UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Submarine canyon and slope processes on the U.S. Atlantic continental margin

By

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ABSTRACT

Two regions on the U.S. Atlantic continental margin were surveyed using single-channel, seismic-reflection profiling techniques: the Mid-Atlantic Continental Slope and Rise seaward of New Jersey in the vicinity of Baltimore Canyon and the Continental Slope and upper Rise just north of Cape Hatteras. Submarine canyons are the dominant morphologic feature in both areas. The Continental Slope in the Baltimore Canyon area has a general sea-floor gradient of 3°-4° and a width of approximately 40 km, whereas the study area north of Cape Hatteras has a general sea-floor gradient of approximately 9° and a width of 20 km. The dominant slope process differs in each area. In the Baltimore Canyon area, subbottom reflectors suggest that sediment deposition with progradation of the slope is related to canyon processes. In the study area north of Cape Hatteras, the canyons appear erosional and mass wasting is the dominant erosional process. Dominant slope processes appear to be correlated with the width and sea-floor gradient of the Continental Slope. Although the absolute age of the canyons is difficult to determine without rotary-drill cores for stratigraphic control, Baltimore Canyon is suggested to be older than the shelf-indenting canyon just north of Cape Hatteras. An anomalously large ridge flanking Baltimore Canyon on the upper rise appears to be related to canyon depositional and erosional processes.

INTRODUCTION

As part of a program to study the transport role of submarine canyons and processes responsible for shaping the U.S. Atlantic continental margin, the U.S. Geological Survey (USGS) in cooperation with the Bureau of Land Management (BLM) during 1982 undertook a seismic-reflection profiling survey of two of the margin's many canyons and their adjacent slope and rise: the Baltimore Canyon seaward of Delaware Bay (fig. 1, area A) and an unnamed canyon north of Cape Hatteras (fig. 1, area B). The Continental Slope and Rise in the study areas are dissected by numerous submarine canyons. The width of the Continental Slope (i.e., the distance between the 200-m and 2,000-m contours) is variable (fig. 1); Baltimore Canyon is located in a wide portion, approximately 40 km wide, of the slope, and the canyon north of Cape Hatteras, in a narrow slope region approximately 20 km wide.

The objectives of the survey in the Baltimore Canyon area were: 1) to characterize canyon and slope processes in the U.S. Mid-Atlantic continental margin region; 2) to extend to the south the existing geophysical coverage around Wilmington Canyon (McGregor, 1982a; McGregor and Hampson, 1982; and McGregor and others, 1982); 3) to extend to the adjacent slope and rise the bathymetric coverage collected earlier by Lamont-Doherty Geological Observatory; and 4) to compare the rise morphology around Wilmington Canyon with that around Baltimore Canyon.

The objectives of the survey of the unnamed canyon north of Cape Hatteras were: 1) to geologically and geophysically evaluate a canyon on the U.S. South Atlantic margin; 2) to compare this canyon with other surveyed canyons; 3) to provide detailed bathymetric data which can be used for later instrument placement for measurements of water movements; and 4) to evaluate the influence of ocean circulation (Gulf Stream) on canyon processes.

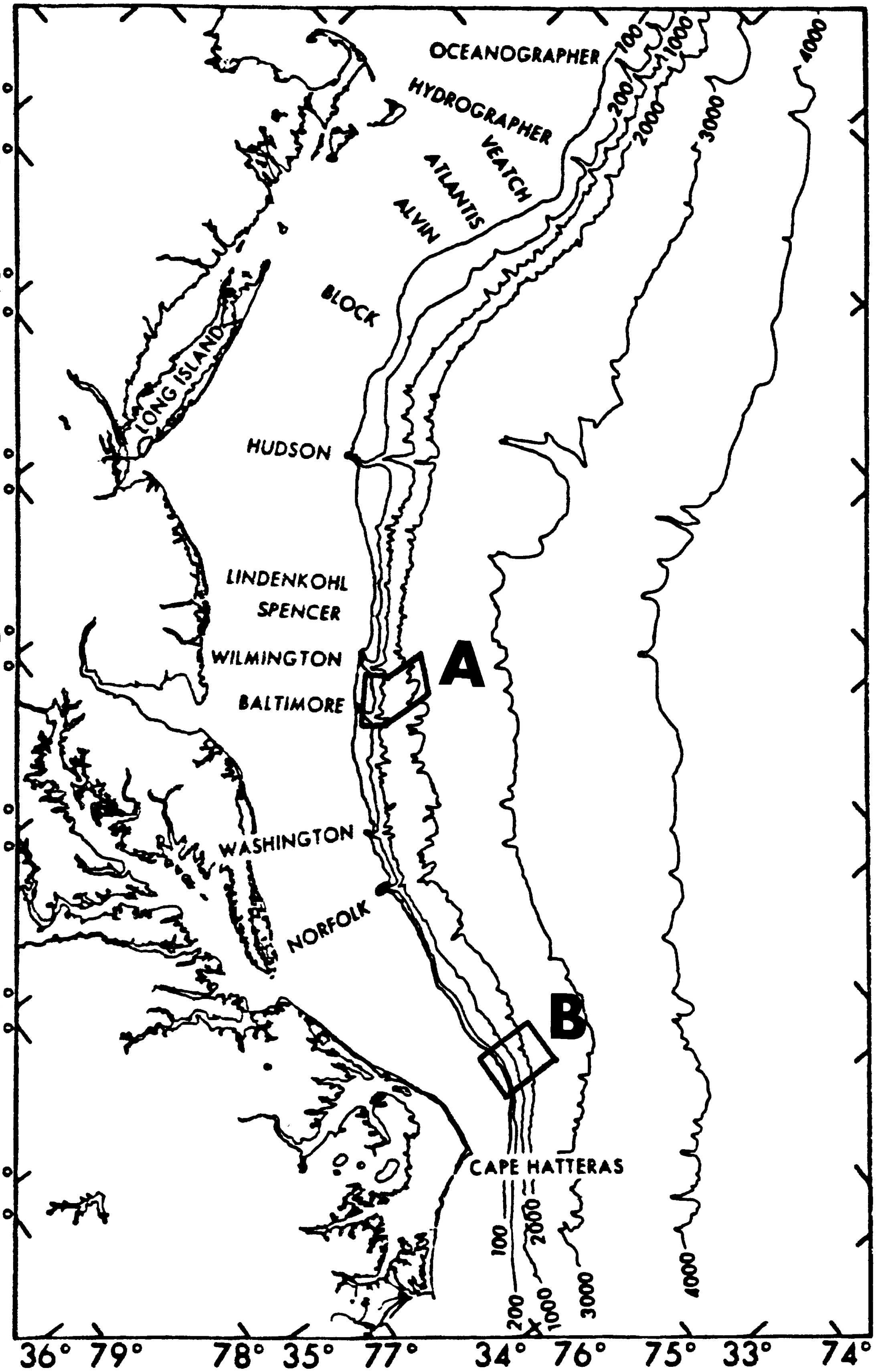


Figure 1. Index map of the U.S. Atlantic continental margin. Contours are in meters. Area A indicates the region surveyed in the Baltimore Canyon region. Area B indicates the region surveyed on the Continental Slope and upper Rise north of Cape Hatteras.

METHODS

On GYRE Cruise 82-G-10B, September 2-13, 1982, two surveys were conducted on the slope and upper rise using one and, in deep water, two 40-in^3 (640×10^{-6} m^3) airguns and a hull-mounted 3.5-kHz profiler. Navigational control for the cruise was based on LORAN-C data updated with transit satellite data. Survey tracklines oriented parallel to the trend of the slope and rise were spaced approximately 1 km apart over the slope and 2 km apart over the rise; crossing dip lines were spaced 6 and 10 km apart in the Baltimore Canyon survey (fig. 2) and 3 km apart in the canyon survey north of Cape Hatteras (fig. 3). Over 1,000 km of each type of single-channel data (airgun and 3.5-kHz) were collected in each survey area. The ship speed for the Baltimore Canyon survey was approximately 9 km/hr; ship speed during the survey north of Cape Hatteras varied between 4 and 12 km/hr depending on the trackline orientation relative to the Gulf Stream. The seismic-reflection profiles collected using a 40-in^3 (640×10^{-6} m^3) airgun sound source and a 200-element hydrophone were recorded at both 2- and 4-second sweep rates. The 4-second data shown here were filtered at 58-150 Hz. Maximum acoustic penetration on the profiles was 0.8 seconds. The 3.5-kHz data were digitized, computer plotted on boat sheets, and contoured to produce the bathymetric maps shown in figures 2 and 3.

BATHYMETRY

Baltimore Canyon (figs. 1 and 2) is a large shelf-indenting canyon that has cut back into the shelf edge approximately 16 km. The canyon has a southeasterly trend from the shelf edge to a water depth of approximately 1,100 m, where it abruptly changes trend to due east on the lower slope and upper rise. The slope on either side of Baltimore Canyon is dissected by smaller canyons that begin on the upper slope and trend downslope in a southeasterly direction. Below 1,500 m, the smaller canyons to the north merge downslope with Baltimore Canyon (fig. 2). The channel of Baltimore Canyon is sinuous and varies in width from 6 km on the upper slope to 1 km on the upper rise. It also varies in depth below the adjacent sea floor from 700 m on the upper slope to 100 m on the upper rise. On the midslope, at a water depth of approximately 1,200 m (fig. 4; profile 10), the floor of Baltimore Canyon is the same depth as the adjacent canyons. Along the lower slope and upper rise, Baltimore Canyon is flanked by leveelike ridges, the larger of which is on the south side (figs. 2 and 5).

The general sea-floor gradient on the slope is 3° to 4° down the crest of the ridges and 6° down the axes of the smaller canyons. The channel of Baltimore Canyon on the slope has a gradient of 2°. On the rise, the sea-floor gradient decreases to less than 2°. Locally on canyon walls, the gradient is considerably steeper, increasing to 15° to 20°.

In the survey area "B" north of Cape Hatteras, an unnamed canyon in the center of figure 3 has eroded back into the shelf edge approximately 4 km. The Continental Slope on either side of this canyon is dissected by numerous smaller canyons that begin at the shelf edge. All of the canyons in the survey area trend downslope in an east-southeasterly direction (fig. 3). The shelf-indenting canyon has a sinuous channel trend and varies in width from 4 km on the upper slope to approximately 1 km on the upper rise. It varies in depth below the adjacent sea floor from 600 m on the upper slope to 200 m on

