The Shelf-Slope Transition—Canyon and Upper Slope Sedimentary Processes on the Southern Margin of Georges Bank

U.S. GEOLOGICAL SURVEY BULLETIN 1782

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By PAGE C. VALENTINE

An examination of sedimentary environments in water depths of 150–600 meters and of how they are determined by the interaction of available sediment, bottom currents, and sea-floor morphology

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DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

UNITED STATES GOVERNMENT PRINTING OFFICE: 1987

For sale by the Books and Open-File Reports Section, U.S. Geological Survey,
Federal Center, Box 25425, Denver, CO 80225

Library of Congress Cataloging in Publication Data

Valentine, Page C.

The shelf-slope transition—canyon and upper slope sedimentary processes on
the southern margin of Georges Bank.
(U.S. Geological Survey bulletin ; 1782)
Bibliography: p.
Supt. of Docs. no. : I 19.3:1782
1. Marine sediments—Georges Bank. 2. Continental shelf—Georges Bank. 3.
Continental slopes—Georges Bank. 4. Ocean bottom—Georges Bank. 5.
Oceanography—Georges Bank. I. Title. II. Series.
QE75.B9 no. 1782 557.3 s 87-600040
[GC383] [551.46'083'345]

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The Shelf-Slope Transition—Canyon and Upper Slope Sedimentary Processes on the Southern Margin of Georges Bank

By Page C. Valentine

Abstract

This study of sedimentary processes on the southern margin of Georges Bank was based on observations from research submersibles of bottom features, on size analyses of sediment samples, and on measurements of current strength and flow direction made from submersibles and from long-term moored current-meter arrays of other investigators. The principal study area was the shelf-slope transition to a depth of approximately 600 m in a region that extends from west of Oceanographer Canyon eastward to Lydonia Canyon.

Sedimentary environments present in the transition from shelf to gullied upper slope and from shelf to submarine canyon floors are determined by the interaction of available sediment, bottom currents, and sea-floor morphology. Georges Bank is isolated from the North American continent by the Gulf of Maine, and the chief source of sediment for the bank margin is Pleistocene glacial deposits on the bank crest. The smooth, gently sloping outer shelf steepens slightly to become the upper slope, which is dissected by gullies having steep walls. Surficial sediment of the outer shelf and upper slope generally is slightly rippled and becomes smoother and finer grained as water depth increases. Superimposed on this terrain, submarine canyons of varying size and wall steepness incise the Georges Bank Shelf and contain a variety of sedimentary facies, including burrowed and collapsed Pleistocene outcrops, sand accumulations surfaced with large and small bed forms, almost featureless silty sand, and a pavement of ice-rafted gravel.

Three patterns of strong bottom currents recognized in the shelf-slope transition region are attributed to tidal currents, Gulf Stream warm-core rings, and an unknown source. Regional tidal currents are very strong on the bank crest, but they diminish in strength as water depth increases toward the shelf edge and are weak on the upper slope. However, tidal flow is affected by canyon morphology, and at outer shelf-upper slope depths (150–600 m) in large canyons having steep walls, the currents are very energetic. Tidal currents reach speeds of 75–100 cm/s in Oceanographer Canyon along a canyon floor covered by coarse sediment and large bed forms; exposures of burrowed Pleistocene silt are present on the lower walls. The silt is disaggregated by extensive bioerosion and by mass-wasting processes and is an important secondary sediment source for large and medium canyons. By contrast, small canyons such as Heel Tapper Canyon are relatively tranquil; they are shallow embayments of the upper slope, and, like the gullied upper slope, their walls and floors are covered by silty sand.

Gulf Stream warm-core rings impinge on the Georges Bank margin intermittently; anticyclonic currents in a ring flow northeastward at about 50 cm/s as the ring drifts southwestward. These strong currents winnow very fine sand and silt and clay from the upper slope between 200 and 300 m water depth. A strong current of unknown origin flows dominantly westward at about 50 cm/s across the rims of Oceanographer and Lydonia Canyons and transports shelf sand onto canyon walls while exposing deposits of ice-rafted gravel.

Within the shelf-slope transition, net transport is off the Georges Bank Shelf onto the gullied upper slope and into the canyons. Sediment movement is most rapid in three areas—from the shelf westward across the east rims of large canyons, in a narrow band northeastward along the upper slope, and along the lower walls and floors of large canyons, where net transport of sand is slow and is directed up or down the canyon and where fine sediment is winnowed and transported away in suspension. Sediment movement is less rapid on the outer shelf; on most of the upper slope, including the gullies; on the floors of small and medium canyons; and around some canyon heads. Moderately energetic canyons such as Lydonia may be accumulating sediment most rapidly; they trap a large volume of shelf sand as well as bioeroded silt from outcrops on their lower walls, and currents along the canyon floors are relatively weak.

Twelve canyons on the southern margin of Georges Bank are ranked by energy level on the basis of sediment texture, bed forms, and current observations. The relationship between energy level and canyon size and shape means that current and sediment dynamics in other canyons may be predicted if their bathymetry and regional tidal flow are known.

INTRODUCTION

At the outer edge of the continental shelf, the gently sloping sea floor steepens and becomes the continental slope. The increase in slope at the shelf break is chiefly a function of sediment supply, the hydrodynamic environment, and the structural transition from continental to oceanic crust. In general, bottom currents decrease in energy as water depth increases, to result in less effective sediment transport and in a reduction in sediment size away from continental sources. The physiographic boundary between the shelf and slope may advance seaward or retreat landward in response to changes in the volume of sediment supplied and to changes in current patterns and water depth. These principles hold in a broad sense, but patterns of sedimentation are modified regionally by many factors. Geological processes of the shelf-slope transition have been extensively researched, and papers on recent advances in the field are collected in two volumes, one describing the geology of continental slopes (Doyle and Pilkey, 1979), and the other describing the shelf break (Stanley and Moore, 1983).

Various sedimentary provinces are present in close proximity where the Georges Bank Shelf passes into two different physiographic provinces, namely, the heads of submarine canyons and the adjacent gullied upper slope. This report examines the transition in sedimentary facies from the outer shelf at about 150 m depth down to about 600 m on the southern Georges Bank margin (fig. 1); describes the sedimentary processes, current patterns, and sea-floor morphology that make the canyon and upper slope environments similar in some respects but very different in others; and provides a synthesis of the sedimentary environment of the shelf-slope transition. For the Georges Bank region, this information may prove useful in predicting and tracking the movement of water masses and currents and of the plankton and sediment particles, including pollutants, transported by them. In a broader sense, this study may contribute to an understanding of the evolution of continental shelf and slope environments during a high stand of sea level.

The principal study area was the shelf-slope transition to a depth of approximately 600 m in a region that extends from west of Oceanographer Canyon eastward to Lydonia Canyon (fig. 1). The most extensive observations and samplings of the sea floor were made in the northern part of Oceanographer Canyon and on the upper slope east (Filebottom Canyon area) and west of the canyon mouth during many dives of the research submersibles *Johnson-Sea-Link, Alvin,* and *Nekton Gamma* in 1974 and from 1980 to 1984 (figs. 2, 3; details of these dives were given by Valentine, Uzmann, and Cooper, 1980, 1984; Valentine, 1983, 1985; Valentine, Cooper, and Uzmann, 1984; Cooper and others, 1987).

A series of dives with the *Johnson-Sea-Link* was made to each of two sites on the east and west rims of Lydonia Canyon (shown by star-shaped symbols in fig. 4; Cooper and others, 1987), and in 1984, a single dive was made to a former current-meter station on the east rim of Lydonia Canyon. In 1984, single dives of the *Johnson-Sea-Link* were made also to the floors of Hydrographer (fig. 5), Gilbert (fig. 4), and Heel Tapper (fig. 2) Canyons. *Alvin* dives were made along the axis and walls of Lydonia Canyon in 1980 (Butman and others, 1983; Twichell, 1983). Sediment from the shelf-slope transition around the head of Oceanographer Canyon and in the area of Filebottom Canyon was collected by grab sampler from the surface ship in 1983 and 1984. All observations were made and all samples were collected during June, July, August, or September.

All samples used in this study were wet sieved to separate gravel, sand, and mud fractions. Size analyses were conducted by sieving for gravel and by using a rapid sediment analyzer for the sand fraction (Schlee, 1966) and a Coulter Counter[1] for the silt and clay fraction. Textural analyses of eight sediment samples from the floor of Lydonia Canyon that were reported in previous studies (Butman and others, 1983; Twichell, 1983) are incorporated here. All size data are given in weight percent. Statistical parameters for all samples were calculated by the method of moments (Krumbein and Pettijohn, 1938).

For purposes of comparing the textural differences of samples and relating these differences to the influence of bottom currents, the weight percentages of sediment size classes were recalculated by omitting data on gravel of pebble size and larger (grain diameter greater than 4 mm or -2ϕ). Thus, sediment samples plotted in figures 6*B*, 7, and 8 and discussed in the related text are compared on the basis of their constituent size classes that are most susceptible to transport by the prevailing currents. Gravel of pebble size and larger most likely was carried into this region by ice rafting during the Pleistocene, and present-day bottom currents are too weak to transport it farther. The samples from the outer shelf-upper slope areas and the floors of Oceanographer, Hydrographer, Gilbert, and Heel Tapper Canyons contained little or no gravel; only three samples contained more than 5 percent gravel of pebble size and larger, and the recalculation without gravel data affected the other size classes by less than 2 percent. Approximately 30 percent of the samples from the rim around the head of Oceanographer Canyon contained appreciable gravel; for most samples, the recalculation affected the finer size classes by less than 10 percent, although four samples were affected by 12–28 percent.

[1]Any use of trade names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

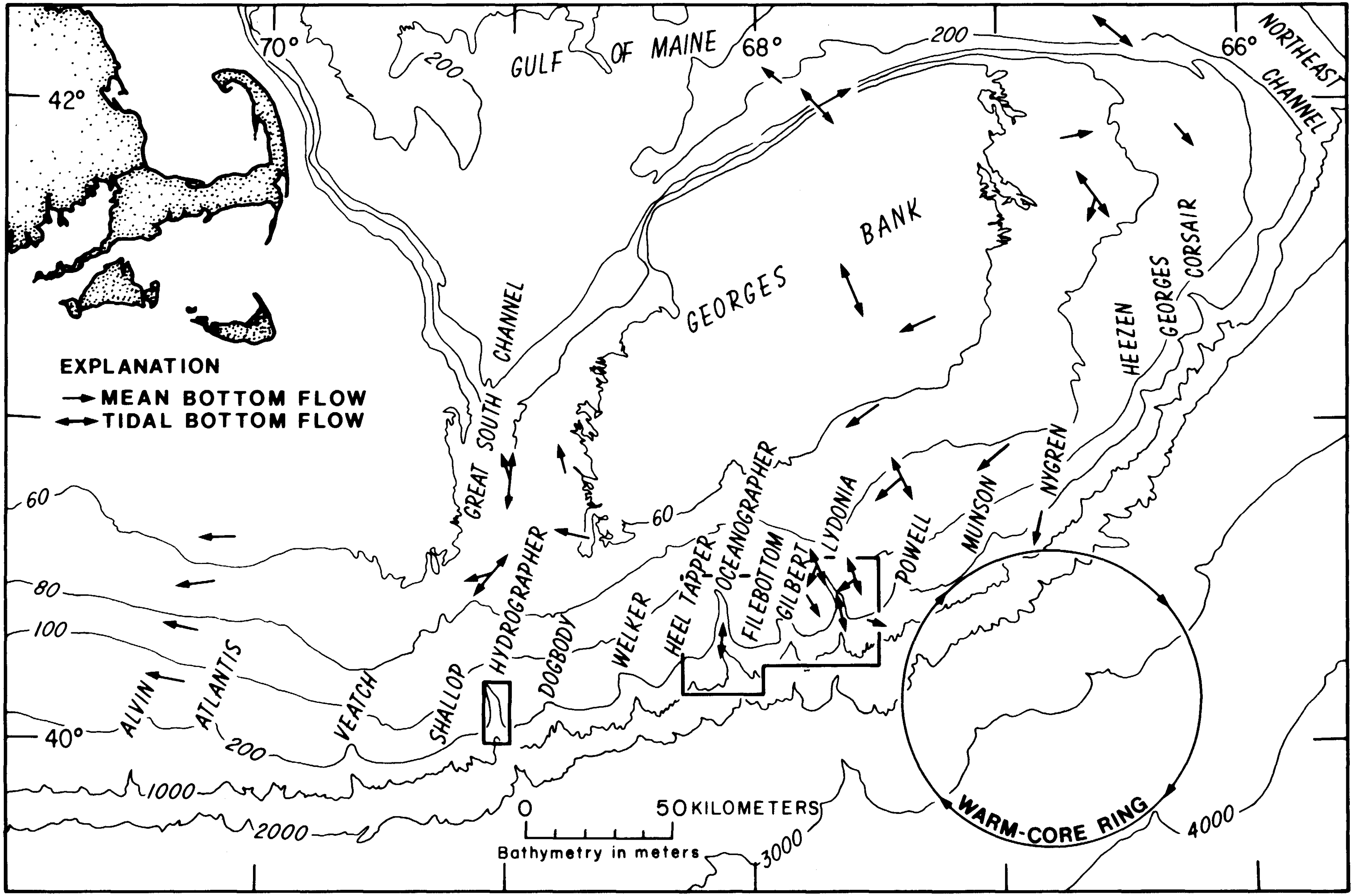


Figure 1. Map of Georges Bank showing physiography of the region, isolation of the bank from continental sediment sources, and major bottom-current patterns. Heavy lines indicate study areas, which are mapped in more detail in figures 2–5, 7, and 12. Major, predictable bottom currents on the bank are described briefly here. (1) The anticyclonic mean residual current flows at speeds of 5 cm/s or less, except on the northern edge where its speed reaches approximately 10 cm/s. (2) Anticyclonic Gulf Stream warm-core-ring currents flow northeastward at speeds of 50 cm/s or more on the upper slope at depths of 200–300 m as the rings drift southwestward along the bank margin. (3) Rotary semidiurnal tidal currents have their strongest flow across the bank—magnitudes of major axes of ellipses are as great as 10–20 cm/s on the bank margin and are more than 40 cm/s on the bank crest. Surface currents have similar patterns but flow faster than do bottom currents. Base map from Uchupi (1965). This figure is based in part on Butman and Beardsley (1987) and Butman and others (1987).

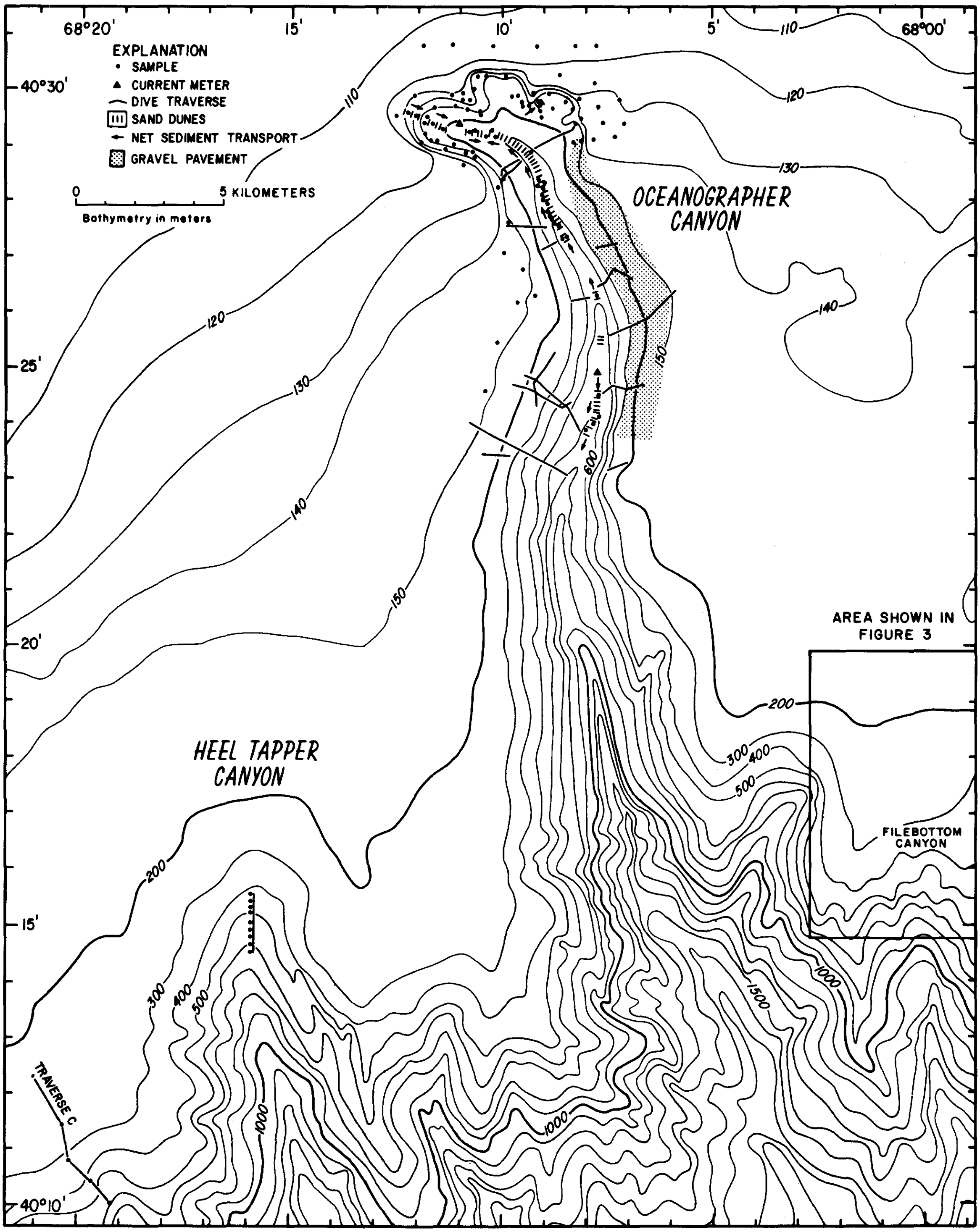


Figure 2. Map of Oceanographer and Heel Tapper Canyons and the two outer shelf-upper slope study areas. One shelf-slope study area was sampled by submersible during traverse C; the other is shown in figure 3. Dive traverses in the head and on the floor of Oceanographer Canyon are not shown (see Valentine, Cooper, and Uzmann, 1984; Valentine, Uzmann, and Cooper, 1984). Map base from Carpenter and others (1982). Information on samples from sites plotted here is given in figures 6–8.

