Bedrock geology in New England submarine canyons

Submarine canyons
Georges Bank
Submersibles
Seabed erosion
Stratigraphy
Canyons sous-marins
Georges Bank
Submersibles
Érosion sous-marine
Stratigraphie

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ABSTRACT

Using the research submersible "Alvin" we explored three deeply submerged canyons along the New England segment of the North American margin. Contemporary submarine erosion in canyon axes provides almost continuous outcrop of Mesozoic and Cenozoic strata. The oldest strata sampled belong to a Neocomian-age carbonate platform with reefs, shoals, lagoons and beaches. A precipitous escarpment, now buried, bounds the seaward edge of the platform. Precursor valleys had already cut into the escarpment during the Cretaceous period. They were excavated prior to the Campanian/Maestrichtian time, again prior to the Middle Eocene and most recently in the Pleistocene. A principal agent of erosion is mass-wasting from cliffs which are oversteepened and undercut by currents accelerated within the narrow thalwegs of a dendritic-type drainage network and which are weakened by biological borings and solution diagenesis. Blocks and slurries episodically avalanche down the canyon walls. As debris flows, they sweep across the floors of plunge pools and spill out onto the upper continental rise apron, transporting some intact allochthonous masses which are larger than the submersible, itself.

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RÉSUMÉ

Géologie des fonds rocheux des canyons sous-marins de la Nouvelle-Angleterre

Au cours de la campagne « Georges 77 » nous avons exploré avec le submersible de recherche « Alvin » trois des canyons sous-marins profondément submergés qui entaillent la marge continentale de la Nouvelle-Angleterre (côte atlantique de l'Amérique du Nord). Dans l'axe des canyons l'érosion actuelle dégage une coupe quasi continue d'affleurements secondaires et tertiaires. L'horizon le plus ancien échantillonné présente un faciès de plate-forme carbonatée où nous distinguons des récifs, des hauts fonds, des lagons et des plages d'âge néocomien. Une falaise escarpée, actuellement enfouie, borde cette plate-forme vers le large. Dès le Crétacé, des vallées entaillent cette falaise. Elles ont été creusées antérieurement au Campanien/Maestrichien, puis recreusées avant l'Éocène moyen et enfin reprises récemment au cours du Pléistocène. Le mécanisme principal de ces érosions est l'effondrement de pans des falaises qui forment les flancs des canyons. Ces falaises sont affouillées à leur base par des courants chargés de matériaux abrasifs,

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courants d'autant plus violents que le thalweg est étroit. Des organismes perforants et une dissolution diagénétique aident cette érosion dans les thalwegs qui forment un réseau de drainage dendritique. Périodiquement des avalanches boueuses entraînant de grands blocs dévalent les canyons. Ces masses boueuses transitent à travers des dépressions surcreusées dans le profil en long des canyons et, en débouchant sur le glacis continental, s'épandent en cône de déjection. Ces avalanches entraînent des masses allochtones atteignant la dimension du submersible.

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INTRODUCTION

The entire length of the continental slope of New England is incised by dozens of submarine canyons and gullies that were discovered, charted and initially sampled some four decades ago (Shepard, *et al.*, 1934; Stetson, 1936; Stephenson, 1936; Daly, 1936; Veatch, Smith, 1939). The heads of the largest canyons extend landward of the shelf break to depths of less than 70 m. The upper parts of the canyons were fed at one time by a network of small streams, all presently buried under the modern shelf carpet of gravel, sand and silt (Wigley, 1961; Roberson, 1964; Emery, Uchupi, 1965; Garrison, 1970). The majority of the canyons on the relatively steep continental slope exit onto the more gently dipping continental rise apron between 1 400 and 2 100 m water depth (Heezen *et al.*, 1959; Uchupi, 1965; Emery, Uchupi, 1972). The axial thalwegs (*) diminish in relief and eventually become small meandering fan-valleys on the upper rise (Heezen, Dyer, 1977). Incision into the slope has exceeded 1 km, exposing strata in the canyon walls as old as the Cretaceous (Gibson *et al.*, 1968; Weed *et al.*, 1974). Many of the slope canyons exhibit dendritic drainage pattern. Some early researchers have compared this configuration to terrestrial counterparts and they have speculated about a hypothetical subaerial origin by means of groundwater sapping (Stetson, 1936, 1949) and the headward erosion of streams (Johnson, 1939; Shepard, 1952). However, modern exploration has led to a general consensus that at least the lower parts of canyons have been recently excavated and subsequently kept clean while deeply submerged. In the search for an appropriate tool with which to examine and evaluate various potential erosion agents in the deep sea, oceanographers have turned to submersibles.

Visual seafloor observations

The first manned descent into a New England canyon was made in 1966 in the research submersible "Alvin". This dive in Oceanographer Canyon (Trumbull, McCamis, 1967) was followed by the exploration of Corsair Canyon and Block Canyon (Ross, 1968; Dillon, Zimmerman, 1970). At the foot of thalweg scarps, ripple marks and scour moats around talus blocks were common. Intermittent currents, attributed to focused tidal surges, flowed in both up-canyon and down-canyon directions. Observers pointed out that the canyon floors and walls contained layers of mobile surface sediments. However, the presence of numerous animal induced pits, mounds and trails indicates that currents do not rework this sediment during each tidal cycle. Sediment on the steep (up to 30°) canyon walls often lie near the angle of repose and could be sent sliding downslope by mechanical impact of submersible appendages. On near vertical cliff faces where the mobile sediment layer was absent, highly burrowed rock strata were visible.

Biological activity was judged to be an important erosional process since it ejects fragments and dust of semi-indurated materials into suspension and weakens the mechanical strength of rock faces. Slumping, as a result of this weakening, lessens the slope of the walls. A constant biologically induced re-suspension of wall detritus allows the tidal currents in the canyons to eventually transport material toward the canyon mouths.

The concept of steady-state erosion gained support with the first really long-duration observations by the late Bruce C. Heezen and his associates using the nuclear powered research submarine "NR-1" of the United States Navy. During 1972 and 1974 they carried out more than 150 hours of on-bottom viewing, in multiple diving campaigns in Hydrographer, Oceanographer, Lydonia and Gilbert Canyons. Heezen's voluminous written notes, audiotapes and personal communications indicate that he made advances in quantifying the relative importance of both the biological and tidal surge processes by carefully documenting the activity of small regions of canyon floor, walls and intercanyon slopes and the strength and directions of bottom currents during the entire duration of a tidal cycle. In an unfinished draft manuscript (1977) he argues for a "balanced concept in which canyons are created by some tectonic forces or drowned river valleys, are shaped and kept alive by the tides and are coursed by turbidity currents at certain long term intervals when especially large supplies of sediment are delivered to the heads of their system".

OBJECTIVES AND METHODS

Our fieldwork, carried out in late August, 1977, was scheduled by Heezen before his untimely death in June, 1977. Using DSRV "Alvin", we aimed at furthering the visual observations of steady-state contemporary erosion at depths greater than the capability of "NR-1" while at the same time attempting detailed stratigraphic

(*) The line joining the deepest points of a stream channel (*Glossary of Geology and Related Sciences*, 1960, American Geological Institute, Washington DC).

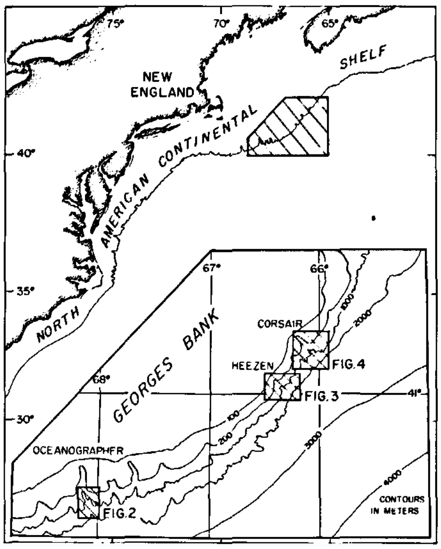


Figure 1
Georges Bank segment of the New England continental margin of North America.

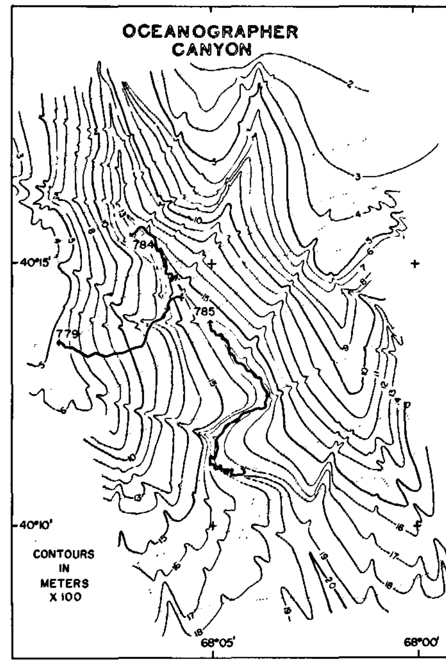
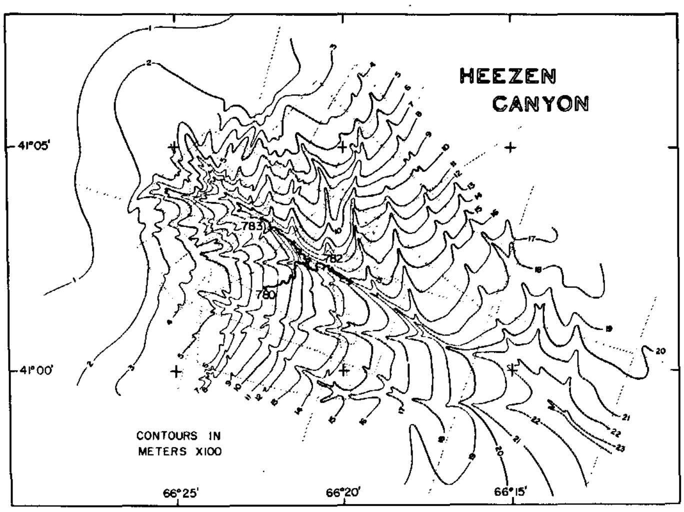


Figure 2
Portion of Oceanographer Canyon showing tracks of Dives 779, 783 and 784 (heavy lines) and tracks of bathymetric survey (dotted lines).

Figure 3
Heezen Canyon with tracks of Dives 780, 782 and 783 (heavy lines) and tracks of bathymetric profiles (dotted lines).



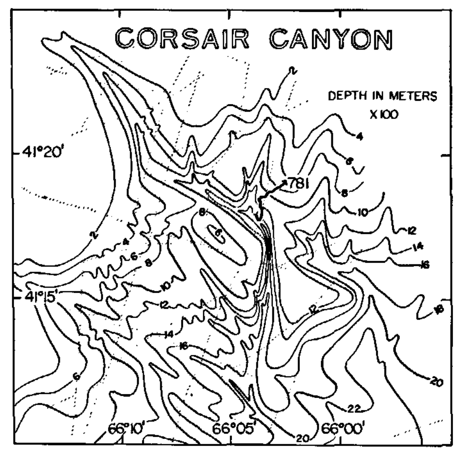


Figure 4
Corsair Canyon with track of Dive 781 (heavy line) and track of our bathymetric survey (dotted lines). Contours have been modified from map of Uchupi et al. (1977).

sampling of outcrops of former shelf and slope strata. We hoped to document the geometry of canyon incision and fill in order to discern whether there were multiple phases of canyon cutting and to find out if the initial entrenchment may have begun at an earlier time than the Pleistocene ice ages.