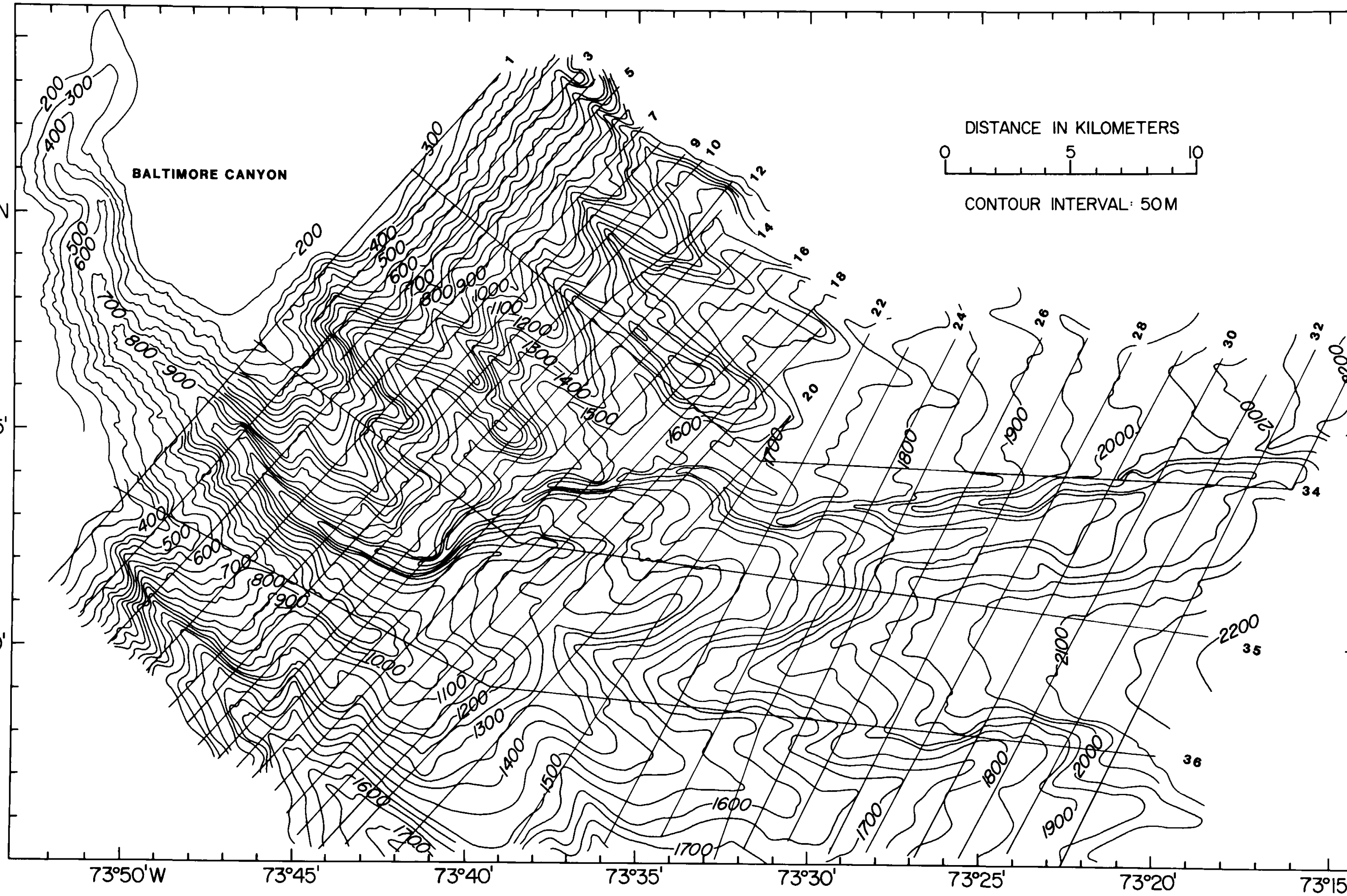


Figure 2. Bathymetric contour map of Baltimore Canyon and the adjacent slope and rise. The contour interval is 50 m. Data in the canyon head with 100 m contour spacing is from studies conducted by Barbara Hecker of Lamont-Doherty Geological Observatory. Lines indicate the location of the ship's track and numbers refer to the profile numbers to identify the location of profiles shown in figures 4 through 6. See figure 1, area A, for location of this map.

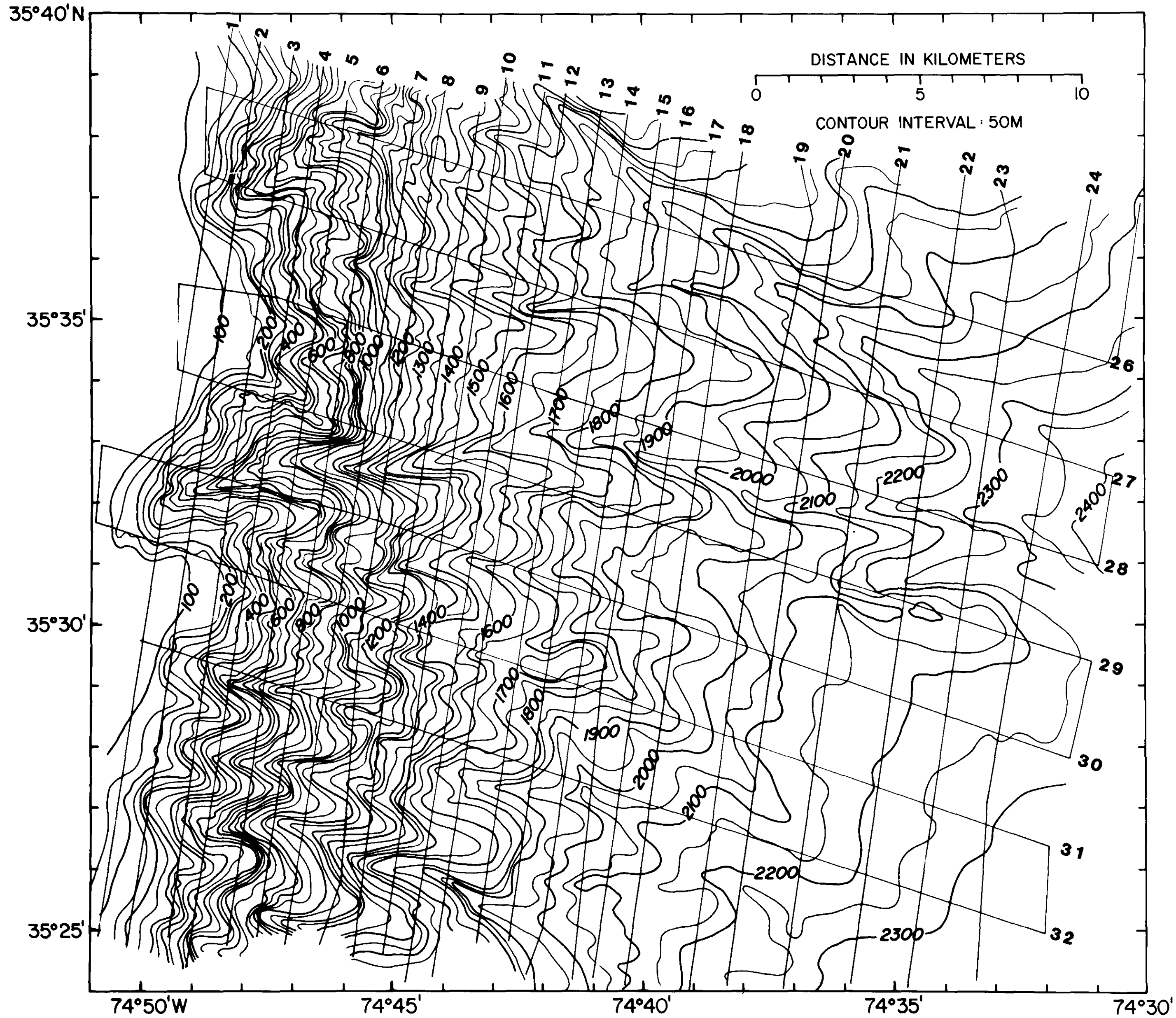


Figure 3. Bathymetric contour map of an unnamed canyon and the adjacent slope and rise north of Cape Hatteras. The contour interval is 50 m. Lines indicate the location of the ship's track and numbers refer to the profile numbers to identify the location of profiles shown in figures 7-9 and 15-19. See figure 1, area B, for location of this map.

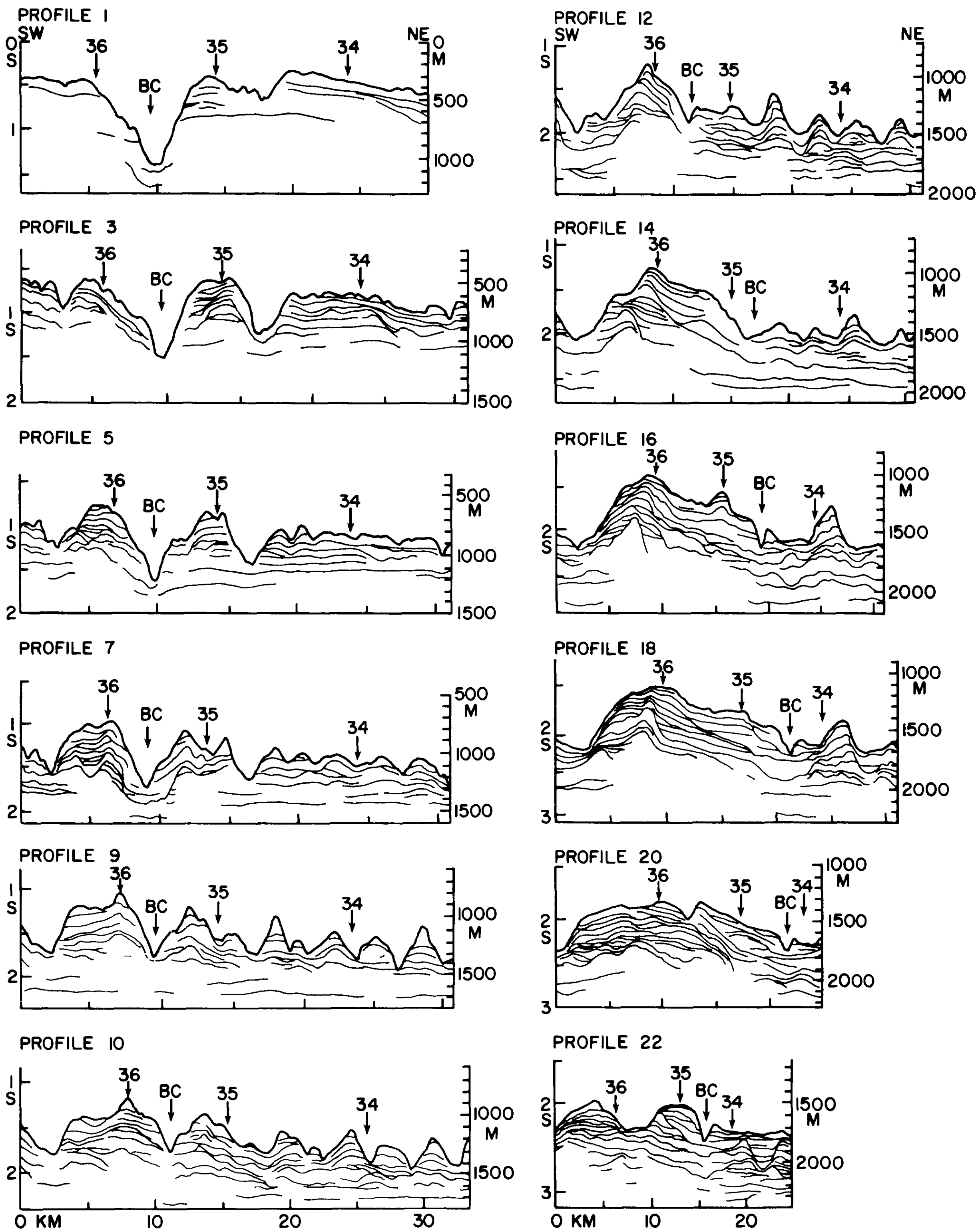


Figure 4. A series of line drawings of the seismic-reflection profiles oriented parallel to the shelf edge in the Baltimore Canyon area. See figure 2 for profile location. BC refers to the location of Baltimore Canyon and the numbered arrows refer to the location of the crossing profiles. Vertical exaggeration is approximately 10 x.

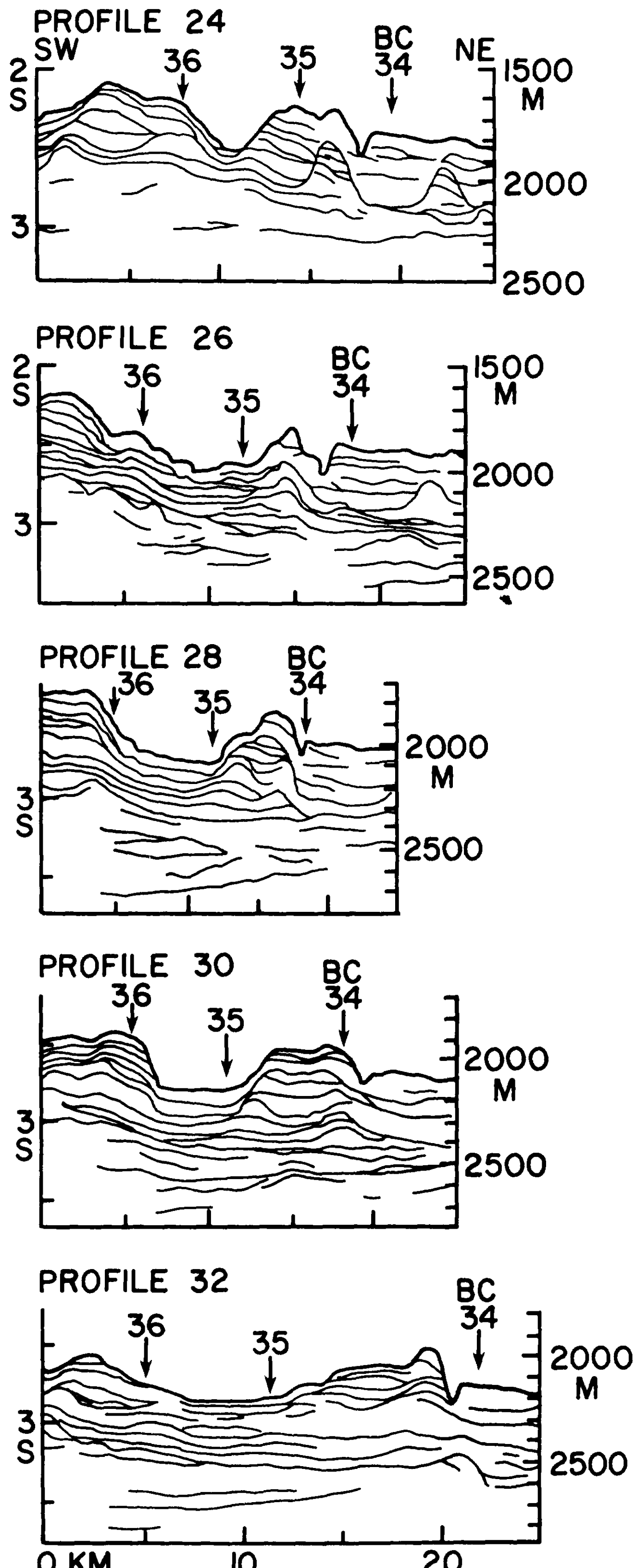


Figure 5. A series of line drawings of the seismic-reflection profiles oriented parallel to the shelf edge in the Baltimore Canyon area. See figure 2 for profile location. BC refers to the location of Baltimore Canyon and the numbered arrows refer to the location of the crossing profiles. Vertical exaggeration is approximately 10 x.

the upper rise. The channel of this canyon is flanked by leveelike ridges on the rise and on the upper rise merges with the channels of the canyons to the north.