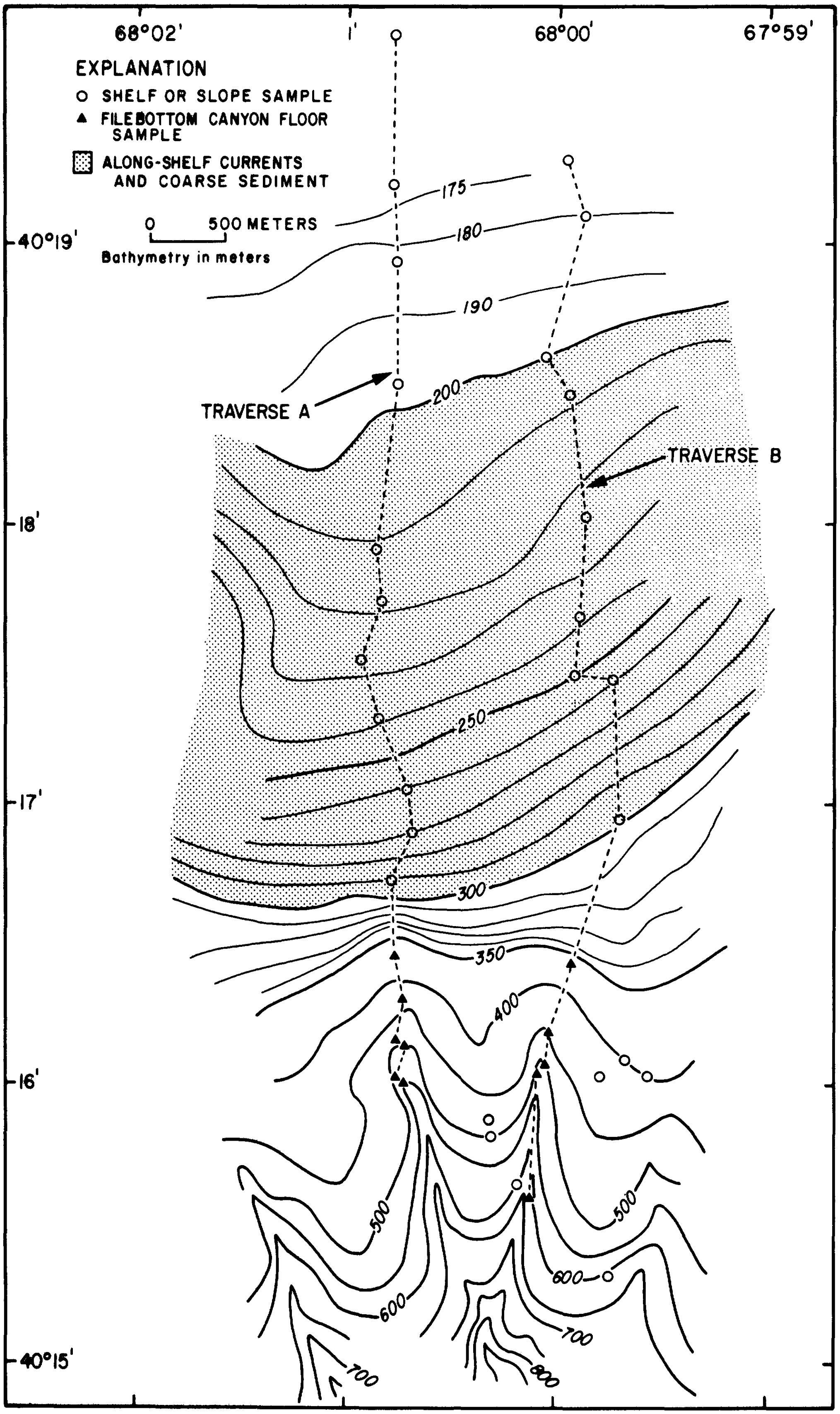


Figure 3. Map of the outer shelf-upper slope study area that includes the branching head of Filebottom Canyon. Information on grain sizes of samples along traverses A and B is plotted in figure 8, and data for all samples are plotted in figure 6. Samples were collected from surface ship and from submersible; all samples from below 350 m were collected by submersible. Sediment coarsens on the upper slope between 200 and 300 m (stippled area) because of winnowing by along-slope currents flowing principally to the northeast. Bathymetry is unpublished work by the author.

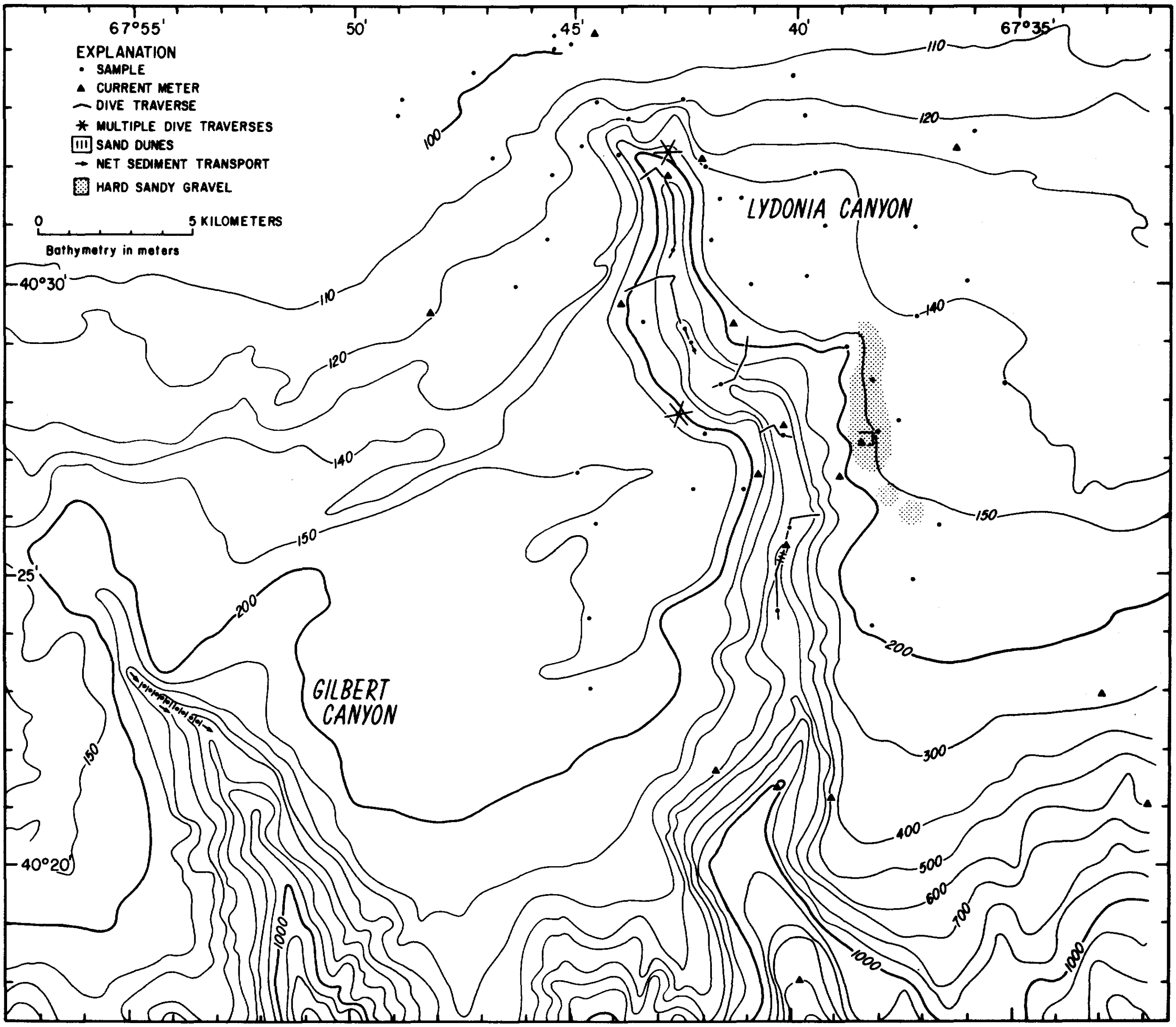


Figure 4. Map of Lydonia and Gilbert Canyons showing where current meters were deployed in 1980–82 as part of the Lydonia Canyon experiment (Butman, 1987; Butman and Conley, 1984; Butman and others, 1983; Moody and others, 1984). Data from only the eight samples from Lydonia Canyon floor and the nine samples from Gilbert Canyon floor are plotted in figure 6. Lydonia samples are part of the data presented by Butman and others (1983) and Twichell (1983), and samples from the canyon rim and the adjacent shelf were used by them to map bottom texture. Map base from Carpenter and others (1982).

The study of sediment texture, bed forms, and sea-floor morphology is complemented by observations made during a recent, long-term investigation by other workers of currents and sediment transport in the shelf-slope transition on Georges Bank. In particular, Lydonia Canyon and its adjacent shelf and upper slope were studied intensively with a network of 20 moored instrument arrays that collected data during periods of several months to 2 years, and the physical oceanography of this canyon is better documented than that of any Georges Bank canyon (Butman, 1987; Butman and Beardsley, 1987; Butman and Conley, 1984; Butman and others, 1983, 1987; Moody and others, 1984).

Acknowledgments

This research was undertaken in cooperation with scientists of the National Marine Fisheries Service of NOAA (U.S. National Oceanographic and Atmospheric Administration), and cruises were funded by NOAA's Office of Undersea Research. I appreciate the support of the crews of the *Johnson-Sea-Link* submersible and support ship R.V. *Edwin Link*, Harbor Branch Oceanographic Institution, and the *Alvin* and support ship R.V. *Lulu*, Woods Hole Oceanographic Institution. In particular, I thank Elliott A. Finkle (NOAA), Joseph R. Uzmann (National Marine Fisheries Service), and Richard A.

Cooper (University of Connecticut) for their interest and support during the course of this study, Brad Butman (USGS, U.S. Geological Survey) for sharing with me his insights on the current and sediment dynamics of Georges Bank and the preliminary results of the Lydonia Canyon experiment, and John S. Schlee (USGS) and Robert Oldale (USGS) for their helpful reviews of the manuscript.

SEDIMENTARY PROVINCES OF THE GEORGES BANK REGION

Georges Bank Shelf

Georges Bank (fig. 1) is part of the continental shelf off New England and is covered by Pleistocene sand and gravel that were deposited when glaciers extended over its northern edge (Schlee, 1973). On the crest of the bank, water depths range from 3 to 40 m. The bank edge to the north is at about 60 m, below which the sea floor dips steeply into the Gulf of Maine. The southern, or seaward, edge of the bank is at about 200 m and is far from the bank crest. At present, the bank is isolated from continental sediment sources by the Gulf of Maine basin. Lateral movement of sediment onto the bank from the Scotian Shelf to the northeast and from the Middle Atlantic Shelf to the southwest is impeded by topographic lows in Northeast Channel and Great South Channel. The seaward edge of the bank is dissected by submarine canyons and gullies.

The most comprehensive regional survey of sediment distribution showed that gravel is concentrated on the northern and eastern parts of the bank and that the remainder of the bank is covered by sand that decreases in size toward deeper water both to the north and to the south, thus suggesting sediment transport in those directions (Schlee, 1973, pl. 1; Schlee and Pratt, 1970). A more recent study based on closer spaced sampling on the shelf in the vicinity of Oceanographer and Lydonia Canyons also recorded a regional decrease in mean grain size toward the shelf edge (Butman and others, 1983). However, the sediment pattern becomes more complex near the canyon heads where local concentrations of very fine sand are present. The silt and clay content of shelf sediment is low, commonly 5 percent or less, and only rarely reaches 10 percent in some areas near the canyons (Hathaway, 1971). Vigorous currents atop the bank decline in strength as water depth increases toward the shelf break (Butman, Beardsley, and others, 1982).

Submarine Canyons

The southern edge of Georges Bank is indented by numerous submarine canyons of varying size that extend across the slope to the deep sea floor. Although canyon rims are northward extensions of the outer shelf edge, canyon environments can vary considerably from those of the outer shelf and upper slope at equivalent depths. The canyons have opposing walls and are oriented normal to the outer shelf edge; thus, they and the bank margin interact in different ways with the major current systems of the region.

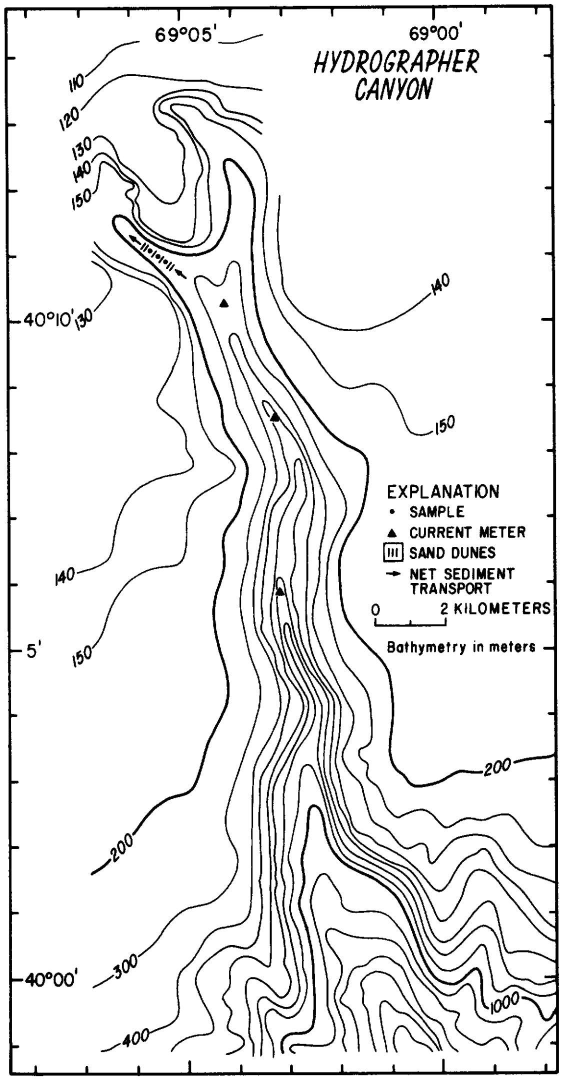


Figure 5. Map of Hydrographer Canyon. Data from samples collected from the canyon floor by submersible in 1984 are plotted in figure 6. Current meters were deployed in 1974 and were reported on by Keller and Shepard (1978) and Shepard and others (1979). Map base from Carpenter and others (1982).