Our campaign comprised seven dives within three different canyons along the seaward slope of Georges Bank, namely Oceanographer and Corsair Canyons (Fig. 1) and a third which we called Heezen Canyon after we completed a most spectacular excursion through an extremely narrow and winding gorge cut into sheer cliffs of massive chalk. Non-diving time was spent in generating precision bathymetric profiles from the support vessel RV "Lulu" in grids navigated with Loran-C. Our bottom time averaged 5.5 hours per dive, thereby permitting the two observers and pilot to cover up to 5 km of seafloor along traverses that ran either from the thalweg up the canyon wall (3 dives) or up-canyon along the thalweg (4 dives).

We sampled both outcrops of the canyon bedrock as well as exposures of canyon fill, including the most recent sedimentary carpet. Between sample stations, continuous video-recordings were made with an externally mounted TV camera. These recordings and 1 000 or more photographs in color and black and white per dive allow review and syntheses of the field observations. Navigation of the submersible was achieved by transponder ranging to the support vessel, which was itself positioned by Loran-C. During the dives the support vessel steamed back and forth across the dive track to allow triangulation of bearings and ranges to the submersible.

Figures 2, 3, and 4 are maps contoured from our sounding, supplemented by some previously existing profiles of earlier expeditions. We worked out the fine detail of the dive tracks by combining the sonar-ranging with the logging of submersible depth, heading and progress on the video-tape playback.

The relative precision of the submersible tracks is estimated at approximately 100 m. We found that we could target the "Alvin" into thalwegs that were as narrow as 20 m and that we could discern meanders in the valley on the scale of a few tens of meters in radius.

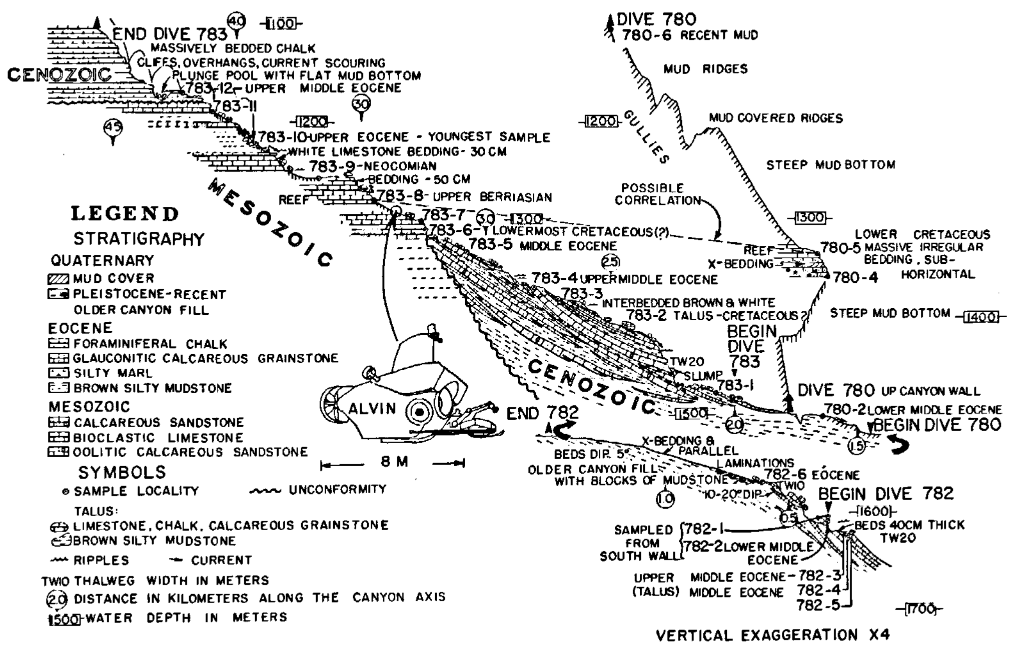


Figure 5
Cross-section of part of Heezen Canyon parallel to linear central thalweg surveyed and sampled during Dives 780, 782 and 783. Dive 780, up the canyon wall has been projected into the plane of cross-section. The transect from 1 420 to 1 350 m reflects a course in a down-canyon direction and not an overhang.

DEFINITION OF STRATIGRAPHIC UNITS AND GEOLOGICAL RELATIONSHIPS

Our observations and samples in the canyons investigated lead to a far more complex interpretation of their geologic history than we had initially suspected. We are able to define at least three, and probably four lithologic sequences, each separated by an inferred erosional unconformity. The oldest sequence of rocks exposed ranges from Lower Cretaceous (Neocomian) (130-120 MY) in age (Heezen Canyon) to possibly Mid-Cretaceous (?) (100-90 MY) in age (Oceanographer Canyon). These older rocks are shallow-water shelf to littoral facies limestones and calcareous sandstones. Hemipelagic Maestrichtian (72-69 MY) sandy mudstone and silty mudstone samples from Corsair and Oceanographer Canyons possibly constitute the second lithologic sequence. Rocks of this age were not recovered from Heezen Canyon. The Neocomian rocks in Heezen Canyon are overlapped by a Middle Eocene sequence of silty mudstones and calcareous chalky grainstones, constituting a third, well-defined, lithologic sequence. These two, and probably three, sequences are all overlapped by the fourth sequence containing Pleistocene to Recent semi-consolidated silty to sandy mudstone.

The present-day canyons incise these four lithologic sequences. Our data indicate that the geometry of the present-day canyons, as well as the geometry of older erosional surfaces, determine the extent of rock exposures belonging to a particular stratigraphic unit. This section describes the four lithologic sequences we have defined and summarizes our visual and sampling data that lead to our interpretation of the geometric relationships between these units. The details of our age assignments and lithofacies analyses for the rocks are presented in the next section. Our understanding of the lithology and relationships of the older rocks is best in Heezen Canyon, where our sampling was most successful. Our visual observations in Oceanographer Canyon, however, provided the clearest understanding of the younger Pliocene-Recent deposits. Our data and interpretations are synthesized in Figures 5 and 6 as cross-sectional views constructed parallel to the canyon axis.

Lower and Mid-Cretaceous rocks

Dive 783, in the axis of Heezen Canyon, traversed and sampled a 140 m thick sequence of subhorizontally stratified, massive to medium bedded, Neocomian-age limestones and calcareous sandstones (see Plate 1 *e* and *f*). The base of the sequence, a 10-20 m high cliff at 1 300 m depth, consists of sandstone at 1 308 m (sample 783-6, illustrated in Plate 2 *c*) and limestone at 1 301 m (sample 783-7). The Neocomian section is not exposed continuously along the canyon thalweg; however, where exposures exist, they are often cliff-like. Above sampling station 7, Dive 783 traversed more limestones (samples 783-8, reefal limestone, and 783-9) up to a depth of 1 232 m. Not far above this, at 1 220 m, the muddy to sandy ripple-marked canyon floor became covered with rubble and talus. One block, of immense size, proved to be Upper Eocene in age (sample 783-10). We interpret this block as having tumbled downslope. We moved upwards through massively bedded white limestones and sandstones (sample 783-11) lithologically and petrographically similar to the Neocomian sequence below.

Dive 780, up the southwest wall of Heezen Canyon, traversed a steep but mud-covered slope, encountering a sheer cliff of subhorizontally bedded rock at approxi-

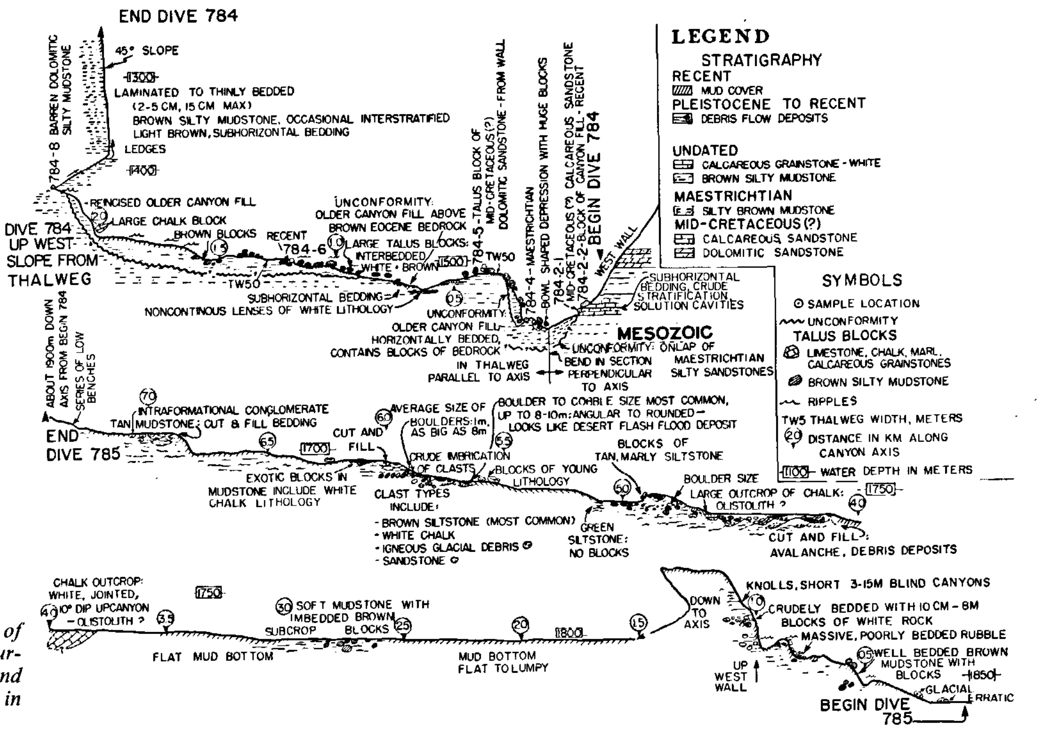


Figure 6
Cross-section of portions of Oceanographer Canyon surveyed during Dive 785 and surveyed and sampled in Dive 784.

mately 1 350 m (right side of Figure 5). Stratification in this exposure was crude, and bedding was thick to massive. The rocks exhibit solution cavities and are covered with an abundance of sessile life forms. Sample 780-4, from the base of the outcrop is a coarse-grained calcareous sandstone, the grains exhibiting oolitic coatings (Plate 2 *f*). We moved up this outcrop, documenting medium-scale festoon cross-stratification, and sampled a Lower Cretaceous reefal limestone (780-5) at a depth of 1 335 m (Plate 2 *d*). This exposure on the slope of Heezen Canyon most likely corresponds to some portion of the Neocomian section sampled in Heezen Canyon thalweg during Dive 783 (left side of Figure 5). If these rocks are truly horizontally bedded, the canyon wall exposure may lie stratigraphically below the thalweg section but if the reefal limestone at 780-5 corresponds to reefal limestones of sampling station 783-8, these units would dip seaward less than 1.5°. The lack of visually discernible dips in these Lower Cretaceous rocks suggests to us that samples 780-4 and 780-5 on the wall of the canyon either lie stratigraphically below the thalweg section or are at least equivalent to the lower units sampled in the thalweg section.

Our one dive in Corsair Canyon (781) did not recover any Lower Cretaceous rocks. Dive 784 (Fig. 6), in Oceanographer Canyon, sampled a solution weathered outcrop of medium-bedded calcite-cemented calcareous sandstone encrusted with benthic organisms (sample 784-2-1, 1 553 m). Although lithologically similar to Neocomian rocks in Heezen Canyon (Plate 2 *b*), we have at present no age date on this rock. Because our seismic interpretation of this region (Ryan *et al.*, in prep.) places Neocomian-age strata at a greater depth than 1 553 m in the Oceanographer Canyon area, we suggest a Mid-Cretaceous (?) age for this sandstone. Further up the axis of Oceanographer Canyon we sampled a talus block of dolomite-cemented, muscovite-rich subarkosic sandstone (sample 784-5, 1 517 m). Although we do not know precisely where this block came from, we interpret it to be derived from the canyon wall at some intermediate distance above the thalweg.