North of Cape Hatteras (fig. 1, area B) where the Continental Slope is narrower, the sea-floor gradient is also steeper (fig. 3). The average sea-floor gradient of the slope along the crest of the ridges and axis of the valleys is 9^{o}; however, the gradient of the channel of the shelf-indenting canyon on the slope is slightly less, 7^{o}, and decreases to 2^{o} on the rise. The general sea-floor gradient on this portion of the rise is 2^{o}. Locally on the canyon walls, the gradient is very steep and approaches 30^{o} in many places.

SEISMIC-REFLECTION PROFILES

Baltimore Canyon area

The profiles oriented parallel to the shelf edge indicate the changes in morphology of the slope and rise with water depth (figs. 4 and 5). Profiles 1 through 12 (fig. 4) show the progressive dissection of the Continental Slope with water depth. Reflecting horizons are truncated in the walls of the canyons. Baltimore Canyon deeply incises the upper slope (fig. 4; profiles 1-7); however, on the midslope it is cut to the same depth as the adjacent canyons (fig. 4; profiles 9-12), and on the lower slope and upper rise, the channel decreases markedly in size (figs. 4 and 5; profiles 16-32).

The slope and rise in the Baltimore Canyon area are underlain by a well-stratified sedimentary sequence (figs. 6-10). On the upper slope the deepest reflectors appear to be smoother and traceable for distances over 10 km (figs. 4 and 6, profile 5). The ridges flanking the canyons, however, are composed of irregular discontinuous reflectors. The irregular nature of the reflectors persists at depth beneath the ridges on the mid to lower slope (figs. 7 and 8; profiles 18, 20, 22, 24), but relief on these reflectors decreases on the rise (fig. 8; profile 32). The geometry of the reflectors suggests that the ridges are related to canyon depositional and erosional processes and are not strictly erosional remnants. The ridge flanking Baltimore Canyon on the south on the lower slope (fig. 4; profiles 16 and 18) is a dominant feature and has many internal unconformities. Beginning with profile 20 (fig. 4), this ridge is progressively eroded by a valley (figs. 4 and 5; profiles 20-32) that begins on the lower slope (fig. 2).

Buried valleys are present beneath Baltimore Canyon (fig. 4; profile 7) as well as under several other canyons (fig. 4; profiles 3 and 12). A large buried channel and levee system is present on the lower slope and upper rise (figs. 4 and 5; profiles 22-28) slightly north of the present channel of Baltimore Canyon.

Three dip lines oriented perpendicular to the trend of the slope are shown in figure 11. Reflecting horizons are generally continuous and dip in a seaward direction. The rise and, in places, the slope are built upward by accumulations of sediments. The channel of Baltimore Canyon obliquely crossed on profile 35 (figs. 10 and 11 between profiles 10 and 14) truncates reflectors. Numerous unconformities are present within the wedge of rise sediments (figs. 9, 10, 11). Generally the slope appears to have prograded

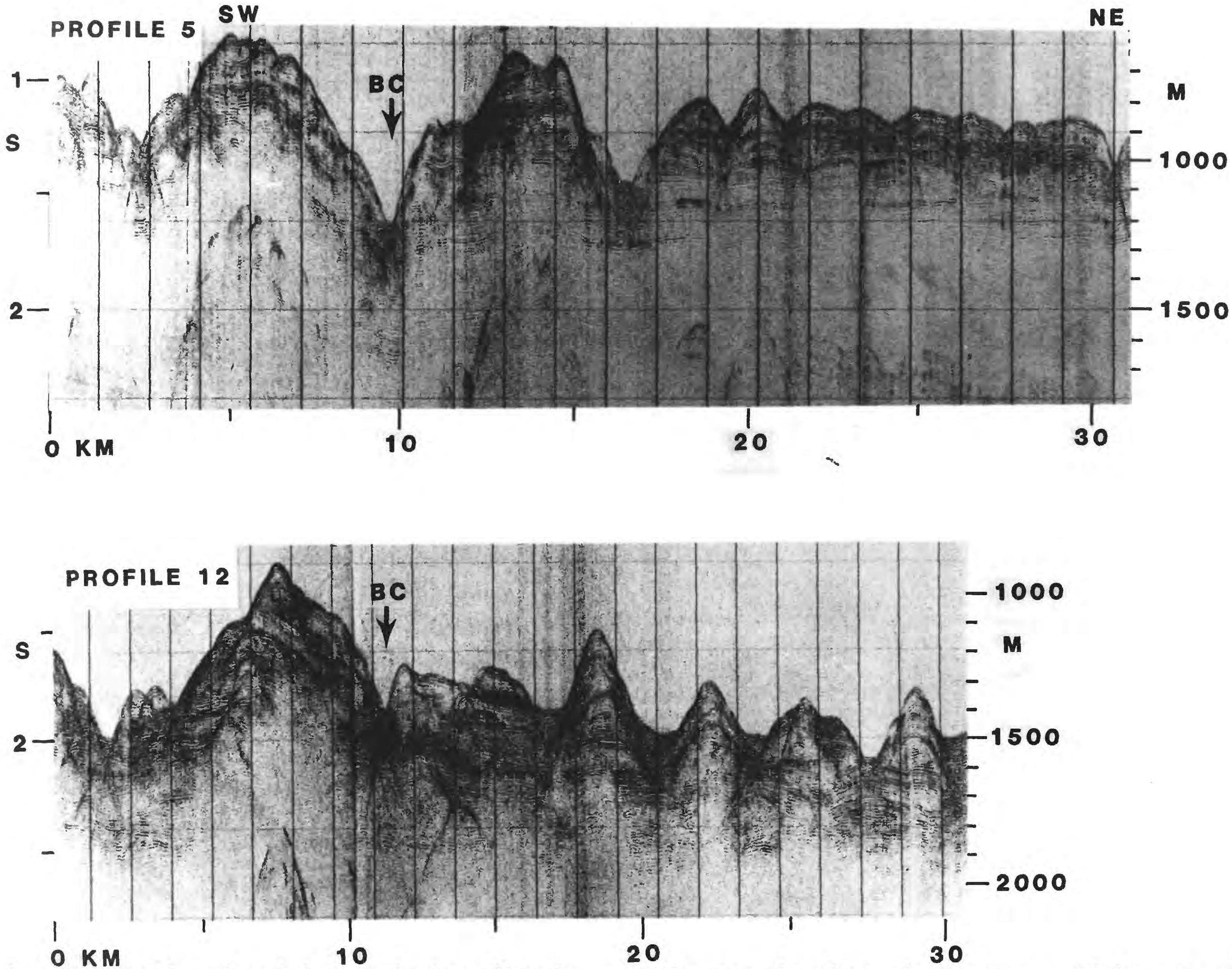
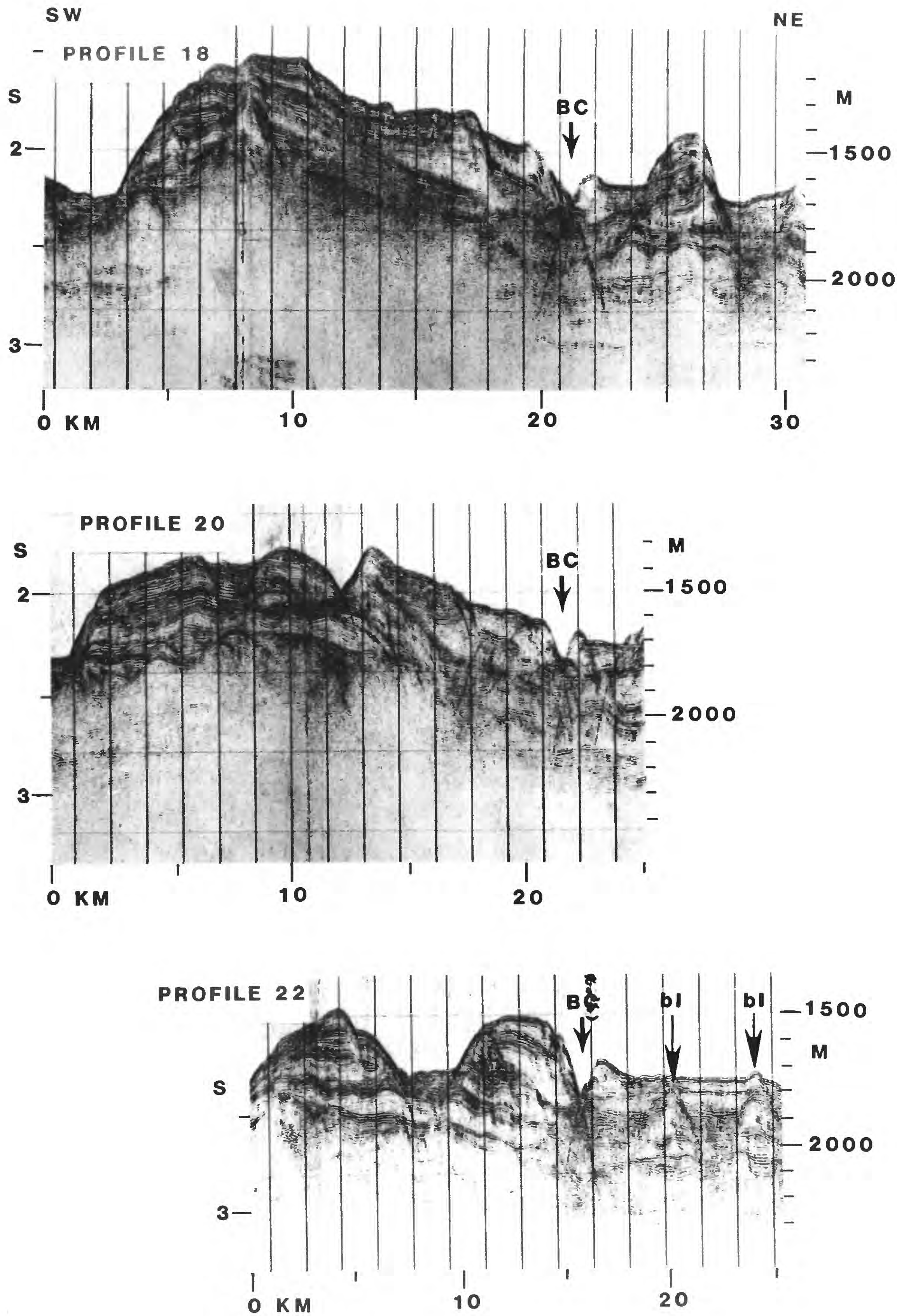


Figure 6. Photographs of original seismic-reflection profile records along the upper to midslope in the Baltimore Canyon area. Depth scales are two-way travel time in seconds and depth in meters based on a sound velocity of 1,500 m/s. BC denotes the axis of Baltimore Canyon. See figure 2 for profile location and figure 4 for line-drawing interpretation. Vertical exaggeration is 10 x.

Figure 7. Photographs of original seismic-reflection profile records along the mid to lower slope in the Baltimore Canyon area. Depth scales are two-way travel time in seconds and depth in meters based on a sound of velocity of 1,500 m/s. BC denotes the axis of Baltimore Canyon and bl refers to the location of buried levees. See figure 2 for profile location and figure 4 for line-drawing interpretation. Vertical exaggeration is 10 x.

