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GEOLOGICAL SURVEY

A REGIONAL ASSESSMENT OF POTENTIAL ENVIRONMENTAL HAZARDS TO AND LIMITATIONS ON PETROLEUM DEVELOPMENT OF THE SOUTHEASTERN UNITED STATES ATLANTIC CONTINENTAL SHELF, SLOPE, AND RISE, OFFSHORE NORTH CAROLINA

by

Peter Popenoe, E. L. Coward, and K. V. Cashman

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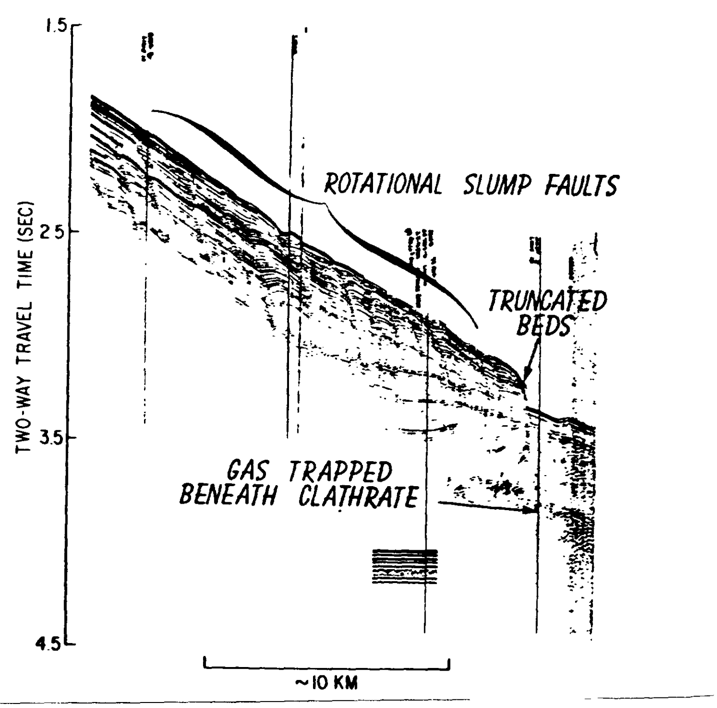

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A REGIONAL ASSESSMENT OF POTENTIAL ENVIRONMENTAL HAZARDS TO AND LIMITATIONS ON PETROLEUM DEVELOPMENT OF THE SOUTHEASTERN UNITED STATES ATLANTIC CONTINENTAL SHELF, SLOPE, AND RISE, OFFSHORE NORTH CAROLINA

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ABSTRACT

More than 11,000 km of high-resolution seismic-reflection data, 325 km of mid-range sidescan-sonar data, and 500 km of long-range sidescan-sonar data were examined and used to construct an environmental geology map of the Continental Shelf, Slope, and Rise for the area of the U.S. Atlantic margin between lats. 32°N. and 37°N. Hardgrounds and two faults described in previous literature also are shown on the map.

On the Continental Shelf, at least two faults, the Helena Banks fault and the White Oak lineament, appear to be tectonic in origin. However, a lack of historical seismicity associated with these faults indicates that they are probably not active at the present time. Hardgrounds are widely scattered but are most abundant in Onslow Bay. Although paleostream channels are common nearshore, they do not appear to be common on the central and outer shelf except off Albemarle Sound where extensive Pleistocene, Pliocene, and late Miocene channels extend across the shelf. Mobile bottom sediments are confined mainly to the shoals off Cape Romain, Cape Fear, Cape Lookout, and Cape Hatteras. Elsewhere the sand cover is thin, and older more indurated rocks are present in subcrop.

No slope-instability features were noted on the Florida-Hatteras slope off North Carolina. The lack of features indicates that this slope is relatively stable.

Evidence for scour by strong currents is ubiquitous on the northern Blake Plateau although deep-water reefs are sparse. The outer edge of the plateau is dominated by a major growth fault and numerous splay and antithetic faults. These faults are the product of salt tectonism in the Carolina trough and thus are not associated with seismicity. Displacements observed near the sea floor and breached diapirs offshore indicate that the main fault is still moving. Associated with the faults are collapse features that are interpreted to be caused by karst solution and cavernous porosity in Eocene and Oligocene limestones at depth.

Major slumps have taken place in two large areas of the Continental Slope. Seismic-reflection profiles of the southern area, centered on the lower slope at lat. 33°N., long. 76°W., show a 80-m-high scarp in which bedding has been truncated. Rotational slump faults are present in this area on the middle and upper slope. Sidescan images show that large blocks have slid downslope from the scarp face, furrowing the bottom. High-resolution (3.5-kHz) records show that the rotational slump faults upslope are active. The association of these slumps and the scarps with salt diapirs suggests subsidence accompanying salt tectonism as the cause. Seismic-reflection records over the northern area, at about lat. 36°20′N., long. 74°40′W., show two steep scarps, each about 225 m high on

the upper and middle-slope. These slump scars and an absence of Pleistocene sediments indicate that large blocks of the slope have been removed by slumping.

The slope north of lat. 35°N. is highly dissected by canyons. Mid-range sidescan-sonar records suggest that the canyons are the product of mass wasting and have probably formed largely by slumping.

Sediments in a wide zone on the upper rise are highly disturbed and faulted owing to salt tectonism. Twenty-six salt diapirs are mapped, as is a zone of disturbed bottom related to salt tectonism.

An area of frozen bottom (clathrate) under which shallow free gas is trapped underlies the outer Blake Plateau, the slope, and the upper rise. Although the hazards of drilling into or through clathrates have not been tested, the release of gas from beneath this frozen layer may prove to be a primary hazard to exploration.

INTRODUCTION

An environmental geologic map depicting features that may be potential geologic hazards and limitations to petroleum development of the Continental Shelf, Slope, and Rise off North Carolina (pl. 1) was constructed from regional high-resolution seismic-reflection profiles and from long-range and medium-range sidescan-sonar images gathered during FY (fiscal year) 1976 to 1980 by the U.S. Geological Survey (USGS) as part of the USGS-U.S. Bureau of Land Management (BLM) Environmental Assessment Program. Figure 1 shows the distribution and spacing of track lines along which data used in the construction of the map were collected. Hardgrounds and two faults, the Helena Banks fault (Behrendt and others, 1981) and the White Oak lineament (Snyder and others, 1981), described in previous literature have been added to the map. Although the average spacing of track lines used in the construction of the environmental map is approximately 10 km, we have mapped large linear features such as the shelf-edge reef and the growth fault at the edge of the Blake Plateau between lines on the basis of bathymetry from 1:250,000 scale NOS (U.S. National Ocean Survey) topographic-bathymetric sheets (Currituck Sound, NJ 18-11; Manteo, NI 18-2; Russell, NI 18-5; Beaufort, NI 18-4; Cape Fear, NI 18-7; Georgetown, NI 17-9; and James Island, NI 17-12 quadrangles) and of projection. Mapped features are discussed by area of occurrence, such as shelf, slope, and rise (fig. 2), and topic, such as faults, slope instability, etc. Because general drilling difficulties or environmental limitations on exploration or production likely to be associated with many of these features have been reviewed thoroughly by Ball and others (1980), McCarthy and others (1980), Carpenter (1981), and Popenoe and others (1981b), they will not be discussed here. Field methods and instruments and processing of high-resolution seismic-reflection data do not differ from those reported by Ball and others (1980) or Pinet and others (1981b). Field methods for the sidescan-sonar surveys were discussed by Somers and others (1978), Popenoe and others (1981b), and Teleki and others (1981).

Figure 1. Location map of track lines along which seismic (narrow solid line) and sidescan-sonar (heavy striped line) data used in the construction of the environmental geology map (pl. 1) were collected. Also shown as heavy track lines are the locations of figures discussed in the text. Track lines are labeled by cruise and line number. Dotted lines show bathymetry.

F = R.V. FAY, legs 17 and 18, 1976

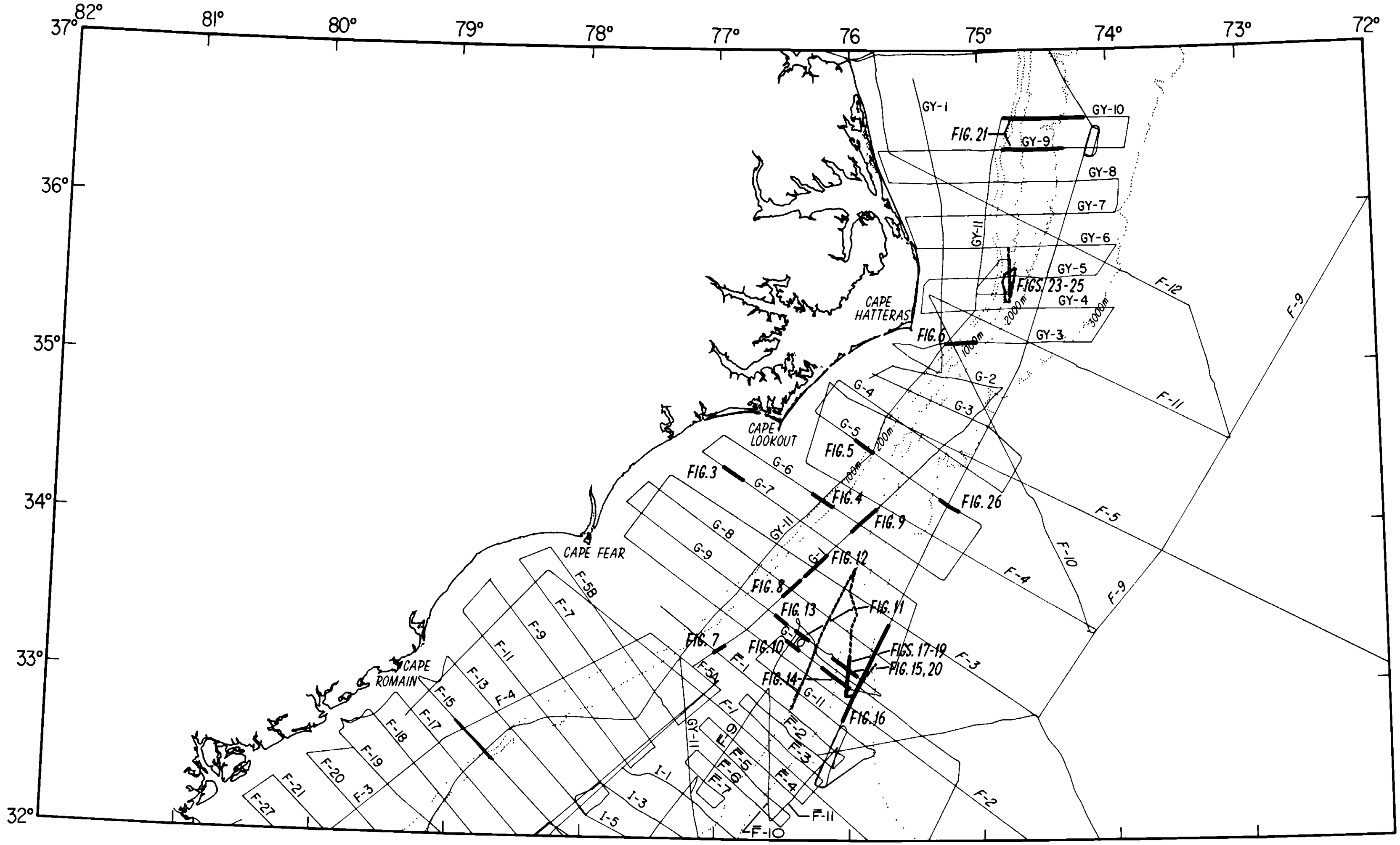
F = R.V. FAY, leg 19, 1976

$\overline{F}$ = R.V. FAY, leg 25, 1976

I = R.V. ISELIN, leg 3, 1978

G = R.V. GILLISS, leg 6, 1979

GY = R.V. GYRE, leg 9, 1980.