Maestrichtian rocks

Dive 781 in Corsair Canyon recovered a talus block of Maestrichtian-age calcareous glauconitic sandy mudstone (sample 781-1) at 1 452 m on the canyon floor. All other outcrops sampled in Corsair Canyon at depths of 1 532 to 1 168 m are Eocene in age. Maestrichtian-age rocks are not exposed in the region we explored in Heezen Canyon, but possibly may be present further down the thalweg or in the subsurface of the shelf edge. In Oceanographer Canyon, a talus block at the base of a brown silty mudstone outcrop (sample 784-4) was sampled at 1 565 m (center of Figure 6) and is Maestrichtian in age. This block appeared to have fallen from the adjacent outcrop. If this outcrop is Maestrichtian, rocks of this age occur at a greater depth than the Mid-Cretaceous (?) calcareous sandstone described above. Sample 784-4 also represents a deeper-water facies than the nearby Mid-Cretaceous (?) calcareous sandstone. These data very tentatively indicate a pre-Maestrichtian period of canyon incision into older rocks of shallower-water facies.

Middle Eocene rocks

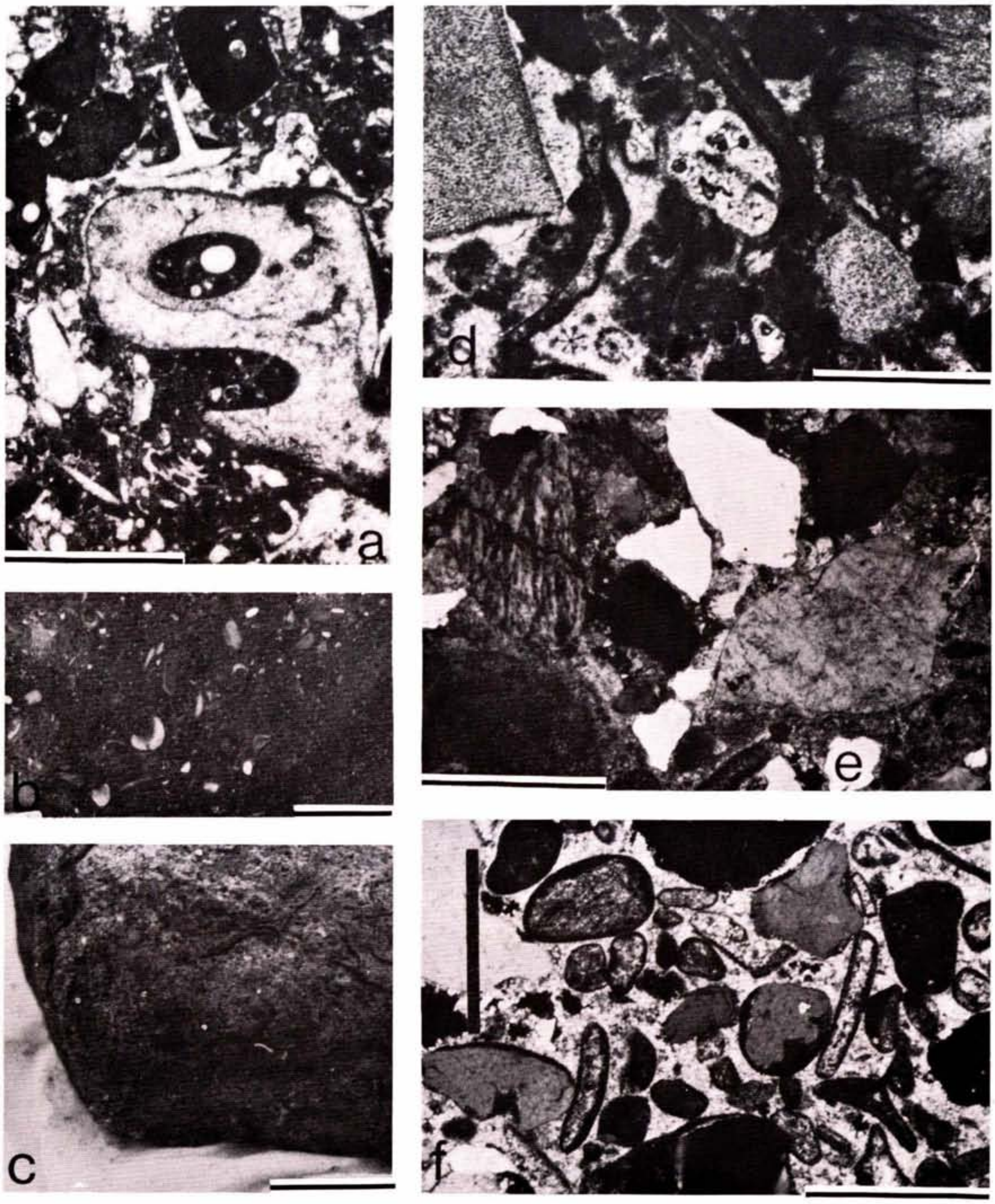
The relationship of Middle Eocene rocks and facies to the older rocks exposed in the canyons is best defined in Heezen Canyon. Here, Eocene rocks form a two-part sequence of seaward-dipping slope-facies silty mudstones and calcareous grainstones and a slightly younger subhorizontally bedded pelagic-facies chalky limestone.

Plate 1

a) *Dive 780, Station 2, Heezen Canyon (1 503 m). Close-up photograph of Lower Middle Eocene brown silty to sandy mudstone, showing fresh fracture surface and boring of rock surface by recent organisms. Fracture about* 10 *cm across.*
b) *Dive 785, Oceanographer Canyon (*1 760 *m). Close-up photograph of debris flow or avalanche rise deposits. Exotic blocks are probably Eocene silty mudstone (brown) and Eocene chalk or calcareous grainstones (white). Octacorals (pink) and Ophiuroid on outcrop. Ophiuroids are approximately* 10 *cm across.*
c) *Dive 782, Heezen Canyon. Approximately* 1 620 *m in thalweg of canyon. White Middle Eocene grainstones with down-canyon dip.* Actinoscyphia saginata *(pink) in center. Fish at left approximately* 30-40 *cm in length.*
d) *Dive 782, Heezen Canyon. Approximately* 1 600 *m. Brown Eocene muddy siltstone with* Actinoscyphia saginata *(*25-30 *cm diameter). White patches are encrusting sponges. Numerous polychaete casings. (Small, White.)*
e) *Dive 783, axis of Heezen Canyon (*1 240 *m). White limestone of probable Neocomian age. Upper bed about* 30 *cm thick.*
f) *Dive 783, axis of Heezen Canyon (*1 191 *m) Station* 11. *Cliff of Neocomian age calcareous quartz-feldspar sandstone. Bedding approximately* 30-40 *cm thick.*

Slope-facies

Dive 782 in the axis of Heezen Canyon traversed spectacular exposures of interbedded glauconitic calcareous grainstone and brown silty mudstone of Middle to upper Middle Eocene-age at a depth of approximately 1 620 m. Steep down-canyon dips of 10-20° are visually discernible in these units (Plate 1 *c*). Dive 782 proceeded up the canyon axis moving at times higher and then lower in section within the same sequence since the dips of the beds were approximately subparallel to the slope of the canyon axis floor (schematically sketched in Figure 5). This dive continued very slowly stratigraphically down-section into monotonous brown silty mudstone (Plate 1 *a* and 1 *d*), as inferred both by our dip estimates and by the lower Middle Eocene-age of the first outcrop sampled in Dive 780 (sample 780-2,



1 553 m). Dive 780, which proceeded up the mud-covered canyon wall after sampling station 780-2, found no further exposures until arriving at the Neocomian-age cliff. These Neocomian rocks are at least 140 m above the lower Middle Eocene exposures in the canyon axis.

Dive 783 began slightly up canyon from where Dive 780 left the canyon axis. The first outcrops were interbedded brown mudstone and white calcareous glauconitic grainstones of Middle Eocene-age with discernible down-canyon dips. Dive 783 proceeded up canyon through the grainstones and sampled a talus block (783-2 at 1 403 m) of probably Lower Cretaceous-age. This block was undoubtedly derived from further

Plate 2

a) *Sample 783-8. Heezen Canyon (1 280 m), Upper Berriasian reefal limestone thin section. Plane light. (Scale bar represents 1 mm.)*
b) *Sample 784-2-1. Oceanographer Canyon (1 553 m), calcite cemented calcareous quartz-feldspar sandstone. Note abundant shell fragments. (Scale bar represents 2 cm.)*
c) *Sample 783-6. Heezen Canyon (1 308 m), calcite cemented calcareous quartz-feldspar sandstone. Note Trigonia imprint in lower left corner of rock. (Scale bar represents 3 cm.)*
d) *Sample 780-5. Heezen Canyon (1 334 m) early Cretaceous reefal limestone. Echinoid fragment in upper left corner, coral in lower left and codiacian algae fragment in upper right. Thin section, plane light. (Scale bar represents 1 mm.)*
e) *Sample 783-11. Heezen Canyon (1 188 m), calcite cemented calcareous quartz-feldspar sandstone. Echinoid fragment in lower left. Thin section, polarized light. (Scale bar represents 1 mm.)*
f) *Sample 780-4. Heezen Canyon (1 359 m), calcite-cemented calcareous sandstone. Note oolitic coatings on grains. Thin section, polarized light. (Scale bar represents 1 mm.)*

upslope, as Dive 783 then traversed more interbedded brown silty mudstones and calcareous grainstones of Middle to upper Middle Eocene-age (samples 783-3, 783-4, 783-5). Sample 783-5, a calcareous mudstone of Middle Eocene-age was the last sample collected before the canyon suddenly steepened as we approached the first exposure of older, more resistant Neocomian sandstones and limestones (Fig. 5). It is important to note that we did not go down section into the lower Middle Eocene silty mudstones as we approached the contact between the Eocene and older Neocomian rocks. The petrography of the white calcareous grainstones indicate that these rocks represent down-slope reworking of shelf facies sediments that interfinger with and are interbedded with hemipelagic slope facies brown silty mudstones.

Pelagic-facies

After sampling the last of the Neocomian-age rocks at a depth of 1 188 m in Heezen Canyon thalweg, Dive 783 sampled unconformably overlying subhorizontally bedded latest Middle Eocene chalks at 1 165 m (sample 783-12) at the base of a massively bedded 70 m high cliff of white chalk. The chalk is not only slightly younger, but of a different facies (pure pelagic) from the brown silty mudstones and interbedded calcareous grainstones encountered further down in the canyon axis.

The Middle Eocene slope-facies silty mudstones and calcareous grainstones of Heezen Canyon are interpreted to have been deposited in an older (pre-Middle Eocene) canyon that was cut into subhorizontally bedded Neocomian-age strata. Several lines of evidence support this relationship.

1) Dive 783 did not go stratigraphically *down*-section within the Middle Eocene sequence into the slightly older lower Middle Eocene mudstones as we approached the first Neocomian-age outcrop (Fig. 5). Hence successively younger Eocene rocks unconformably onlap the older rocks.