Figure 7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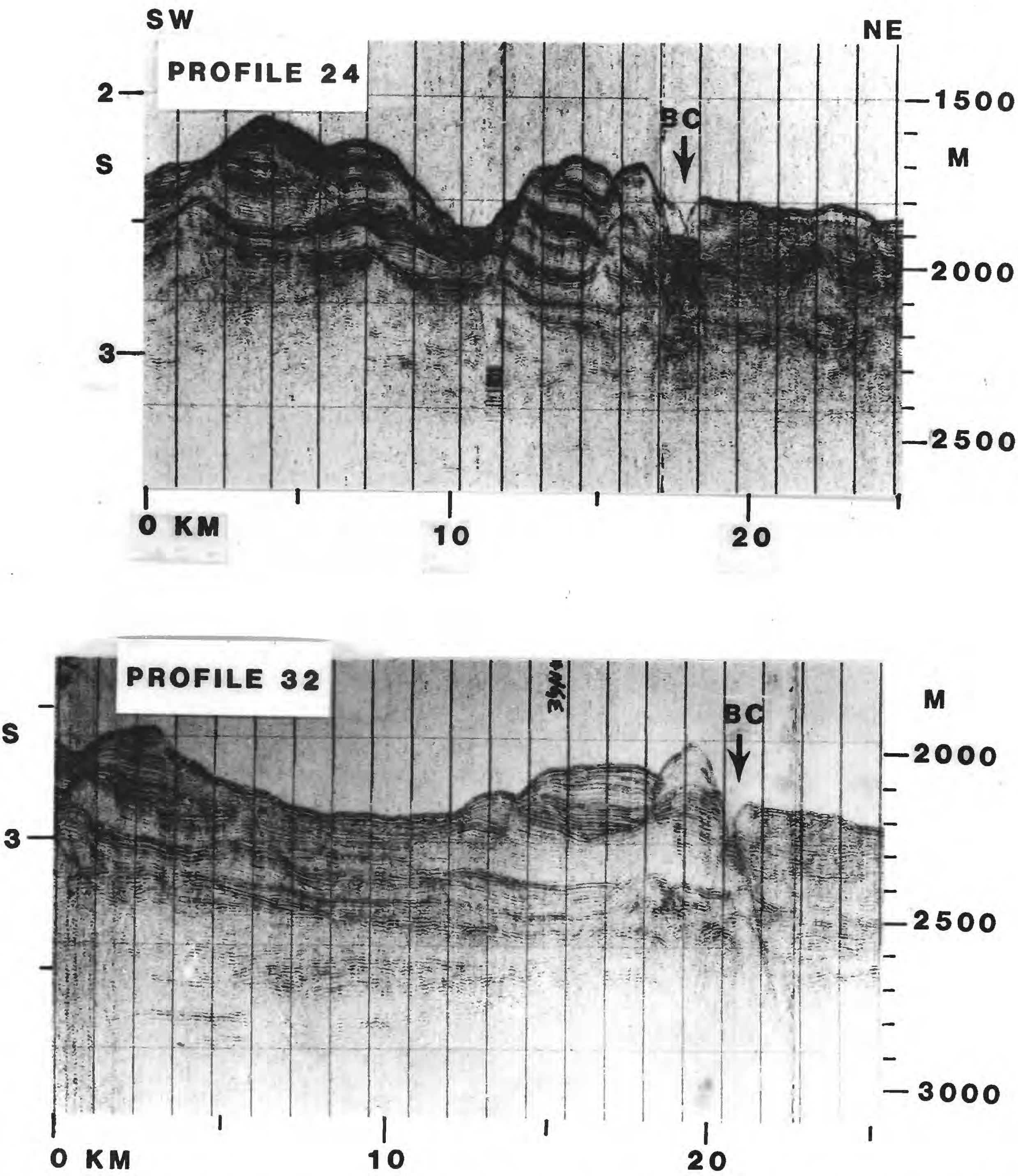


Figure 8. Photographs of original seismic-reflection profile records on the upper rise in the Baltimore Canyon area. Depth scales are two-way travel time in seconds and depth in meters based on a sound velocity of 1,500 m/s. BC denotes the axis of Baltimore Canyon. See figure 2 for profile location and figure 5 for line-drawing interpretation. Vertical exaggeration is approximately 10 x.

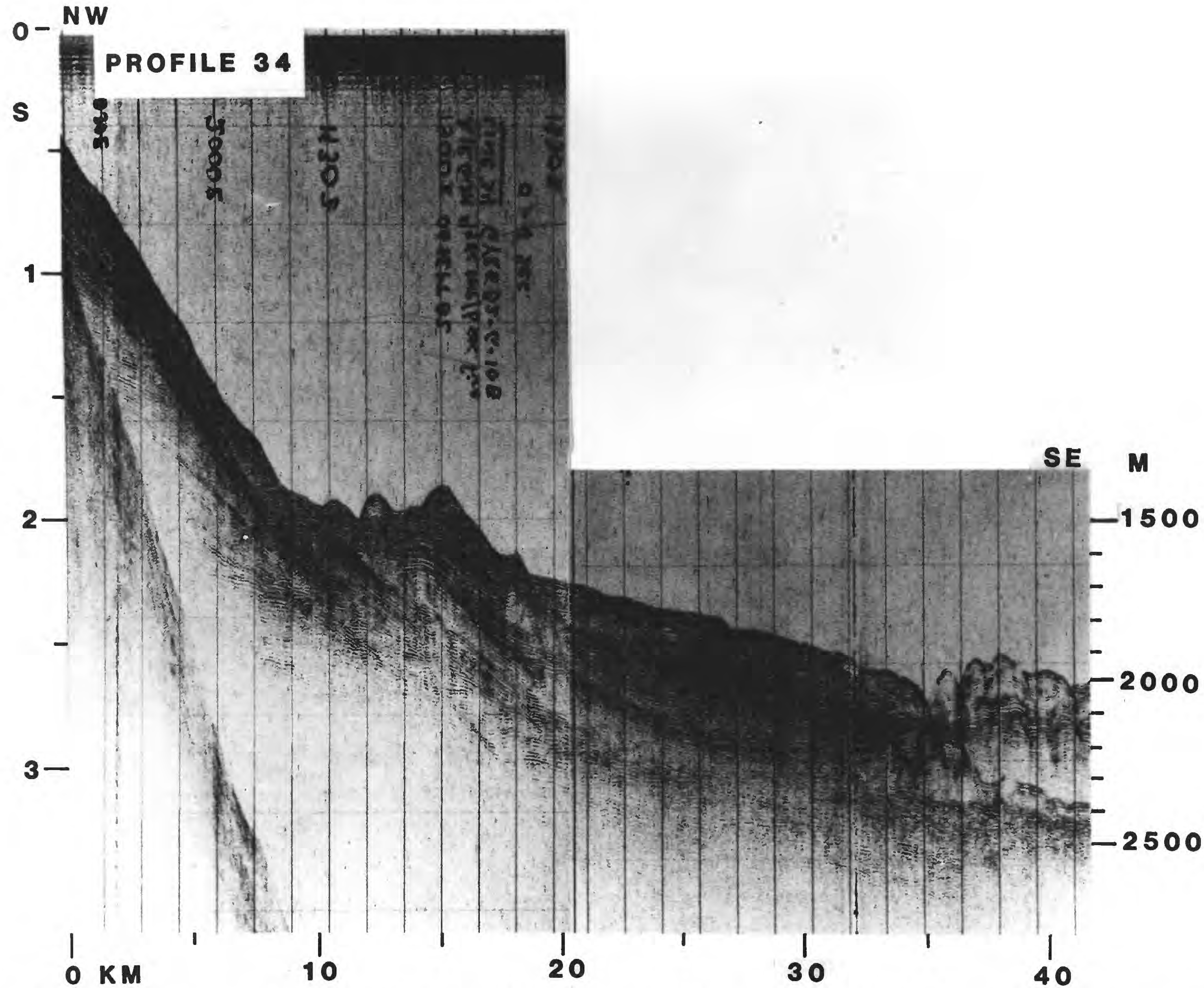


Figure 9. Photograph of original seismic-reflection profile record with the trackline oriented perpendicular to the continental margin slightly north of Baltimore Canyon. Depth scales are two-way travel time in seconds and depth in meters based on a sound velocity of 1,500 m/s. See figure 2 for profile location and figure 11 for line drawing interpretation. Vertical exaggeration is approximately 12 x.

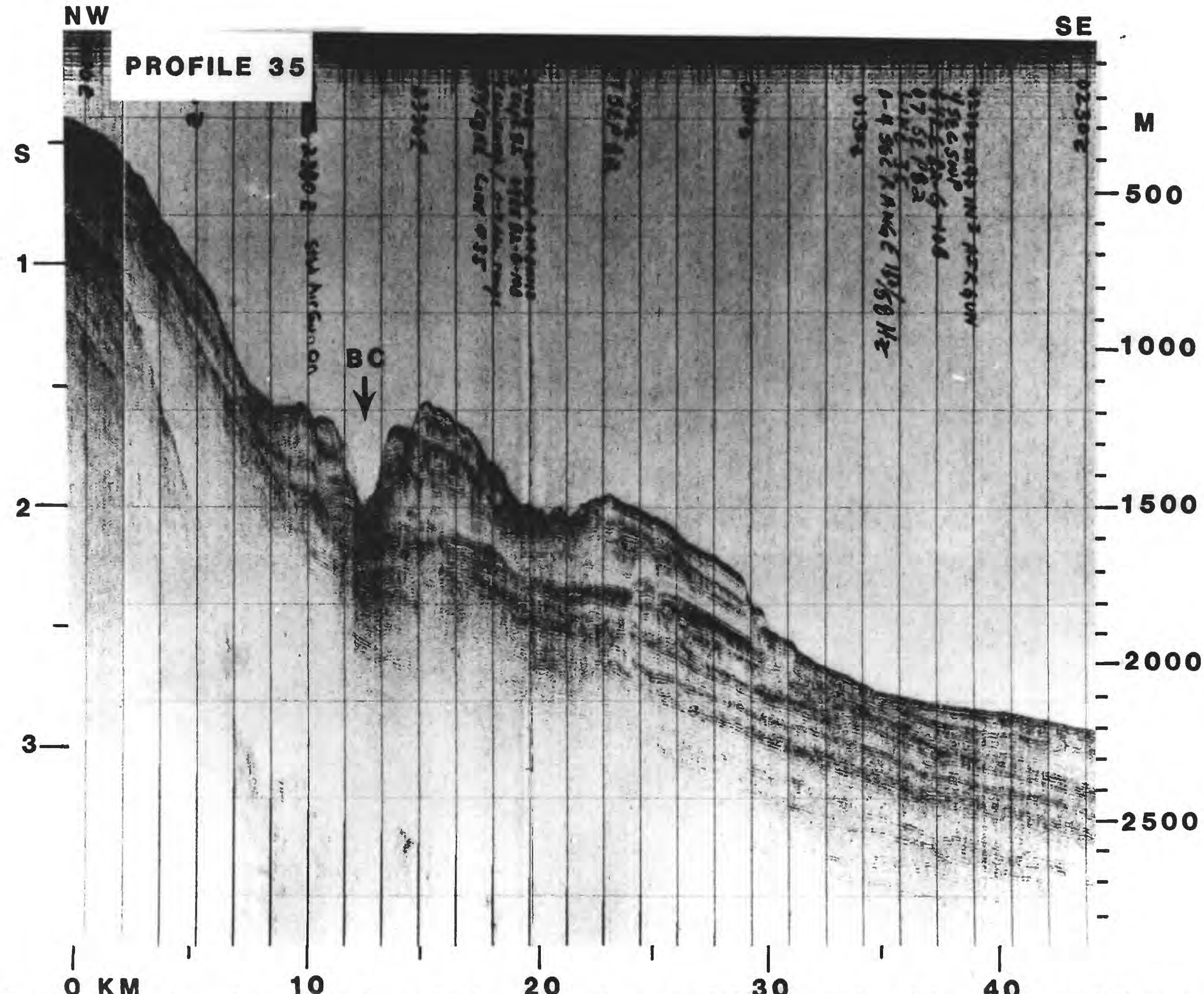


Figure 10. Photograph of original seismic-reflection profile record with the trackline oriented perpendicular to the continental margin crossing Baltimore Canyon on the lower slope. Depth scales are two-way travel time in seconds and depth in meters based on a sound velocity of 1,500 m/s. BC refers to the location of Baltimore Canyon. See figure 2 for profile location and figure 8-11 for line-drawing interpretation. Vertical exaggeration is approximately 12 x.

seaward and the rise has built up with onlapping of rise sediments onto the slope (figs. 9, 10, and 11; profiles 34 and 35).

