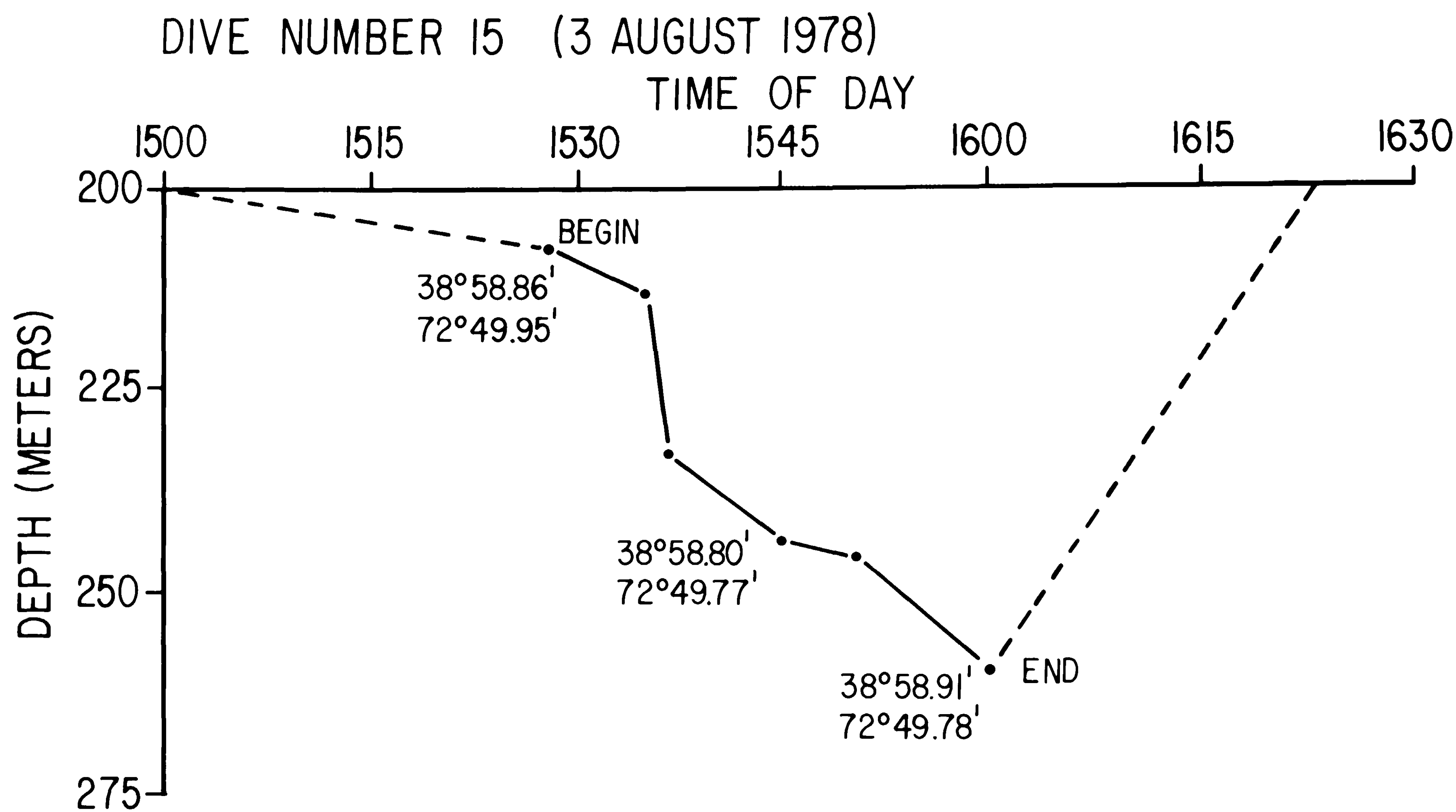

Figure 20. Dive 15 - Time vs. depth.

DISCUSSION AND CONCLUSIONS OF SUBMERSIBLE DIVE OBSERVATIONS

Our observations corroborate other investigators' findings that the edge of the Continental Shelf is covered with moderately well-sorted, slightly gravelly, tan to greenish-tan sand (Hollister, 1973; Schlee, 1973). The sand is mainly well rounded with some iron-stained quartz grains and probably was deposited in beach and dune environments during Pleistocene lowstands of sea level (Uchupi, 1963; Freeland and Swift, 1978). After the last rise of sea level, these relict deposits were reworked and some spilled over onto the upper Continental Slope. Modern mollusc fragments, crab carapaces, and bivalve shells (mainly concave upward) are abundant on the sea floor; crabs and starfish are the most common epifauna.