Of the many incisions into the southern edge of Georges Bank, only a few extend an appreciable distance into the shelf. Oceanographer Canyon is the largest of these, and it reaches 22 km north of the shelf-slope transition (fig. 2). This canyon is the most thoroughly studied of all the Georges Bank canyons. It contains a wide range of sedimentary environments, and in many ways, it resembles other large and medium canyons (Hydrographer, Gilbert, Lydonia), but it differs from the smaller ones. The canyon rim carries the shelf break from a depth of approximately 200 m on the outer shelf to about 130 m at the canyon head. The canyon is a smooth-walled, broadly sinuous feature except for its lobate head formed by several tributary side valleys. The canyon floor ranges in depth from about 190 m in its head to about 1,200 m at its mouth, where it crosses the outer edge of the shelf.

The sedimentary facies in the northern part of Oceanographer Canyon are much more complex than those found on the surrounding shelf; they have been described and their origin has been discussed elsewhere (Valentine, Uzmann, and Cooper, 1980, 1984; Valentine, Cooper, and Uzmann, 1984). The facies are briefly described below. The canyon rim is veneered by gravelly sand and gravel or by a tightly packed gravel pavement; the gravel probably was transported by ice rafting and now is immobile. The upper walls are covered by sand transported from the shelf; this sand is commonly rippled and is somewhat silty as a result of mixing by burrowing organisms with an underlying sandy silt deposit. Ripples extend down to a depth of 350 m in some places on the upper walls, and their crests are oriented normal to the canyon rim, indicating transport along canyon walls. Similarly oriented ripples are also present in patches on the lower walls and are abundant on the canyon floor from the head down to at least 630 m, the depth limit of this study in Oceanographer Canyon. The lower canyon walls are exposures of Pleistocene semiconsolidated sandy silt that in places is covered by a thin layer of sand. The silt drapes the canyon walls and is part of a thick wedge of glacial outwash that was deposited before and during the last rise in sea level and that now underlies the outer shelf and upper slope. Silt outcrops commonly are disaggregated by bioerosion and by related spalling, sliding, and slumping. The canyon floor down to at least 630 m is covered by sand containing little silt and clay (generally 5 percent or less); the sand has been transported from the shelf and forms dunes as high as 3 m. Strong bottom currents have been observed to flow from the shelf across the eastern canyon rim and also up and down the canyon along the walls and floor.

By contrast, the sedimentary environments of small canyons are less diverse. Observations in Heel Tapper (fig. 2), Atlantis, and Veatch Canyons indicate that their walls and floors north of the shelf edge generally are covered by silty sand that is slightly rippled in some places; bioeroded Pleistocene silt is exposed locally on the upper walls.

Outer Shelf-Upper Slope

Two areas of the outer shelf-upper slope of Georges Bank have been sampled for this study (fig. 2). The most thoroughly studied area is 8 km east of the mouth of Oceanographer Canyon and encompasses the branching head of Filebottom Canyon, a gully that does not penetrate the shelf edge (fig. 3). Four dives and grab sampling from a surface ship were conducted here from 1982 to 1984. During a single dive in 1982 (traverse C, fig. 2) in a similar geologic setting 20 km west of Oceanographer Canyon, five samples were collected; they are included in the data base.

In the area east of Oceanographer Canyon, the outer shelf from 175 m water depth is relatively flat and smooth and dips gently seaward. At the shelf break (220 m), the inclination of the sea floor increases to about 5°. The upper slope extends uninterrupted down to the heads of two gullies that commence at 300–350 m and that are part of the branching head of Filebottom Canyon. Between the gully heads, the sea floor slopes 10°–15°. The gullies are narrow and steep walled, and their relief is as much as 150 m.

The outer shelf-upper slope sampled in traverses A–C is almost completely covered by sand in which the silt and clay content increases with depth, ranging from less than 5 percent on the outer shelf to about 36 percent at 640 m, the greatest depth examined in this setting. Rippled sand was observed above 190 m on traverse B in August 1982. The asymmetrical ripples were parallel to the shelf edge and had their steep faces oriented downslope, indicating offshelf transport at that time. This pattern is probably altered by variations in the strength and direction of bottom currents with time. The sea floor on the outermost shelf and upper slope below the rippled sand is commonly shaped into conical mounds 5–10 cm high and 10–15 cm in diameter that presumably are constructed by burrowing annelid worms; these features are also characteristically present on the upper canyon walls. In addition, patches of glacial gravel are present between about 200 and 300 m on the uppermost slope.

The sand sheet that covers the outer shelf and upper slope is thin, revealing in small, isolated exposures the Pleistocene semiconsolidated sandy silt that is so prevalent on the walls of Georges Bank canyons. On the gully walls of Filebottom Canyon, slopes of 20°–40°, similar to the slopes of outcropping silt observed on canyon walls, suggest that the gullies are cut into the underlying silt. The thin layer of sand on the gully walls appears to lie at its angle of repose, for on one occasion, a slight disturbance of the sea floor by the submersible triggered a sand flow. A sample from the gully floor at a depth of 558 m and just below the flow area is composed of 51 percent very fine sand and 25 percent silt and clay. The supply of sand to the gully walls apparently is adequate to replace sand removed by mass-wasting processes, as silt exposures are sparse there. Moreover, the lack of exposed silt and the instability of the sand layer on the steep walls limit burrowing by crabs, and bioerosion is negligible compared to that observed in Oceanographer Canyon.

The sand that covers the narrow gully floors is unrippled. Abandoned tubes of epibenthic worms collect in small piles along the axes and serve as a somewhat unstable substrate for concentrations of large venus flytrap anemones. The presence of anemones and fine-grained sediment and the absence of rippled sand suggest weak currents, low turbidity, and slow sediment movement on the gully floors, in direct contrast to the energetic sedimentary environment on the floor of Oceanographer Canyon at equivalent depths.

CURRENTS AND SEDIMENT TRANSPORT

Currents on Georges Bank

Currents can be described as Eulerian flow, which is flow past a fixed point measured by a current meter, and as Lagrangian flow, which is the path of a water particle and is measured by current drifters. The clockwise motion of the mean residual current on Georges Bank was first identified by Bigelow (1927) and has been substantiated by both Eulerian and Lagrangian measurements (Butman, Beardsley, and others, 1982). Recently, students of currents on the southern flank of Georges Bank have described bottom currents in terms of Eulerian flow, and the current speeds cited in the present paper refer to Eulerian flow measured at stations in shelf, slope, and canyon environments. In predicting the effect of currents on sediment transport, we must keep in mind that Eulerian flow speed and direction at one site may differ greatly from flow in adjacent areas, especially if the sea floor changes markedly in depth or if the bottom topography is irregular.

Long-term current observations provide information on the origin and interaction of the many kinds of currents present on Georges Bank (Brown and Moody, 1987; Butman, 1987; Butman and Beardsley, 1987; Butman, Bothner, and others, 1982; Butman, Beardsley, and others, 1982; Butman and others, 1983, 1987; Moody and others, 1984). The major elements of the current regime are (1) the mean residual current; (2) low-frequency (subtidal) currents that have periods of greater than 24 hours to 1 month and that are caused by density effects, wind stress, and ocean circulation phenomena such as Gulf Stream warm-core rings; (3) semidiurnal tidal currents that have periods of 12–24 hours; and (4) unpredictable high-frequency currents that have periods of 12 hours or less and that are caused by surface and internal waves. The results of the studies cited above are used in the following summary of flow patterns on Georges Bank (fig. 1).

The mean residual current is stronger near the surface than it is near the sea floor. It is most vigorous in a narrow band along the steep northern flank of the bank where flow is to the northeast at almost 30 cm/s near the surface and at 10 cm/s near the bottom. On the southern flank, the mean current is weaker; near-surface flow is about 15 cm/s, and bottom flow is 5 cm/s or less. The mean flow is anticyclonic around the bank and generally follows the isobaths.

Low-frequency currents are also primarily oriented along isobaths, but in contrast to the mean residual flow, they are characterized by flow reversals lasting several days. These currents vary greatly in strength. For example, along the upper slope, anticyclonic currents associated with southwestward-drifting Gulf Stream warm-core rings flow northeastward at speeds of 80 cm/s or more near the surface and 50 cm/s near the bottom (Butman and Conley, 1984).

Semidiurnal tidal currents are the most consistently energetic currents on Georges Bank. The tidal current can be represented by a vector that extends from the center of an ellipse to its perimeter; the tidal vector makes one revolution around the ellipse in a tidal period, reaching two maxima and two minima along the major and minor axes, respectively (Moody and others, 1984). Tidal flow and direction usually are averaged for a 29-day period. The strongest tidal flow on Georges Bank is oriented northwest-southeast across isobaths; near-surface currents along the major axis of the tidal ellipse reach speeds of 80–100 cm/s on the shallow bank crest and 30–40 cm/s on the northern and southern flanks of the bank. Near-bottom tidal currents reach speeds of more than 40 cm/s on the bank crest and 10–20 cm/s on the bank margin (Moody and others, 1984).

High-frequency currents are not discussed here. Storm-generated currents are intermittent and vigorous on the sea floor of the bank crest (3–40 m), but they do not play a significant role in the shelf-slope transition (150–600 m) under study here. The occurrence and effects of high-frequency internal waves are poorly understood.

The currents described above rework sediment on the bank and transport it away from the crest. Observations and sampling from a submersible dive on the northern flank of the bank in 1983 revealed that sand and gravel are moving downslope and mixing with silt and clay in the Gulf of Maine. On the southern flank of the bank, sediment moves south onto the upper slope and into the submarine canyons that incise the bank and southwest toward the shelf off southern New England (Butman, 1987; Butman and Moody, 1983; Valentine, 1983; Valentine, Uzmann, and Cooper, 1980, 1984; Valentine, Cooper, and Uzmann, 1984). There is also evidence that silt and clay, and perhaps very fine sand, are transported southwestward in suspension and are deposited on the shelf off Martha's Vineyard (Bothner and others, 1981; Twichell and others, 1981).

Currents in Lydonia Canyon and Environs

In an effort to define patterns of circulation and sediment movement in a submarine canyon and on the adjacent shelf and upper slope, an array of moored current meters was deployed in and around Lydonia Canyon (fig. 4) for periods ranging from 4 months to 2 years (Butman, 1987; Butman and Beardsley, 1987; Butman and Conley, 1984; Butman and others, 1983, 1987). This canyon is about 35 km east of Oceanographer Canyon and the upper slope area under study here. Oceanographer Canyon is larger than Lydonia Canyon, but they have similar geologic and hydrodynamic settings. The instrument array included 20 stations (18 of which are shown in fig. 4) where current meters were placed at different depths. Fourteen stations were on the canyon floor, walls, and rim; three stations were on the shelf near the canyon head; and three stations were on the upper slope near the canyon mouth.

Monthly mean flow on the shelf and upper slope to 245 m near Lydonia Canyon measured 1 to 5 m above bottom (1–5 mab) was weak, generally less than 6 cm/s, and was directed offshelf and downslope across isobaths (Butman and Conley, 1984). During months when Gulf Stream warm-core rings touched bottom on the upper slope, monthly mean flow was reversed to the northeast and reached 18–24 cm/s. Mean near-bottom flow on the canyon floor calculated for periods of 5–6 months had a speed of 5–6 cm/s or less (Butman and others, 1983). In the canyon head, it was directed downcanyon at 277 m (5 mab) and upcanyon at stations at 554 m (6 mab) and 584 m (6 mab).

Low-frequency, or subtidal, near-bottom currents on the shelf and upper slope near Lydonia Canyon principally flowed northeast and southwest along isobaths (Butman and Conley, 1984). On the shelf at 100–120 m near the canyon head, the speed of these currents along the major axis of the current ellipse (computed for monthly segments) was on the order of 10 cm/s or less. Longshelf wind stress in large part was responsible for this flow. On the upper slope at 245 m (5 mab), the magnitude of the major axis of the ellipse ranged from about 6 to 12 cm/s and could be attributed, in part, to flow within Gulf Stream warm-core rings. In the canyon, low-frequency currents were oriented approximately north and south along the canyon axis, and the magnitude of the major axis of the current ellipse was less than 5 cm/s.

The lunar semidiurnal (M_2) tidal current having a period of 12.42 hours is by far the strongest tidal flow in the Georges Bank region. According to Moody and others (1984), it causes more than 80 percent of the tidal variance represented by the five major components of the astronomical tide. The major axis of the tidal ellipse (computed for monthly segments and averaged for periods of 2–6 months) is oriented normal to isobaths on the shelf and slope (Butman and Conley, 1984). The bank crest experiences the most vigorous tidal currents, and their speeds decrease as water depth increases. Nevertheless, the currents measured at two stations on the shelf near the canyon were strong, and the magnitudes of major axes of ellipses for near-bottom currents ranged from 15 to 18 cm/s. Currents were somewhat weaker at a slope station, reaching speeds of only about 6 cm/s at 245 m (5 mab). Tidal currents in Lydonia Canyon were oriented along the canyon axis and parallel to isobaths on the walls. On the floor of the canyon head, the major axis of the tidal ellipse was oriented along the canyon, and its magnitude was about 6 cm/s at 277 m (5 mab), similar to speeds observed at an equivalent depth on the upper slope. However, farther downcanyon, analogous tidal currents on the floor at 595 m (5 mab) were significantly stronger and reached speeds of about 16 cm/s.

Sediment Transport

The discussion of regional current patterns so far has been presented in terms of monthly mean currents and the magnitudes of major axes of tidal and low-frequency current ellipses based on hour-averaged observations computed for monthly segments. In order to determine better when and where sediment is moved, we must evaluate short-term current speeds near the sea floor and their effect on sediment transport. The steady current speed required to initiate movement of uniformly sized quartz sediment on a flat bed has been determined empirically under ideal conditions (table 1; Butman, 1987, and references therein). However, these values are only an approximation of natural conditions because variations in sediment texture and bottom roughness and biological binding of sediment particles influence the shear velocities required for particle movement. For a smooth bottom, the required current speed 1 mab to move sediment ranges nonuniformly from 30 to 44 cm/s for grain sizes ranging from coarse silt (5 ϕ) to coarse sand (1 ϕ), whereas for a bottom roughness of 3 cm, the required current speed is lower and ranges from 15 to 28 cm/s.

The strongest currents on the shelf near Lydonia Canyon and in the canyon itself are those generated by the semidiurnal tide and possibly by high-frequency internal wave motion; higher on the bank, tidal and storm currents are most important; and on the upper slope, low-frequency currents associated with Gulf Stream warm-core rings dominate (Butman, 1987; Butman and Moody, 1983; Moody and others, 1984). The maximum hour-averaged bottom-current speeds recorded during periods of 1.5 months from late 1980 to late 1982 at stations on the shelf at 99 m (1 mab), 119 m (1 mab), and 126 m (1 mab) near Lydonia Canyon ranged from 42 to 62 cm/s. During a 5-month period in 1980–81, two stations in the canyon axis

Table 1. Steady current velocities required for initiation of movement (u_c) and for suspended transport (u_s) of quartz sediment of uniform size

[u_c is the steady current velocity needed for grains to become part of the bed load, and u_s is the velocity needed for grains to be transported in the suspended load. Critical shear velocities for threshold of movement (u_{*c}) and for suspension (u_{*s}) are given for quartz particles of each size. For the calculations of u_c and u_s, logarithmic flow in the bottom layer and a flat sea floor were assumed. Currents were calculated for 1 and 5 m above bottom (mab) for a smooth bottom having a roughness equal to grain diameter (d) and for a rough bottom having a constant roughness of 3 cm. For example, the equation for initiation of movement is $u_{c,z} = (u_{*c}/k) \ln (z/z_0)$, where u_{*c} is shear velocity (in millimeters per second); k is von Karman's constant (0.4); z is distance above bottom (in millimeters); z_0 is a roughness length scale, where z_0 = roughness/30 (for smooth bottom, z_0 = d (mm)/30; for rough bottom, z_0 = 30 mm/30). Adapted in part from Butman (1987, table 1; see references therein)]

				Smooth bottom		Rough bottom	
d (ϕ)	d (mm)	u_{*c} (cm/s)	u_{*s} (cm/s)	Bed load u_c (cm/s) 1 mab/5 mab	Suspended load u_s (cm/s) 1 mab/5 mab	Bed load u_c (cm/s) 1 mab/5 mab	Suspended load u_s (cm/s) 1 mab/5 mab
5	0.031	0.86	0.2	30/33	7/8	15/18	3/4
4	.063	1.07	.8	35/39	26/29	18/23	14/17
3	.125	1.25	3.1	39/44	96/108	22/27	54/66
2	.250	1.38	9.4	40/46	275/313	24/29	162/200
1	.500	1.60	21.9	44/50	602/690	28/34	378/466

at 277 and 595 m (both 5 mab) recorded maximum hour-averaged current speeds of 49 cm/s; during four deployments from December 1980 to July 1982, a station on the nearby slope at 245 m (5 mab) recorded maximum current speeds ranging from 45 to 69 cm/s (Butman, 1987; Butman and Conley, 1984; Butman and others, 1983).