Canyon survey north of Cape Hatteras

The strike-oriented profiles are shown as two separate figures because of the difference in vertical exaggeration caused by the influence of the Gulf Stream on ship's speed (figs. 12 and 13). This variability of the ship's speed over the bottom affords an opportunity to evaluate the influence that speed and vertical exaggeration have on the resolution and acoustic penetration of the seismic-reflection profiles. Subbottom reflectors are poorly recorded on the upper slope (figs. 12 and 14; profiles 1-4) and the midslope (figs. 12, 13, 15, and 16; profiles 6-13). This is not attributable to ship speed because even at slow speeds, subbottom returns are few (fig. 13, profile 11). However, the reflectors that are shown are truncated by the numerous valleys that dissect the slope. Throughout much of the area, a very strong, continuous reflector is present approximately 300 m beneath the sea floor (fig. 12; profiles 5-10); but on profiles 8-10 north of crossing profile 30 (figs. 12 and 13), this reflector drops down 200 m to the north and truncates underlying reflectors. The canyon that indents the shelf edge (fig. 3) deeply incises the upper and middle slope (fig. 12; profiles 1-8, canyon is adjacent to crossing profile 30), whereas on the lower slope and upper rise, the canyon decreases in size (figs. 12 and 13; profiles 11-24, canyon is located between crossing profiles 28 and 29). On the rise the canyon appears to have cut below the level of the adjacent rise.

The dip-oriented profiles (figs. 14, 17, 18, 19) show almost no subbottom acoustic penetration from the slope except in profile 30. Unconformities are numerous, especially on the rise where channeling appears to have occurred parallel to the strike of the Continental Slope (figs. 14, 17; profiles 26 and 27). In places reflectors can be traced seaward from the slope under the rise; sediment onlaps the base of the slope above these reflectors (figs. 14, 18, 19; profiles 28-32).

CONTINENTAL SLOPE AND RISE STRATIGRAPHY AND PROCESSES

Baltimore Canyon area

The lack of any deep rotary-drill cores from the slope or rise in the vicinity of Baltimore Canyon precludes an exact age designation for any of the reflectors shown here. The closest deep rotary-drill cores and seismic stratigraphy for the slope is located 120 km to the northeast just north of Lindenkohl Canyon (Robb and others, 1981). Although seismic-reflection profile data are available along the intervening slope between the Lindenkohl Canyon study area (Robb and others, 1981) and Baltimore Canyon, a major change in the depositional pattern at Wilmington Canyon greatly reduces the confidence of correlating reflecting horizons across the canyon (McGregor, 1982b). A rotary-drill core (Atlantic Slope Project (ASP) core 23) from the midslope adjacent to Washington Canyon, 85 km to the south of Baltimore Canyon, bottomed in and recovered 300 m of Pleistocene sediment (Poag, 1979). The Continental Slope at both Washington and Baltimore Canyons is quite wide (fig. 1). If the width of the slope reflects upbuilding and progradation of the slope as indicated on the seismic profiles (fig. 11), then possibly the contribution of Pleistocene material may be similar throughout

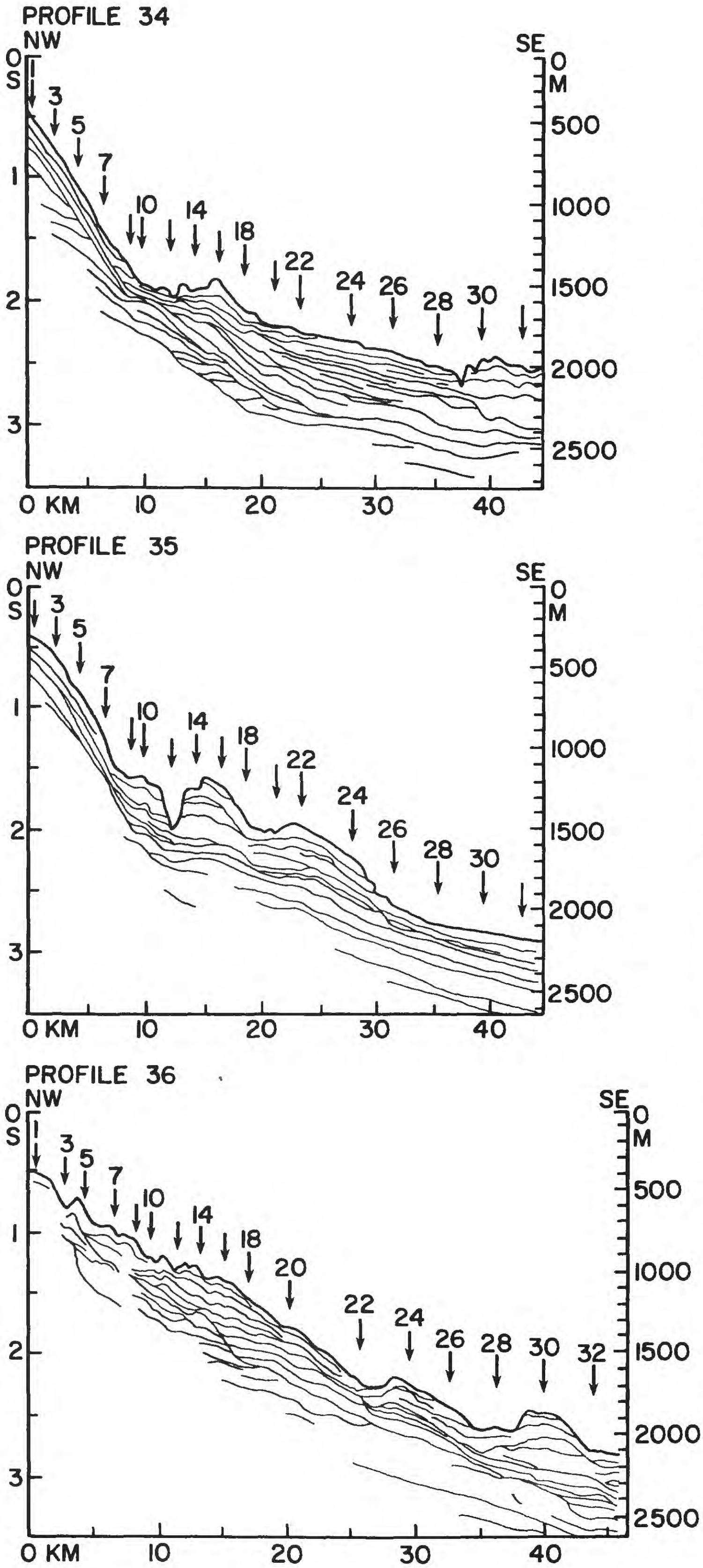


Figure 11. Line drawings of seismic-reflection profiles oriented perpendicular to the shelf edge in the Baltimore Canyon area. See figure 2 for profile location. Numbered arrows refer to the location of the crossing profiles shown in figures 4 and 5. Vertical exaggeration is approximately 15 x.

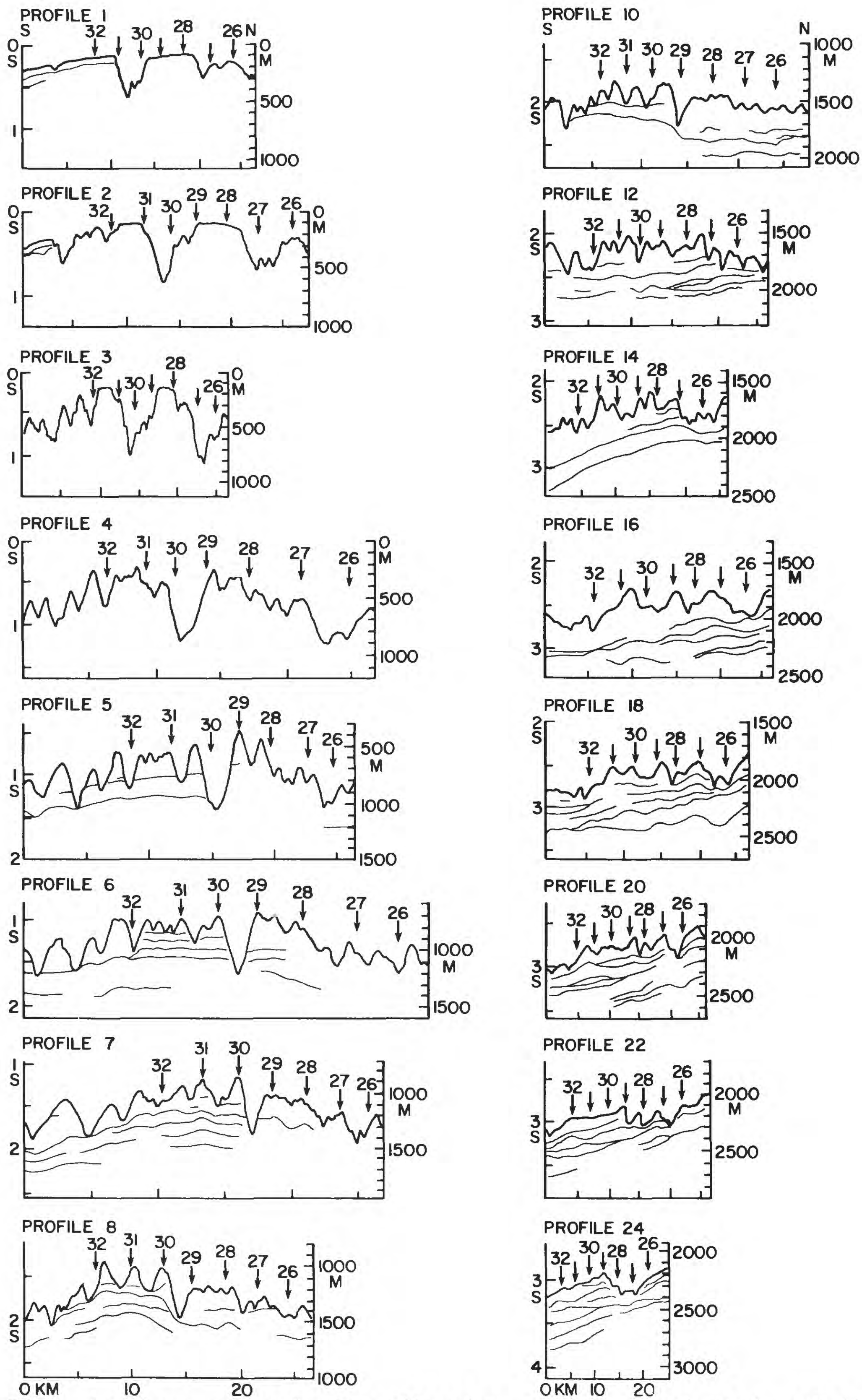
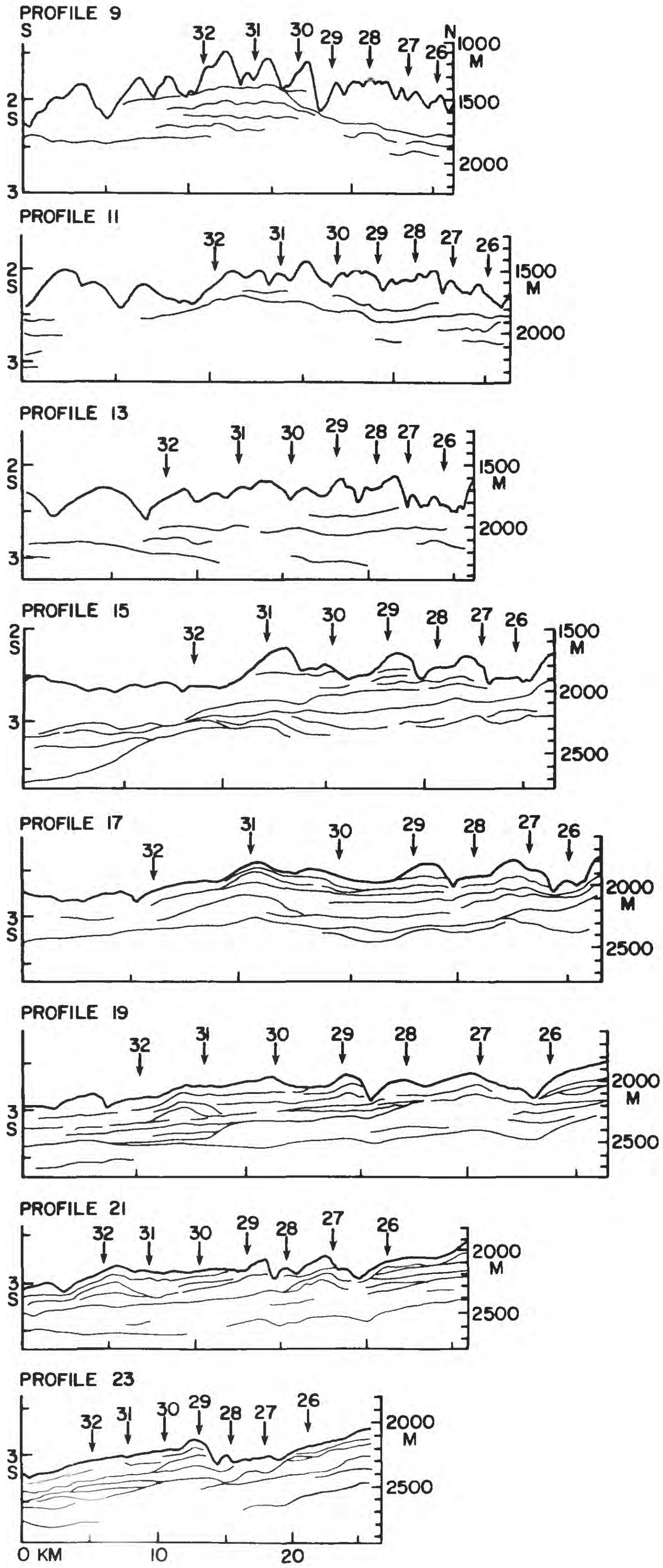


Figure 12. Line drawings of seismic-reflection profiles oriented parallel to the shelf edge just north of Cape Hatteras. See figure 3 for profile location. Numbered arrows refer to the location of crossing profiles. Vertical exaggeration varies because of the Gulf Stream influence between 8 x and 25 x.