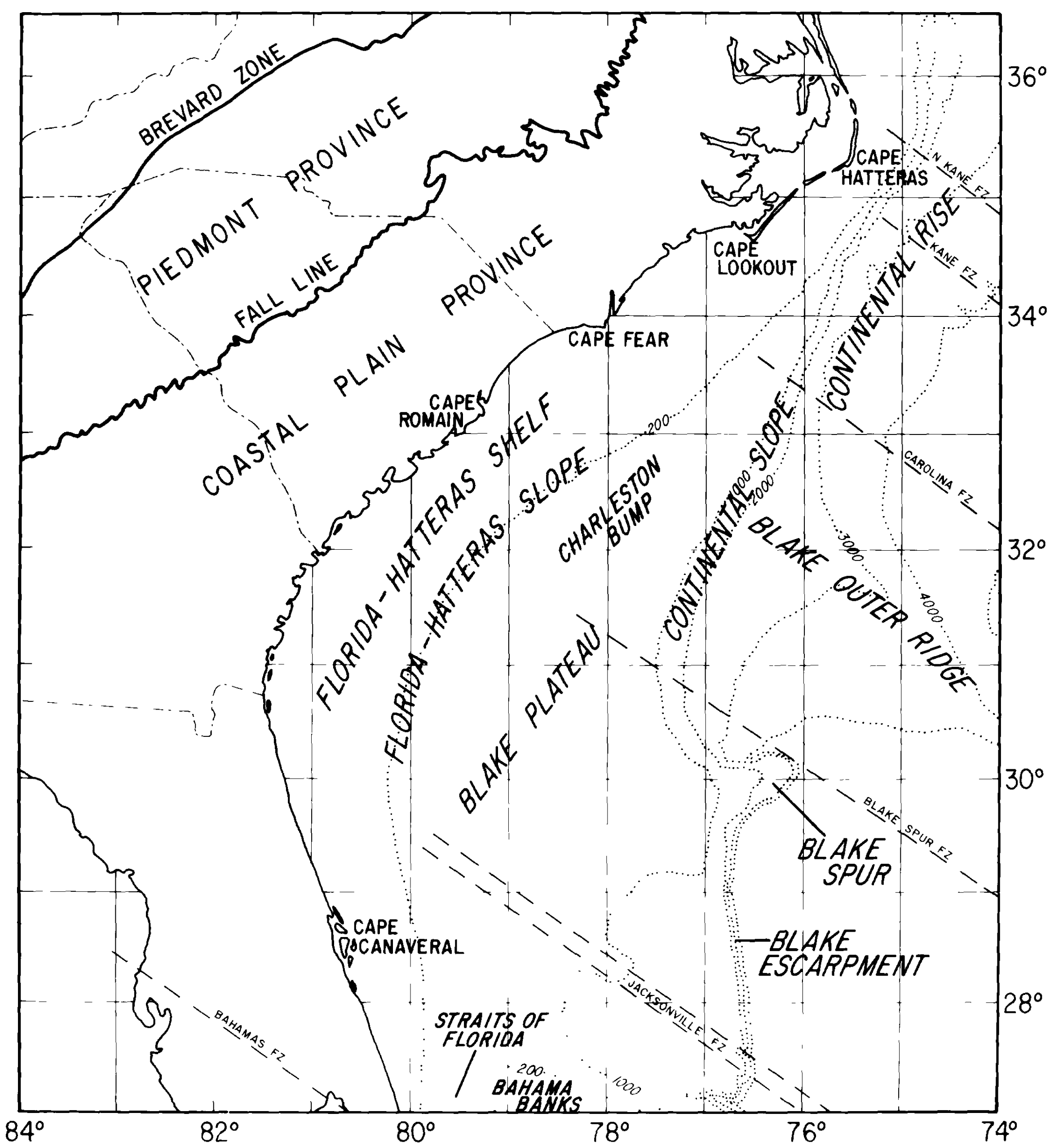


37°
36°
35°
34°
33°
32°
82°
81°
80°
79°
78°
77°
76
75°
74°
73°
72°
CAPE HATTERAS
CAPE LOOKOUT
CAPE FEAR
CAPE ROMAIN
GY-1
GY-3
GY-4
GY-5
GY-6
GY-7
GY-8
GY-9
GY-10
GY-11
FIG. 21
FIGS. 23-25
FIG. 6
FIG. 5
FIG. 3
FIG. 4
FIG. 9
FIG. 26
FIG. 12
FIG. 8
FIG. 13
FIG. 11
FIG. 7
FIG. 10
FIGS. 17-19
FIG. 15, 20
FIG. 14
FIG. 16
100m
200m
2000m
3000m
G-1
G-2
G-3
G-4
G-5
G-6
G-7
G-8
G-9
G-10
G-11
F-1
F-2
F-3
F-4
F-5
F-5A
F-5B
F-6
F-7
F-9
F-10
F-11
F-12
F-13
F-15
F-17
F-18
F-19
F-20
F-21
F-27
I-1
I-3
I-5

Figure 1

Figure 2. Physiographic features of the southeastern U.S. margin. FZ, major oceanic fracture zone.

PHYSIOGRAPHY OF THE SOUTHEASTERN MARGIN



CONTINENTAL SHELF

The Continental Shelf south of Cape Hatteras consists of both the Florida-Hatteras shelf and the northern part of the Blake Plateau. North of Cape Hatteras, the Continental Shelf is a flat, essentially uniform surface. The boundary between the Florida-Hatteras shelf and Blake Plateau is physiographic, not structural. The Florida-Hatteras shelf off North Carolina consists of a thickened depositional wedge of sediments, chiefly of Neogene and Pleistocene age, that have prograded out to the Gulf Stream, which has prevented further advance.

FLORIDA-HATTERAS SHELF

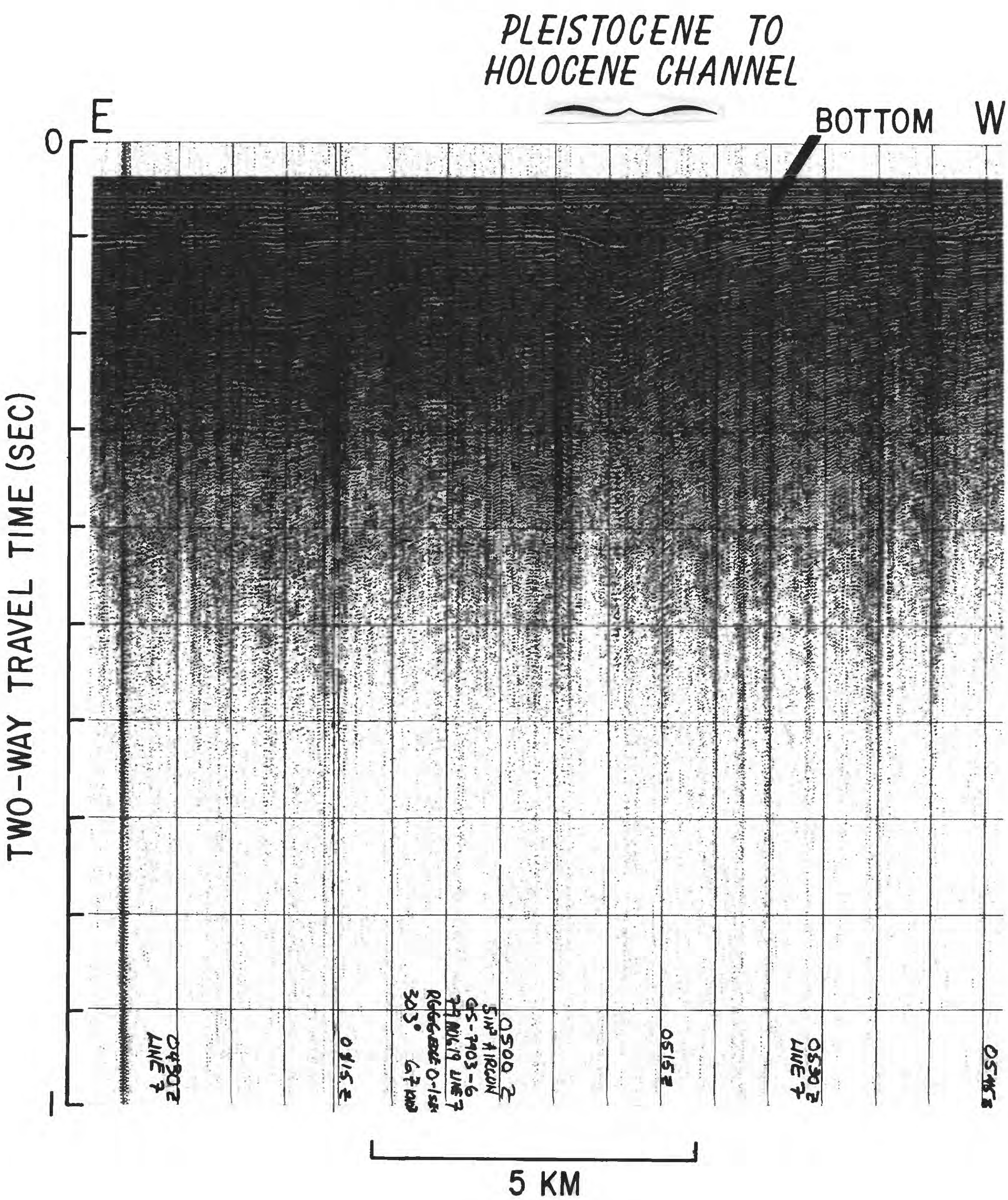
Sediment Cover

The surficial cover of the Florida-Hatteras shelf off North Carolina is composed dominantly of sand that forms a thin veneer (generally 2 m or less) over older sedimentary rocks. Small patches of mud occur south of Cape Lookout and Cape Hatteras (Pilkey and others, 1980). The sand cover is well sorted and reworked by both currents and benthic infauna. It does not appear to move significantly during storms except near Cape Hatteras, Cape Romain, Cape Fear, and Cape Lookout, where large sand-wave fields are present (pl. 1). The sand-wave fields offshore of the capes shown on plate 1 are based on published shelf bathymetry and are diagramatic by intent, as we were not able to survey in the nearshore shoal areas with the large research ships that were required for the outer shelf. In Onslow and Long Bays, the thickness of the sand cover from the shore to 26 km offshore has been studied by Meisburger (1977), who recorded as much as 13 m of coarse quartzose sand in Frying Pan shoal. Otherwise, little is known of the thickness of the sand sheet in the shoal areas.

Lagoonal mud and peat, stream-channel fillings, and some cut-and-fill structures occur on the shelf, but they are patchy and scattered (Meisburger, 1979; McCarthy and others, 1980; Henry and others, 1981; Pilkey and others, 1981). In the nearshore zone, many large channels having as much as 33 m of relief extend offshore between Cape Lookout and the South Carolina border (Meisburger, 1977, 1979); however, our regional data further offshore showed that large stream channels appear to be widely scattered. This apparent sparseness may be due, in part, to the width of the bubble pulse in our airgun data, which obscures the upper 10 m of the record, so that small channels are difficult to detect, and also to the orientation and spacing of our track lines which were oriented chiefly in a cross shelf direction. Only scattered channels were noted in our 3.5-kHz records, and only a few large channels are shown on plate 1 south of Cape Hatteras. These channels are depicted as circular, as our data spacing did not allow us to trace them along strike. An example of a large channel is shown in figure 3. North of Cape Hatteras, a very large fluvial channel (>10 km) filled by lenticular bedded sediment crosses the shelf off Albemarle Sound. Nearshore this channel is filled by Pleistocene sediments (Shideler and Swift, 1972). It overlies a series of larger and deeper channels of Pliocene and late Miocene age. Because of the widespread and repeated channeling in the area off Albemarle Sound, the load-bearing properties of near-surface sediments could vary widely within short distances.