Although these speeds are substantial, maximum hour-averaged data (and the magnitudes of major axes of current ellipses) tend to obscure the presence of even stronger currents of short duration that are important in the transport of coarse sediment. For instance, observations averaged for 7.5-minute intervals recorded at the station at 277 m in the head of Lydonia Canyon during late November and December 1980 show a series of speed peaks that are strongly correlated with the semidiurnal tide having a period of 12.42 hours. During the 33-day period, the bottom-current speed exceeded 50 cm/s four times when the current flowed upcanyon (north); it exceeded 40 cm/s sixteen times, mostly when the current flowed upcanyon; and it exceeded 30 cm/s twenty-eight times when the current flowed upcanyon and twenty-two times when the current flowed downcanyon. Hour-averaged data for the same period do not show speeds greater than 50 cm/s and show only four peaks exceeding 40 cm/s (Butman and others, 1983, figs. 8–25b, 8–25c). Most of the energy in these short bursts of speed can be attributed to tidal forces that were strengthened at times by high-frequency internal waves; the low-frequency component generally accounted for less than 10 cm/s (hour-averaged data) of the total current speed and was directed south and east (Butman and others, 1983, fig. 8–25b). The magnitude of the major axis of the tidal ellipse at this station was only about 6 cm/s, and the monthly mean current speed was about 4 cm/s downcanyon. A short record of 7.5-minute observations at the station at 595 m in the axis of Lydonia Canyon shows a similar series of strong flows that correlate with semidiurnal tides (Butman and others, 1983, fig. 8–26c). The strongest near-bottom currents at the shelf, upper slope, and canyon stations in the Lydonia Canyon region are capable of transporting as bed load sediment particles as large as coarse sand (1 ϕ) even if current speeds calculated for a smooth bottom are required (table 1).

As part of the Lydonia Canyon experiment, current meters also were deployed from January to July 1982 in the axis of Oceanographer Canyon 35 km to the west (fig. 2; Butman and others, 1983). One station was in the head at 223 m (4 mab), and the other was farther downcanyon at 554 m (6 mab). Mean flow was downcanyon at both stations. The strongest currents were tidal and were oriented along the axis; mean and maximum speeds observed in 7.5-minute data without regard to direction were 20 cm/s and 73 cm/s, respectively, in the canyon head and 28 cm/s and 96 cm/s at the deeper station. These relatively long term records support direct observations of strong currents from submersibles in Oceanographer Canyon and conclusions based on asymmetry of sand dunes that net sediment transport is downcanyon at the two stations (Valentine, Cooper, and Uzmann, 1984).

Observations of currents, sediment texture, and bed forms during dives in Oceanographer Canyon and other canyons and on the adjacent slope suggest that the circulation patterns revealed in the study of Lydonia Canyon and its environs are generally applicable to an investigation of the sediment dynamics in the shelf-slope region in and around Oceanographer Canyon.

SEDIMENT TEXTURE OF THE SHELF-SLOPE TRANSITION

We have seen that the strongest currents in the large Georges Bank canyons are related to tidal flow up and

Table 2. Grain-size distribution of samples from 11 stations on 2 traverses in the shelf-slope transition study areas near Oceanographer Canyon with and without carbonate matter

[Samples were collected by the submersible *Alvin* in 1982. Traverse B is east of Oceanographer Canyon (fig. 3); traverse C is west of it (fig. 2)]

Traverse	Depth (m)	Carbonate content (weight percent)	Weight percentage of sediment in major size classes with (and without) carbonate matter: a Gravel and sand (−1 ϕ − 4 ϕ)	b Silt (5 ϕ − 8 ϕ)	c Clay (9 ϕ − 11 ϕ)	Differences in weight percentages in each size class caused by removal of carbonate content: δa	δb	δc	δb + δc
B	180	2.32	98.51 (99.50)	0.91 (0.35)	0.57 (0.13)	+0.99	−0.56	−0.44	−1.00
B	200	3.53	96.02 (97.64)	2.24 (1.76)	1.75 (0.60)	+1.62	−0.48	−1.15	−1.63
B	250	3.03	95.81 (97.03)	3.03 (2.28)	1.16 (0.68)	+1.22	−0.75	−0.48	−1.23
B	356	3.05	92.10 (93.80)	5.51 (4.77)	2.37 (1.42)	+1.70	−0.74	−0.95	−1.69
B	455	4.54	80.10 (82.22)	16.48 (12.45)	3.40 (5.33)	+2.12	−4.03	+1.93	−2.10
B	608	6.22	67.35 (69.44)	27.11 (22.20)	5.55 (8.37)	+2.09	−4.91	+2.82	−2.09
C	206	4.39	93.74 (95.46)	4.35 (3.54)	1.91 (0.98)	+1.72	−0.81	−0.93	−1.74
C	250	3.20	95.92 (96.62)	2.95 (2.46)	1.12 (0.89)	+0.70	−0.49	−0.23	−0.72
C	350	5.24	88.91 (90.95)	8.68 (7.13)	2.40 (1.92)	+2.04	−1.55	−0.48	−2.03
C	445	6.86	77.14 (79.04)	18.79 (16.17)	4.07 (4.81)	+1.90	−2.62	+0.74	−1.88
C	595	6.74	64.21 (66.30)	24.76 (25.98)	11.04 (7.73)	+2.09	+1.22	−3.31	−2.09

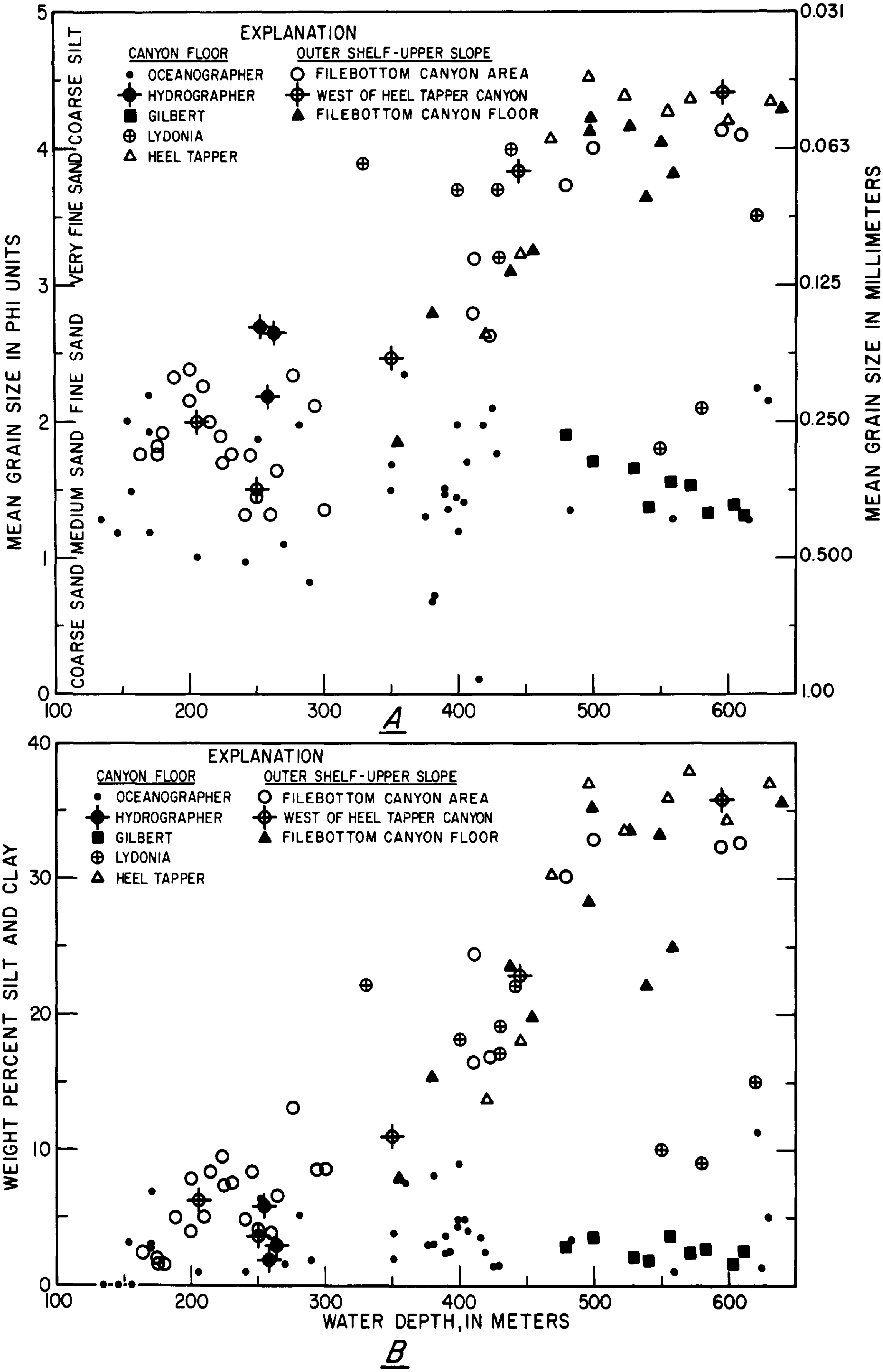
down the canyons along the floors and walls, parallel to the major regional tidal forces that transport water in and out of the Gulf of Maine across Georges Bank. In contrast, although the seaward-facing outer shelf-upper slope is oriented approximately east-west, normal to the major regional tidal forces, the strongest currents here flow east and west along the slope and are related to Gulf Stream warm-core rings. The effect of currents on sediment transport through the shelf-slope transition in canyons and on the outer shelf-upper slope of the bank margin can be assessed indirectly by comparing the texture of surficial sediment in the same depth interval in both regions.

Textural comparisons of sediment from different environments could be complicated by the fact that fine-grained biogenic carbonate matter becomes an increasingly important component of upper slope sediment as water depth increases. Foraminifers and calcareous nannofossils in abundance could increase the proportion of the finer size classes in the sediment. Samples collected by submersible at eleven stations on two traverses on the outer shelf-upper slope were split and analyzed with and without the carbonate fraction (table 2). West of the mouth of Oceanographer Canyon (traverse C, fig. 2), carbonate contents ranged from 4.39 percent at 206 m to 6.74 percent at 595 m; east of the canyon (traverse B, fig. 3), contents ranged from 2.32 percent at 180 m to 6.22 percent at 608 m. As expected, carbonate matter increased as depth increased, but the amount of increase was small. Size analysis showed that the maximum combined decrease in the weight percentage of silt- and clay-sized particles in samples treated with 20 percent glacial acetic acid did not exceed about 2 percent in any sample. Thus, comparisons of surficial sediment texture at the same depth in different environments of the shelf-slope transition are not significantly affected by carbonate matter. The following observations on sediment texture are mainly from Oceanographer Canyon and the nearby gullied outer shelf-upper slope; they are supplemented by observations from the floors of Lydonia, Gilbert, Hydrographer, and Heel Tapper Canyons (figs. 2–5).

Texture of Canyon Floors

The shelf-slope transition of Georges Bank contains a variety of sedimentary environments within and between the canyons. Sedimentary processes are very active in large canyons, and striking differences in the sedimentary environments are evident when comparing the sediment found on the floors of large canyons with that on the outer shelf and upper slope in the same depth interval. The texture of the canyon-floor sand is described here in terms of the median grain size of the sand fraction, following the practice of Folk (1980); these descriptive terms are not to be confused with the mean grain size of the whole sample, which is plotted in figure 6*A*. The discussion of currents in

Figure 6. Graphs of (*A*) mean grain size versus water depth and (*B*) silt and clay content versus water depth of samples from canyon floors and the outer shelf-upper slope study areas on the southern margin of Georges Bank. Data plotted in both graphs are for the same samples. *A*, Sediment coarsens on the upper slope between 200 and 300 m as a result of winnowing by along-slope currents. Upper slope sediment from water depths greater than about 300 m is finer grained than sediment from Oceanographer, Hydrographer, and Gilbert Canyons from the same water depths, indicating that currents on the canyon floors are stronger than those on the upper slope. Sediment from the floors of Heel Tapper Canyon and slope gullies (Filebottom Canyon floor) is no coarser than upper slope sediment at equivalent depths. *B*, The weight percentages of silt and clay plotted here were calculated after data on gravel of pebble size (4 mm; −2 ϕ) and larger were deleted. Silt and clay contents of Georges Bank Shelf samples to depths of 200 m (not plotted) are typically 5 percent or less (fig. 8; Hathaway, 1971). Note decrease in silt and clay in upper slope sediment between 200 and 300 m and increase below 300 m (see fig. 8). Sediment from the floors of Heel Tapper Canyon and slope gullies (Filebottom Canyon floor) contains a large percentage of silt and clay. ▶


EXPLANATION
CANYON FLOOR
OCEANOGRAPHER
HYDROGRAPHER
GILBERT
LYDONIA
HEEL TAPPER
OUTER SHELF-UPPER SLOPE
FILEBOTTOM CANYON AREA
WEST OF HEEL TAPPER CANYON
FILEBOTTOM CANYON FLOOR
MEAN GRAIN SIZE IN PHI UNITS
MEAN GRAIN SIZE IN MILLIMETERS
COARSE SAND
MEDIUM SAND
FINE SAND
VERY FINE SAND
COARSE SILT
0.031
0.063
0.125
0.250
0.500
1.00
A
WEIGHT PERCENT SILT AND CLAY
WATER DEPTH, IN METERS
B

a previous section showed that bottom flow in Oceanographer Canyon is more vigorous than that in Lydonia Canyon. This observation is supported by differences in sediment texture and bed forms on the floors of the two canyons. Oceanographer Canyon, the largest on western Georges Bank, has dunes as high as 3 m composed of coarse to medium sand containing little silt and clay down to 630 m; the floor of Lydonia Canyon is covered by rippled fine to very fine sand containing 15 to 20 percent silt and clay except for an interval from about 550 to 600 m, where small dunes of medium sand are present (fig. 6; Butman and others, 1983; Twichell, 1983). These two canyons lie 35 km apart on the southern flank of the bank and are subject to the same regional current regimes. Although Lydonia Canyon is the fourth largest canyon in the region, it has only one-fifth the volume of Oceanographer Canyon. The differences in current strengths on the canyon floors may be due to differences in canyon size and shape. Hydrographer Canyon is the second largest canyon. Its sedimentary environments resemble those of Oceanographer Canyon, as strong currents flow up and down its axis, and dunes and rippled sand are present on its floor (Southard and Stanley, 1976, p. 368; Keller and Shepard, 1978).

In 1984, the floors of Hydrographer, Gilbert, and Heel Tapper Canyons were visited to observe bed forms and collect sediment samples that would provide a broader base for estimating the relative strengths of bottom currents in large and small canyons. In the head of Hydrographer Canyon at a depth of 254–263 m, the floor of the western arm is covered with rippled sand and dunes as high as 0.5 m. They are asymmetrical and have steep lee faces oriented upcanyon to the northwest. Sediment collected at three locations in this area is medium to fine sand containing less than 6 percent silt and clay (figs. 5, 6). During the dive, a current having a velocity of 5–10 cm/s flowed upcanyon from the southeast; during a period of 15 minutes, its velocity increased to at least 75 cm/s (estimated), and the current flowed at that velocity for more than an hour. Sand was observed moving across the bottom, and the water became very turbid, making visibility poor. The current theoretically was strong enough to transport coarse and medium sand in the bed load and fine sand in suspension. The dive was ended because the submersible had to exert maximum power to remain stationary and could not be maneuvered safely in the strong current. Two similar events of strong upcanyon flow have been observed on the floor of Oceanographer Canyon—one in the main axis at 292 m (Valentine, Cooper, and Uzmann, 1984), and the other in the east arm at 175 m.

Gilbert Canyon is the third largest canyon, and a dive along its floor between the depths of 611 and 479 m revealed rippled, asymmetrical sand dunes as high as 1.5 m, whose shapes indicated that net flow and sediment transport were downcanyon there. Nine samples collected from the dunes consisted of coarse to medium sand at 611 m becoming medium to fine sand upcanyon; the silt and clay content was less than 4 percent (figs. 4, 6*B*).