2) The visually discernible difference in dips between the older Neocomian rocks and the slope-facies Eocene rocks indicate that younger rocks were deposited in an entirely different environment characterized by steep depositional gradients equal to or greater than the mean regional dip of the continental slope (approximately 8°).

3) The location of the Neocomian-age outcrops on the wall and thalweg of Heezen Canyon with respect to the location of Eocene-age rocks necessitates deposition of the Eocene rocks in a topographic depression, cut into the older rocks, or in a pre-existing canyon.

4) The Eocene silty mudstones and calcareous grainstones in Heezen Canyon are slightly older than the subhorizontally bedded pelagic-facies chalk which unconformably overlies Neocomian rocks further up the canyon. This indicates that the mudstones and grainstones were not deposited as a sedimentary drape over the older rocks but were filling a topographic depression. The sedimentology of the Eocene grainstones indicates that these rocks are reworked down-slope from contemporaneous shelf deposits. They overlie and interfinger with silty mudstones deposited in a hemipelagic environment either within the axis of an older incision or along one of its walls. At a slightly later time in the Middle Eocene, pelagic chalks prograded over the erosional surface above the highest exposures of Neocomian-age rocks (top left of Figure 5).

In Corsair Canyon, Upper Eocene silty mudstones (sample 781-3) occur at depths greater than 264 m below Lower Middle Eocene mudstones of the same facies, substantiating Eocene paleorelief in the canyon region.

Although lower Middle Eocene age silty mudstones were extensively sampled in Corsair Canyon, no calcareous grainstones were encountered. The lithology and ages of the mudstones indicate that they probably correspond to the lower units of the Middle Eocene section in Heezen Canyon.

In Oceanographer Canyon, the relationship of Maestrichtian rocks (sample 784-4, Fig. 6) to the rest of the silty mudstone exposures is not entirely clear. Because sample 784-8 was barren, we do not know if part of the section exposed here is Eocene in age. Both of these samples appear to be hemipelagic, slope-facies deposits. Sampling during dive 784 was restricted due to the disfunction of the sampling arm. Blocks of white as well as brown talus were seen on the canyon floor, possibly corresponding to the Eocene white chalk and grainstone facies sampled in Heezen Canyon, but calcareous grainstones were not detected in outcrop with the exception of occasional thin white lenses discovered in brown silstone exposures. Possibly part of the undated portion of the section observed in Oceanographer Canyon lies stratigraphically slightly below the Middle to Upper Eocene interbedded white and brown sequence observed in Heezen Canyon. Sample 784-8 was taken at the base of a steep 160 m cliff of brown, thinly bedded silty mudstones. These rocks were subhorizontally bedded, contrasting strongly with the steep dips observed in the Eocene rocks of Heezen Canyon. We infer that both the Maestrichtian rocks and the undated, possibly in part Eocene, rocks of Oceanographer Canyon (784-4, 784-8) represent lithologies that unconformably overlap the shallow water Mid-Cretaceous (?) rocks (784-2-1 and 784-5). Samples from earlier "Alvin" dives in Oceanographer Canyon (Gibson *et al.*, 1968; Weed *et al.*, 1974) indicate that Maestrichtian-Campanian sandstones with shallow-water microfossils occur at similar depths to our brown silty mudstone sequence (sample 784-8), supporting this suggestion.

Pleistocene to Recent strata

Semi-consolidated Pleistocene to Recent deposits were frequently observed in all three canyons investigated. These rocks are whitish in color and are subhorizontally bedded, with thin to massive bedding. They are strongly bored by living organisms. Pleistocene to Recent outcrops were observed and sampled in the thalweg of Oceanographer Canyon during dive 784 where they often contained imbedded pieces of brown silty mudstone of possible late Cretaceous or Eocene-age. In places, we observed the young cover to actually overlap onto the brown silty mudstone bedrock (see Fig. 6 at 1 520 and 1 430 m). Dive 785 from 1 880 to 1 660 m in Oceanographer Canyon was restricted to visual observations due to a breakdown of the sampling arm. At these depths, near the continental slope/rise contact, the present-day channel of Oceanographer Canyon incises probable Pleistocene (?) avalanche and debris-flow deposits containing primarily allochthonous blocks of brown silty mudstone and white chalky lithology, visually similar to Eocene-age rocks sampled in Heezen Canyon (Plate 1 *b*). These debris-flow deposits are crudely stratified to massive and structureless, contain cut and fill structures, and often contain blocks exceeding tens of meters in diameter. One of these blocks was exposed for 150 m along the thalweg outcrop.

Semi-consolidated Pleistocene to Recent deposits are present on the walls of Oceanographer Canyon up to a depth of at least 1 072 m (Dive 779, samples 779-6, 779-8, 779-9). In Heezen Canyon such deposits are present to a depth as shallow as 1 031 m (samples 780-7, 780-8, 780-9). None of these outcrops contain exotic blocks.

Present morphology of canyons

We found that in order to successfully sample canyon bedrock exposures, an understanding of the present-day canyon morphology was necessary. Our first three dives, 779, 780 and 781, proceeded up the steepest walls of Oceanographer, Heezen and Corsair Canyons but proved to be unsuccessful in terms of finding significant rock exposures. Although sometimes precipitous, the walls of the canyons are either mud-covered and/or expose only the semi-consolidated Pleistocene to Recent deposits. Our dive up the wall of Heezen Canyon (780) traversed a complex terrain of mud ridges and steep gullies (see upper right of Figure 5). This morphology perhaps reflects the non-resistant nature of the underlying Pleistocene to Recent deposits. Occasional glacial erratics litter the canyon slopes.

We found the thalwegs and immediately adjacent walls to provide the most continuous exposure of canyon bedrock. The rather flat canyon floors themselves are often muddy to sandy. They are rippled by discernible currents moving primarily downslope. B . C. Heezen's unpublished investigations of the Georges Bank Canyons indicate that currents measured at 5-30 cm/sec velocity sweep both up and down the canyons in this region roughly following the tidal cycle. Rock exposures in and along the thalwegs are fresh and exhibit large scour features and undercut ledges. The thalwegs can be broad (> 50 m or more) and flat, such as in Oceanographer Canyon (Dive 784) or extremely narrow (< 3 m) and rocky such as in portions of Heezen Canyon (Dive 782, 783). Rock debris and talus blocks and slump blocks in the canyon axes (Plate 1 *c*) indicate that mass wasting and gravitational collapse of bedrock is an active process along the steep walls of the present-day canyon. The thalwegs of the canyons meander on a scale often too small to be shown on the bathymetric maps. Rock exposures are best (freshest) on the undercut outer bank of meanders, whereas they are overlapped and hidden by recent sediments on the inner side of the meanders. At places where Heezen Canyon traverses more resistant lithologies, the canyon becomes steeper and continuous bedrock exposures are present. We documented several bowl-shaped depressions resembling "plunge-pools" or "splash pools" along the course of Heezen Canyon. The most striking of these, at 1 170 m in Heezen Canyon, is scoured into upper Middle Eocene chalk. It is approximately 10 m deep and has a flat muddy bottom littered with large talus blocks of chalk (upper left of Figure 5). Immediately above this feature, Heezen Canyon becomes a spectacular narrow-walled (3-5 m wide) gorge incised into a massive 70 m high cliff of white Eocene chalk.

The bathymetric maps of the New England Canyons show distinctively different morphologies. Heezen Canyon follows a very linear course. In contrast, Oceanographer and Corsair Canyons exhibit large right-angle bends. Heezen Canyon posseses a complex dendritic pattern reminiscent of "badlands" topography, while the tributaries of Oceanographer Canyon are subparallel and orthogonal to each other as if controlled by a tectonic fabric. In all canyons the subsidiary dendritic drainages cut headward into the regional slope and most of the down-slope tributaries are not fed from the shelf edge.

LITHOSTRATIGRAPHY AND BIOSTRATIGRAPHY

The lithologic, petrographic and biostratigraphic data for all samples collected during our dives are summarized in Tables 1, 2, and 3. This section discusses the data crucial to the stratigraphic and geologic reconstruction discussed in the previous section.

Lower Cretaceous and Mid-Cretaceous (?)

Lithostratigraphy

Rocks of this age-span consist of: 1) limestones, and 2) carbonate-cemented calcareous sandstones and subarkosic sandstones. Samples 783-7, 783-8, 783-9 and 780-5 (Plate 2 *a* and 2 *d*) are representative of the older limestone sequence exposed at depths of 1 334 to 1 257 m in Heezen Canyon. These four samples are all bioclastic limestones containing little or no terrigenous debris. The limestone sequence in Heezen Canyon thalweg (783-7, 8, 9) is both overlain and underlain by calcite-cemented calcareous quartz-feldspar sandstones (783-11, 783-6) (Plate 2 *c* and 2 *e*). These clastic rocks contain well-rounded to angular coarse sand-size quartz (40-50%), feldspar (10-15%), and 20% bioclastic material which includes some reworked micritic carbonate debris in a micritic to sparry-calcite matrix. The limestone on the wall of Heezen Canyon (780-5) is underlain by coarse-grained calcareous sandstone that contains 25% quartz, 5% feldspar and 60-70% carbonate particles (Plate 2 *f*) that have thin, micritized oolitic coatings, in a matrix of sparry calcite.

Table 1

Litho- and biostratigraphy Heezen Canyon samples

Dive	Sta.	Depth (m)	Location N. Lat. W. Long.	Setting	Lithology	Color	Fossil groups	Selected Species	Age	Environment
780	9	1 031	41°02.07′ 66°21.42′	Canyon wall outcrop	*Silty mud* Coarse fraction : 70-80 % quartz 5-15 % foraminifera 2- 3 % glauconite, pyrite	Greenish gray	Plankt. and benthonic foraminifera Rare Radiolaria Plant debris Sponge spicules	*Globorotalia inflata* *G. truncatulinoides* *Globigerina eggeri* *G. pachyderma*	Pleistocene	Hemi-pelagic
780	8	1 051	41°02.29′ 66°21.40′	Canyon wall outcrop	*Sandy mud* Coarse fraction : 80-90 % quartz 10-15 % pyrite 2- 3 % glauconite	Greenish brown	Few foraminifera Plant debris	*Globorotalia inflata* *G. atlantisae* *Globigerina pachyderma*	Pleistocene	Older canyon fill with oxygen starvation
780	7	1 073	41°02.38′ 66°21.42′	Canyon wall outcrop	*Sandy mud* Coarse fraction : quartz, mica, pyrite glauconite foraminifera	Gray greenish	Few foraminifera Few Radiolaria	*Globigerina pachyderma*	Pleistocene	Slope with oxygen minimum, older canyon fill
780	6	1 105	41°02.38′ 66°21.42′	Bottom sediments on canyon wall	*Sandy mud* Coarse fraction : 85-95 %quartz 2 % glauconite 5-10 % foraminifera	Gray greenish	Plankt. and benthonic foraminifera		No date Recent (?)	Slope drape
783	12	1 165	41°03.22′ 66°22.15′	Thalweg outcrop	*Chalk* 1 % terrigenous : quartz, feldspar 1 % glauconite	White	Plankt. and benthonic foraminifera	*Globorotalia spinulosa* *G. cerroazulensis cerroazulensis* *Truncorotaloides rohri* *T. topilensis* *Globigerinatheka*	Latest part of Middle Eocene (upper part of *T. rohri* Zone)	Pelagic
783	11	1 188	41°03.21′ 66°22.07′	Thalweg outcrop	*Calcareous quartz-feldspar sandstone* 60 % terrigenous : quartz, feldspar rock fragments	Light brown yellow	Micritized echinoderm fragments Shell fragments		Lower Cretaceous (?)	Beach/ hi-energy
783	10	1 231	41°03.19′ 66°21.96′	Thalweg (talus)	*Calcareous mudstone* Coarse fraction : quartz, glauconite white mica	Brown	Diatoms Radiolaria Siliceous sponge spicules Benthonic foraminifera Nannofossils	Radiolaria (*): *Lithocyclia aristotelis* *Theocampe pirum* Coccoliths (**) : *Ismolithus recurvus* Diatoms (**) : *Pterotheca* sp. *Stephanopyxis turris* *Hemiaulus danicus* *Melosira architecturalis* *Aulacodiscus* cf. *A. stelliformis* *Triceratium* cf. *Tr. schulzii* *Coscinodiscus* cf. *C. argus*	Upper Eocene (*)	Pelagic with upwelling
783	9	1 257	41°03.08′ 66°21.82′	Thalweg talus at base of outcrop	*Bioclastic limestone* (bio-pelsparite) 1 % terrigenous 5 % glauconite	Greenish gray	Benthonic foraminifera Ostracods, bryozoans Gastropods, tintinnids Extremely abundant echinoderm fragments	*Trocholina infragranulata* *T. conica* *Lenticulina*	Neocomian	Hi-energy carbonate shelf