Figure 3. Seismic-reflection record showing a large buried channel of probable fluvial origin on the inner Florida-Hatteras shelf at lat. 34°20′N., long. 76°53′W. in Onslow Bay. The channel has a width of several kilometers and a depth of about 50 m. The channel is cut into a hard Miocene substrate, and reverberations from the substrate make the channel appear deeper than it is. The identification of near-surface material as Pleistocene to Holocene is speculative.

GILLISS LINE 7



Older sedimentary rocks of Pleistocene to Cretaceous age underlie the sand veneer of the shelf. The oldest sediments are exposed in Long Bay, where Upper Cretaceous fine to very fine muddy quartzose sand forms the subcrop nearshore (Meisburger, 1979). These muddy sediments are overlain in the offshore by Paleocene quartz sands, Eocene calcareous silts and sands, Oligocene sand and calcareous rock, and a wide band of Miocene and Pliocene deposits composed of silty sands, phosphatic sands and clays, and shell hash of the "Silverdale beds" and the Pungo River and Yorktown Formations (Meisburger, 1979; Snyder and others, 1981). These sedimentary units form bands that onlap in the offshore direction and strike approximately N.25°E. across the shelf following the general underlying structure of the Carolina trough (Dillon and others, 1981). The strike, however, is locally modified by buried topography and by paleodelta systems. Pleistocene rocks are confined chiefly to a thin veneer in scattered areas on the shelf and a thick wedge near the shelf edge and on the Blake Plateau. Pleistocene-age sediments generally increase in thickness north of Cape Hatteras and become more than 400 m thick near the shelf edge off the North Carolina-Virginia border.

Marine habitats and live bottoms

Rock outcrops on the North Carolina shelf of more than several meters relief were not noted in our data except near the shelf edge. Moderate-relief and low-relief (1-3 m) hardgrounds on the inner shelf, particularly in Onslow Bay, have been studied and mapped by Huntsman and Macintyre (1971), Newton and others (1971), and Continental Shelf Associates (1979) and are shown on plate 1.

The shelf-edge reef off North Carolina has been studied by Menzies and others (1966), Zarudski and Uchupi (1968), Macintyre and Milliman (1970), and Continental Shelf Associates (1979). Our definition of the shelf-edge reef (pl. 1) is based on identification from our high-resolution seismic survey lines (fig. 1) and on extension between our seismic lines utilizing bathymetry from the Beaufort, Cape Fear, Manteo, and Russell 1:250,000 series topographic-bathymetric quadrangle sheets and data from McCarthy and others (1980) and Carpenter (1981) within nominated lease block areas for OCS (Outer Continental Shelf) Sales 43 and 56. Examples of reef crossings in our seismic data are shown in figures 4, 5, and 6.

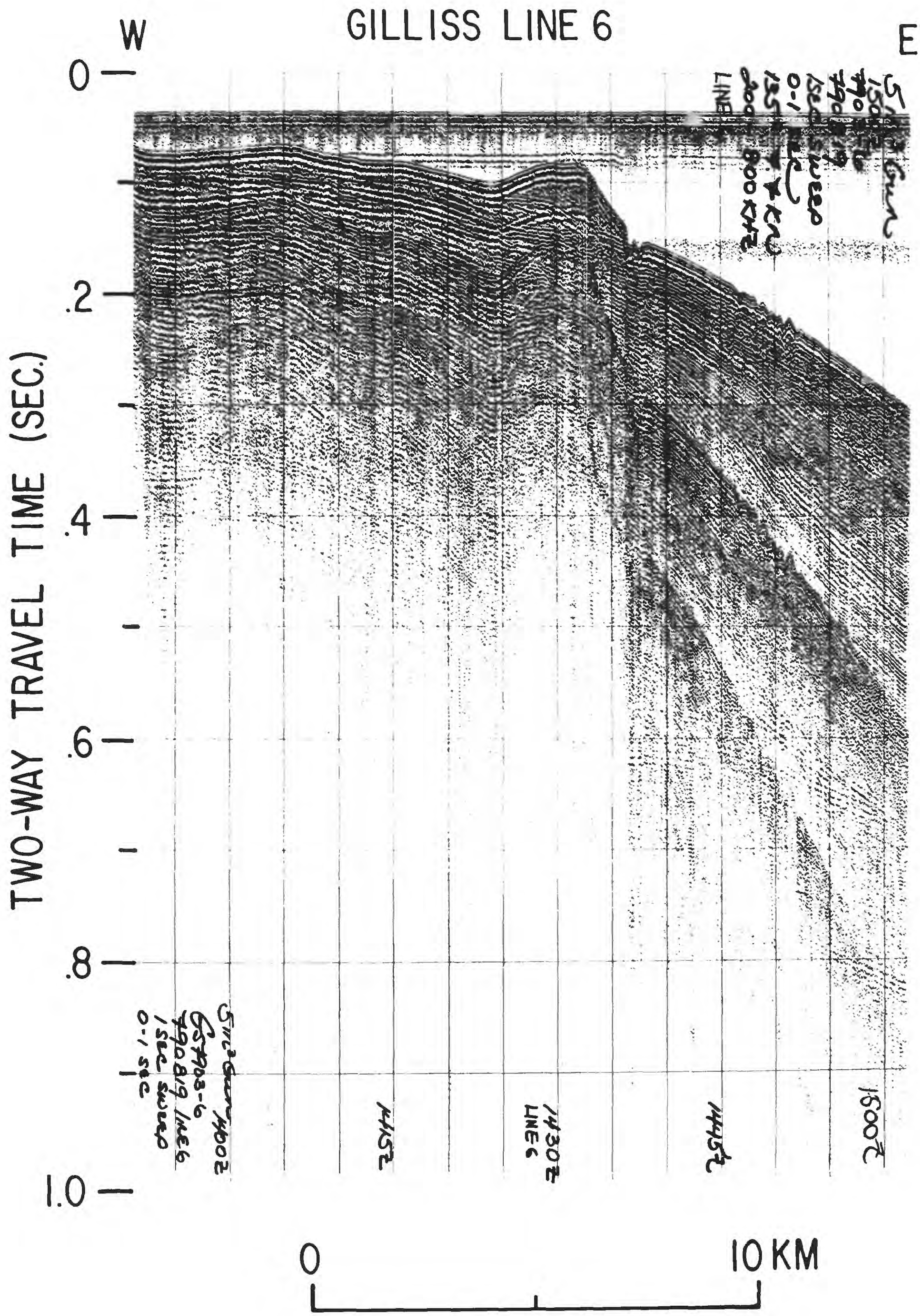
Faults

Two faults that may reflect a tectonic origin have been mapped on the shelf (pl. 1). The Helena Banks fault (pl. 1) was traced at least 30 km and possibly 70 km by means of common-depth-point (CDP) and high-resolution seismic-reflection data offshore Charleston and Cape Romain, S.C. (Behrendt and others, 1981). This fault displaces basement about 80 m down to the southeast and may be a high-angle reverse fault. Behrendt and others (1981) described a "warping" or monoclinal flexure of near-surface rocks that they think indicates that the fault has moved in post-Pliocene time.

Snyder and others (1981) have traced what they believe to be a structural lineament across the shelf in Onslow Bay, N.C. This feature, named the White Oak lineament (pl. 1), is characterized in Uniboom

Figure 4. Seismic-reflection record showing a prominent shelf-edge reef on the Florida-Hatteras shelf southeast of Cape Lookout near lat. 34°08'N., long. 76°11'W. The reef top is in 60 m of water and projects about 35 m above the normal bottom contour. Note scour moat near the base of the reef and rough bottom which may be reef rubble or an older reef downslope. Subbottom reflectors below the reef suggest that this reef is built on a small older reef. Both reefs are late Pleistocene to Holocene in age.

Figure 4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1.0
TWO-WAY TRAVEL TIME (SEC.)
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1430Z LINE 6
1445Z
1500Z
0
10 KM

Figure 5. Seismic-reflection record showing the character of the shelf-edge reef at lat. 34°30′N., long. 75°52′W. The reef is in about 85 m of water and has about 10 m relief. Note the water-column anomalies upslope and downslope from the reef which reflect large schools of fish.