Heel Tapper Canyon is one of the smallest canyons in the region. It lies just west of Oceanographer Canyon, in the same oceanographic setting, and one would assume that they both experience the same regional tides and currents. However, a dive along the floor of Heel Tapper Canyon from 631 to 422 m revealed a uniform expanse of very fine to fine silty sand; silt and clay contents decreased from 37 to 13 percent as depth decreased (figs. 2, 6*B*). Ripple marks were rare. The floor of this small canyon most resembles the surface of the upper slope near the mouth of Oceanographer Canyon and represents a much less vigorous environment than that in the large canyon.

The upper slope east of Oceanographer Canyon is cut by gullies that are oriented north-south parallel to the trend of the adjacent canyon. The texture of the bottom sediment in the relatively shallow gullies should indicate whether they, like Oceanographer Canyon, affected currents by channeling the flow. However, samples collected from the floors of two gullies that form the head of Filebottom Canyon do not differ systematically in the amount of silt and clay they contain from samples collected at equivalent depths elsewhere on the slope (figs. 3, 6*A*, *B*). The gully heads extend up to about 350 m water depth, which is below the level at which along-slope currents dominate the bottom circulation. Although the gullies are aligned parallel to the major axes of tidal ellipses, tidal currents apparently are weak there; for example, the magnitudes of tidal ellipses are 6.3 cm/s or lower at analogous sites west of Lydonia Canyon (Butman and others, 1983, fig. 8–24, table 8–3), and bottom morphology does not appear to play a role in modifying current patterns.

Texture of Canyon Rims

The orientation of Oceanographer Canyon is normal to the shelf edge and parallel to the regional tidal flow, and without more information, there was little reason to suspect significant differences in the sedimentary environments of the opposing eastern and western canyon rims. However, observations from submersibles revealed that the eastern rim is covered by an extensive deposit of densely packed gravel (gravel pavement), whereas the western rim is covered by gravelly sand (fig. 2; Valentine, Uzmann, and Cooper, 1980, 1984; Valentine, Cooper, and Uzmann, 1984). Gravel in the pavement probably was ice rafted during the last glaciation. Dives on the eastern rim in 1978 and 1982 between lat 40°24′ N. and 40°27′ N. (fig. 2) encountered a strong bottom current flowing westward at speeds as great as 50 cm/s. The large area of exposed gravel and the presence of deposits of shelf sand in the downslope lee of cobbles and boulders suggest that the current is strong enough to maintain the gravel exposure on the eastern rim but has no similar effect on the western rim.

An analogous, but finer grained, gravel deposit is present on the eastern rim of Lydonia Canyon (fig. 4; Twichell, 1983), and a long-term current-meter record indicates that bottom flow there is dominantly to the west (station LCQ of Butman and others, 1983). A dive to the current-meter site (fig. 4) documented the presence of packed, coarse sandy gravel and corroborated previous interpretations based on grab sampling and side-scan sonographs. Moreover, a bottom current having a speed of about 40 cm/s flowed to the west throughout the 90-minute duration of the dive.

The origin of the westward-flowing current is not known. Observations of current speed and direction and sediment texture indicate that it is a persistent flow across the eastern rims of Oceanographer and Lydonia Canyons. The wide extent of the exposed gravel and evidence that shelf sand is moving through it into the canyons suggest that the eastern canyon rims are an important pathway for the transport of sand off the shelf. By contrast, the gravelly sand on the western rim of Oceanographer Canyon probably reflects the presence of weaker or less favorably oriented currents there and a slower transport rate of shelf sand into the canyon.

Distribution of Silt and Clay—The Mudline

The transport of silt- and clay-sized particles is very sensitive to current strength. Relatively strong currents of some tens of centimeters per second are required to place them in suspension, but they remain in the water column and can be transported long distances by currents of only several centimeters per second (Reineck and Singh, 1980, fig. 2, modified from Sundborg, 1967). The strong tidal and storm currents on Georges Bank have winnowed most of the silt and clay out of the shelf sediment. Today there is little or no silt or clay on the bank crest, less than 5 percent in sediment on the southern flank of the bank, and not more than about 10 percent in sediment from the shelf near the heads of Oceanographer and Lydonia Canyons (Hathaway, 1971; Schlee, 1973; Butman and others, 1983). Most samples from the floors of Oceanographer, Gilbert, and Hydrographer Canyons contain less than 5 percent silt and clay down to at least 630 m, whereas the fine fraction of samples from the outer shelf-upper slope and Heel Tapper Canyon steadily increases below 300 m and reaches 35–40 percent at about 640 m (fig. 6*B*). The marked decrease in grain size on the upper slope below 300 m is related to a decrease in current energy that is not observed in the same depth interval on the floors of the more energetic Oceanographer, Gilbert, Hydrographer, and Lydonia Canyons.

The level at which silt and clay do not increase significantly with depth was termed the "mudline" by Stanley and Wear (1978) and Stanley and others (1983), who interpreted it to represent an energy boundary below which deposition prevails over erosion. Those authors have shown that the mudline may be above or below the shelf edge, depending on factors that include shelf width, sediment supply, and current strength, and that it rarely coincides with the shelf edge. The four types of mudline outlined by Stanley and others (1983) are defined by depth and position relative to the shelf edge; type I, the deepest, is on the upper slope, and type IV is shoreward of the shelf edge. The slope near Oceanographer Canyon best represents a type I setting. The mudline appears to be below 640 m, the deepest site sampled here. The amount of silt and clay in the sediment increased steadily to that level and did not exceed 36 percent, whereas the amount of very fine sand (4 ϕ) exceeded that of silt and clay in almost all samples from water depths greater than 350 m. Hathaway (1971) reported that samples collected in this area from lower on the slope than 640 m water depth contained 70–95 percent silt and clay. Several factors are responsible for the relatively deep mudline in this part of Georges Bank. The supply of silt and clay is low because the bank is isolated from continental sediment sources and strong currents have swept the shelf and uppermost slope sand clean of fine-grained sediment. A relatively large amount of very fine sand (4 ϕ) is being transported off the shelf in this region, and the upper slope in water shallower than 300 m experiences strong along-slope currents that remove very fine sand, silt, and clay.

Distribution of Very Fine Sand (4 ϕ)

Although sediment examined in the present study from the shelf adjacent to Oceanographer and Lydonia Canyons had uniformly low concentrations of silt and clay, the amount of very fine sand (4 ϕ) it contained ranged from 1 percent to more than 50 percent. Particles in the 4-ϕ size class range in diameter from 0.125 mm (3 ϕ) to 0.063 mm (4 ϕ). Particles of silt, clay, and very fine sand all require a stronger current to initiate transport than to maintain them in suspension (table 1). Once in suspension, they may travel long distances in weak currents. In contrast, sand having a diameter of 3 ϕ or larger requires a substantially stronger current to place it in suspension than to move it as bed load. Butman and Moody (1983) suggested that suspension of 4-ϕ sand is common on Georges Bank. Although 4-ϕ sand travels in suspension, it requires a current three to four times as strong as that required by coarse silt (5 ϕ) to remain in suspension (table 1). Thus, in a region of strong current activity, the distribution and abundance of 4-ϕ sand may be a sensitive indicator of relative current strength. A concentration of 4-ϕ sand in sediment that contains little silt and clay may identify an area where currents are too strong to allow the deposition of finer particles from suspension. Sediment from the bank crest, where currents are strong, commonly contains little or no 4-ϕ sand; samples from deeper water, where currents are weaker and circulation patterns less uniform, contain larger and more variable amounts of 4-ϕ sand, and discrete areas having high concentrations of 4-ϕ sand are near Oceanographer (fig. 7) and Lydonia Canyons (Butman and others, 1983, fig. 8–10c).

Samples from the floor in the northern part of Oceanographer Canyon and samples from the adjacent shelf had markedly different contents of 4-ϕ sand. Samples from the shelf had a wide range of 4-ϕ contents, possibly reflecting variable flow directions, current strength, and source areas around the canyon head. Deposition predominated in areas east and west of the canyon head, where 4-ϕ sand made up 50–60 percent of the sediment. On the other hand, samples from the floors of both Oceanographer and Gilbert Canyons contained less than 3 percent very fine sand and supported observations that strong persistent bottom currents flow up and down the narrow axis to depths of at least 630 m, winnowing 4-ϕ sand from coarser sediment and transporting it out of the canyon.

The shelf-slope transition on the outer edge of Georges Bank is not as varied texturally as it is in and around Oceanographer Canyon; the change from outer shelf to upper slope depths is gradual, and surficial sediment is more uniform in texture. The outer shelf-upper slope sediment along traverses A, B, and C (figs. 2, 3) from about 150 to 300 m depth contained less 4-ϕ sand by weight than did shelf sediment in some areas at depths of 120–160 m near the canyon head. Therefore, the differences in weight percentage of 4-ϕ sand alone indicate that currents on the outer shelf-upper slope are stronger than those in several shallower areas adjacent to the canyon head. This difference in current strength would not have been detected if only the silt and clay contents of sediment from the two areas had been compared, for they are similar (fig. 6*B*).

Texture of Outer Shelf-Upper Slope

In general, very fine sand (4-ϕ), silt, and clay contents increase as water depth increases on the outer shelf and upper slope. At depths shallower than about 200 m, the outer shelf texturally resembles the floors of large canyons. On the upper slope from 200 to 300 m, sediment texture is variable (and patches of glacial gravel are present), but between 350 and 600 m, the surficial sediment is much finer than it is in the same depth interval on the floors of large canyons (figs. 6*A*, *B*). A closer look at the trends of individual sediment size classes along two parallel traverses (A and B) that extend from the outer shelf onto the upper slope and into the gullied head of Filebottom Canyon reveals the expected decrease in coarse sediment and increase in fine sediment with increasing depth (fig. 8). Sediment samples from 475 to 600 m on the slope between the two gullies had the same textural variations observed on traverses A and B at equivalent depths.

However, the increase in fine sediment with depth was reversed between 200 and 300 m, where mean grain size coarsened from fine to medium sand. Very fine sand (4 ϕ) was present in low percentages on the outer shelf, but between 170 and 200 m, it increased as water depth increased. This trend was interrupted between 200 and 300 m, where very fine sand contents declined and were variable, but it resumed below 300 m, and 4-ϕ sand accounted for 40–50 percent of the sediment at about 600 m. The silt and clay content varied similarly.

Fine-sand (3 ϕ) content increased from a range of 20 to 30 percent on the outer shelf to 40 to 50 percent near 200 m. It then decreased abruptly and fluctuated between about 7 and 23 percent in the interval from 200 to 300 m; below 450 m, it made up 10–20 percent of the sediment.

Medium sand (2 ϕ) was the most abundant sediment on the outer shelf, declining from 50–60 percent there to 0–10 percent on the upper slope. However, between 200 and 300 m, medium sand fluctuated in abundance and constituted 30–50 percent of the sediment. Coarse sand (1 ϕ) was present in low percentages along each traverse except in the depth interval from 200 to 300 m, where it ranged from 10 to 27 percent on traverse A and from 30 to 45 percent on traverse B.

Sediment shoaler than 180 m was moderately sorted (standard deviation ranged from 0.82 to 1.03 ϕ), but that from deeper water contained greater percentages of fine sediment and generally was poorly sorted (st. dev. = 1–2 ϕ). The depletion of fine sediment in the depth interval from 200 to 300 m was a local reversal in a trend toward increasing fines with depth and was not reflected in sorting values. The textural patterns described here were present also in the shelf-slope transition some 30 km to the west, as indicated by five samples collected along a traverse from 200 to 600 m water depth near Heel Tapper Canyon (figs. 2, 8, traverse C).

These textural variations within the shelf-slope transition suggest that the size classes most sensitive to transport increase in abundance on the outermost shelf down to about 200 m in response to a general decrease in the strength of bottom currents. Fine sand (3 ϕ), which in this environment moves as bed load, is deposited preferentially, followed by very fine sand (4 ϕ), silt, and clay, which travel in suspension (fig. 8; table 1). The marked decline in abundance of medium sand (2 ϕ) and coarse

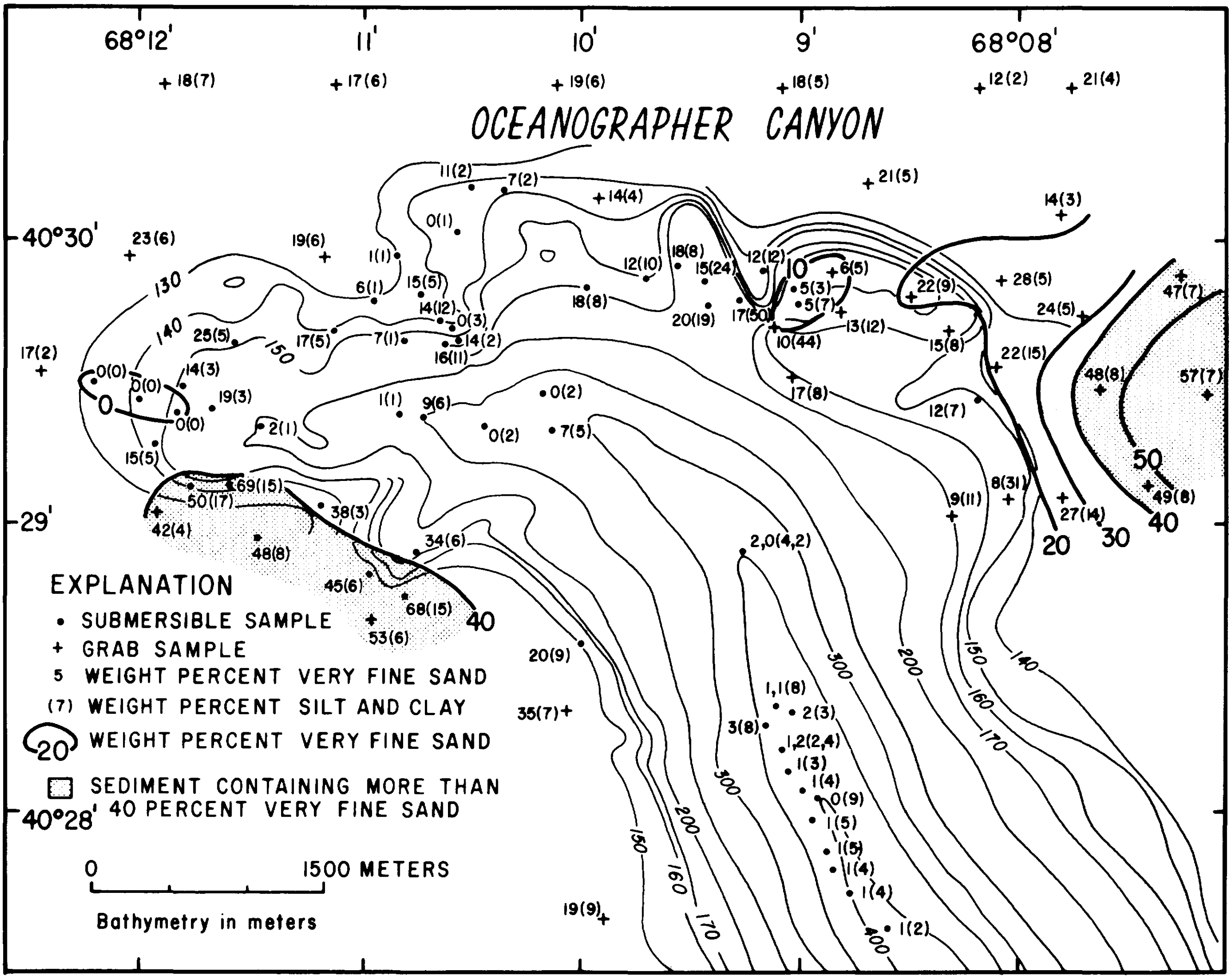


Figure 7. Map of the head of Oceanographer Canyon showing the distribution of very fine sand (0.063 mm; 4 ϕ) and of silt and clay in samples from the canyon rim and floor. The weight percentages plotted here were calculated after data on gravel of pebble size (4 mm; -2 ϕ) and larger were deleted. Silt and clay content is generally low in all areas, except in several samples collected in the eastern arm below an escarpment of semiconsolidated sandy silt. Very fine sand content is also low except in areas on the east and west rims where it is 50 percent or more and, thus, defines areas where bottom currents are relatively weak. See text for further explanation. Map base from Valentine, Uzmann, and Cooper (1984). Bathymetry does not extend north of the canyon head to where the northernmost samples were collected. Bathymetry differs somewhat from that shown in figure 2, which was obtained by different methods.

sand (1 ϕ) from shallow areas to 200 m is caused largely by the increase in finer sediment there. The trend toward increased fine sediment with depth is reversed between 200 and 300 m, and this reversal can be attributed to the erosion of fine sediment by strong currents that flow northeastward along the upper slope when anticyclonic Gulf Stream warm-core rings are present on the margin (figs. 3, 8). These currents, in combination with tidal flow, reached maximum hour-averaged speeds of 69 cm/s at 245 m (5 mab) near Lydonia Canyon (Butman, 1987). By contrast, the magnitude of the major axis of the M_2 tidal current ellipse was less than 10 cm/s at this depth near Lydonia Canyon (Moody and others, 1984), and storm currents do not affect the bottom on the southern flank of Georges Bank at water depths below about 100–150 m (Butman and Beardsley, 1987).