783	8	1 280	41°02.98' 66°21.68'	Thalweg outcrop	*Bioclastic limestone* (bio-pelmicrite/sparite)	Pale gray	Abundant echinoderm fragments Hydrozoans Benthonic foraminifera Pelagic crinoids Sponge spicules Gastropods, serpulids *Trocholina* Calpionellids	*Saccocoma* *Tintinnopsella carpathica* *Calpienellopsis oblonga* *Bracholina alpina* *Trocholina alpina*	Neocomian : Upper Berriasian Stage (*C. simplex/* *C. oblonga* Zone)	Reef tract
783	7	1 301	41°02.93' 66°21.58'	Thalweg outcrop	*Bioclastic limestone* (bio-pelsparite) 3-5 % terrigenous	Reddish Hematitic	Bryozoans, mollusks Coralgal fragments Benthonic foraminifera Ostracods Abundant echinoderm fragments	*Meandrospiranella* *Lenticulina*	Mesozoic (?)	Inner carbonate platform
783	6	1 308	41°02.93' 66°21.58'	Thalweg outcrop	*Calcareous quartz-feldspar sandstone* 60-65 % terrigenous : quartz, feldspar	Light brown yellow	Echinoderm fragments Shell fragments	*Trigonia* molds in hand specimen	Lower Cretaceous	Beach deposit
783	5	1 332	41°02.86' 66°21.50'	Thalweg outcrop	*Calcereous mudstone*	Chocolate brown	Foraminifera Radiolaria Siliceous sponge spicules Fish teeth	*Globigerinata boweri* *G. venezuelana* *G. linaperta* *Globigerinata inicava* Diatoms (**) : *Aulocodiscus* cf. *A. stelliformis* *Stephanopyxis grunowii*	Middle Eocene	Hemi-pelagic with upwelling
780	5	1 334	41°02.26' 66°20.90'	Canyon wall outcrop	*Bioclastic limestone* (biosparite)	Pale gray	Corals, calcareous algae Crinoids, echinoids Sponges, pelecypods Gastropods	*Lithocodium* cf. *L. jurassicum*	Lower Cretaceous	Reef tract
780	4	1 359	41°02.23' 66°20.79'	Canyon wall outcrop	*Calcite cemented oolitic calcareous-quartz grainstone* (coarse-grained) 30 % terrigenous : quartz, feldspar	Dark gray	Shell fragments Echinoderm fragments Coralline algae fragments		Lower Cretaceous	Hi-energy carbonate shelf with shoals
783	4	1 370	41°02.76' 66°21.37'	Thalweg outcrop	*Silty marl* Coarse fraction : quartz glauconite pyrite, mica	Light brown	Plankt. foraminifera Sponge spicules	*Globigerina boweri* *Truncorotaloides rohri* *T. topilensis* *Globorotalia spinulosa* *Globigerinatheka*	Upper Middle Eocene (*O. beckmanni* or *T. rohri* Zone)	Hemi-pelagic
783	3	1 381	41°02.73' 66°21.30'	Thalweg outcrop	*Slightly calcareous silty mudstone*	Brown	Coccoliths			Hemi-pelagic
783	2	1 403	41°02.61' 66°21.16'	Thalweg talus block	*Calcareous glauconitic sandstone* 40 % terrigenous : quartz, feldspar rare mica 3-5 % glauconite	Gray greenish	Echinoderm fragments Bryozoans Foraminifera tests Pelleted intraclasts Pelecypod fragments Coralgal material Phosphatic fossil fragments		Lower Cretaceous (?)	Carbonate shelf/ lagoonal

(*) Age and species identification by David Johnson, Woods Hole Oceanographic Institution, Woods Hole, Mass.
(**) Age determination on diatoms by Lloyd Burkle, Lamont Doherty Geological Observatory.
(***) Palynomorphs and dinoflagellates determined by Daniel Habib, Dept. of Earth and Environmental Sciences, Queens College of the City University of New York.

Table 1 (continued)
Litho- and biostratigraphy of Heezen Canyon samples

Dive	Sta.	Depth (m)	Location N. Lat. W. Long.	Setting	Lithology	Color	Fossil groups	Selected Species	Age	Environment
783	1	1 477	41°02.50′ 66°20.96′	Thalweg outcrop	*Silty mudstone* Coarse fraction : quartz glauconite foraminifera	Chocolate brown	Coccoliths Benthonic foraminifera (Eocene affinity) Plankt. foraminifera (contaminants from Quarternary	*Siphonodosaria* *Plectofrondicularia* *Angulogerina*	Eocene mixed	
780	2-2	1 503	41°02.40′ 66°20.63′	Thalweg floor	*Sandy to silty mud* (unconsolidated) Coarse fraction : 80-90 % quartz 10-20 % foraminifera 1-5 % glauconite	Gray	Plankt. and benthonic foraminifera	*Globorotalia inflata* *G. tumida* *Globigerina eggeri* *Globigerinoides ruber*	Quaternary	Modern current swept axis
780	2-1	1 503	41°02.40′ 66°20.63′	Thalweg outcrop possibly slumped	*Silty mudstone* Coarse fraction : 40 % quartz 1-2 % white mica 2-5 % glauconite 40 % diatoms 10 % Radiolaria	Chocolate brown	Benthonic foraminifera Radiolaria Micrascidites of tunicates Siliceous sponge spicules Diatoms	*Globigerina boweri* Radiolaria (*): *Astrophacus limckian formis* *Entapium regulare* *Xiphospira circularis* *Amphisphaera minor* *Stylosphaera coronata sabaca* Diatoms (**) : *Aulacodiscus* cf. *A. stelliformis* *Stephanopyxis grunowii* *Hemiaulus danicus* *Melosira architecturalis*	Lower Middle Eocene (*Phomocyrtis striata striata* zone)	Hemi-pelagic with upwelling
782	6	1 569	41°02.05′ 66°20.05′	Canyon wall outcrop	*Silty mudstone* 3-5 % glauconite 10 % quartz, feldspar mica	Chocolate brown	Diatoms Foraminifera Radiolaria Siliceous sponge spicules Micrascidites of tunicates	Diatoms (**) : *Hemiaulus danicus* *Melosira architecturalis* *Pyrgopyxis gracilis* Coccoliths (**) : *Chiasmolithus grandis*	Eocene (?)	Hemi-pelagic with upwelling
782	2	1 604	41°01.95′ 66°19.82′	Thalweg, talus at base of outcrop	*Silty mudstone* Coarse fraction : 40 % quartz 5-10 % white mica minor biotite 10-15 % glauconite 25 % diatoms 15 % Radiolaria	Chocolate brown	Diatoms Radiolaria Siliceous sponge spicules Micrascidites of tunicates	Radiolaria (*) : *Amphisphaera minor* *Xiphospira circularis* *Periphaena heliastericus* *Lychmocanoma* sp. cf. *L. bellum* *Stylosphaera coronata laevis* *Axoprunum pierinae* *S. coronata sabaca* *Theocyrtis turberosa* *Podocyrtis* sp. cf. *P. mitra* Diatoms (**) : *Coscinodiscus* cf. *C. argus* *Aulacodiscus* cf. *A. stelliformis* *Hemiaulus danicus* *Pyrgopyxis gracilis* *Melosira architecturalis* *Stephanopyxis grunowii* *Cymatosira* sp.	Probably lower Middle Eocene	Hemi-pelagic with upwelling

782	1	1 608	41°01.95' 66°19.82'	Canyon wall outcrop	*Dolomitic silty mudstone* 2-5 % glauconite 10-20 % terrigenous : quartz, feldspar, mica 50-70 % detrital (?) dolomite	Chocolate brown	Rare Radiolaria Foraminifera tests		Eocene (?)	Hemi-pelagic
782	5	1 620	41°02.02' 66°19.75'	Thalweg outcrop	*Glauconitic calcareous sandstone* 10-15 % glauconite 40 % terrigenous : quartz, feldspar	White	Plankt. and benthonic foraminifera Echinoderm fragments Sponge spicules		Eocene (?)	Downslope re-working of shelf sediments
782	4-1	1 628	41°02.01' 66°19.74'	Thalweg talus block	*Glauconitic chalky sandstone* 1-3 % glauconite 25 % terrigeneous : quartz, feldspar trace mica	Light brownish white	Calcareous sponge spicules Rare foraminifera Radiolaria tests Shell fragments		Eocene (?)	Downslope re-working of shelf sediments
782	4-2	1 628	41°02.01' 66°19.74'	Thalweg talus block	*Slightly calcareous silty mudstone* Coarse fraction : 45 % glauconite 45 % quartz mica, pyrite	Chocolate brown	Nannofossils Diatoms Radiolaria Siliceous sponge spicules Microscidites of tunicates Plankt. foraminifera Fungal spores Small acanthomorphid acritarchs (***)	Radiolaria (*) : *Theocorys acroria,* *Stylosphaera coronata sabaca* *Axoprunum pierinae* *Xiphospira circularis* *S. coronata laevis* *Periphaena decora* *Thecosphaera larnacium* Foraminifera : *Globigerinatheka* *Globigerina linaperta* *G. boweri* *G. hagni* Diatoms (**) : *Stephanopyxis grunowii* *Pyrgopyxis gracilis* *Hyalodiscus subtilis* *Coscinodiscus* cf. *C. argus* *Aulacodiscus* cf. *A. stelliformis* Coccoliths (**) : *Ismolithus recurvus* *Chiasmolithus grandis* Spiniferites (***)	Middle Eocene (possibly Upper Eocene**)	Hemi-pelagic with upwelling
782	3	1 629	41°02.00' 66°19.73'	Canyon wall outcrop	*Calcareous glauconitic sandstone* 5-10 % glauconite 10-15 % terrigenous : quartz, feldspar rare muscovite	White	Plankt. and benthic foraminifera	*Globigerinatheka* *Globorotalia spinulosa* *G. broedermanni* *G. lehneri* *Truncorotaloides rohri* *T. topilensis* *Globigerina hagni* *G. boweri* *G. senni*	Middle Eocene (*O. beckmani* or *T. rohri* Zone)	Downslope re-working of shelf sediments

(*) Age and species identification by David Johnson, Woods Hole Oceanographic Institution, Woods, Hole, Mass.
(**) Age determination on diatoms by Lloyd Burkle, Lamont Doherty Geological Observatory.
(***) Palynomorphs and dinoflagellates determined by Daniel Habib, Dept. of Earth and Environmental Sciences, Queens College of the City University of New York.