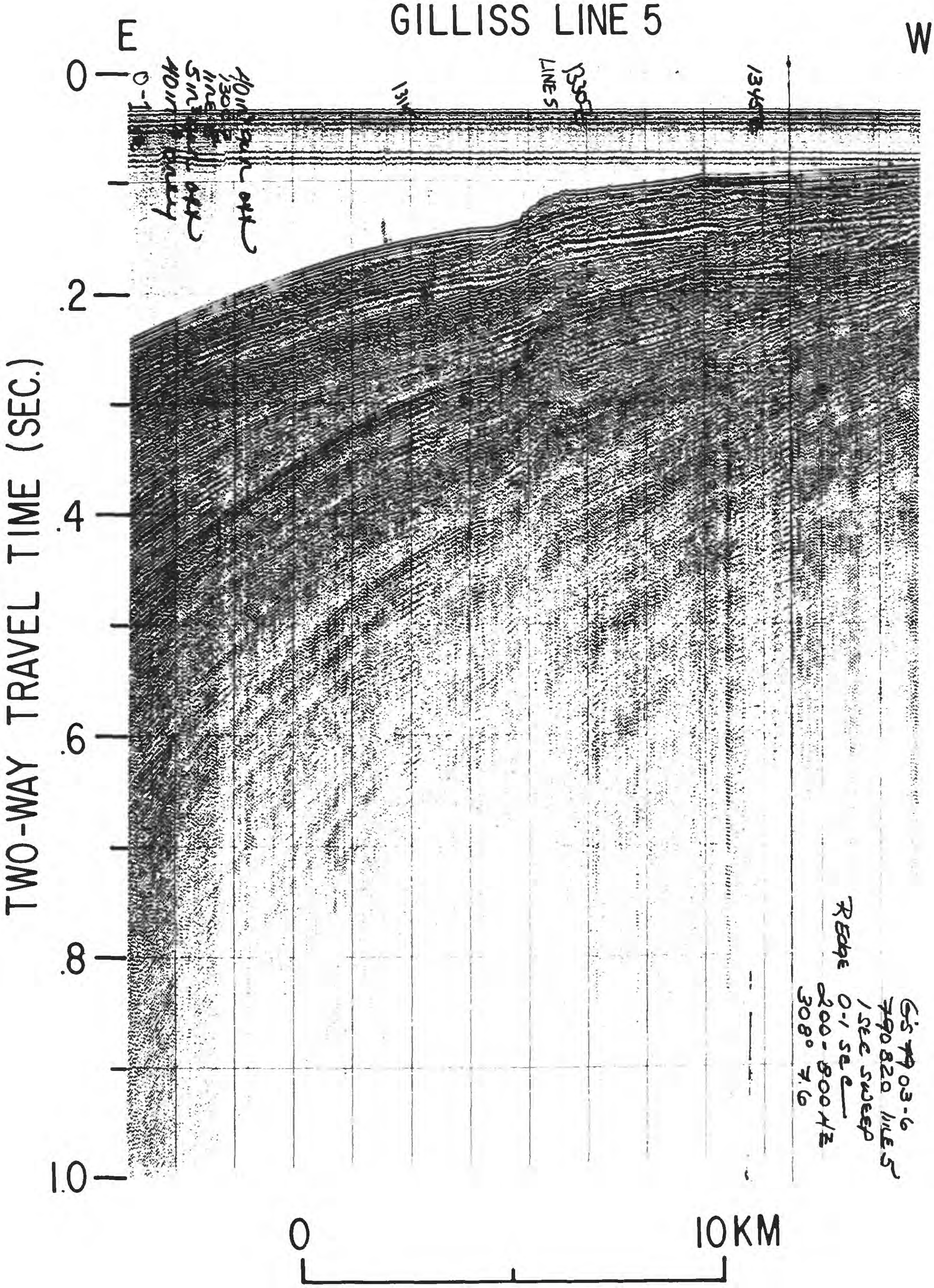
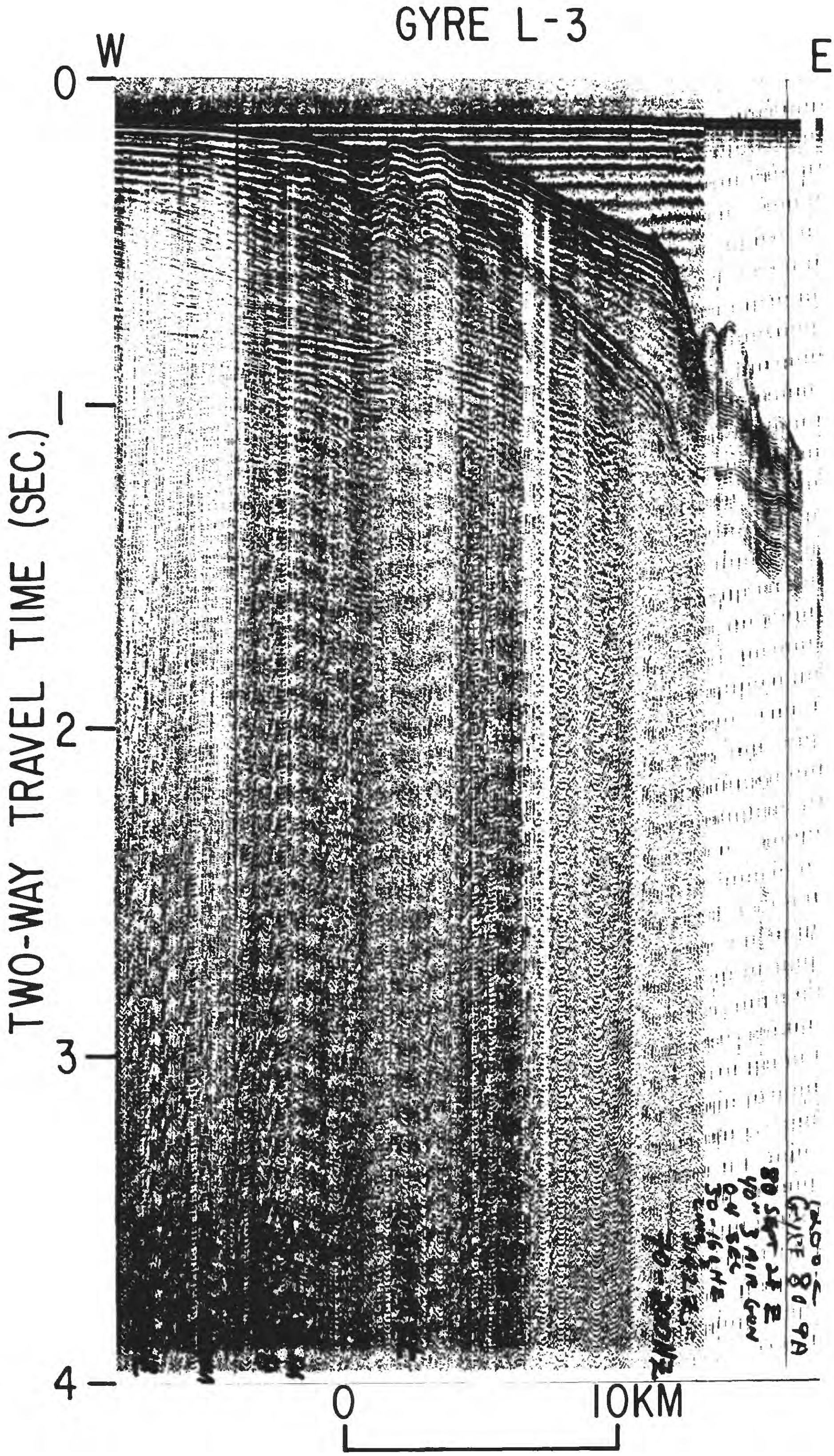

GILLISS LINE 5
E
W
TWO-WAY TRAVEL TIME (SEC.)
0
.2
.4
.6
.8
1.0
0
10KM

Figure 6. Seismic-reflection record showing a large shelf-edge reef east of Cape Hatteras near lat. 35°09'N., long. 75°10'W. near the top of the Continental Slope. The reef top is at about 85 m depth and has a large channel or scour moat on its upslope side. Downslope of the shelf break, the bottom is cut by submarine canyons that are carved in Pleistocene-age rocks and give the bottom a very rough appearance.


GYRE L-3
W
E
0
1
2
3
4
TWO-WAY TRAVEL TIME (SEC.)
0
10KM

seismic-reflection data (Snyder and others, 1981) as a broad monoclinal structure in Boague Sound, an abrupt thickening of the Pungo River Formation offshore, and a subbottom scarp having more than 25 m relief on the midshelf. The lineament closely approximates the orientation of several structural lineaments mapped onshore (Spangler, 1950; Brown and others, 1972) that are described as flexure zones or fault zones related to basement tectonism. On the basis of apparent relative movement, regional extent, local vertical relief, and the coincidence of the feature with a major change in basement slope (Dillon and others, 1981), Snyder and others (1981) suggested that the lineament is the consequence of recurrent movement on a basement normal fault.

With the exception of a possible small displacement in seismic reflectors on our R.V. GILLISS line 7 near where it intersects the White Oak lineament of Snyder and others (1981), our seismic data do not support a fault origin for the feature, particularly on the outer shelf. The strongest evidence for a fault is that the lineament coincides with (1) a pinchout of Albian-aged strata on the basement surface at depth (Dillon and others, 1981) along a trend about 25^{o} west of the strike of the Carolina trough and (2) an increase in basement declivity. Our data do not preclude a fault origin for the feature, however, as reflections from small-displacement basement faults along which recurrent movement has taken place can be extremely subtle features when translated through unconsolidated sediments to the near surface. On this basis, we have included the feature on our environmental geology map (pl. 1) although we think that, at present, the evidence for a fault is tenuous.

FLORIDA-HATTERAS SLOPE

Sediment cover

The Florida-Hatteras slope (fig. 2) off North Carolina forms a gentle (~1.5^{o}) transitional drop of about 150 m to the inner Blake Plateau. The shelf edge is capped along much of its length by shelf-edge reefs, which usually have erosional moats at their bases. Slope sediments are mainly of Pleistocene age and are generally coarse sand near the shelf edge and become finer grained downslope (Doyle and others, 1979) with the exception of a small area of mud just southeast of Hatteras (Pilkey and others, 1981).

The surface of the slope appears rough on a few seismic-reflection profiles, indicating active scour. No evidence of slope instability was noted off North Carolina. Its absence is probably due to a low declivity and a scarcity of fine-grained sediments due to winnowing and scour by the Gulf Stream currents and reworking of slope sediments by benthic infauna.

Wrecks

Although the area off Cape Hatteras is known to be littered with wrecks (Newton and others, 1971), only one large wreck was directly crossed by our seismic profiles (pl. 1). This wreck is on GILLISS line 3 at lat. 34^{o}50.5´N., long. 75^{o}32.5´W in 80 m of water. An examination of a compilation of reported sinkings and known wrecks (Newton and others, 1971) suggests that this wreck, which was identified on our records both seismically and by a high-amplitude and short-wavelength magnetic anomaly, is the wreck of the E.M. CLARK, a tanker of 6,020 net tons, that was torpedoed on March 18, 1942.

BLAKE PLATEAU

Sediment cover

Only the northern tip of the Blake Plateau is included in the study area of this report. This part of the plateau is capped by Pleistocene sediments that are dominated by sands which become finer grained, grading to silts, toward the slope (Hathaway, 1971). The plateau is both an area of non-deposition and in part an erosional terrace cut by the Gulf Stream, and little sediment accumulates on the northern plateau at the present time. Sediments swept off the shelf by waves, tides, and currents are carried north by the Gulf Stream ultimately to be deposited on the Continental Slope south of Hatteras, or presumably, they are swept down the canyon systems to the upper rise and Hatteras Abyssal Plain. Scour and erosion appear to be the dominant processes.

Scour and sand waves

Rough bottom due to current scour and sand waves were noted on all lines of the R.V. GILLISS, R.V. FAY, and R.V. ISELIN survey data across the plateau. Scour was also noted within the nominated lease blocks for Sale 56 and has been mapped in detail by Carpenter (1981). Large asymmetric sand waves approximately 10 m high and 800 m in wavelength were found on GILLISS line 1 in 320 m of water (fig. 7). These sand waves have their steep face to the north, suggesting that they are caused by north-flowing Gulf Stream currents acting on the bottom. A deep-water reef (fig. 8) crossed on GILLIS line 1 that projects about 35 m above the bottom has a conspicuous scour moat indicating active current erosion.

Deep-water coral reefs

With the exception of the extensive deep-water coral reef areas south of lat. 33°N. (pl. 1) we found only one deep-water reef mound off North Carolina (fig. 8).

Deep-water reefs are not common on the Blake Plateau north of lat. 33°N., probably because of the meandering of the Gulf Stream in this area caused by its deflection off the Charleston bump to the south (Pinet and others, 1981a). These reefs depend on strong bottom currents to supply food and help remove metabolic wastes as well as to keep the polyps clean of fine sediment. A regional compilation of deep-water reef areas on the Blake Plateau (USGS, unpublished data) shows clearly that extensive reef development follows the path of the Gulf Stream across the inner Blake Plateau from the Straits of Florida to about lat. 32°N. From there, the reefs diagonally cross the plateau following the path of the Gulf Stream as it is deflected by the Charleston bump.

Figure 7. Seismic-reflection record showing a large sand-wave field in 320 m of water on the northern Blake Plateau at lat. 33°14´N., long. 76°56´W. The steep faces on these sand waves are facing north, indicating that they are the result of north-flowing currents (Gulf Stream) acting on the bottom.