During an 8-year interval from 1976 through 1983, 89 warm-core rings were identified west of long 60° W. by use of satellite imagery (Celone and Chamberlin, 1980; Celone and Price, 1983; Fitzgerald and Chamberlin, 1981, 1983, 1984; Mizenko and Chamberlin, 1979a, b; Price and Celone, 1984). Many of the rings did not encounter the upper slope of Georges Bank, but 19 rings are judged to have affected the sea floor in the area of Hydrographer, Oceanographer, and Lydonia Canyons during a cumulative period of 17 months (fig. 9). In general, these rings ranged in diameter from 50 to 150 km and drifted southwestward at speeds of 3–8 km/day. Occasionally they

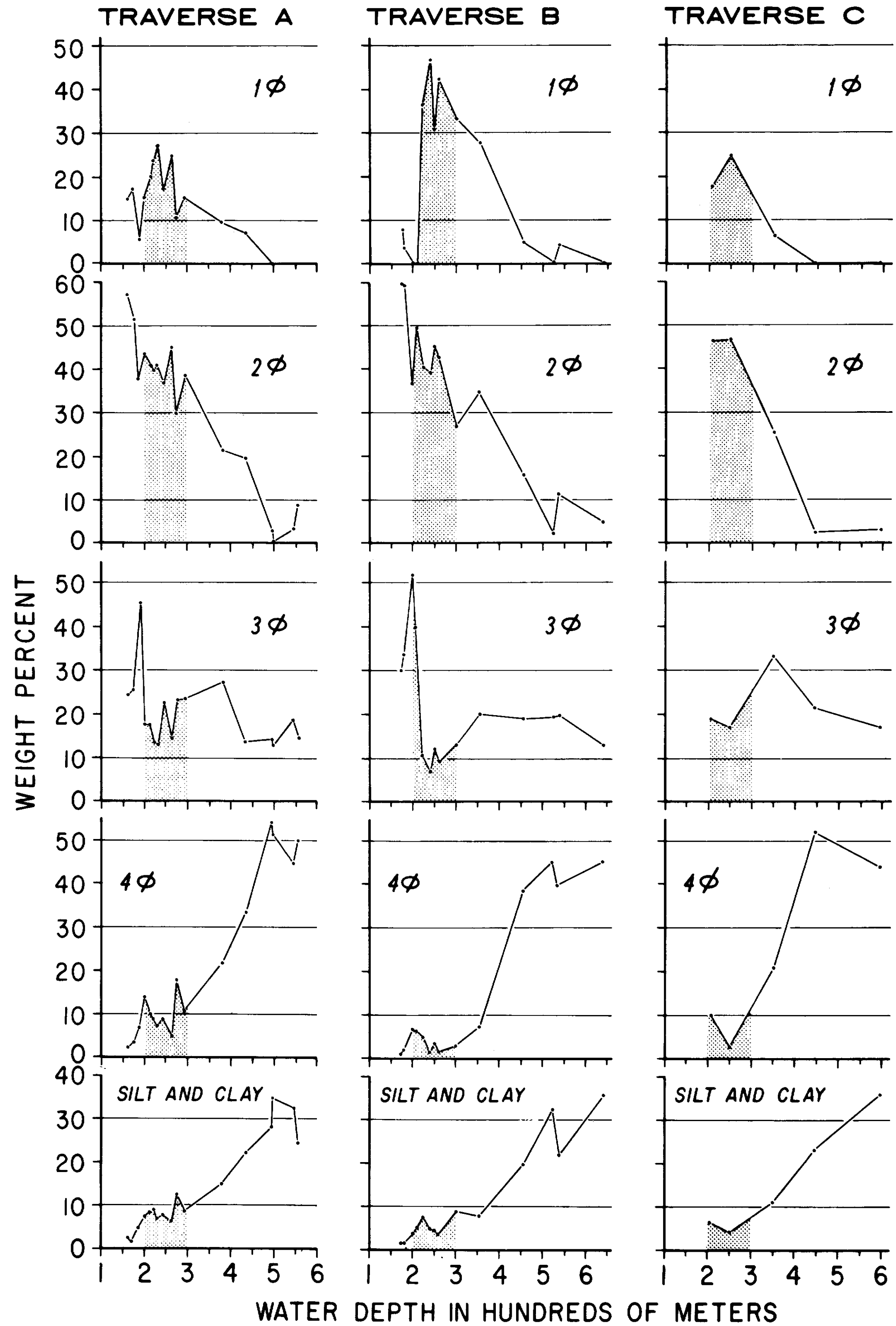


Figure 8. Graphs showing textural variations along three traverses across the shelf-slope transition. Traverses A and B are parallel and extend from the outer shelf onto the upper slope and onto gully floors in the head of Filebottom Canyon (fig. 3). Traverse C extends from the outer shelf onto the upper slope west of Heel Tapper Canyon (fig. 2). Weight percentages plotted here were calculated after deletion of data on gravel of pebble size (4 mm; $-2\ \phi$) and larger. Graphs for each size class show that as water depth increases, the weight percentages of fine sediment (3 ϕ, 4 ϕ, silt and clay) increase and the weight percentages of coarse sediment (2 ϕ, 1 ϕ) decrease. An exception to this trend is the interval on the upper slope from 200 to 300 m (stippled pattern) where fines have been winnowed by along-slope currents (see also fig. 3).

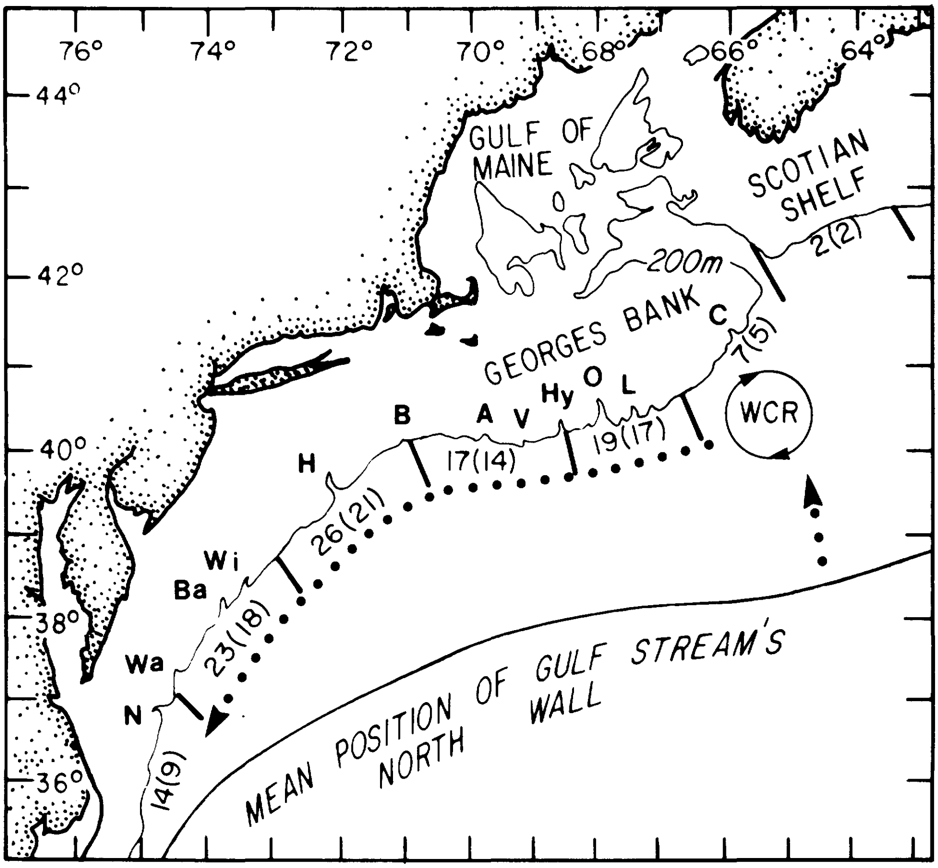


Figure 9. Map showing the number of warm-core rings (and their residence time in months) in segments along the western North Atlantic margin from 1976 to 1983. During the 8-year period, 89 rings spawned by the Gulf Stream drifted west of long 60° W., but many of them did not touch the continental margin. Note that 19 rings were active in the study area for a total of 17 months, or for about 2 months per year on average. Dotted line is typical path of warm-core ring (WCR). For sources of data, see references in text. Canyon names: C, Corsair; L, Lydonia; O, Oceanographer; Hy, Hydrographer; V, Veatch; A, Atlantis; B, Block; H, Hudson; Wi, Wilmington; Ba, Baltimore; Wa, Washington; N, Norfolk.

remained in an area of the margin for several weeks. For example, a long-term current-meter record from 245 m (5 mab) on the upper slope east of Lydonia Canyon shows that two rings produced strong northeastward currents that reached hour-averaged speeds of 30–35 cm/s and dominated bottom flow for 8 consecutive weeks in late 1980 and early 1981. When these currents combined with high-frequency (tidal) currents, bottom flow reached hour-averaged speeds of 40–45 cm/s and even greater short-term speeds (see station LCI data in Butman and others, 1983; Butman and Conley, 1984). Presumably, very fine sand (4 ϕ), silt, and clay were winnowed and transported in suspension, while fine sand (3 ϕ) was moved as bed load, along and down the slope and into gullies and canyons that incise the margin here. The removal of fine sediment by warm-core-ring currents could also account for the patches of lag gravel in the depth interval from 200 to 300 m on the upper slope.

CANYON MORPHOLOGY AND BOTTOM CURRENTS

Previous studies have shown that the most energetic currents in submarine canyons off eastern North America (1) are characterized by a semidiurnal tidal period, similar to that of the M_2 barotropic tide, and (2) are much stronger than M_2 tidal currents on the continental slope at equivalent depths (Keller and Shepard, 1978; Butman, 1987; Butman and Conley, 1984). The strong semidiurnal flows in canyons have been attributed partly to M_2 tidal flow and partly to the movement of internal tides (internal gravity waves of tidal frequency) along a density interface. Internal tides have been recognized by the presence of: (1) changes in temperature and density profiles that are correlated with current flow; (2) time delays of current flows at a series of stations along a canyon floor; and (3) packets of high-frequency currents having periods of less than 4 hours (Shepard, 1975; Gordon and Marshall, 1976; Keller and Shepard, 1978; Shepard and others, 1979; Hotchkiss and Wunsch, 1982; Butman, 1987).

Hudson Canyon

Hotchkiss and Wunsch (1982) studied tidal currents in Hudson Canyon. Data were collected during a 15-week deployment of current meters and temperature-pressure sensors (September 1977 to January 1978). The instrument arrays were placed in the axis between 350 and 780 m water depth and extended 275–375 m into the water column. On the basis of their own study, of observations in canyons by other workers, and of theory, Hotchkiss and Wunsch concluded that: (1) surface tides generate internal tides at the edge of both the shelf and the canyon that are trapped when they enter the canyon; (2) the strength of internal tides depends on the strength of surface tides; (3) internal tides increase in strength as canyon length increases (in a canyon of uniform cross section); (4) internal tides increase in strength as cross-sectional area decreases within a canyon; and (5) in general, internal tidal currents are strongest in long canyons that are located in regions of strong surface tides, that have nearly parallel walls, and that have walls and floors sloping at appropriate angles.

Hudson Canyon is by far the largest and longest canyon on the U.S. East Coast. The floor is covered predominantly by silt and clay, although sand has been reported in the canyon head; axial currents have been reported to reach speeds of 33 cm/s at 221 m (3 mab), 30 cm/s at 795 m (5 mab), and, in a storm-related event, 60 cm/s at about 725 m (Keller and others, 1973; Keller and Shepard, 1978; Stanley and Freeland, 1978; Hotchkiss and Wunsch, 1982).

Georges Bank Canyons

Tidal currents also are enhanced in some of the Georges Bank canyons. The largest of these canyons are smaller and shorter than Hudson Canyon. For example, landward of the shelf edge, Oceanographer Canyon is only about 0.7 as large and 0.8 as long as Hudson Canyon; other Georges Bank canyons are much smaller. Nevertheless, Oceanographer, Hydrographer, Gilbert, and probably Lydonia are more energetic than Hudson Canyon, as indicated by bottom currents, sediment texture, and bed forms observed on the canyon floors.

Speed of Bottom Currents

Direct measurements of bottom flow by current meters are notably sparse in the Georges Bank canyons and are limited to Gilbert, Hydrographer, Lydonia, and Oceanographer Canyons. Short-term observations 25 cm above the bottom lasting approximately 30 minutes were made by Stetson (1937) in Gilbert Canyon at 402 m and 421 m, where speeds of less than 5 cm/s were recorded, and on the floor of Lydonia Canyon at three stations between 384 and 475 m, where speeds of approximately 5 cm/s were recorded. Stetson's observations were too brief to characterize adequately the flow regime in these canyons.

In 1974, three stations were occupied for 11.5 days on the floor of Hydrographer Canyon at 348 m, 512 m, and 713 m (fig. 5), and maximum speeds greater than 50 cm/s (3 mab) were recorded (Keller and Shepard, 1978). Recently, current-meter arrays were deployed for 4–5 months at several stations on the floor of Lydonia Canyon (282 to 1,554 m) and at two stations in Oceanographer Canyon at 223 m and 554 m (figs. 2, 4; Butman and others, 1983; Butman and Conley, 1984). Of the two canyons, Oceanographer has more active bottom currents. As described in the section, "Sediment Transport," maximum bottom-current speeds (7.5-minute average) in Lydonia were 50–60 cm/s (5 mab), and those in Oceanographer were 96 cm/s (6 mab). The most consistently strong currents observed in Lydonia Canyon were semidiurnal tidal flows (Butman and Conley, 1984; Butman and others, 1983). They were part of the Georges Bank tidal regime in which major axes of tidal ellipses were oriented approximately north-south across the shelf edge and parallel to both the canyon axes and the dip of the continental slope. However, near-bottom mean tidal flow on the upper slope near the canyon (about 6 cm/s at 245 m) was much weaker than that on the canyon floor (about 16 cm/s at 595 m), suggesting that the strength of tidal currents is enhanced in the medium to large canyons such as Lydonia and Oceanographer.

Sediment Texture and Bed Forms

Indirect indicators of sediment dynamics such as bed forms and texture also suggest that the floors of the Georges Bank canyons are characterized by varying levels of current activity. Oceanographer Canyon may be the most energetic canyon, for it has extensive areas of rippled sand on its walls and large asymmetrical dunes as high as 3 m on its floor down to 630 m (Valentine, Cooper, and Uzmann, 1984; Valentine, Uzmann, and Cooper, 1984). Dunes and rippled sand are also present in Hydrographer Canyon (Southard and Stanley, 1976; Keller and Shepard, 1978) and were observed in 1984 during dives to the floors of both Hydrographer and Gilbert Canyons. Lydonia Canyon appears to be less active. The rippled sand on its floor is finer grained (Butman and others, 1983; Twichell, 1983) than that found in Oceanographer, Gilbert, and Hydrographer Canyons, although the source is the same (figs. 6*A*, *B*). The floor of Lydonia Canyon was traversed by a submersible in a series of dives from 630 to 220 m, and low dunes were observed on the floor only at 600 m (B. Butman, unpub. data, 1980). Limited observations of bed forms and sediment texture in Veatch and Atlantis Canyons at about 450 m on the canyon floors have recorded rippled sand only (J.R. Uzmann, unpub. data, 1975–77) and suggest that these two small canyons are even less energetic than Lydonia. Heel Tapper Canyon is somewhat larger than Atlantis but smaller than Veatch. The texture of sediment on the floor of Heel Tapper Canyon resembles that of sediment on the adjacent upper slope and indicates that small canyons and the upper slope are in similar, relatively low energy, sedimentary environments (figs. 6*A*, *B*).