The nearly horizontal sea floor of the outermost Continental Shelf has a lumpy appearance caused by numerous, 5-15 cm high, conical mounds (polychaete?) and small depressions 15-30 cm across (probably made by crabs and fish). Many tracks and trails are evidence of considerable biological activity in the area. Sediments in this zone are reworked by currents and biological activity; most of the silt and clay have been removed by winnowing. Current indicators, such as ripple marks, are quickly destroyed by biological activity. Occasional flat-lying outcrops of underlying gray-green clay (Pleistocene?) are seen in large burrows or low areas of the sea floor. No potential geologic hazards were observed in this outermost Continental Shelf area.

The upper part of the Continental Slope in the study area was covered with sediment similar to that on the outer shelf (i.e., greenish-brown silty sand). The sediment becomes siltier in deeper water and at water depths of 300 m or more, the sediment is silt or clayey silt. The surficial sediment varies in thickness (3-10 cm) and in many places, a sticky, consolidated clay (Pleistocene?) lies just under the sea floor. The hydraulic arm of the submersible was able to penetrate to clay in most attempts during several of the dives. The clay was also seen in burrows and as chunks or balls on the sea floor that were apparently brought to the surface by burrowing organisms.

The thin silty sand veneer on the upper slope is reworked by organisms into mounds, burrows, and depressions. Tracks and trails as well as numerous shell fragments and man-made debris cover the surface. The debris seems to collect in bathymetrically low areas where it is probably concentrated by bottom currents. Only weak currents were noticed during the dives but ripples marks in a few areas attest to occasional stronger currents. In places the silty sand layer is covered with a thin (<1 cm), flocculated, discontinuous layer of gray-brown silt that gives the sea floor a mottled appearance. Passing animals (and submersibles) resuspend this silt, which is redistributed by the weak bottom currents as it settles. Gradually, this material works its way downslope. Evidence of man is everywhere in the study area. Trawl marks crisscross the sea floor on the outer shelf and upper slope down to depths of approximately 210 m. Man-made debris is extremely common on the sea floor and includes wire, cans, bottles, fishing equipment, rope, clothing, and garbage.

White sea pens, crabs, and fish are the most common epifauna at depths shallower than 250 m. Deeper than 250 m, burrowing anemones, red crabs, and fish predominate. The biota are widely spread over the sea floor and are not concentrated as are the animals in shallower water. The infauna are unknown with the exception of polychaete worms which have built numerous mounds commonly observed on the sea floor. Tracks and trails are more evident in depths greater than 265 m, probably because they are preserved in the siltier sediment. Most of the tracks seem to be made by crabs.

The uppermost Continental Slope in the study area can be divided into two quite different terrains, the submarine canyons and the intercanyon areas. The intercanyon sea floor is characterized by sparse fauna, few changes in the monotonous relief, and shows little or no evidence of potential geologic hazards such as slumps. Most of the biological and sedimentological activity occurs in the submarine canyons.

The acquisition of data stemming from energy development programs on the outer shelf and uppermost slope leads to a renewed interest in studies of the origin and geologic history of submarine canyons. Figure 21 shows a diagrammatic sequence of development of the canyons on the upper slope. As the Pleistocene deposits at the top of the Continental Slope in the area are about 450 m thick (Robb and others, 1981) (fig. 21A) and the canyon heads cut into them, the canyon heads either formed after the Pleistocene sediments were deposited or were formed contemporaneously by nondeposition along transit-ways or channels. Most of the mid-Atlantic canyon heads appear to be incised into slightly seaward-dipping Pleistocene strata although the resolution on available seismic data is limited (Robb and others, 1981; Bonnie McGregor, personal communication, 1980). Late Pleistocene-Holocene clay beds (younger than 200,000 years B.P.; Page C. Valentine, personal communication, 1980) were observed to be dipping at the same angle as the canyon walls (fig. 21C). These sediments were probably draped over the existing canyon during highstands (interglacial) of sea level. The draped clays are too thin to be resolved by our seismic profiler, but their thickness is presumed to be less than 10 m. These