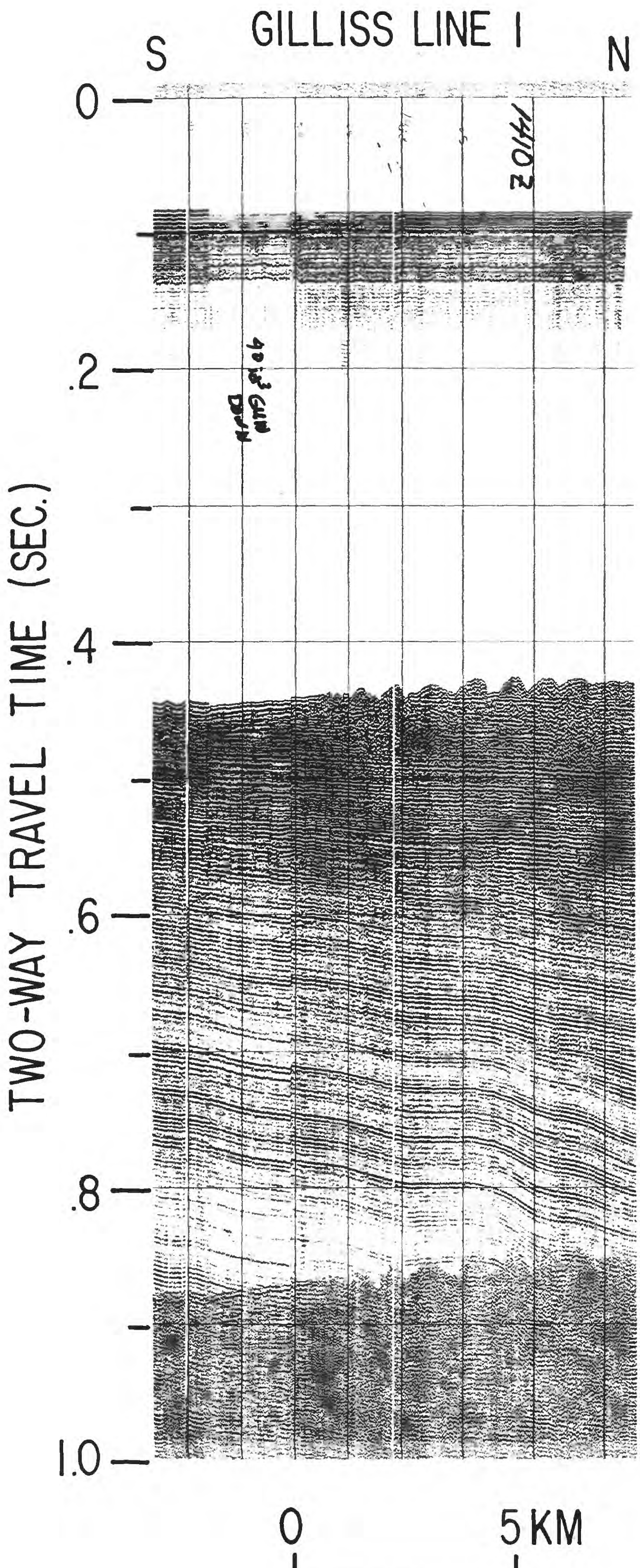
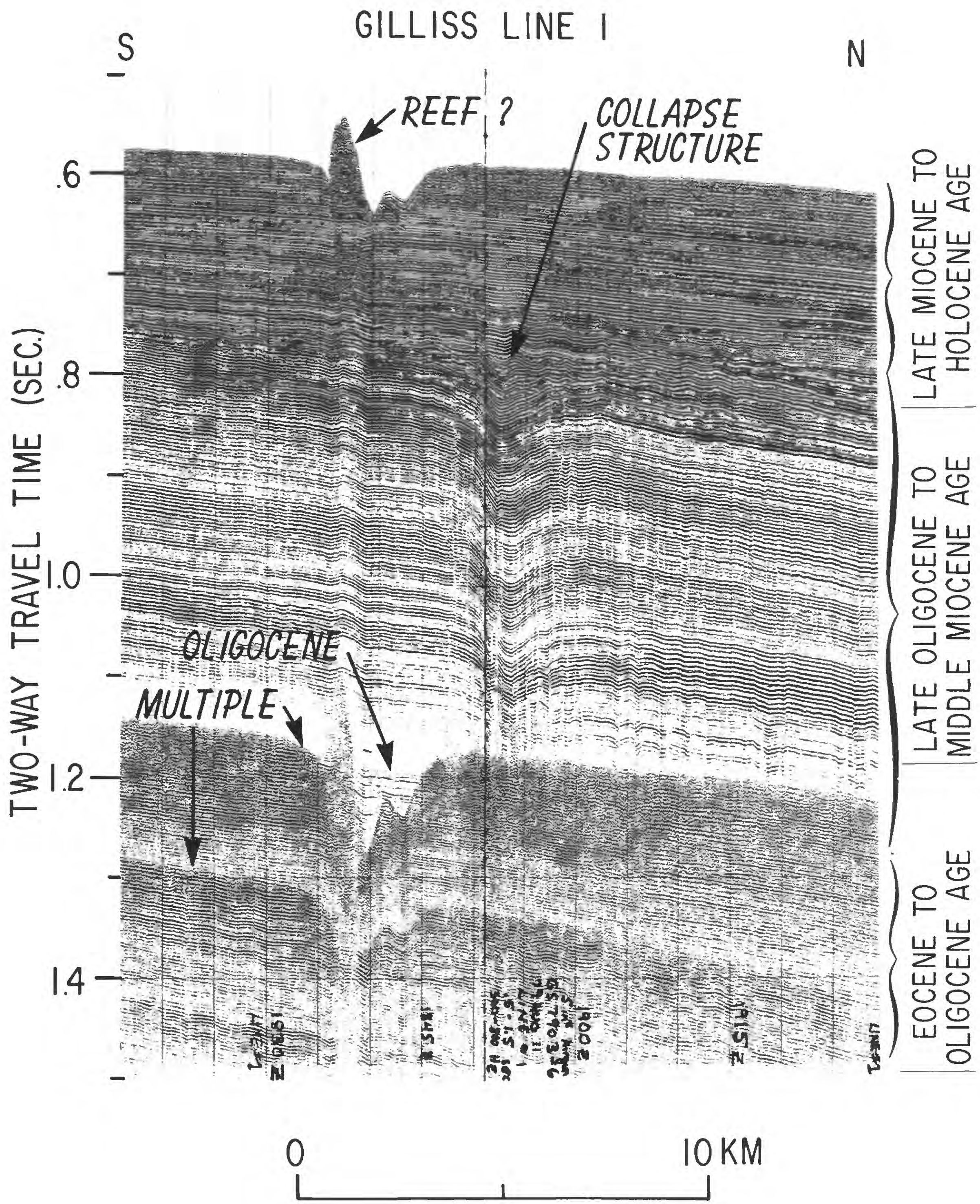

GILLISS LINE I
S
N
0
.2
.4
.6
.8
1.0
TWO-WAY TRAVEL TIME (SEC.)
0
5 KM

Figure 8. Seismic-reflection record showing a feature that projects above the bottom on the northern Blake Plateau at lat. 33°34'N., long. 76°28'W. This feature is interpreted to be a deep-water coral-reef mound surrounded by a scour moat. The reef projects about 30 m above the normal bottom contour, and the moat is eroded about 40 m deep, making the overall relief about 70 m. The flexure in the subsurface rocks north of the reef is interpreted to be a collapse structure related to cavernous porosity in subsurface Oligocene- and Eocene-age limestones. These solution and collapse structures are along faults related to the major growth fault near the outer edge of the Blake Plateau. They do not affect rocks above the middle Miocene unconformity or below the Eocene. At least 32 small displacement faults affect the late Oligocene- and early Miocene-age rocks seen in this figure.


GILLISS LINE I
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REEF ?
COLLAPSE STRUCTURE
OLIGOCENE
MULTIPLE
TWO-WAY TRAVEL TIME (SEC.)
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.8
1.0
1.2
1.4
LATE MIOCENE TO HOLOCENE AGE
LATE OLIGOCENE TO MIDDLE MIOCENE AGE
EOCENE TO OLIGOCENE AGE
0
10 KM

Faults

A major growth fault (figs. 9, 10, 11) occurs along the eastern edge of the Blake Plateau and beneath the Continental Slope between lats. 32°N. and 35°N. (Sylwester and others, 1979; U.S. Dept. of Interior, 1980; Carpenter, 1981; Dillon and others, 1981). From our data, this fault has been traced more than 380 km. The throw of this fault increases from about 1 m at 10 m depth to 450 m at 5 km depth, indicating a long history of movement contemporaneous with deposition. Displacements near the sea floor indicate the fault is still active (figs. 9, 10).

The growth fault dips steeply eastward, strikes about N.22°E., and extends to a maximum depth of about 11 km where it terminates against a strong reflector believed to be the top of a Jurassic salt layer (Dillon and others, 1981). Its location is coincident with the western edge of the Carolina trough along its length. The association of the fault with a line of salt diapirs on the Continental Rise further offshore (pl. 1) strongly suggests that the fault is a subsidence feature caused by the flow of salt at depth from the western part of the Carolina trough into the diapirs on the Continental Rise, thus removing support from the overlying sediments (Grow and others, 1979; Dillon and others, 1981; Grow, 1981). This interpretation is supported by calculations of the volume of salt in the diapirs offshore (4,100 km^3) and the volume of material lost in subsidence within the Carolina trough and taken up by the growth fault (4,400 km^3) (Dillon and others, 1981).

Associated with the main growth fault are hundreds of small-displacement antithetic and splay faults of similar strike that extend many kilometers west and east of the main fault (pl. 1) (U.S. Dept. of Interior, 1980; Carpenter, 1981). Only a few of these splay faults are shown on plate 1 because of the map scale and data spacing. However, figures 8-12 illustrate the abundance of these faults. In addition, figure 12 shows a probable "bright spot" caused by shallow gas. The position of this "bright spot" near many small-displacement faults suggests that the gas may have migrated up the faults into the shallow subsurface and been trapped in a relict barrier-bar sequence.

Collapse features

Large buried collapse features as much as 2 km across (figs. 8, 13) were noted on R.V. GILLISS lines 1(2 features), 8(2), 9(3), and 10A(1) and R.V. FAY 19 line 2, (fig. 1) near the edge of the Blake Plateau (pl. 1). In each feature sediments of Miocene age have collapsed into pits observed in the Oligocene unconformity. The collapse structures terminate upward against the middle Miocene unconformity and are shown not to extend downward below the Eocene. Multiple track crossings suggest that the collapse features are elongate and aligned in about a N.20°E. direction, essentially parallel to the growth fault on the outer Blake Plateau. This trend suggests that their location is structurally controlled by splay faults of the growth fault system. Eocene and Oligocene strata are principally limestones both beneath the Continental Slope (Fitchko, 1976) and onshore (Brown and others, 1972). The deep pits in these units and collapse structures over them suggest karst solution (sink holes), and the cavernous porosity of these units may

Figure 9. Seismic-reflection record near lat. 34°00′N., long. 75°56′W. (GILLISS line 1) showing the major growth fault near the eastern edge of the Blake Plateau. As shown in this picture, beds at about 450 m subbottom are displaced about 20 m by the fault.

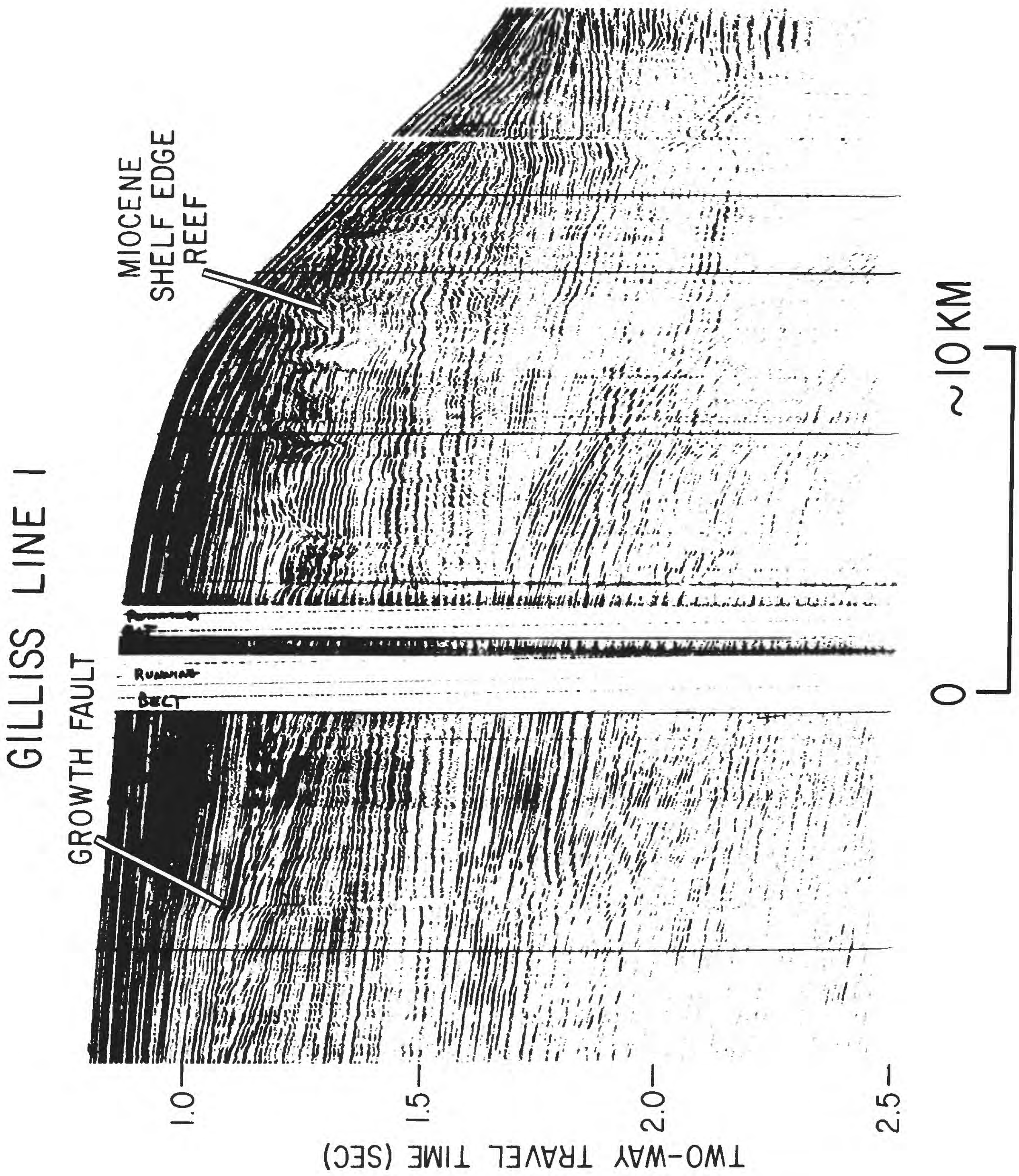

GILLISS LINE I
GROWTH FAULT
MIOCENE
SHELF EDGE
REEF
~10KM
0
1.0
1.5
2.0
2.5
TWO-WAY TRAVEL TIME (SEC)