Canyon Shape and Volume

The canyons of western Georges Bank have similar physiographic and hydrographic settings. They all incise the shelf edge and open seaward, they all receive sediment from the adjacent continental shelf, and in general, they would be expected to experience the same tidal, storm, and oceanic currents. However, we have seen that some of the canyons are more energetic than others in terms of bottom-current strength and sediment transport. The most obvious differences exhibited by the canyons are their volume and shape. Hotchkiss and Wunsch (1982) concluded that the strongest internal tides should occur in long canyons having nearly parallel walls and having walls and floors sloping at appropriate angles. The authors did not treat canyon volume as a characteristic that enhances current flow. An empirical correlation between volume and energy level exists for the Georges Bank canyons, and apparently the largest canyons naturally approach the criteria set forth by Hotchkiss and Wunsch for amplifying tidal energy. Canyon volume was calculated for the part of the canyon between the head, the deepest penetration of the shelf, and the mouth, which lies in a vertical plane drawn through the nominal shelf break at the 200-m isobath (table 3). The volume calculation has been restricted to the part of each canyon that incises the shelf and encompasses water depths characteristic of the shelf-slope transition where bottom currents are most active. Canyon volumes presented here are crude first approximations as they were calculated without data on variability in width and wall steepness along the length of the canyon.

The 12 Georges Bank canyons listed in table 3 range widely in volume, from Shallop Canyon, the smallest (0.66 km^3), to Oceanographer Canyon, the largest by far (37.72 km^3). Sections drawn across these canyons show that each is much wider at its mouth than it is deep (fig. 10); canyon width ranges from 5.80 to 12.46 km, and height ranges from 0.20 to 1.02 km (table 3). The canyons are broad and shallow in cross section, although several of them can be described as narrow and deep relative to the others. Canyon length and mouth height determine the differences in canyon volume (the correlation is significant at r = 0.88 and 0.92, respectively), as the width of the canyon mouth varies surprisingly little among the 12 canyons.

Canyon Energy Levels

The two largest canyons, Oceanographer and Hydrographer, also are the most energetic, as indicated by sediment texture, bed forms, and a few current-speed observations (fig. 11). The largest canyons are long and relatively deep. Lydonia Canyon is the third longest canyon (17.87 km) and is 4.72 km longer than Gilbert Canyon (13.15 km), but the bed forms on the canyon floors indicate that currents in Gilbert are stronger. An explanation may lie in the facts that Lydonia has a much shallower mouth than Gilbert has, its volume is only two-thirds as large, and its walls are sinuous and highly digitated.

Hotchkiss and Wunsch (1982) implied that canyons having steep walls trap internal tidal energy most effectively. Therefore, it may be possible to evaluate the energy level of the canyons by comparing the steepness of their walls. Bathymetry shows that canyon walls vary greatly in slope angle and that lower walls are generally steepest (fig. 10). Observations suggest that the strongest currents flow along the canyon floor. A comparison of the slope angle of the lower walls that extend 100–400 m above the floor at the canyon mouths reveals a correlation between canyon energy and wall steepness. The most energetic canyons have lower walls that slope 25°–35°, whereas the lower walls of the most tranquil canyons slope only 4°–7° (fig. 11, table 3).

Oceanographer and Hydrographer Canyons are large, long, and relatively narrow and deep; have steep lower walls; and display strong bottom currents. Gilbert also is an energetic canyon; it is large and deep and has steep walls, but it is much shorter than the other two canyons. Lydonia is long, but it is shallow and sinuous, has rough walls, and is only moderately active. The somewhat smaller and shorter canyons, Veatch, Powell, and Welker, are poorly known but may be less energetic than Lydonia. The remaining canyons, Dogbody, Atlantis, Heel Tapper, Shallop, and Alvin, are significantly smaller than the others. Their heads are very shallow and wide, their walls are gently inclined, and they can be regarded as little more than embayments of the upper slope. If observations in Heel Tapper Canyon are typical, these small canyons are the least energetic of all Georges Bank canyons and probably experience relatively weak currents similar to those reported from the outer shelf and upper slope by Butman and Conley (1984).

The chief reasons for currents in some of the Georges Bank canyons being stronger than those in the much longer and larger Hudson Canyon off New Jersey are presumably the regional difference in tidal energy and the relatively low angle of Hudson's lower walls (15°–22° at the mouth). (Here we are considering semidiurnal and

Table 3. Dimensions of 12 submarine canyons on southern Georges Bank and of Hudson Canyon on the U.S. Middle Atlantic Shelf

[Canyons are listed in order of increasing volume. Mouth width was measured across the canyon along the projection of the shelf edge at the 200-m isobath. Mouth height was measured from the canyon floor at the mouth to the 200-m isobath. Canyon length was measured along the axis from the rim at the canyon head to the center of the canyon mouth at the 200-m isobath and closely approximates the axis length along the canyon floor. Canyon dimensions are first approximations and were measured without regard to variations in canyon width and wall steepness. Measurements for Georges Bank canyons are from bathymetric maps of Carpenter and others (1982), and measurements for Hudson Canyon are from a U.S. National Oceanic and Atmospheric Administration bathymetric map (1975)]

Canyon	Location (lat N., long W.)	Mouth width = a (km)	Mouth height = b (km)	Canyon length = c (km)	Volume = abc/6 (km^3)	Slope (°) of lower wall at mouth West	East
Shallop........	40°02′, 69°11′	7.93	0.20	2.48	0.66	4	4
Atlantis........	40°05′, 70°11′	6.11	.20	5.11	1.04	5	5
Dogbody.......	40°08′, 68°50′	6.28	.30	3.67	1.15	10	5
Heel Tapper....	40°17′, 68°17′	8.00	.30	3.65	1.46	5	7
Alvin..........	40°05′, 70°27′	12.46	.20	4.98	2.07	5	4
Powell.........	40°31′, 67°26′	5.80	.32	7.96	2.46	10	15
Welker........	40°14′, 68°33′	8.83	.45	7.93	5.25	12	15
Veatch........	40°01′, 69°39′	7.40	.52	9.13	5.86	15	15
Lydonia.......	40°31′, 67°42′	5.90	.45	17.87	7.91	8	15
Gilbert........	40°23′, 67°54′	7.46	.73	13.15	11.93	15	20
Hydrographer...	40°11′, 69°04′	6.22	.75	20.28	15.77	25	35
Oceanographer..	40°29′, 68°10′	8.94	1.02	24.82	37.72	35	35
Hudson........	39°35′, 72°25′	11.40	.85	35.60	57.49	22	15

diurnal flows in the canyon and not relatively rare nontidal events such as turbidity currents and storm-related currents.) The surface tides, from which the internal tides are generated, are appreciably stronger on the southern edge of Georges Bank and on the bank itself than they are along the shelf edge and shelf off New Jersey. The magnitude of the major axis of the M_2 bottom-current ellipse is 15–18 cm/s near the Georges Bank canyons, whereas it is about 7 cm/s or less near the Middle Atlantic canyons (Moody and others, 1984, pl. 9). Comparisons of

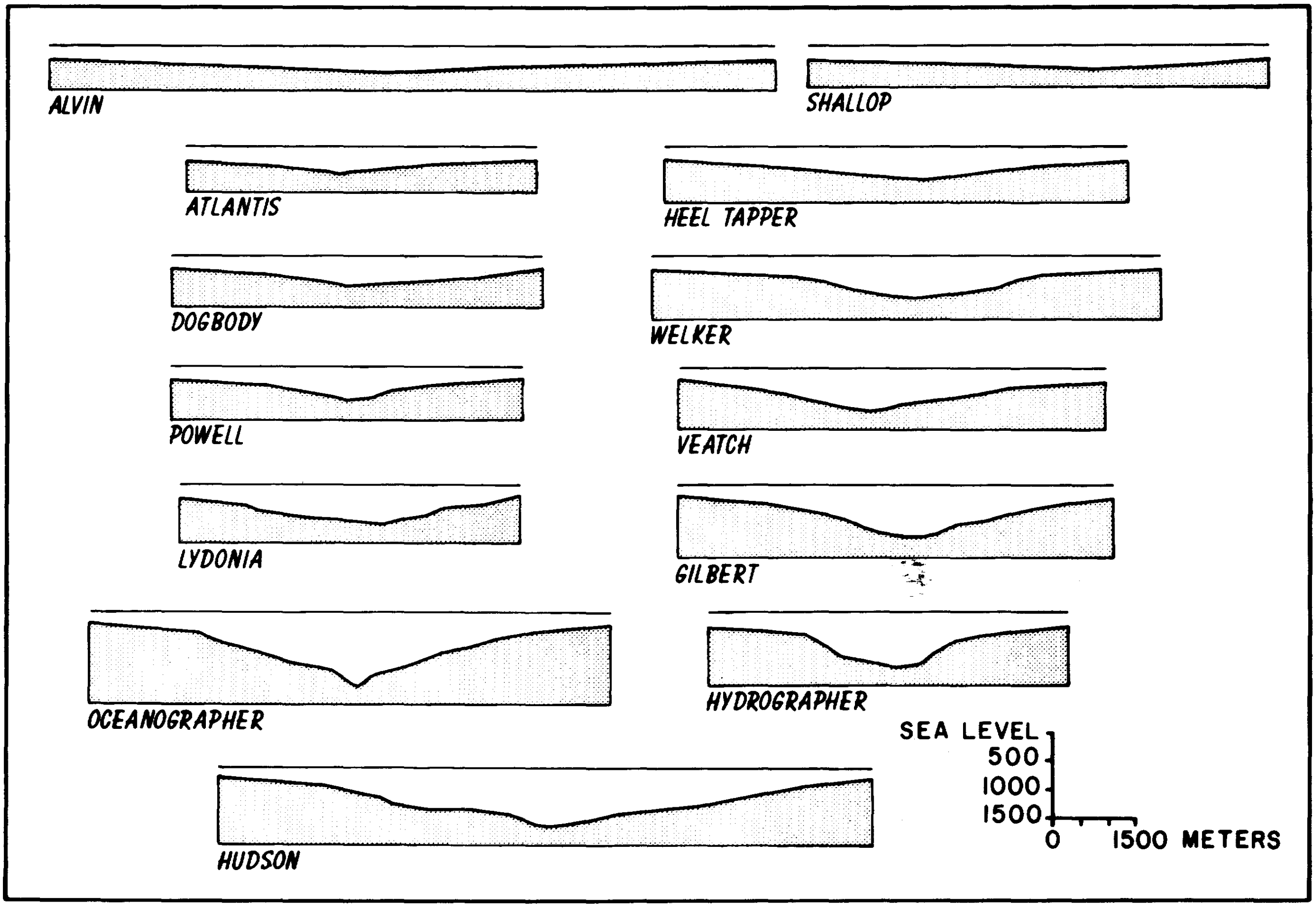


Figure 10. Cross sections of canyon mouths at the 200-m isobath. Horizontal line above each section is sea level. No vertical exaggeration.

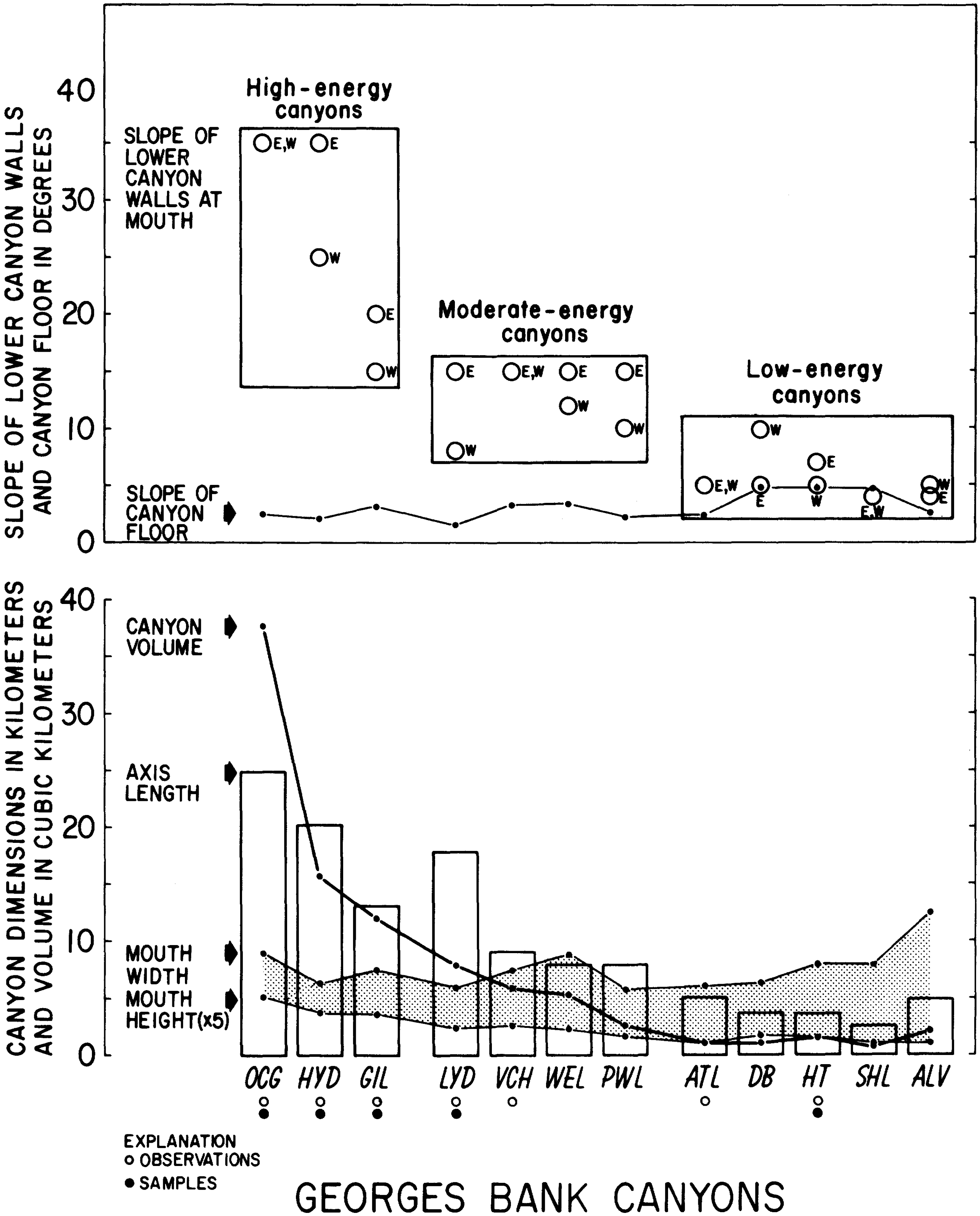


Figure 11. Graphs showing the relationship between canyon morphology and energy level for 12 Georges Bank canyons. Energy levels shown are based on sediment texture, bed forms, and current observations. The most dynamic canyons are large and long and have relatively deep mouths and steep lower walls (E, east wall; W, west wall). Observations include visual, film, and video documentation; samples are sediment collections. See discussion in text for explanation of ranking of canyons for which no direct observations or samples are available. Canyon dimensions and slope of walls measured from bathymetric maps by Carpenter and others (1982). Canyon names: OCG, Oceanographer; HYD, Hydrographer; GIL, Gilbert; LYD, Lydonia; VCH, Veatch; WEL, Welker; PWL, Powell; ATL, Atlantis; DB, Dogbody; HT, Heel Tapper; SHL, Shallop; ALV, Alvin.

canyon energy levels based on canyon size and shape probably are most valid when limited to canyons within the same hydrodynamic region. Indeed, a comparative study of canyon energetics based on morphology, sediment texture, and bed forms of modern (or ancient) canyons that fails to result in a logical ranking may indicate that regional differences existed in the energy of modern (or ancient) surface tides.

If the relationships among canyon shape, size, energy levels, and surface tides are valid, we should be able to determine relative energy levels in a suite of canyons within the same region in parts of the world that are not as well studied as Georges Bank. If bathymetry were adequate, canyons could be ranked by energy level on the basis of size and shape, including wall steepness. A knowledge of the strength and orientation of surface tides and relatively few sediment samples from the floors of a few canyons in a region conceivably could be used to estimate maximum bottom current speeds and to determine where erosion, transport, and deposition were most likely.