Table 2
Litho- and biostratigraphy of Oceanographer Canyon samples

Dive	Sta.	Depth (m)	Location N. Lat. W. Long.	Setting	Lithology	Color	Fossil groups	Selected Species	Age	Environment
779	9	1 072	40°13.42′ 68°06.78′	Canyon wall outcrop	*Sandy mud* Coarse fraction : 85 % quartz 10 % pyrite glauconite rare foraminifera	Olive gray	Rare plankt. foraminifera Echinoid spines Ophiuroid sclerites	*Glogigerina pachyderma* *G. bulloides*	Pleistocene	Slope oxygen minimum, some displaced older canyon fill
779	8	1 124	40°13.70′ 68°06.61′	Canyon wall outcrop	*Sandy mud* Coarse fraction : 95 % quartz glauconite pyrite rare foraminifera	Olive brown	Rare foraminifera Echinoid spines	*Globigerina pachyderma*	Pleistocene	Slope, low productivity, older canyon fill
779	6	1 154	40°13.74′ 68°06.58′	Canyon wall outcrop	*Sandy mud* Coarse fraction : 50 % quarts 50 % foraminifera shell fragments, pyrite glauconite	Greenish blue gray	Echinoderm spines Plankt. and benthonic foraminifera (many large agglutinated forms present)	*Globorotalia menardii* *Globigerina eggeri* *Bathysiphon* *Cyclammina*	Recent	Slope, older canyon fill
779	5	1 212	40°13.80′ 68°06.55′	Canyon wall	*Silty mud* Coarse fraction : 80-90 % quartz 10-20 % pyrite rare foraminifera glauconite	Green gray	Rare plankt. foraminifera Echinoid spines	*Globorotalia inflata* *Globigerina bulloides* *G. pachyderma*	Pleistocene	Slope, low productivity
784	8	1 420	40°15.70′ 68°06.80′	Canyon wall outcrop	*Dolomitic silty mudstone* Coarse fraction : 80-90 % aggregate dolomite 10 % quartz trace glauconite	Brown	Unfossiliferous			Hemi-pelagic
779	4	1 464	40°14.26′ 68°06.06′	Canyon wall outcrop	*Sandy mud* Coarse fraction : 70 % quartz 20 % foraminifera 10 % glauconite mica	Greenish gray	Plankt. and benthonic foraminifera Rare Radiolaria Plant debris	*Globorotalia inflata* *Globigerina pachyderma*	Pleistocene	Hemi-pelagic, older canyon fill
779	3	1 473	40°14.30′ 68°06.04′	Canyon wall outcrop	*Siltstone* Coarse fraction : quartz rare glauconite mica	Dusky brown	Foraminifera Dinoflagellates Fine optically translucent debris (xenomorphic)	*Globorotalia inflata* *G. tosaensis* *G. truncatulinoides* *Globigerina pachyderma* *Gonyaulax* (*Spiniferites*) (*) *Ceratium* (*)	Pleistocene	Hemi-pelagic, older canyon fill
779	2	1 483	40°14.32′ 68°06.02′	Canyon wall outcrop	*Sandy mud* Coarse fraction : quartz foraminifera glauconite mica	Olive brown	Foraminifera Small acanthomorphid acritarchs (***) Fine opaque organic debris (micronitic)	*Globorotalia inflata* *G. truncatulinoides* *Globigerina bulloides* *G. pachyderma*	Pleistocene	Hemi-pelagic, older canyon fill

784	6	1 497	40°15.30′ 68°06.32′	Thalweg outcrop	*Sandy clay* Coarse fraction : 50-60 % quartz sand 20 % glauconite 30 % rock fragments	Dark green	Foraminifera	*Globigerinoides ruber* (pink) *Globorotalia inflata* *Globigerina pachyderma*	Recent	Older canyon fill
784	5	1 517	40°15.15′ 68°06.15′	Thalweg talus	*Dolomite-cemented* *subarkosic sandstone* 40-50 % quartz 15-20 % feldspar 10 % aggregate quartz 5 % white mica	Dark gray	Highly recrystallized shell fragments Echinoderm fragments		Mid- Cretaceous (?)	Beach rock (?)
784	2-2	1 553	40°14.65′ 68°06.05′	Thalweg talus	*Sandy mud* Coarse fraction : 40-50 % quartz 40-50 % foraminifera 1-2 % glauconite mica	Olive gray	Foraminifera Echinoid spines	*Globigerinoides ruber* (pink) *Globorotalia menardii* *Globigerina eggeri* *Bathysiphon* *Ammobaculites*	Recent	Hemi-pelagic, older canyon fill
784	2-1	1 553	40°14.65′ 68°06.05′	Thalweg outcrop	*Calcite-cemented* *calcareous sandstone* 60-70 % terrigenous : quartz feldspar mica trace glauconite	Dark gray	Abundant echinoderm fragments Bryozoan fragments Shell fragments Coraline algae fragments Biseniol foraminifera (micritized) Pelloidal intraclasts		Mid- Cretaceous (?)	Hi-energy shelf
784	4	1 565	40°14.83′ 68°06.04′	Thalweg talus	*Calcareous* *silty mudstone* Coarse fraction : foraminifera quartz mica glauconite	Brown	Plankt. and benthonic foraminifera Echinoid spines Organic matter Micrascidites of tunicates Siliceous sponge spicules	*Globotruncana gagnebini* *G. gansseri dicarinata* *G. arca* *Rugoglobigerina reicheli* *exacamerata* *Trinitella scotti* *Pseudotextularia elegans*	Upper Cretaceous Middle Maastrichtian stage (*G. gansseri* Zone)	Hemi-pelagic
779	1	1 567	40°14.38′ 68°05.78′	Thalweg floor	*Silty to sandy mud* Coarse fraction : 80 % quartz 2-3 % glauconite 10-15 % foraminifera rare Radiolaria sil. sponge spicules	Dark olive gray	Plankt. and benthonic foraminifera	*Globorotalia menardii* *G. truncatulinoides* *Globigerina eggeri* *Pulleniatina obliquiloculata*	Recent	Canyon axis sediment
784	3 A	1 571	40°14.75′ 68°06.00′	Thalweg outcrop	*Sandy mud* Coarse fraction : 95 % quartz glauconite, muscovite biotite, sponge spicules pyrite	Green gray Portion of sample	Unfossiliferous		Undated	Older canyon fill
784	3 B	1 571	40°14.75′ 68°06.00′	Thalweg outcrop	*Sandy mud* Coarse fraction : 70-80 % quartz 2-3 % glauconite 20-30 % foraminifera mica	Black portion of sample	Radiolaria Organic matter Echinoid spines Foraminifera	*Globorotalia inflata* *Globigerina bulloides*	Pleistocene	Hemi-pelagic

(*) Palynomorphs and dinoflagellates determined by Daniel Habib, Dept. of Earth and Environmental Sciences, Queens College of the City University of New York

Table 3
Litho- and biostratigraphy of Corsair Canyon samples

Dive	Sta.	Depth (m)	Location N. Lat. W. Long.	Setting	Lithology	Color	Fossil groups	Selected Species	Age	Environment
781	5	1 168	41°18.45′ 66°03.55′	Slope	*Silty mudstone* Coarse fraction: 60 % quartz 10 % white mica 3 % glauconite 20-25 % histrico-sphaerids	Chocolate brown	Abundant histricosphaerids Radiolaria Siliceous sponge spicules	Radiolaria (*): *Stylosphaera coronata sabaca* *Xiphospira circularis* *Lychnocanoma* sp. *Hexacontium palaeocenieum* Diatoms (**): *Pyrgopyxis gracilis* *Melosira architecturalis* *Stephanopyxis grunowii* *Hemiaulus danicus* *Coscinodiscus* cf. *C. argus*	Probably lower Middle Eocene, (*P. striata striata* Zone)	Pelagic upwelling
781	4	1 342	41°18.20′ 66°03.70′	Slope	*Silty mudstone* Coarse fraction: 95 % mineral grains 4 % diatoms 1 % Radiolaria	Dark chocolate brown	Radiolaria Diatoms Micrascidites of tunicates Plant debris Plankt. and benthonic foraminifera	*Globigerina boweri* *Chiloguembelina* Radiolaria (*): *Xiphospira circularis* *Lithomitia limeata* *Stylosphaera coronata sabaca* Diatoms (**): *Pyrgopyxis gracilis* *Hemiaulus danicus* *Stephanopyxis grunowii*	Probably lower Middle Eocene (P. *striata striata* Zone)	Pelagic upwelling
781	3	1 432	41°17.85′ 66°03.75′	Canyon wall	*Silty mudstone* Coarse fraction: quartz glauconite white mica trace biotite	Chocolate brown	Radiolaria Diatoms Micrascidites of tunicates Holothurian sclerites Benthonic foraminifera	*Siphonodosaria* *Plectofrondicularia* *Angulogerina* Radiolaria (*): *Xiphospira circularis* *Lychnocanoma limeata* *Theocyrtis tuberosa* *Theocampe* sp. cf. *T. amphora* *Entapium regulare* Diatoms (**): *Pyrgopyxis gracilis* *Hemiaulus danicus* *Melosira architecturalis* *Aulacodiscus* cf. *A. stelliformis* Coccoliths (**): *Chiasmolithus grandis* *Ismolithus recurvus*	Middle or Upper Eocene	Hemi-pelagic with upwelling
781	2	1 452	41°17.79′ 66°03.79′	Thalweg floor	*Sandy mud* Coarse fraction: 90 % quartz 2-3 % glauconite pyrite, foraminifera	Blue gray	Almost unfossiliferous Plankt. foraminifera	*Globorotalia inflata* *Globigerina pachyderma*	Pleistocene	Thalweg floor sediment low productivity
781	1	1 452	41°17.80′ 66°03.80′	Thalweg talus	*Calcareous glauconitic sandy mudstone* 10-20 % glauconite 20 % terrigenous: quartz, feldspar trace white mica	Black	Plankt. and benthonic foraminifera	*Globotruncana arca* *G. stuartiformis* *Rugoglobigerina* *Pseudotextularia elegans* *Pseudoguembelina excolata*	Upper Cretaceous, Lower Maastrichtian stage (*G. arca* Zone)	Hemi-pelagic with terrigenous influx and downslope reworking

(*) Age and species identification by David Johnson, Woods Hole Oceanographic Institution, Woods Hole, Mass.
(**) Age determination on diatoms by Lloyd Burkle, Lamont Doherty Geological Observatory.

Sample 784-2-1 from Oceanographer Canyon (Plate 2 *b*) is highly similar petrographically to the clastic rocks of Heezen Canyon containing 40-50% quartz, 5% feldspar, 1% mica, and 10-20% bioclastic particles cemented by sparry calcite. Sample 784-5, a talus block from Oceanographer Canyon is a distinctive rock, unlike any of the clastic rocks we recovered in that it is a dolomite cemented subarkosic sandstone containing 5% large muscovite grains.

All of these clastic rocks contain minor percentages of metamorphic rock fragments, and most of the feldspar is microcline indicating that the terrigenous material was derived from a plutonic metamorphic source area.

Biostratigraphy

All of the rocks described above are fossiliferous, and Tables 1, 2, and 3 list all fossil groups present. Briefly, our best control on the age of the Heezen Canyon limestone sequence is based on the occurrence of an Upper Berriasian calpionellid assemblage in sample 783-8 (*Calpionellopsis simplex/Calpionellopsis oblonga* zone of Catalano and Liguori, 1971). Sample 783-9, above 783-8 is Neocomian in age but not as closely dated as 783-8. Sample 780-5, very similar to sample 783-8, can also be assigned to the Lower Cretaceous.