Figure 10 Part of R.V. GILLISS seismic-reflection line 10 across the major growth fault near lat. 33°14′N., long. 76°25′W. About 25 additional small displacement faults can be seen in this picture upslope and downslope of the main splay of the fault. At this crossing of the fault, beds 70 m subsurface are displaced about 10 m, and beds 450 m subsurface are displaced about 60 m. This area is upslope of a breached salt diapir complex on the upper Continental Rise and probably has subsided more than areas to the north and south owing to salt dissolution from the breached diapirs.

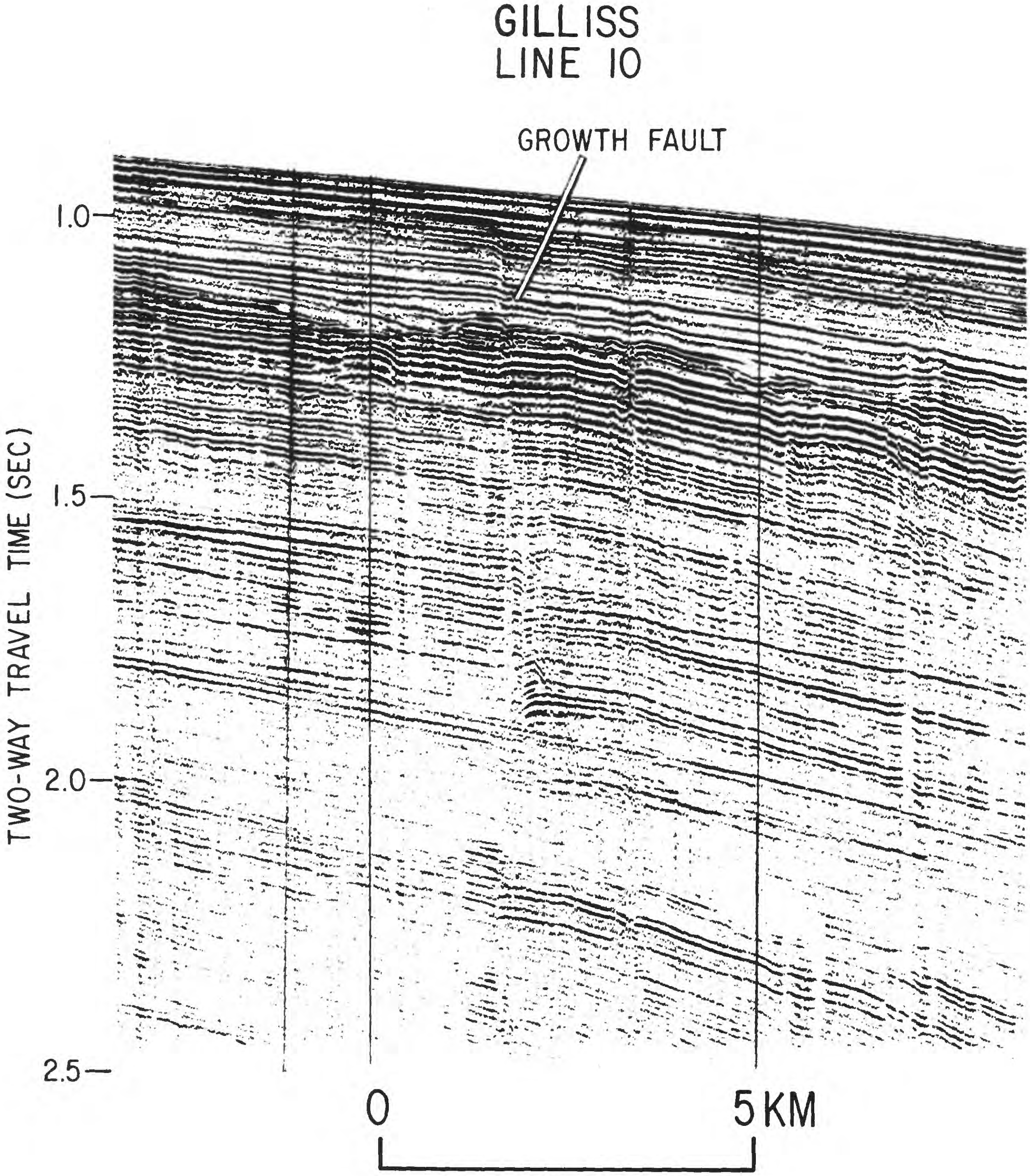

GILLISS
LINE 10
GROWTH FAULT
1.0
1.5
2.0
2.5
TWO-WAY TRAVEL TIME (SEC)
0
5 KM

Figure 11. Part of a seismic-reflection record from near lat. 33°19′N., long. 76°23′W. showing the detail of the growth fault near the shelf edge and splay faults of the growth-fault system. More than 40 small displacement faults are obvious in this picture, of which about six show very near surface displacement. The major splay of the growth fault (f) displaces beds about 1 m at 10 m subsurface and 45 m at 175 m depth. This area is upslope from two breached salt domes on the Continental Rise and probably shows more subsidence than any other area along the growth fault.

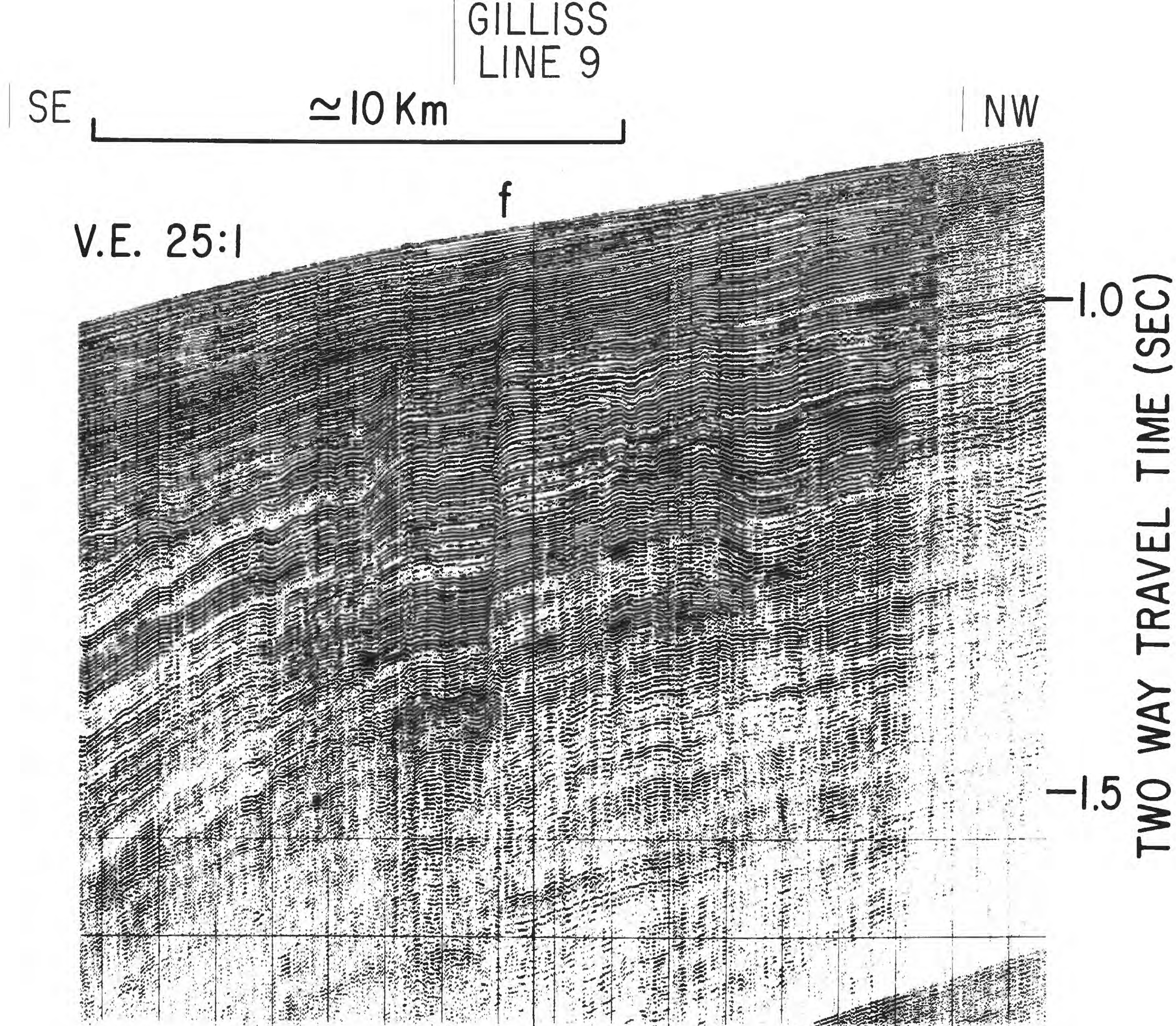


Figure 11

Figure 12. Seismic record from near lat. $33^{o}45'$N., long. $76^{o}15'$W. showing an area of strong reflectance in the shallow subbottom which may be a "bright spot" caused by the strong impedence contrast of free gas within the sediments. The location of this feature above many small-displacement faults (marked with arrows at top of picture) suggests that gas may have migrated up the fault traces from depth and become trapped in the shallow subsurface. Indications of free gas (such as "bright spots" seen beneath reflection from clathrates) associated with the Carolina trough suggest that this area may have an economic potential as proposed by Dillon and others (1980).