SYNTHESIS

Georges Bank is a recently drowned coastal plain, underlain by Cretaceous and Tertiary strata that are covered by a relatively thin veneer of Pleistocene sediment derived from glacial transport and fluvial outwash. The youngest beds include a seaward-thickening wedge of Pleistocene semiconsolidated sandy silt that is at least 300 m thick below the southern shelf edge; it is overlain by unconsolidated sand and gravel that thins and becomes finer toward the southern margin.

The bank crest is shallow (3–40 m) and sediment is coarse; it marks the terminus of Pleistocene glaciers that scoured the Gulf of Maine, and strong tidal and storm currents have removed much of the finer sand and silt and clay. The bank is physically isolated from continental sediment sources, and currents are actively transporting sediment from the bank crest into deeper water. Although sediment is being transported away from the bank in all directions, the shelf-slope transition areas that surround the bank are dissimilar texturally. The northern and eastern margins separate the bank from the Gulf of Maine and Northeast Channel and are covered by gravel and gravelly medium to coarse sand. These areas lie close to the coarse bank crest, are relatively shallow (100–200 m), and are subjected to vigorous tidal and storm currents that transport coarse material as bed load and winnow away fines in suspension. By contrast, the surficial sediment on the southern, or seaward, margin of the bank is medium to fine sand; it is far from the crest, it is deep (200 m or greater), and it is affected by currents that are generally weaker than those on the northern and eastern bank margins.

Sedimentary processes are very complex within the shelf-slope transition on the southern margin of Georges Bank. Variations in the sedimentary environment result from the interaction of many factors: (1) Bottom-current patterns are diverse in this region. Currents vary in strength, flow direction, and frequency. The most effective currents in sediment transport are energetic, strongly oriented, and areally limited. (2) The chief sediment source for the bank margin is sand and gravel from the crest and middle shelf, but an additional important source is the semiconsolidated silt exposed on canyon walls and extensively eroded by burrowing organisms and mass-wasting processes. The presence of ice-rafted gravel increases the textural complexity of the sea floor. The gravel deposits are present on canyon rims, in some areas of the outer shelf and upper slope, and as scattered clasts in all environments of the shelf-slope transition. (3) Finally, the morphology of the sea floor provides the setting for the diverse sedimentary environments that characterize the shelf-slope transition. On the southern bank margin, the sea floor varies from gently inclined outer shelf, upper slope, and canyon floors to more steeply dipping and sinuous canyon and gully walls. The shape of the sea floor affects the strength and direction of bottom currents and the downslope movement of sediment particles.

Major aspects of sedimentary processes and environments in the shelf-slope transition on the southern Georges Bank margin to a depth of about 600 m are summarized as follows.

Bottom Currents

Mean bottom flow is anticyclonic around Georges Bank and has an off-shelf component at the bank margins. This flow generally has a speed of 5 cm/s or less on the southern flank of the bank and transports silt and clay in suspension off the bank and southwestward to the shelf off southern New England.

The semidiurnal M_2 tidal flow is the major, persistent bottom current that transports sediment on the bank and in the large canyons. The orientation of the major axes of tidal ellipses is across Georges Bank and the upper slope and parallel to the trend of the canyons. The magnitudes of the major axes of tidal ellipses are more than 40 cm/s on the bank crest, are 15–18 cm/s on the shelf near the heads of large canyons, and diminish to about 6 cm/s on the upper slope. Within large canyons, the strongest currents flow up and down the canyon along the floors, have a period similar to that of the M_2 tide, and reach short-term speeds of 50–100 cm/s.

A strong current of unknown origin flows westward across the east rims of Oceanographer and Lydonia Canyons at speeds of about 50 cm/s. This current transports shelf sand onto the canyon walls and exposes large areas of pavement made of ice-rafted gravel.

Gulf Stream warm-core rings move onto the upper slope and then drift southwestward toward the Middle Atlantic region. During 8 years, 19 rings were present near Hydrographer, Oceanographer, and Lydonia Canyons for a total of 17 months, or about 2 months per year. A single ring may remain in an area for a month. Anticyclonic currents in the rings flow northeastward along the upper slope at speeds as great as 50 cm/s or more and winnow very fine sand, silt, and clay from the sea floor between 200 and 300 m water depth, exposing patches of glacial gravel. The fine sediment presumably is transported alongslope and downslope and into adjacent canyons and gullies.

Sediment Texture and Transport

The texture of sediment on the canyon floors is an important indicator of bottom-current strength. All canyons receive sediment from the shelf and, to varying degrees, from the erosion of canyon walls. Sediment on the floors of large canyons resembles that on the adjacent shelf. Sediment in medium canyons has a variable texture but generally is finer grained than that in large canyons. The floors of small canyons are similar to the upper slope in texture.

Lower canyon walls in medium and large canyons are Pleistocene semiconsolidated silt covered locally by sand being transported to the canyon floor. These walls are major sites of erosion. Bioerosion, chiefly burrowing, produces small chunks of semiconsolidated silt. Weakened and oversteepened walls erode further by the spalling and sliding of large pieces of the wall. The clasts are abraded and softened by moving sand on the canyon floor; they disintegrate, and in large canyons, individual particles are transported away by strong currents. Near the mouth of a large, deep canyon (Oceanographer), lower walls are subvertical exposures of Tertiary and Upper Cretaceous limestone and siltstone that erode by a combination of biological activity, fracturing caused by unloading, and rock falls.

The upper slope is veneered by silty sand that has been transported from the shelf. The sand is thin near the heads of steep gullies, revealing the underlying Pleistocene semiconsolidated silt into which the gullies are cut. Gully walls are steep (20°–40°) and are covered by silty sand lying at its angle of repose. This sediment flows periodically onto the gully floors, where apparently it accumulates, as bottom currents are too weak to transport it downslope. Perhaps the sand deposits grow until turbidity flows or mass-wasting processes carry it onto the lower slope and rise. At present, the sand is pervasive and is accumulating too rapidly for organisms to construct burrows into the underlying silt; thus, bioerosion of the gully walls is minimal.

Silt and clay constitute only a small percentage of the surficial sediment on the bank crest and on the outer shelf. Their distribution is a measure of the vigor of bottom currents in those areas. On the slope, silt and clay increase in abundance as depth increases; they constitute about 35 percent of the sediment near 600 m. The mudline is below this level as silt and clay increase to 70–95 percent on the lower slope. On the floors of large canyons, silt and clay constitute a small percentage of the surficial sediment, but on the floors of smaller canyons, they are more abundant.

Very fine sand (4 ϕ) is a good indicator of subtle changes in the strength of bottom currents. Like silt and clay particles, it travels in suspension, but to remain suspended, it requires stronger currents than do silt and clay. Very fine sand constitutes a small percentage of shelf sediment but increases in abundance as depth increases on the outer shelf and upper slope. An exception to this trend has been observed on the upper slope, where 4-ϕ sand and silt and clay have been removed by the erosive action of Gulf Stream warm-core-ring currents between 200 and 300 m. Very fine sand is accumulating in several areas around the heads of Oceanographer and Lydonia Canyons, where bottom currents apparently weaken locally but remain strong enough to transport silt and clay.

Canyon Size and Energetics

Large canyons such as Oceanographer, Hydrographer, and Gilbert are much more energetic than small canyons, and their sedimentary environments are more diverse. Bottom currents are strong, are reversing, and presumably are produced by the M_2 semidiurnal tide, at times enhanced by high-frequency internal waves. Canyon-floor currents have speeds of 50–100 cm/s, and ripples and dunes are present to depths of at least 600 m. Somewhat weaker currents flow along canyon walls and transport sand from the shelf to the canyon floor. Extensive outcrops of the Pleistocene semiconsolidated silt that drapes the lower walls are eroded by organisms and by processes of mass wasting. Fine-grained sediment is winnowed from the canyon floor deposits and transported out of the canyon. Sand moves upcanyon and downcanyon along the floor, and net transport varies in different areas of the canyon floor. Benthic fauna and habitats are diverse in large canyons.

Small canyons such as Heel Tapper are relatively tranquil, as indicated by sediment texture. Bottom currents are weak, and the magnitude of the major axis of the M_2 tidal ellipse probably is less than 10 cm/s, as it is on the adjacent upper slope. Ripples and other bed forms are largely absent. Silty sand transported from the shelf veneers the canyon walls and floor, which are cut into the underlying Pleistocene silt. Exposures of the silt are uncommon, and burrows are rare. Sediment becomes finer grained as depth increases, and texture resembles that of the adjacent gullied upper slope. The small canyons are embayments of the upper slope. Benthic fauna and habitats are not as diverse as those in large canyons; however, a faunal depth zonation based on water temperature was observed in both small and large canyons.

Medium canyons such as Lydonia are less energetic than large canyons. Tidally induced bottom currents are weaker; ripples and large bed forms are present to a limited extent. Sediment on the canyon floor is finer grained than that in large canyons, and much of the silt eroded from the walls remains on the canyon floor. Sediment accumulation may be most rapid on the floors of medium-sized canyons because they trap considerably more shelf sand and eroded silt than do small canyons, and less sediment is transported away than in large energetic canyons.

Canyons and the outer shelf-upper slope areas experience the same regional tide. However, within the same depth interval (200–600 m), the sediments on the floors of large canyons and on the adjacent gullied slope are dissimilar because bottom currents are not uniform in strength. The flow of water through large canyons is enhanced by the canyon shape; a correlation exists between canyon size and shape and current strength within the canyons. All Georges Bank canyons generally are shallow and wide at their mouths. Within the morphological limits of the canyons, those that are large, long, narrow, deep, and steep walled, such as Oceanographer and Hydrographer, experience strong tidally induced bottom currents. Small, wide, shallow canyons, such as Heel Tapper, experience weak currents similar to those on the upper slope. We do not yet know whether warm-core-ring currents affect the small canyons. Small, narrow gullies on the upper slope, like those in the head of Filebottom Canyon, do not enhance the strength of bottom currents, as indicated by the presence of fine-grained sediment on their floors and by the absence of ripples and other bed forms.

If the strength and orientation of the regional tide and the size and shape of canyons determine current dynamics within canyons, and if current strength and canyon morphology are related in a systematic way, then it may be possible to make a preliminary assessment of current and sediment dynamics in canyons in poorly studied areas of the world by analyzing bathymetry and tidal data.

Regional Sediment Transport

In a broad sense, the bank crest is a shallow topographic high, constructed of coarse, glacially and fluvially transported sediment that is wasting away under the effect of strong tidal and storm currents. On the southern bank margin, net sediment movement is downslope off the shelf into canyons or onto the gullied upper slope. However, because of local variations in current strength and bottom morphology, sediment transport is not uniform throughout the shelf-slope transition (fig. 12). Transport is most rapid in areas of strong currents such as the east rims of Oceanographer and Lydonia Canyons where gravel pavement is exposed, along the upper slope where Gulf Stream warm-core rings winnow sediment, and in large canyons where strong currents move sand along the canyon floor and remove fine-grained sediment. Net transport is upcanyon in response to strong axial currents along some reaches of Oceanographer and Hydrographer Canyons. Sediment movement is slower and sediment is accumulating on the upper slope, including in the gullies, on the floors of medium and small canyons, and on the shelf around the heads of some canyons. Thus, for example, sand moves rapidly across the exposed gravel pavement on the east rim of Oceanographer Canyon; it slows and accumulates on the upper wall where along-canyon currents are weak; and it moves more rapidly across the lower walls owing to an increase both in wall steepness and in the speed of tidal currents. On the canyon floor, it moves most rapidly as it is transported short distances back and forth, up and down the canyon by strong currents. Net movement on the floor is slowly up or down the canyon, depending on the asymmetry of current flow.

The current systems and related sediment-transport pathways described in this study are important aspects of the sedimentary environment on the Georges Bank outer margin. Understanding these systems and pathways can help us to elucidate the sedimentary history and modern development of the margin and to predict and track the movement of water masses and indigenous plankton and larvae, as well as pollutants that may be introduced into the environment.

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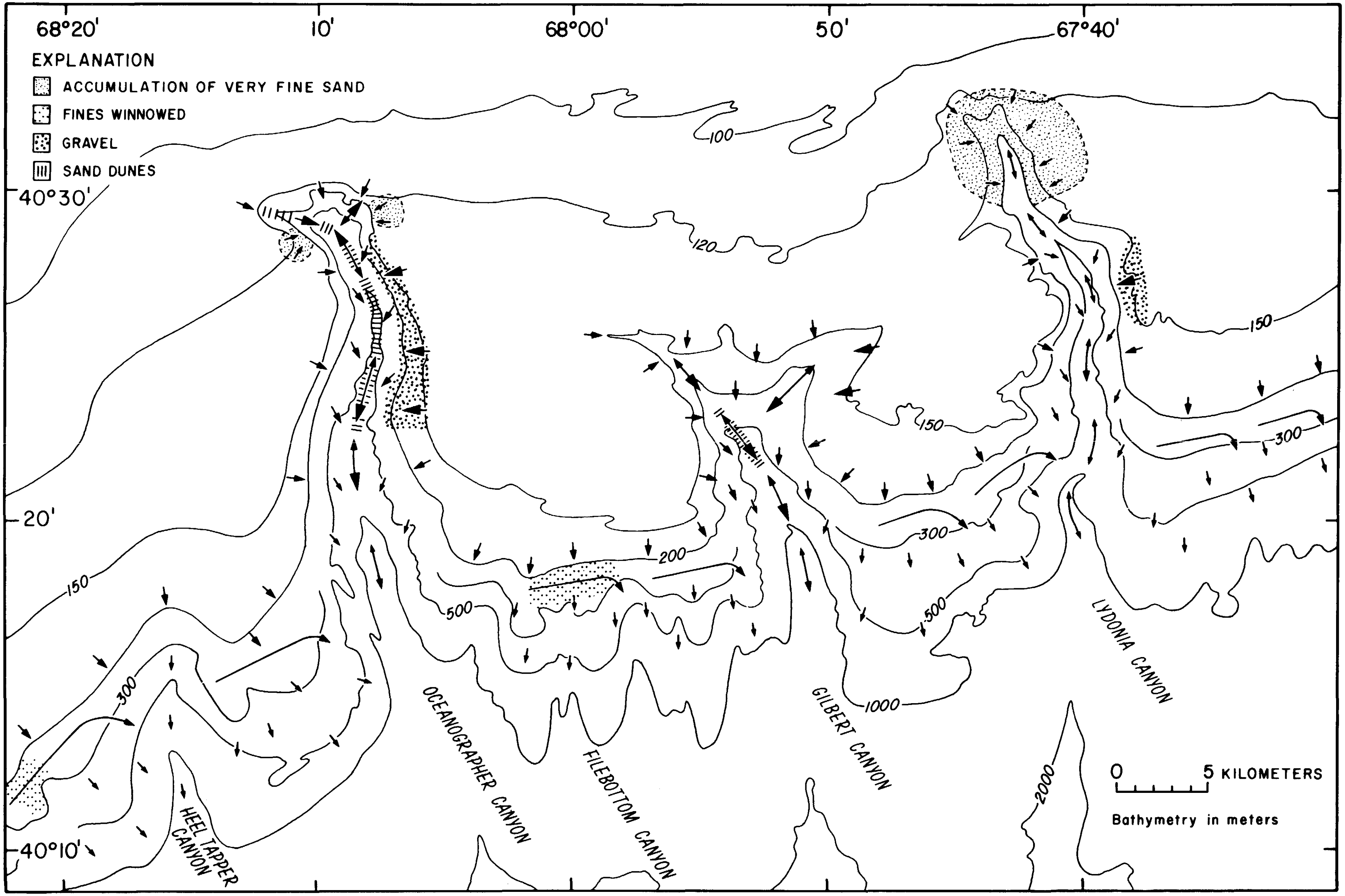

Figure 12. Map of the Oceanographer Canyon-Lydonia Canyon area. Sediment transport directions in the shelf-slope transition area are shown by arrows; arrow weight represents relative current strength. The interpretation is based on observations of sediment texture, bed forms, and current speed and direction and is extended by analogy in areas where data are unavailable. Movement is most rapid on the eastern rims of canyons (where ice-rafted gravel is exposed) and on the canyon floors. Net movement is offshelf and downslope, but movement varies in direction along the axes of large canyons. Major currents are generally tidal except for westward flow across the eastern canyon rims and for along-slope flow associated with Gulf Stream warm-core rings. Very fine sand (4 ϕ) accumulates around canyon heads, and 4-ϕ sand, silt, and clay are eroded from the upper slope by warm-core-ring currents. Sand dunes are present on the floors of high-energy canyons.

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