Figure 13. Line drawings of seismic-reflection profiles oriented parallel to the shelf edge just north of Cape Hatteras. See figure 3 for profile location. Numbered arrows refer to the location of crossing profiles. Vertical exaggeration is approximately 7 x. These profiles were run against the Gulf Stream reducing the vertical exaggeration of the profiles.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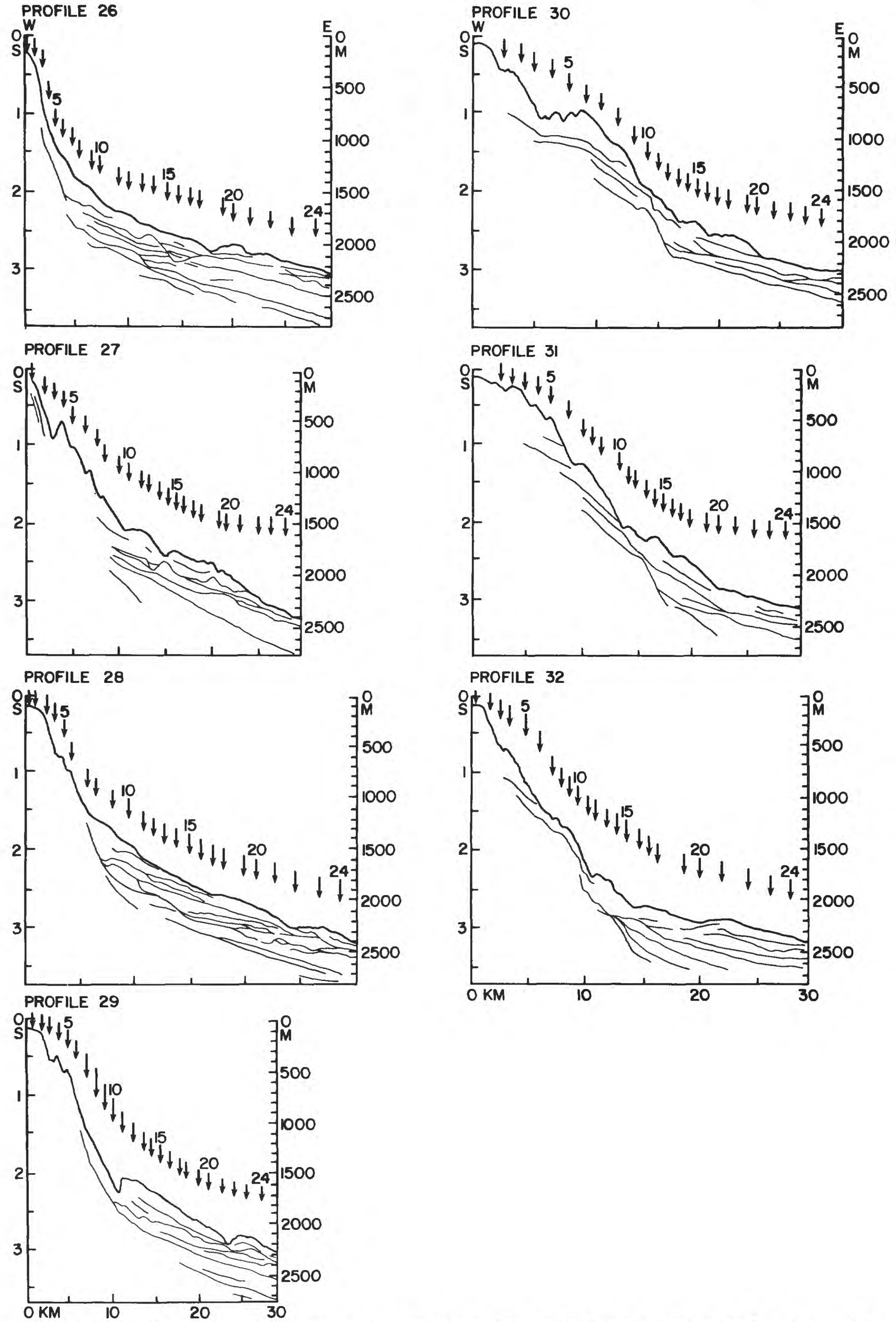


Figure 14. Line drawings of seismic-reflection profiles oriented perpendicular to the shelf edge in the survey area just north of Cape Hatteras. See figure 3 for profile location. Numbered arrows refer to the location of crossing profiles. Vertical exaggeration is approximately 10 x.

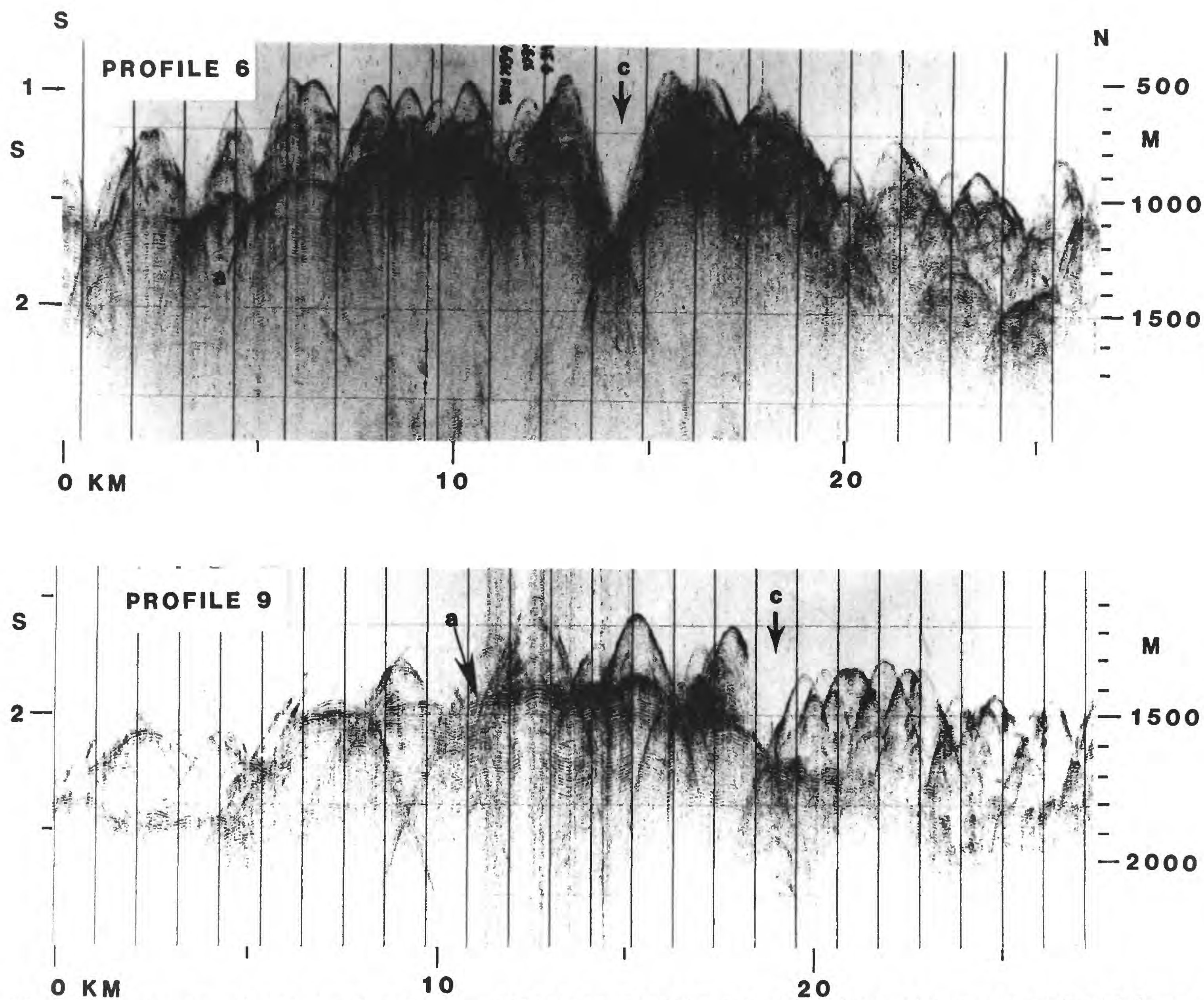
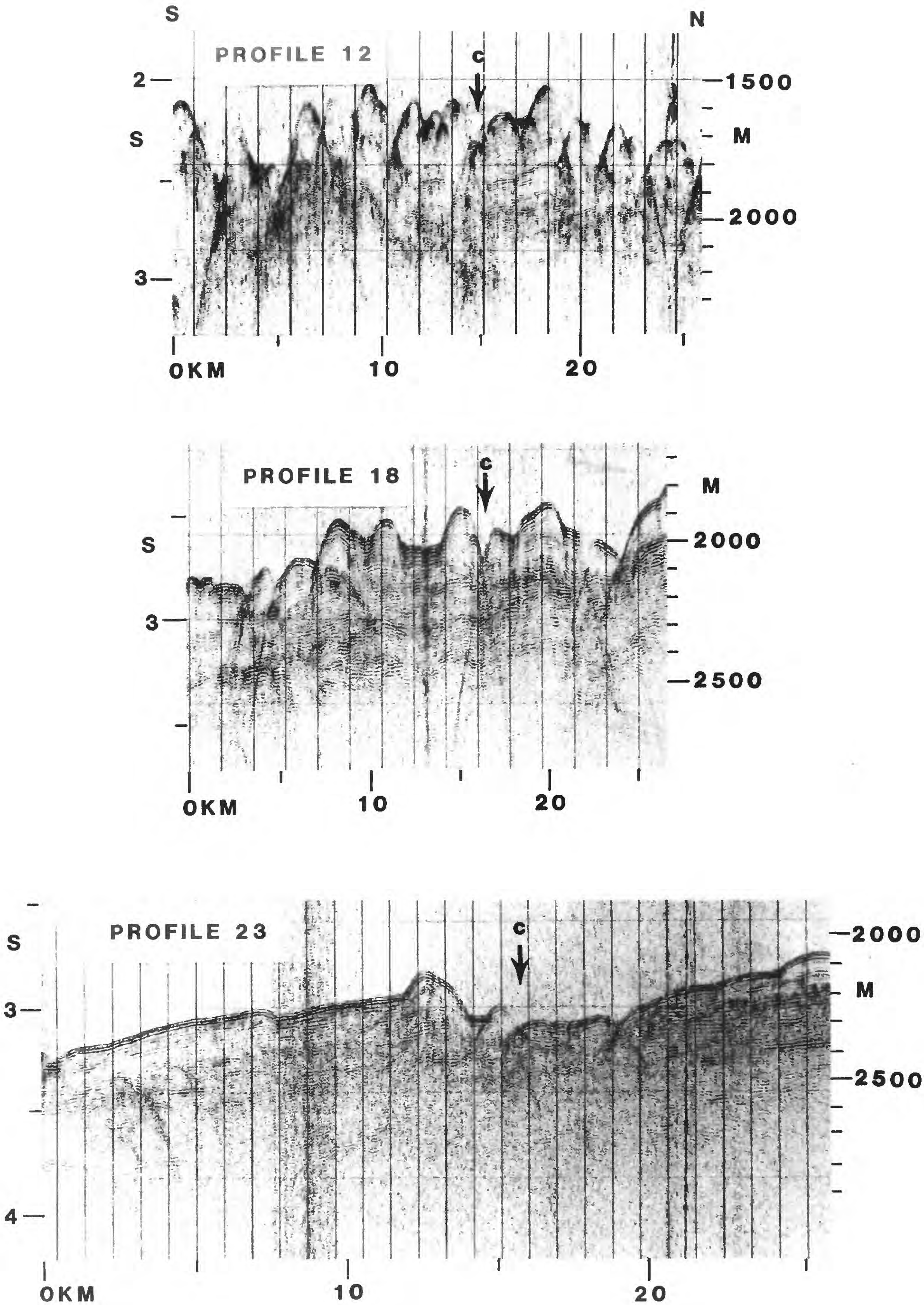


Figure 15. Photographs of original seismic-reflection profile records along the upper and midslope north of Cape Hatteras. Depth scales are two-way travel time in seconds and depth in meters based on a sound velocity of 1,500 m/s. "C" denotes the axis of the shelf indenting canyon in the study area and "a" is a strong acoustic reflector. See figure 3 for profile location and figures 12 and 13 for line-drawing interpretation. Vertical exaggeration is approximately 7 x.