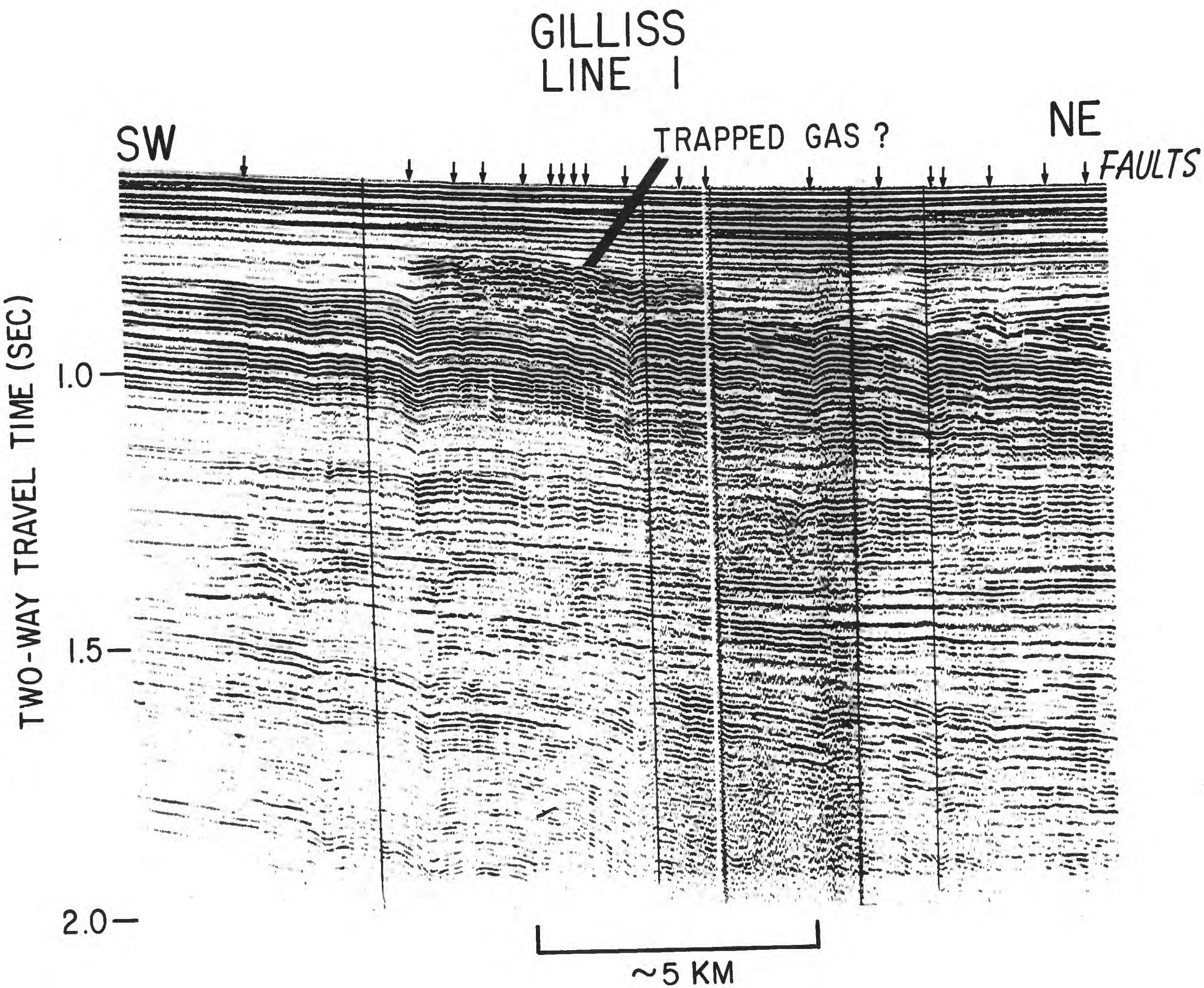

GILLISS
LINE 1
SW
NE
TRAPPED GAS ?
FAULTS
1.0
1.5
2.0
TWO-WAY TRAVEL TIME (SEC)
~5 KM

Figure 12

Figure 13. Seismic-reflection record showing a sag of early to middle-Miocene-age sediments into a deep pit in the Oligocene unconformity near lat. 33°25'N., long. 76°32'W. on the outer Blake Plateau. This and other similar features in this area are interpreted to be caused by collapse of cavernous Eocene and Oligocene limestones (sink holes) into which the early to middle-Miocene-age sediments have sagged during subaerial exposure of the shelf in middle-Miocene time. Sediments above the middle-Miocene unconformity are not affected except for several small-displacement faults above the feature that displace near-surface rocks. Seismic-reflection profiles show that these features do not extend deeper than Eocene sediments. These probable solution features appear to be associated with and elongated along splay faults of the growth-fault system. Note the many small-displacement faults shown within the record.

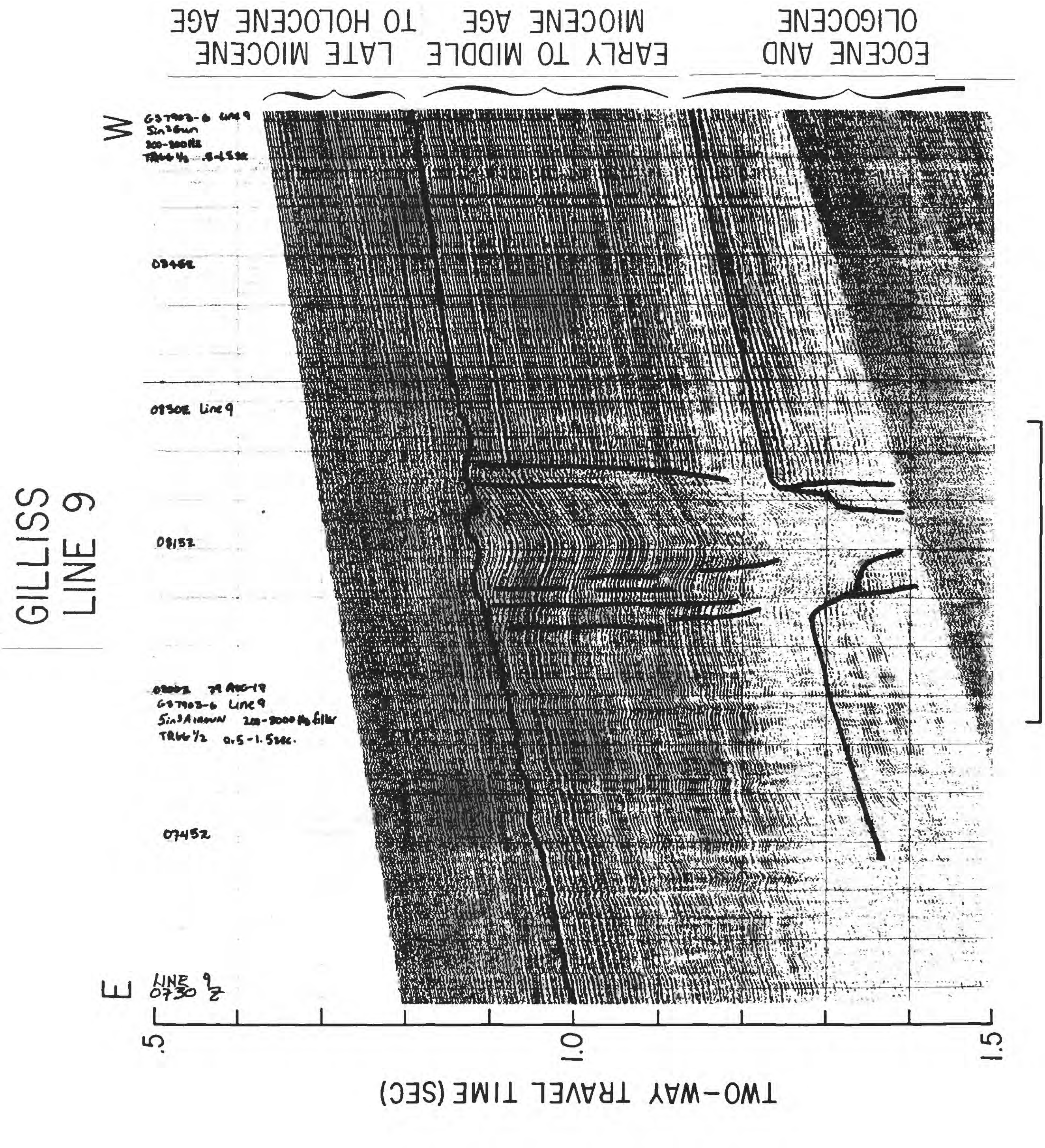

GILLISS
LINE 9
W
E
LATE MIOCENE
TO HOLOCENE AGE
EARLY TO MIDDLE
MIOCENE AGE
EOCENE AND
OLIGOCENE
5 KM
.5
1.0
1.5
TWO-WAY TRAVEL TIME (SEC)

Figure 13

reflect subaerial exposure of the shelf during middle Miocene time. The lack of collapse features above the middle Miocene unconformity suggests planation and erosion during the late-Miocene transgression and burial by subsequent clastic deposition.

CONTINENTAL SLOPE

Bottom conditions

Continental Slope sediments are finer grained than those of the shelf. Most slope sediments off North Carolina are silts and clays (Hathaway, 1971). The North Carolina Continental Slope appears from seismic records to be an area dominated by erosion and mass wasting north of lat. 33°30′N.; deposition is minor. Sediments swept off the plateau by the Gulf Stream are either swept south by the Western Boundary undercurrent or swept downslope onto the rise and Hatteras Abyssal Plain.

The declivity of the slope off North Carolina varies widely from a inclination of about 3.5° where the slope joins the Blake outer ridge at lat. 32°30′N. to a maximum of about′ 16° off Cape Hatteras (Fitchko, 1976). The slope averages about 8° to 10° between Cape Fear and Cape Lookout and north of Hatteras averages approximately 7°. Because of the dominance of erosion, rocks of Cretaceous to Pleistocene age crop out on the slope between lat. 33°25′N. and Cape Hatteras. This area contrasts with the slope between lats. 32° and 33°15′N. where the slope has a low declivity (3°-4°) and is mantled by a thick blanket of Pleistocene and Holocene sediments. South of lat. 33°15′ in the area of our mid-range sidescan-sonar survey (fig. 1) (Popenoe and others, 1981a), the slope is remarkably smooth and featureless except where slump features have been observed (pl. 1). Reflection profiles (3.5 kHz) show unbroken shallow subbottom reflectors which mantle the slope, indicating a quiescent and active depositional regime in this area. North of Cape Hatteras, the slope is steeper (average 7°) and highly dissected by steep-walled canyons cut into a thick section of Pleistocene sediments (see fig. 20).

Slope instability and mass wasting

A large scar caused by a sediment slump has been described by Carpenter (1981) on the upper Continental Slope in nominated lease blocks NI 18-7-874,-875,-876, -918, and -919 of Lease Sale 56. This slump feature also was observed in our mid-range sidescan-sonar data, and its location is shown on plate 1 centered on lat. 33°04′, long. 76°18′.

Many small gravity faults were observed in our seismic-reflection data along the Continental Slope between lat. 32°N. and Cape Hatteras. In most areas, these faults are not extensive, and the slope appears relatively stable. This stability is probably due to the presence of older, more indurated units which crop out on the slope.

Near lat. 33°N., long. 76°W., a major slump was found (K.V. Cashman and P. Popenoe, unpub. data, 1981) in which a large arcuate area of the lower slope (about 60 km across) has been removed (pl. 1). Truncated bedding in a 60-80-m-high scarp and shallow rotational gravity faults and smaller scarps upslope were first noted in the R.V. GILLISS seismic-reflection lines 10 and 9 (figs. 14 and 15). Long-range sidescan sonographs (GLORIA) (Somers and others, 1978; Teleki and others, 1981)

Figure 14. Seismic-reflection record from R.V. GILLISS line 10 near lat. 33°03′N., long. 76°08′W. on the lower Continental Slope showing rotational faults and an 80-m-high scarp of truncated beds caused by massive slumping. These slump features are in an area of great subsidence caused by salt dissolution from two salt diapirs downslope. Note the disturbed and upturned beds beneath the slump scarp (truncated beds) caused by salt tectonism and the "bright spots" caused by free gas trapped beneath the frozen clathrate layer. The slump scarp shown in this picture is the same feature as shown in figures 16-19.