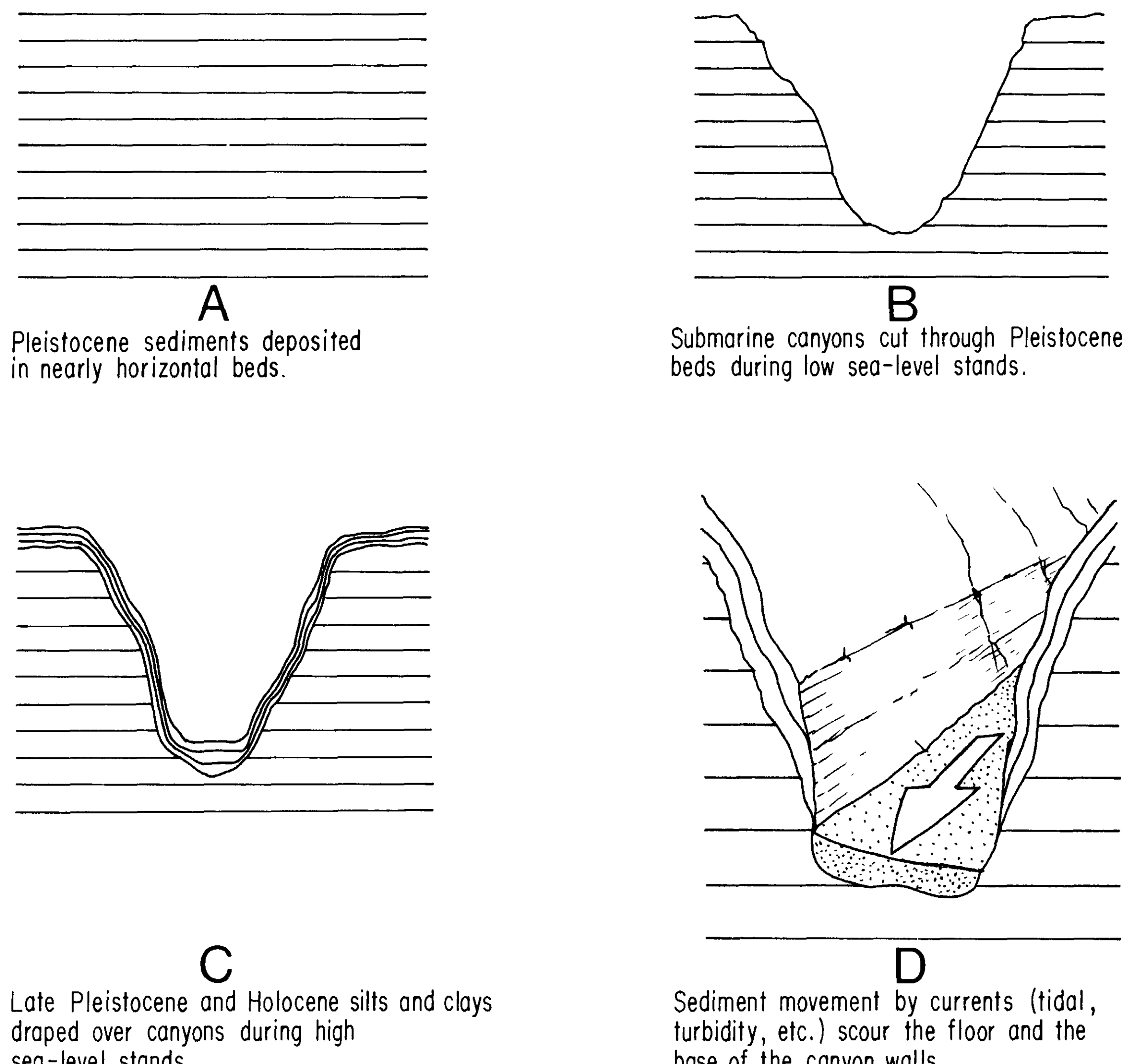

Figure 21. Diagrams showing sequence of submarine canyon development along the mid-Atlantic upper Continental Slope of North America.

semiconsolidated sticky clay beds are in turn overlain by a veneer of recent silty sands and sandy silts. During sea-level highstands, similar to present conditions, current activity is concentrated along the submarine canyon floors (Shepard and others, 1979). Currents may be generated by tidal forces, internal waves, or storms. Their action is periodic, not constant (Bradford Butman, personal communication, 1980). The combination of steep walls (many over 45^{o}), the steeply dipping draped clay beds, undercutting by modern currents and biological activity, causes instability and slumping (fig. 21D).

Slumps occur in the clay beds and are typically observed as a series of steps (fig. 16) which expose the semiconsolidated clay at the surface. This clay is heavily burrowed and bored by the local fauna until the small cliffs are honeycombed ("pueblo villages").

SUMMARY

The 15 submersible dives in South Toms and Carteret submarine canyons and in the intercanyon area provide oral and photographic documentation of the geology, geological processes, and biota along the upper slope of the continental margin in the area of lease sales 40 and 49.

The overall advantages of direct visual assessment of the sea-floor features and biota cannot be overemphasized. This survey, and other similar surveys (Uzmann and others, 1977), have shown that in rough or steep terrain such as in submarine canyons, a submersible is a very effective survey instrument.

If drilling continues in the area, drill cuttings, drilling mud, formation waters, and oil that may escape from the drilling sites may be transported to these submarine canyons. We have only spot-checked these canyon areas in the past few years (always in the summer), and know nothing of the daily or seasonal variations of the physical and biological processes that may occur there. A submersible piloted by the senior author in Oceanographer Canyon was caught in a turbidity current in 1974 offering evidence that these currents occur occasionally. Tidal currents frequently scour the canyon floors (Shepard and others, 1979). Slumping is common along the canyon walls. Observations of canyon and intercanyon areas indicate that the canyons harbor the majority of the upper slope fauna. These facts make it important that further detailed investigations of the canyon environment continue.

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