We cannot precisely determine the age of limestone sample 783-7. Similarly, no age determinations were possible on the clastic-rich samples from Heezen Canyon, 783-6, 783-11, and 780-4. Trigonia (?) imprints in sample 783-6 (Plate 2 *c*) are compatible with a Lower Cretaceous stratigraphic position. The close proximity of these undated samples to our Upper Berriasian, Neocomian and Lower Cretaceous samples 783-8, 783-9 and 780-5 lead us to believe that the entire sequence is Neocomian in age.

We have no age determination on sample 784-2-1 from Oceanographer Canyon. Although petrographically similar to Neocomian rocks in Heezen Canyon, we have tentatively assigned it a Mid-Cretaceous (?) age as our seismic interpretation for this region (Ryan *et al.*, in preparation) indicates that Neocomian age strata should be at greater depths in the region of Oceanographer Canyon. We are not certain of the age assignment of sample 784-5, a talus block in Oceanographer Canyon. We infer that it was possibly derived from the wall of the canyon from part of the Mid-Cretaceous (?) sequence but its unusual mica rich mineralogy and its dolomitic cement makes this age assignment tentative at best.

Depositional environments

The Lower Cretaceous sequence of limestones and calcareous sandstones in Heezen Canyon contains fairly diverse lithologies deposited under shallow, open-marine conditions in a carbonate platform setting.

We interpret samples 783-8 and 780-5 from Heezen Canyon as limestones formed along the seaward portion of a Neocomian-age reef tract. The reefal character is indicated by abundant and locally dominant colonial organisms such as corals, hydrozoa, calcareous algae and large foraminifera. The fairly abundant and diversified assemblage of Calpionellids and the pelagic crinoid Saccocoma suggest that this reef tract faced the open ocean where these planktonic organisms lived.

Sample 783-7 contains benthonic foraminifera, bryozoan and molluskan fragments, ostracoda, and abundant echinoid fragments but no corals or other colonial organisms, and only fragments of calcareous algae. These data suggest that this rock was deposited further away from the reef tract, probably in an inner carbonate platform environment.

The fossil content of sample 783-9 indicates deposition in an open-marine carbonate shelf environment. Slight coating of grains and sparry cement are diagnostic of deposition in a high-energy environment near shoals. Sample 783-2, presumably derived from the Neocomian section upslope, contains pelletal intraclasts which appear to be partially altered reefal limestone, as well as a diverse assemblage of carbonate particles which include foraminifera tests and fragments of echinoderms, bryozoans, rudistids, pelecypods and coralline algae. The terrigenous grains show surface corrosion, indicative of residence in a silica undersaturated and calcite saturated environment. We interpret this rock to have been deposited in a back-reef lagoon receiving reworked reefal debris from the seaward side as well as terrigenous clastics from the landward side. Sample 780-4, a cemented oolitic calcareous grainstone with 30% terrigenous material (Plate 2 *f*) was deposited in a hi-energy carbonate shelf environment characterized by shoals where both bioclastic and terrigenous constituents were reworked, rounded, and oolitically coated.

Mid-Cretaceous (?) sample 784-2-1 from Oceanographer Canyon is similar to samples described above and is interpreted to have formed on a high energy beach or shoal region within a carbonate shelf environment.

Samples 783-6 and 783-11, the coarsest and most clastic units sampled within this sequence are probably beach deposits. They contain abundant echinoid and shell fragments brought in from an adjacent marine seaway. Terrigenous grains in 783-11 are chemically corroded, and micritic clasts are present in 783-6 indicating the proximity of a dominantly carbonate regime.

We are not certain of the depositional environment of sample 784-5 from Oceanographer Canyon. Its high dolomite content might reflect diagenesis within the phreatic zone.

Maestrichtian

Lithostratigraphy

Two samples of Maestrichtian age were recovered; one from Corsair and one from Oceanographer Canyon. Dive 781 in Corsair Canyon (Fig. 4) sampled a talus block in the canyon thalweg at a depth of 1 452 m (sample 781-1). This sample, a black glauconitic calcareous sandy mudstone, contains 10-20% quartz, 2-5% feldspar, 10-20% glauconite, 5-10% foram tests, and rare white mica grains supported in a matrix of fine-grained silty clay. Its coarse fraction contains 50-60% quartz, 30% glauconite, and 10-15% foraminifera. The quartz grains range from very coarse (1-2 mm) and well-rounded with pitted and frosted surfaces down to fine sand-size (0.2 mm), angular to subangular grains. The glauconite is botryoidal to well-rounded. Sample 784-4 from a depth of 1 565 m in Oceanographer is a brown calcareous silty mudstone. It contains 10-20% foraminifera, quartz, mica, glauconite, and sponge spicules in its coarse fraction.

Biostratigraphy

Sample 781-1 from Corsair Canyon contains a fairly abundant and diverse foraminiferal fauna that indicate a Lower Maestrichtian-age (*Globotruncana arca* zone, *sensu* Cita, Gartner, 1971). The foraminifera in this sample are dominantly planktonic. Sample 784-4 from Oceanographer Canyon also contains a fairly abundant and diversified foraminiferal fauna that indicate a Maestrichtian age (*Globotruncana gansseri* zone). This sample is quite similar in its mineralogy and fossil assemblage to lower Middle Eocene samples from Heezen and Corsair Canyons.

Depositional environment

Sample 781-1 from Corsair Canyon is unusual in that it contains a large percentage of coarse, rounded quartz grains and large glauconite grains in a much finer hemipelagic matrix. Texturally, this sample bears strong similarities to the Pleistocene and Recent canyon deposits. We interpret 781-1 to have been deposited in a slope or canyon region characterized by hemipelagic sedimentation with influx of coarse clastics derived from a shelf environment. Sample 784-4 is a hemipelagic deposit. As discussed in the previous section, we believe that this sample belongs to older Maestrichtian-age canyon fill deposits.

Eocene and rocks of questionable Eocene-age

Eocene-age rocks from Corsair, Heezen, and Oceanographer Canyon represent the most widely exposed and best-developed stratigraphic sequence in the region investigated. Three major lithologies are represented within this sequence: brown silty mudstone, glauconitic calcarenites and calcareous sandstones, and white pelagic chalk. Finer grained, light brown calcareous mudstones or marls are also present. As the brown silty mudstone lithology is in places interbedded with calcarenites, these light brown calcareous mudstones probably represent a transitional lithology between these two distinctive end members.

Lithostratigraphy of brown silty mudstones

The chemical analyses (Table 4) indicate that the brown silty mudstones generally fall into two groups: non-calcareous samples and somewhat calcareous samples. The less calcareous rocks contain variable amounts of radiolarians, diatoms, siliceous sponge spicules, micrascidites of tunicates, phosphatic material and no or very rare foraminifera. Well-preserved radiolarian assemblages in non calcareous samples 780-2-1, 782-2 (Heezen) and 781-5, 781-4 (Corsair) provide a lower Middle Eocene-age.

The slightly more calcareous silty mudstones contain variable percentages of foraminifera. Samples 783-5 and 783-3 (Heezen) were taken from brown silty mudstone horizons that are interbedded with white calcarenite and calcareous grainstone horizons (Fig. 5): the former sample yields a foraminiferal assemblage of Middle Eocene age and Eocene-age respectively. Sample 783-4, a light brown silty marl is the most highly calcareous of the brown silty mudstone samples. This sample contains a foraminifera assemblage that can be referred to the later part of the Middle Eocene or the *Orbulinoided beckmanni* or *Truncorotaloides rohri* zone (Bolli, 1966). These rocks, then, appear to be slightly younger than the less calcareous mudstones, substantiating our interpretation, based on visual estimates of dip, that a thick sequence of monotonous mudstone stratigraphically underlies the interbedded silty mudstones and calcarenites in Heezen Canyon. Samples 781-5 and 781-4 from Corsair are lower Middle Eocene based on radiolarians and suggest that part of the section sampled in this canyon corresponds lithologically and chronologically to the lower mudstone sequence in Heezen Canyon.

The two samples containing large percentages of detrital (?) dolomite 782-1, (Heezen) and 784-8 (Oceanographer) are barren. All other samples from depths greater than that of sample 782-1 in Heezen Canyon are Eocene in age, therefore, sample 782-1 is probably also Eocene in age. As both of these dolomitic samples contain no calcite (Table 4) they may be both Eocene in age as Maestrichtian samples from Oceanographer and Corsair Canyons are far more calcareous.

Depositional environment

We interpret the more siliceous, lower Middle Eocene rocks as hemipelagic canyon fill deposits, containing variable percentages of silt-size and occasionally fine sand-size terrigenous material. The environment of deposition of these rocks was possibly characterized by calcite dissolution and/or by upwelling and higher productivity of siliceous organisms as evidenced by the lack of calcareous fossil groups and the abundance and good preservation of radiolaria. The somewhat more calcareous samples of Middle Eocene to Upper Eocene age are also hemipelagic deposits, but the better preservation and higher abundance of more calcareous organisms is noted, although these samples contain siliceous organisms as well. Our diatom data on samples 781-3, 782-6, and 782-4-2 indicate generally shallower water (outer shelf) deposition. In order to explain their concentration in a deeper-water canyon-fill setting, we suggest that the diatoms may have been transported from the continental shelf into this deeper-water environment.

Lithostratigraphy of glauconitic calcarenites and calcareous grainstones

Eocene-age glauconitic calcarenites and calcareous grainstones are well-developed and exposed in Heezen Canyon

Table 4
Chemistry and mineralogy of selected samples from Corsair, Heezen and Oceanographer canyons.

Sample No.	Age	Chemistry												Ignition loss	Total	X-ray mineralogy
		SiO_2	Fe_2O_3	MnO_2	P_2O_5	Al_2O_3	TiO_2	Na_2O	K_2O	$CaCO_3$	$Mg.Ca(CO_3)$	CaO	MgO			
								Corsair								
781-3	Middle or Upper Eocene	59	5.43	0.015	0.20	15.50	1.60	1.17	1.95	2.85	–	–	1.45	11.65	100.81	Q, I-Cl
781-4	Lower Middle Eocene	57	6.43	0.06	0.20	17.00	1.25	1.25	1.95	–	–	0.60	2.10	12.7	100.54	Q, Cl-I
781-5	Lower Middle Eocene	58.5	6.86	0.11	0.50	15.80	0.85	1.33	2.15	–	–	0.58	2.25	10.1	94.03	Q, Cl-I
								Heezen								
782-1	Eocene (?)	38.5	5.72	0.04	0.50	12.40	0.80	0.50	1.60	–	37.28	–	–	3.26	100.56	Q, Cl-I
782-2	Lower Middle Eocene	60	5.85	0.01	0.20	17.50	0.95	1.25	2.20	–	–	0.35	1.40	10.0	99.72	Q, Cl-I
782-4	Middle Eocene	51.5	6.85	0.04	0.20	16.00	1.25	0.95	1.95	6.60	–	–	2.00	13.34	100.64	Q, Cl > I
782-6	Eocene (?)	55.5	4.71	0.01	0.50	15.50	2.00	1.10	2.00	4.20	–	–	1.35	13.66	100.52	Q, Cl > I
783-1	Eocene	55.0	6.85	0.015	0.10	15.70	1.75	0.87	2.05	4.20	–	–	1.75	12.66	100.93	Q, Cl-I
783-3		57.0	4.71	0.015	0.40	12.80	1.20	0.90	1.45	7.50	–	–	1.27	12.31	99.54	Q, Cl-I
783-4	Middle Eocene	40.0	4.00	0.015	0.20	5.50	0.36	0.80	1.80	41.00	–	–	1.80	4.00	99.47	Q, Cl-I
783-5	Eocene	59.0	3.86	0.015	0.40	13.30	1.00	0.50	1.70	9.80	–	–	1.50	9.71	100.77	Q, Cl-I
783-7	Mesozoic (?)	9.0	3.14	0.04	0.30	3.50	0.14	0	0.90	79.40	–	–	1.30	2.34	100.02	Q
783-10	Upper Eocene	61	4.57	0.01	0.20	14.0	1.10	1.13	1.80	4.90	–	–	1.30	9.61	99.61	Q, Cl-I
783-12	Upper Middle Eocene	24.5	2.00	0.03	0.40	2.70	0.14	0.30	0.80	66.10	–	–	1.80	2.83	100.47	Q
								Oceanographer								
784-2	Recent	65.5	4.00	0.04	0.10	9.30	0.62	1.40	2.30	8.90	–	–	1.40	7.38	99.90	Q, I-Cl
784-4	Maestrichtian	49.0	3.00	0.01	0.10	12.00	1.15	0.70	1.80	23.20	–	–	1.70	7.94	100.59	Q, I-Cl
784-8		21.00	4.00	0.04	0.40	7.50	0.35	0	1.10	–	54.15	–	–	11.00	99.49	Q, I-Cl