Figure 16. Photographs of original seismic-reflection profile records along the lower slope and upper rise north Cape Hatteras. Depth scales are two-way travel time in seconds and depth in meters based on a sound velocity of 1,500 m/s. "C" denotes the axis of the shelf-indenting canyon in the study area. See figure 3 for profile location and figures 8-12 and 8-13 for line-drawing interpretation. Vertical exaggeration for profiles 12 and 18 is 14 x and for profile 23 is 10 x.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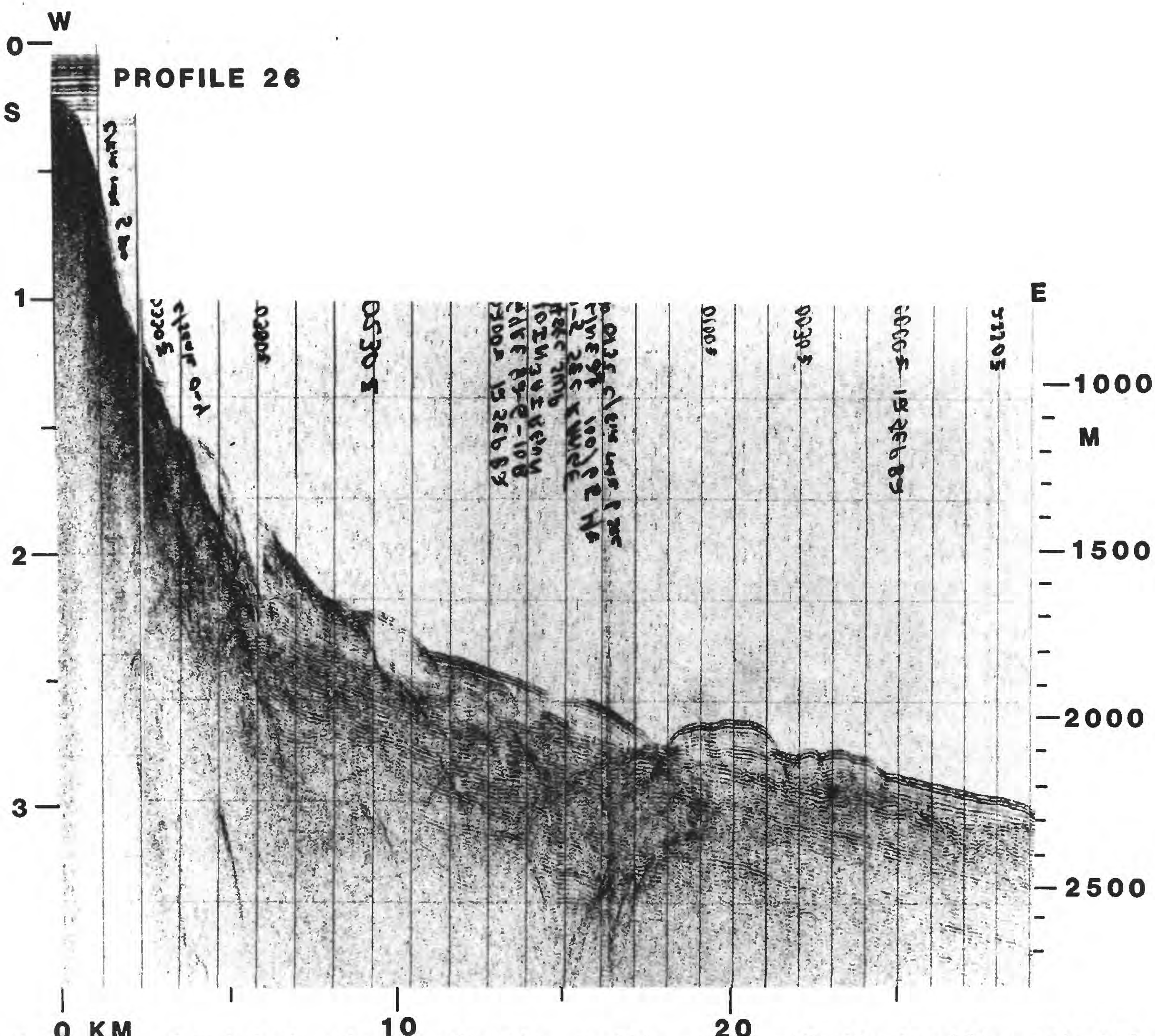

Figure 17. Photograph of original seismic-reflection profile record with the trackline oriented perpendicular to the margin north of Cape Hatteras. Depth scales are two-way travel time in seconds and depth in meters based on a sound velocity of 1,500 m/s. See figure 3 for profile location and figure 14 for line drawing interpretation. Vertical exaggeration is approximately 10 x.

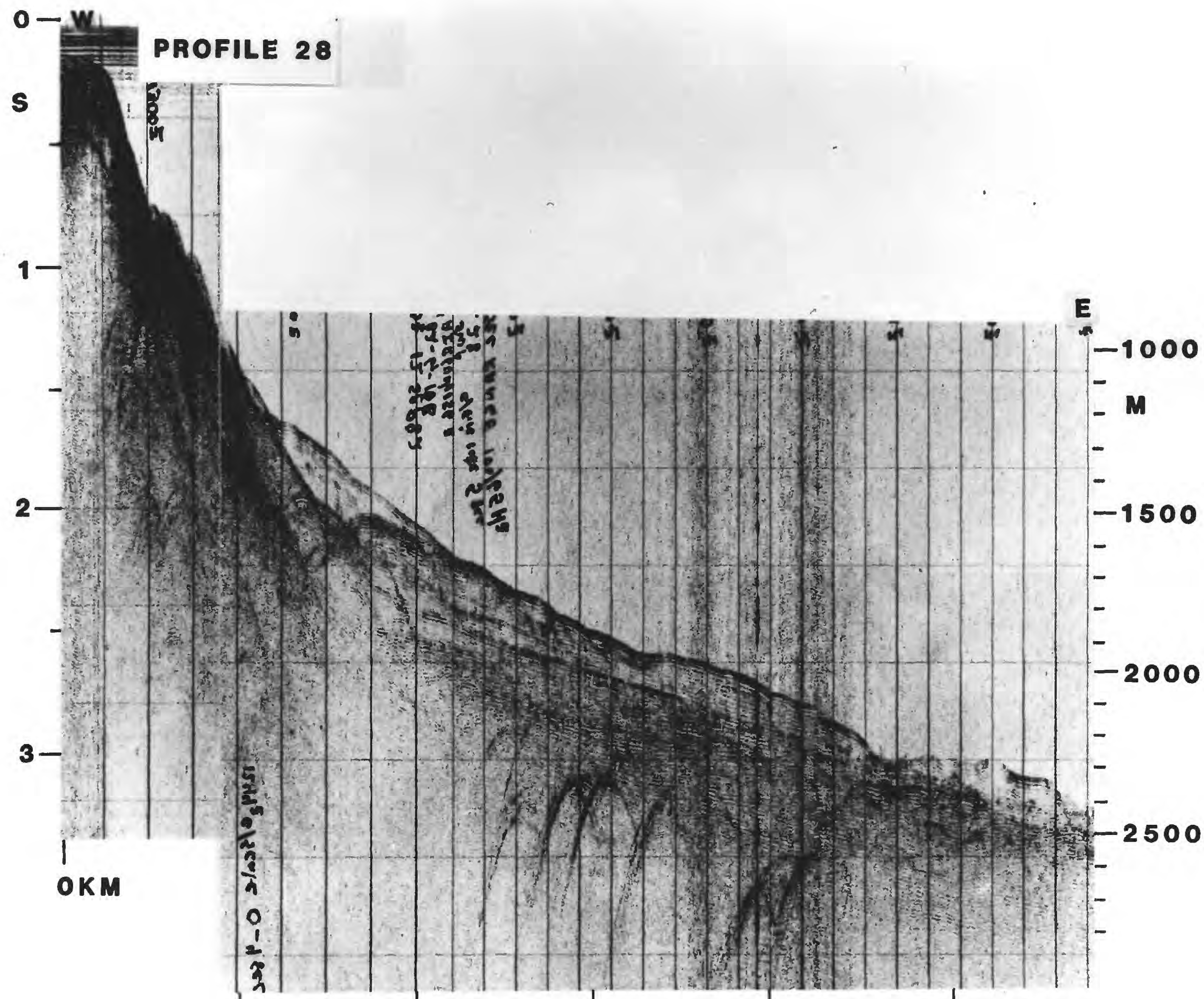

Figure 18. Photograph of original seismic-reflection profile record with the trackline oriented perpendicular to the margin north of Cape Hatteras. Depth scales are two-way travel time in seconds and depth in meters based on a sound velocity of 1,500 m/s. See figure 3 for profile location and figure 14 for line-drawing interpretation. Vertical exaggeration is approximately 10 x.

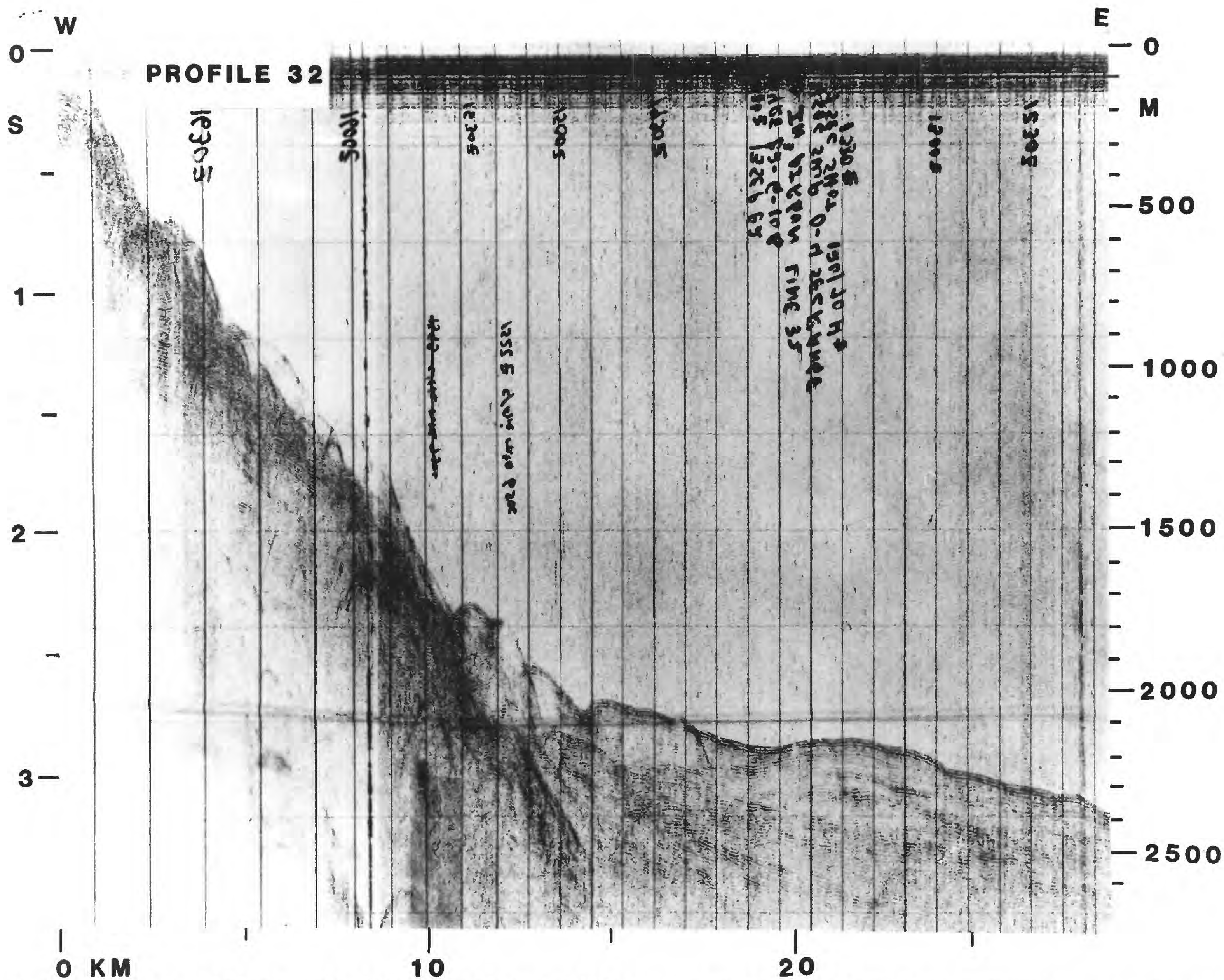

Figure 19. Photograph of original seismic-reflection profile record with the trackline oriented perpendicular to the margin north of Cape Hatteras. Depth scales are two-way travel time in seconds and depth in meters based on a sound velocity of 1,500 m/s. See figure 3 for profile location and figure 14 for line drawing interpretation. Vertical exaggeration is approximately 10 x.