(samples 782-3, 782-4-1 and 782-5). They apparently overlie non-calcareous lower Middle Eocene silty mudstones and are interbedded with slightly more calcareous silty mudstones (Fig. 5). In thin-section, the above three samples contain 15-40% quartz, minor feldspar, rare mica, 3-15% glauconite, and 20-40% carbonate particles in a matrix of fine-grained chalky marl.

Biostratigraphy

Sample 782-3 yielded a foraminiferal assemblage fairly similar to that of calcareous mudstone sample 783-4, and can be referred to the upper part of the Middle Eocene, the *Orbulinoides beckmanni* or *Truncorotaloides rohri* zone (Bolli, 1966).

Depositional environment of glauconitic calcarenites and calcareous grainstones

The lithology of the white chalky calcarenite and calcareous grainstones of Heezen Canyon contrast sharply with the brown, hemipelagic silty mudstones with which they are interbedded. Their coarse grain size, and content of rounded quartz and glauconite suggest these rocks are not *in situ* deposits but represent the products of down-slope reworking of biogenic and authigenic shelf sediments in the form of grainflow or debris-flow deposits.

Lithostratigraphy of chalk

Above the highest Neocomian-age sample in Heezen Canyon, we recovered overlying white chalk at 1 165 m. Sample 783-12 was taken at the *base* of a 70 m high white chalk cliff. In thin-section, sample 783-12 contains about 1% silt-size quartz, less than 1% glauconite, and 15-20% carbonate particles in a fine-grained matrix of calcareous mud. The carbonate particles are primarily planktonic forams.

Biostratigraphy

The foraminiferal assemblage yielded by sample 783-12 can be very precisely dated using the recently proposed zonation founded on the evolution of *Globorotalia cerroazulensis* in the Middle and Upper Eocene succession of Possagno (Northern Italy) (Toumarkine, Bolli, 1975; Cita, 1975). The concurrent range of *Globorotalia cerroazulensis cerroazulensis* (previously known as *G. centralis*) and of its ancestor *G. cerroazulensis pomeroli* is very limited in time and corresponds to the upper part of the *Truncorotaloides rohri* zones, or, that is to the uppermost part of the Middle Eocene.

Depositional environment

The lack of terrigenous detritus and the abundance of planktonic organisms suggests that the rocks constituting the 70 m high chalk cliff are pelagic deposits.

Pleistocene to Recent Deposits

Lithostratigraphy

The younger sediments of the canyons are divisible into two groups: 1) the semi-consolidated, subhorizontally bedded sandy mudstones that are cut by the present-day canyon, and 2) the surficial muds and sandy muds which drape the walls and line the floors of the canyons. The semi-consolidated rocks are very soft and generally had to be sampled with a tube core. The outcrops of these strata are highly bored by recent organisms and easily sculpted and eroded by currents. The surficial muds and sandy muds drape over, and/or overlap the exposures of slightly older rocks. Both the older and younger sediments are mineralogically similar. They are non-calcareous and their coarse fractions contain mostly fine sand-size quartz. Many samples contain variable percentages of coarse-grained (0.5-1 m) well-rounded, frosted and pitted quartz grains. All of the samples contain variable percentages of glauconite and pyrite and more rarely, sponge spicules, echinoid spines and shell fragments. Foraminifera are absent to rare in many samples and fairly abundant in others.

Sample 784-6 was taken from a white, bedded, semi-consolidated older canyon fill outcrop in the axis of Oceanographer Canyon. Blocks of locally derived brown silty mudstone were seen in this exposure. The coarse fraction of sample 784-6 contains 30% lithic fragments (1-2 mm diameter) of silty mudstone reworked by erosion from the older units within the canyon. Lithic fragments of presumably older lithologies were seen in several other older canyon fill samples from both Oceanographer and Heezen Canyon.

Biostratigraphy

The distinction between Recent and Pleistocene foraminiferal assemblages in our samples has been based on the following criteria:

1) The occurrence of pink-colored tests of *Globigerinoides ruber*.

2) The occurrence of *Globorotalia menardii* and of other members of the so-called "tropical" faunal assemblage such as *Globigerinoides ruber*, *G. sacculifer*, *Hastingerina siphonifera*, and *Pulleniatina obliquiloculata*.

All samples termed "outcrops of older canyon fill" in Tables 1, 2, and 3 are overlapped by present-day canyon sediments and hence are somewhat older than the present-day sediments. Some of these "older" deposits, however, are dated as Recent. The criteria we used for distinguishing Recent from Pleistocene may permit some of these older exposures to have been deposited during warmer interglacial periods. All the sampled exposures of older canyon fill are heavily bored by living organisms, and the borings are usually filled with contemporary mud. Therefore, if these exposures are Pleistocene in age, they could possibly yield either a mixed or a present-day faunal assemblage.

Depositional environment

All of the Pleistocene and Recent samples have been termed hemipelagic. They all contain fractions of silt and fine sand-size grains in a mud matrix. The samples that contain much coarser frosted quartz grains and large glauconite grains probably indicate down-canyon clastic input from the continental shelf. Some of the older canyon fill deposits, with coarse particles of older lithologies exposed in the canyons, indicate re-working and local derivation of portions of these sediments.

CONTEMPORARY EROSION

In the confines of narrow thalwegs, the canyon walls are smoothed and fluted by abrasion. Because anemones, polychaetes, encrusting sponges and octocorals now adhere to many of these surfaces (Plate 1 *d*), we infer that the abrasion is not a steady-state phenomenon. Outcrops on benches higher up on the canyon walls are not, in general, fresh. They display pock marks possibly created by boring bivalves. Cavities in recovered samples contained brachiopods and occasional polychaetes. Differential weathering related to variable lithologies in bedded sequences is common. Joints and small crevaces on the scale of a meter in size could be identified on the scanning sonar display (CTFM).

Meanders exist, even within the narrowest gorges such as the one cut into Eocene chalk in Heezen Canyon and traversed on Dive 783. Using the CTFM we could document near right-angle bends in thalwegs only 20 m in width, as well as sinuous stretches where the radius of curvature for each bend is on the order of 100 m.

The sediment-draped canyon walls are gullied. Scree fans feed into the gulleys from small semi-circular slump scars only a few tens of centimeters to a few meters in height. Migrating ripples (parallel, orthogonal, and of the cross-cutting interference type) occur on the tops and at the base of some sediment draped benches. Moats are present around loose talus and glacial erratics.

Impact of submersible appendages with the seafloor causes clouds of flocullent sediment to be stirred up. At times of tidal current activity, the clouds would dissipate in a fraction of a minute. Infrequently, more than ten minutes is required before good visibility is reattained. Modest backscattering of light from natural nepheloid layers characterizes the axis of each canyon, especially when the thalweg is narrow. The backscattering, present at touchdown for Dive 779 at 1 567 m in Oceanographer Canyon, diminished noticably in going up a few hundred meters of the west wall.

Browsing animals consistently disturb a significant amount of loose sediment. The infauna eject the sediment as clouds which form pits and small mounds. Greater portions of the suspension settle on the downhill side of the holes. Some of the rat-tail fish dive into the substrata in the search for food. The flounder buries itself in it for shelter. When alerted by our presence, some of the latter take flight, streaming behind turbulent sediment eddies. Visual observations show that for minutes after the sediment returns to the seabed, it is carried by currents for a considerable distance as a very thin milky film.

SUMMARY OF PRINCIPLE OBSERVATIONS AND CONCLUSIONS

The New England margin contains a Mesozoic-age carbonate platform with reef-tracts, shoals, lagoons, and beaches. Sedimentary units deposited in these ancient settings are exposed in some of the submarine canyons along this margin. The canyons are not simple stratigraphic windows into the subhorizontally stratified continental margin miogeosynclinal wedge. The erosion of the canyons has been multi-phase, beginning at least prior to the Campanian-Maestrichtian time. The early erosion is deduced from the fact that younger strata have a greater vertical range than older strata, implying an increase in paleo-relief through time. Bedrock geology carried out by direct visual observation from the submersible and reinforced by controlled sampling reveals that the canyon regions are characterized by a complexity of interfingering sedimentary units, erosional unconformities, and chaotic mixing that would be impossible to understand by means of surface dredging, and seismic profiling alone. Older canyon fill deposits may be recognized by their significant seaward dip, by interbedded grainflow deposits containing materials transported from the shelf, and by faunal assemblages indicating susceptibility to carbonate dissolution and relatively low levels of oxygenation. Mass wasting of canyon walls causes avalanching of allochthonous blocks of former shelf-edge outcrops, slope outcrops, and units of previous canyon fillings. These older materials funnel through narrow thalwegs in the canyon system and discharge from the canyons onto the continental rise as boulder and olistolitic-carrying debris flows.

The contemporary canyons seaward of Georges Bank have little sediment in their axial thalwegs. Tidal currents are present and they transport some sediment down-canyon, both in suspension as thin nepheloid layers and as migrating sandy mud ripples seen along the floors of the canyons. Animal boring and encrustation are mechanisms assisting the weathering of outcrops. The daily burrowing and feeding habits of large epifauna such as crabs, flounder, and nose-diving rat-tail fish cause material to preferentially work its way down steep slopes where the sediment cover lies close to its angle of repose. The semi-permanence of tracks, trails, mounds and pits of these animals, however, indicate that much of the canyon is spared from significant denudation by steady-state tidal currents. Therefore, we feel there is still a need to call upon episodic events for the actual sculpturing of the complex subaqueous canyon systems in this region. Soft-sediment slumping, sand flows, gravitational collapse of undercut and/or weakened rock cliffs, and density-driven currents are all viable mechanisms to explain the actual canyon-cut phenomena documented by our field observations. Substantiation of these phenomena, which occur sporadically over longer time-spans then represented by our 8-10 hour dives, will require the installation of remote sea-bed monitors and repeated visits to key localities within the canyon cataract systems. Plunge-pools and narrow parts of gorges with overhanging walls are such locales and might be expected to best record this episodic history.

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