the area. Because of the lack of stratigraphic data in the Baltimore Canyon area, the suggested ages of reflecting horizons will be correlated with the postulated ages from the literature. Baltimore Canyon is believed to have cut back into reflectors younger than approximately 25 my B.P. (Thompson and others, 1980). Much of the sequence of unconformable reflectors within and beneath the ridges (figs. 4, 5, and 11) may represent Pleistocene-age material. On the upper and middle slope, the continuous flat-lying reflecting horizons (fig. 4; profiles 1-9) probably represent mid-Tertiary to possibly Eocene-age material (Kelling and Stanley, 1970). This would suggest that the buried valley of Baltimore Canyon (fig. 4; profile 7) is probably early Pleistocene or Pliocene in age. The canyon itself, however, may well be older than Pleistocene, because Wilmington Canyon just to the north (fig. 1) is believed to be as old as late Miocene based on buried shelf valleys at its head (McGregor, 1981). Based on morphology, Kelling and Stanley (1970) also suggested that Baltimore Canyon was more mature than Wilmington Canyon and that Baltimore Canyon was cut in two periods: first in the late Tertiary and again in the Pleistocene. They characterized the canyon as a purely erosional feature. Several profiles suggest that Baltimore Canyon has not been exclusively erosional during its evolution but has had depositional periods, as indicated by the filled channel which the present canyon incises (e.g., figs. 4 and 6; profiles 5-9). On the upper rise, a buried channel and levee system is present slightly northeast of Baltimore Canyon (figs. 4, 5, 7, and 8, profiles 22, 24, and 26). This buried channel is twice as large as the present-day channel of Baltimore Canyon. Because of its size, it may represent an older channel of Baltimore Canyon, possibly of Pleistocene age when the canyon might have been transporting large volumes of sediment during lower stands of sea level, or it may correlate with the buried valley on the midslope (fig. 4; profile 7) and be as old as late Tertiary.

The origin of submarine canyons has long been debated as to whether they are continuations of land rivers and cut subaerially or are submarine features cut by turbidity currents (Shepard, 1981). Studies on the U.S. Mid-Atlantic continental margin suggest that they are submarine features with characteristics similar to subaerial rivers and occasionally associated with a river. Baltimore Canyon resembles a fluvial drainage system in that it has side gullies or tributaries some of which are hanging valleys, and a 500-m wide flat floor with a sinuous thalweg as it crosses the slope (Thompson and others, 1980). Wilmington Canyon was also found to have similarities to a fluvial system, including a meandering channel, undercutting of the side walls, and features resembling a point bar (McGregor and others, 1982; and Stubblefield and others, 1982).

The canyons in the vicinity of Wilmington and Baltimore Canyons are of two types: those that indent the shelf-edge (e.g., Wilmington and Baltimore), and those that begin on the upper slope seaward of the shelf edge. This difference in the canyons is suggested to represent differences in maturity or age of the canyons with the shelf-indenting canyons being older (McGregor and others, 1982; and Farre and others, 1983). Both Baltimore and Wilmington Canyon have channel gradients on the slope of approximately 2^{o} whereas the axial gradients of adjacent canyons that begin seaward of the shelf edge are approximately 6^{o}. On the midslope all canyons are cut to about the same depth (fig. 4; profiles 9 and 10), suggesting that differences in the axial gradients are due to the canyons cutting to grade similar to subaerial rivers (Schumm, 1977). Scarps around the canyon heads observed on mid-range sidescan sonographs (McGregor and others, 1982) suggest that headward erosion may be an important process in canyon evolution.

On the lower slope, the large ridge flanking Baltimore Canyon on the southwest is progressively dissected by a valley beginning with profile 20 (between crossing profiles 35 and 36) and continuing seaward (figs. 2, 4, 5, and 8). Because this valley heads at a water depth of approximately 1,500 m, its origin must be submarine. Sediment instability resulting from rapid deposition on the southern levee of Baltimore Canyon may have caused sediment failure by slumping or mass wasting forming a gully or small valley which, by headward erosion, has progressively cut into the levee. The gully system on the walls of the canyons, where the sea-floor gradients are large, is attributed to similar mass-wasting processes (McGregor and others, 1982).

As mentioned previously, Baltimore Canyon has a major deflection in its trend direction on the lower slope, shifting from a southeasterly trend straight down the slope to due east on the lower slope and upper rise. Wilmington Canyon displays a similar change in trend direction, however, all the other canyons in the vicinity have a straight southeasterly trend down the slope and upper rise. The deflection of Wilmington Canyon to the east is interpreted to be caused by a large slump block on the rise (McGregor and Bennett, 1981; and Stubblefield and others, 1982). The ridge flanking Baltimore Canyon on the southwest is morphologically similar to that at Wilmington Canyon, but the seismic-reflection profiles indicate that it is a depositional feature related to Baltimore Canyon (figs. 4, 5, 7, and 8). Therefore this ridge origin does not account for the major deflection in canyon trend. Pratt (1967) suggests that seven of the large east coast submarine canyons are deflected to the left at the top of the rise and have a higher right bank in response to the Coriolis force. The fact that all canyons (fig. 2) do not exhibit deflections would seem to argue against a uniform force like Coriolis controlling channel trend.

Study area north of Cape Hatteras

The stratigraphy of the shelf and slope in the South Atlantic region is somewhat better defined than in the Mid-Atlantic. The narrowness of the Continental Shelf allows wells at Cape Hatteras to be used in conjunction with rotary-drill core data from the Atlantic Slope Project (ASP) cores 7 and 8 (Poag, 1979). Pliocene-age strata were recovered in ASP 7 on the upper slope just south of the survey area (Poag, 1979). The age of reflector "a" (fig. 15; profile 9) could be Miocene or Pliocene in age (P. Popenoe, pers. comm., 1983). A strong acoustic reflector of Eocene age may also crop out on the mid to lower slope (King and Costain, 1982). Reflectors that intersect or closely approach the sea floor at a two-way travel time of 2 seconds on profiles 30, 31, and 32 (fig. 14) may be of Eocene age.

The strong acoustic reflector "a" (fig. 15; profile 9) steps down 200 m just north of the axis of the shelf-indenting canyon, "c". This horizon is present on dip profiles 26, 28, and 29 (figs. 14, 17, and 18) and could easily be interpreted as a side reflector from adjacent topography were it not for the strike-oriented profiles. This surface appears to be erosional; it may have been cut during a Miocene or Pliocene sea-level lowstand (Vail and others, 1977).

The slope just north of Cape Hatteras is highly dissected (figs. 15 and 16). The numerous hyperbolic echoes on the upper to midslope with poor subbottom acoustic penetration and morphology definition make the seismic-reflection profiles difficult to interpret. A blanket of surficial sand can inhibit subbottom penetration and with the ocean current regime active in the Cape Hatteras area, shelf sand spillover might be expected (Stanley and others, 1972, 1981). Six-meter-long piston cores on the slope in the region, however, show sand layers are present at depth in the cores, but no anomalous thickness of surficial sand is present (Doyle and others, 1979). The reduced resolution of the seismic-reflection profiles on the upper slope, therefore, is probably due to steepness of the slope and the degree of dissection (figs. 12 and 14). Reflecting horizons on strike-oriented profiles have less relief than do those in the Baltimore Canyon area (figs. 12, 13, 15, and 16). Although the hyperbolic echoes from the ridges between the canyons prevent the resolution of the shallow internal reflectors within the upper 200 m of the ridges, the reflecting horizons do not appear to be related to depositional processes directly associated with the canyons. In this area the canyons are dominated by erosional processes. Popenoe and others (1982) suggest that the canyons in the region are a product of mass wasting and slumping. The canyons are cut in Pleistocene sediment and expose older strata in their axes (Popenoe and others, 1982). Older material is exposed not only in the canyon axes, but in the canyon walls as well (fig. 15, profiles 5 and 9).

The rise sediments which lap onto the base of the slope (figs. 17, 18, and 19) may be primarily composed of material eroded from the slope by mass wasting or, as suggested by Betzer and others (1974), material deposited from the nepheloid-laden Western Boundary Undercurrent. Also some sediment is probably contributed by the canyons via turbidity currents and overbank deposition (figs. 13 and 16; profiles 19-23). Stratified units which thin and slope away from the canyon axis are believed deposited by overbank deposition. Although sediment has been removed from the slope by mass wasting and slumping (Popenoe and others, 1982), no large blocks of material are obvious on the rise profiles (figs. 13, 16, 17, and 18). Compared to the rise in the Baltimore Canyon area, the rise just north of Cape Hatteras has a very subdued relief. This may be due to the influence of ocean currents, i.e., either the Gulf Stream or the Western Boundary Undercurrent redistributing the sediments (Betzer and others, 1974; Richardson and Knauss, 1971). Some evidence of channeling is present buried within the rise (figs. 14, 17, 18, and 19). This channeling is observed on the dip-oriented profiles, indicating flow is along the bathymetric contours parallel to the margin and suggesting that the Western Boundary Undercurrent or the Gulf Stream, if it extends to the sea floor as Richardson and Knauss (1971) report, is responsible for the erosion. During the past, deep ocean circulation also may have been more active than today.

SUMMARY

The U.S. Mid- and South Atlantic Continental Slope and Rise are dissected by numerous submarine canyons. The dominant slope process appears to be different in the two regions, which may be related to the difference in width and general sea-floor gradient of the Continental Slope. In the Baltimore Canyon area in the U.S. Mid-Atlantic region, the subbottom reflectors suggest that they formed by deposition associated with the canyon. The width of the

slope and gentle gradient reflect the region where the slope and rise have been prograded and built up. Baltimore Canyon has had both a depositional and erosional history. In the study area north of Cape Hatteras in the U.S. South Atlantic region, the canyons are erosional features and mass wasting is the dominant erosional process. The Continental Slope in this area is narrow and the general sea-floor gradient is steeper.

Determining the age of the canyons relies on stratigraphic control from a limited number of rotary-drill cores on the slope and rise which are not contiguous to the study areas. Although an exact age could not be determined for the canyon, a buried valley indicates that Baltimore Canyon may be as old as late Tertiary. The canyon that indents the shelf edge just north of Cape Hatteras is suggested to have originated in the late Pleistocene (Popenoe and others, 1982). Although subbottom reflectors show that the slope just north of Cape Hatteras underwent a late-Tertiary period of erosion, buried valleys coincident with the present-day canyons are not reflected in this surface.

These two survey areas were used to test the observation made in the Wilmington Canyon area that canyons which indent the shelf edge have a lower axial gradient and may be more mature than the canyons which do not indent the shelf edge. Baltimore Canyon and Wilmington Canyon have eroded back into the shelf edge a comparable distance and both have a similar 2^{o}-axial gradient compared to 6^{o} for the adjacent canyons that begin on the upper slope seaward of the shelf edge. The shelf-indenting canyon north of Cape Hatteras has only begun to cut back into the shelf edge and has a steeper gradient of 7^{o}, but still 2^{o} less than that of the adjacent canyons that begin on the upper slope. All canyons, regardless of where they head, have cut to the same depth on the midslope, suggesting that the decrease in axial gradient may reflect differences in maturity. The shelf-indenting canyons may have been cut to grade similar to a fluvial system.

Although the rise morphology adjacent to Baltimore Canyon is similar to that at Wilmington Canyon, it appears to have a different origin. Wilmington Canyon is believed to be flanked by a large slump block, whereas the ridge flanking Baltimore Canyon is related to depositional and erosional processes of the canyon. Mass wasting has, however, modified the ridge.

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