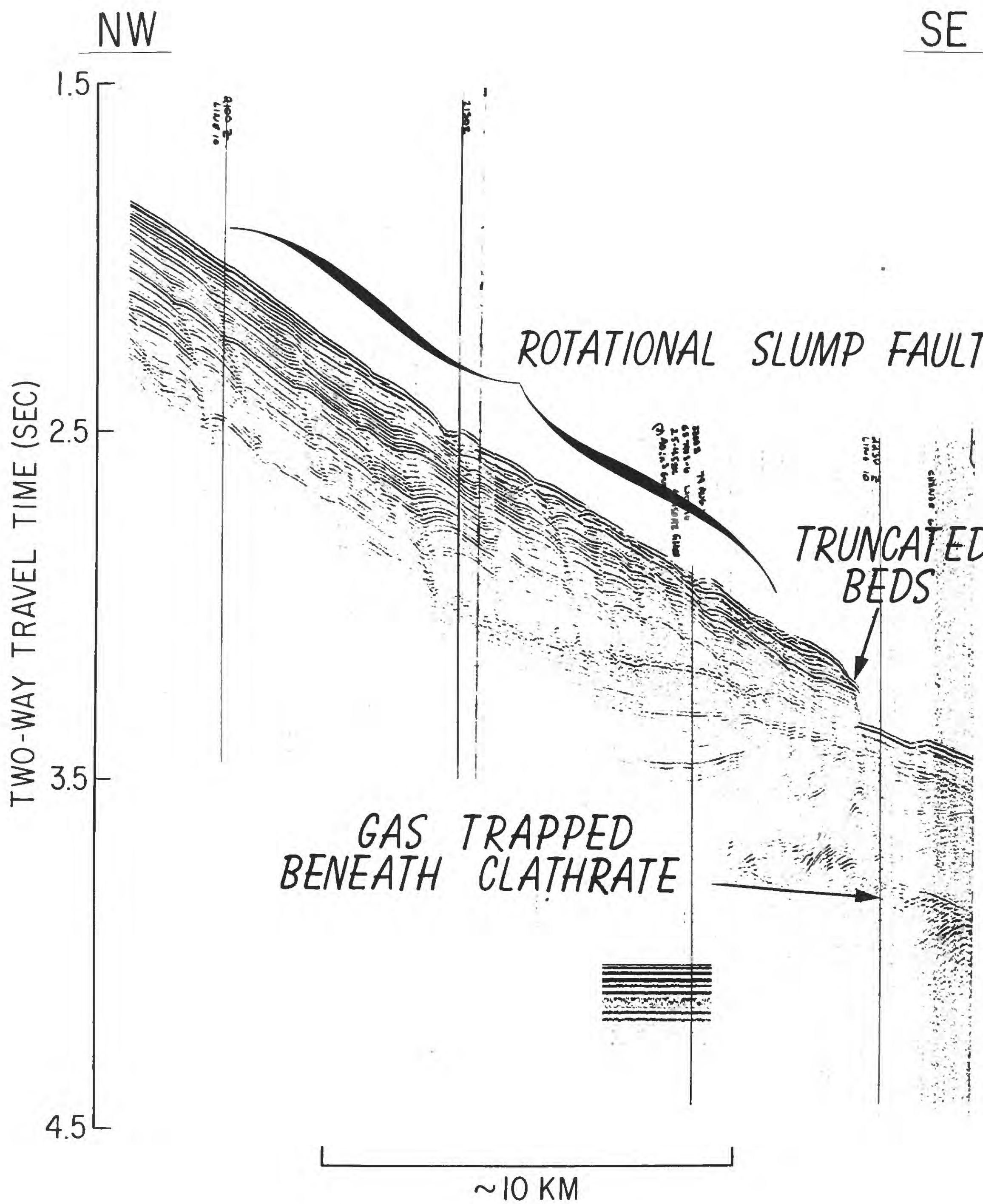
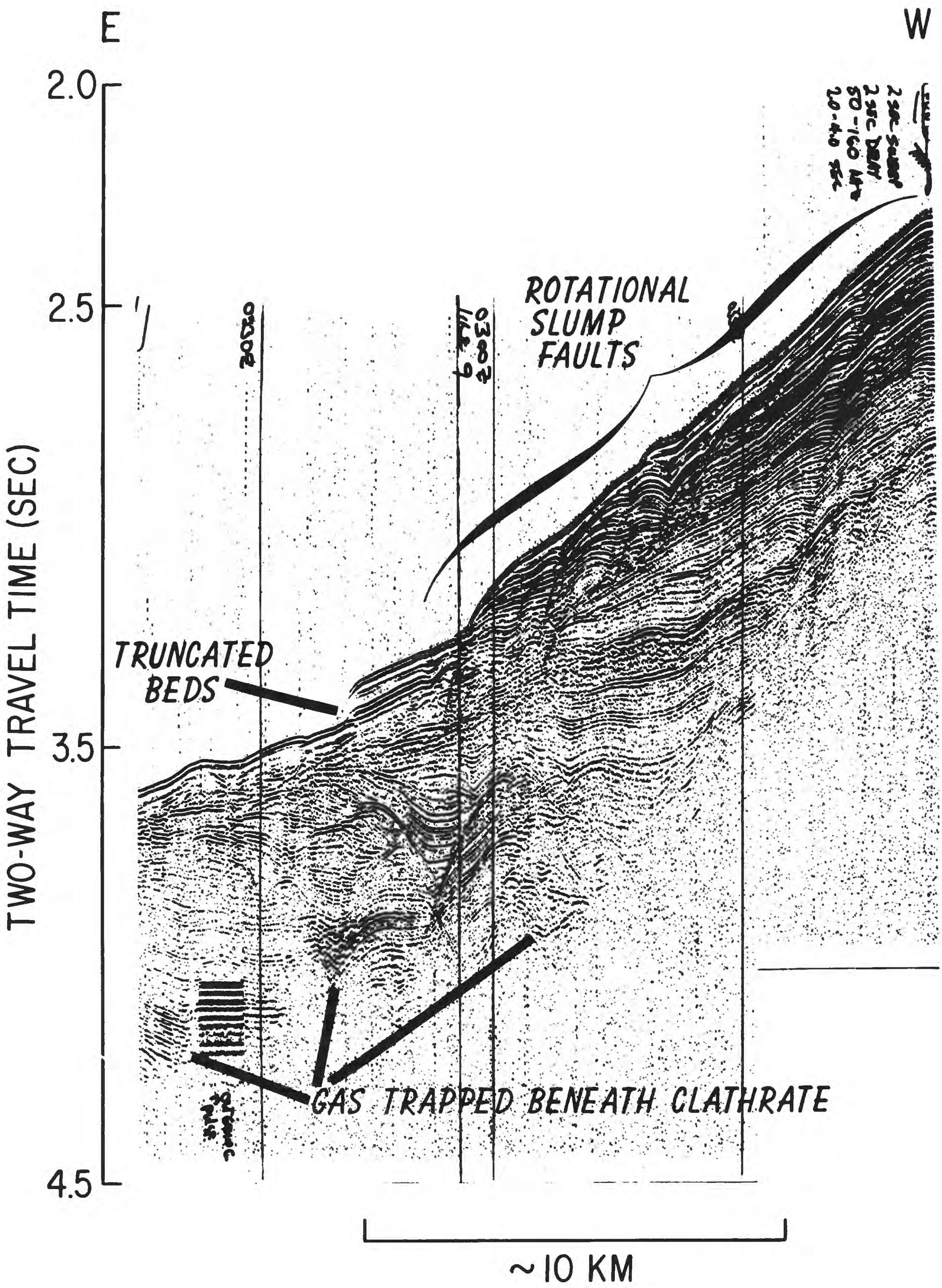

NW
SE
1.5
2.5
3.5
4.5
TWO-WAY TRAVEL TIME (SEC)
ROTATIONAL SLUMP FAULTS
TRUNCATED BEDS
GAS TRAPPED BENEATH CLATHRATE
~10 KM

Figure 15. Seismic-reflection record from R.V. GILLISS line 9 showing slump features on the middle and lower Continental Slope. Note the highly disturbed and folded beds in the shallow subbottom associated with salt tectonism, and the "bright spots" which reflect shallow trapped gas. This is the same profile as that shown on figure 20. The dimpled bottom over fault traces and the thickened beds within fault traces indicate that the rotational slump faults are active and have moved contemporaneously with deposition for a long period of time.


E
W
2.0
2.5
3.5
4.5
TWO-WAY TRAVEL TIME (SEC)
ROTATIONAL
SLUMP
FAULTS
TRUNCATED
BEDS
GAS TRAPPED BENEATH CLATHRATE
~10 KM

obtained in 1979 showed that the scarp is arcuate in plan view and that it encompasses three diapir structures (K.V. Cashman and P. Popenoe, unpub. data, 1981) (fig. 16). Interpretation of mid-range sidescan sonographs (figs. 17, 18, and 19) obtained in 1980 (Popenoe and others, 1981a) indicates that repeated slumping has created the scarp. In these images, tracks of slump blocks 3-10km wide can be seen etched as deep as 10 m into the bottom downslope of the main scarp, and rubble trains are visible extending downslope to lobate debris deposits. Truncated beds are clearly visible on the scarp face (fig. 18), and additional slump tracks that affect only the upper layers of slope sediments are seen upslope of the main scarp (fig. 19).

The sharp nature of the boundaries of many slump tracks and a lack of marine sedimentation within depressions caused by sliding suggest that slumps have taken place relatively recently and may still be moving. Seismic records (fig. 20) show that the bottom is dimpled over rotational slump faults upslope of the 80-m-high slump scarp and that mantling units are thicker within the fault traces of the rotational slumping. This thickening indicates that slump blocks (fig. 20) have been moving downslope contemporaneous with deposition, and probably are still moving. A large fault about 2 km upslope of the main scarp is shown in figures 15 and 20. This fault and the dimpled bottom over it suggest that a block 80 m high, 2 km deep, and of unknown length is slowly failing. This area of slope instability is believed to be caused by oversteepening of the slope caused by subsidence accompanying leaching of salt from the two large salt diapirs immediately downslope of the slumps (fig. 16, this report; K.V. Cashman P. Popenoe unpub. data, 1981). The two large salt diapirs downslope of the features are the only two diapirs of the linear chain of 26 diapir structures along the upper rise off North Carolina (pl. 1) that have breached the surface of the sea floor (J.A. Grow and others, unpub. data, 1981).

North of Cape Hatteras on the upper Continental Slope at lat. 36°20′N., long. 74°40′W. another large slump scar about 20 km across is present (pl. 1). This scar is characterized by two steep scarps showing truncated bedding (profile B-B′, fig. 21). This feature has been studied and described by Bunn and McGregor (1980) and McGregor (1981), who suggested that slope failure, which involved a 300-m-thick block of sediment, took place along a smooth, seaward-dipping horizon of very dry, friable silty clay of early Pleistocene age. Our seismic-reflection data (fig. 21) clearly show the slump scars on a section of slope dissected by many submarine canyons cut into Pleistocene-age sediments (figs. 21, 22). Slumping has locally removed the eroded surface and the Pleistocene sediments, leaving an anomalously smooth segment of slope (fig. 21). Rotational slump faults have formed upslope of the scarps (pl. 1). We infer from these data that slumping took place in late Pleistocene or Holocene time.

Canyons

Beginning just south of Cape Hatteras and continuing northward, the Continental Slope is cut by submarine canyons. Off Cape Hatteras, the canyons dissect most of the slope, and mass wasting and slumping associated with the canyons are probably the most important mechanisms of sediment transport from the slope to the Continental Rise or Hatteras

Figure 16. Long-range sidescan-sonar image (GLORIA) of the lower slope and its interpretation (below) showing the arcuate pattern of the 60-80-m-high slump scarp centered on lat. 33°N., long. 76°W. and its relationship to three salt diapirs. The two largest diapirs uplift and breach the sea floor. On this image, high-reflectance areas or surfaces facing the detector (center line) are white, and shadows are dark. The salt diapirs appear as double concentric rings which reflect subsidence moats around rising salt "pillows." The scarp appears as a white line (high-reflectance surface) encircling the upslope side of the diapirs (see plate 1).

Figure 16

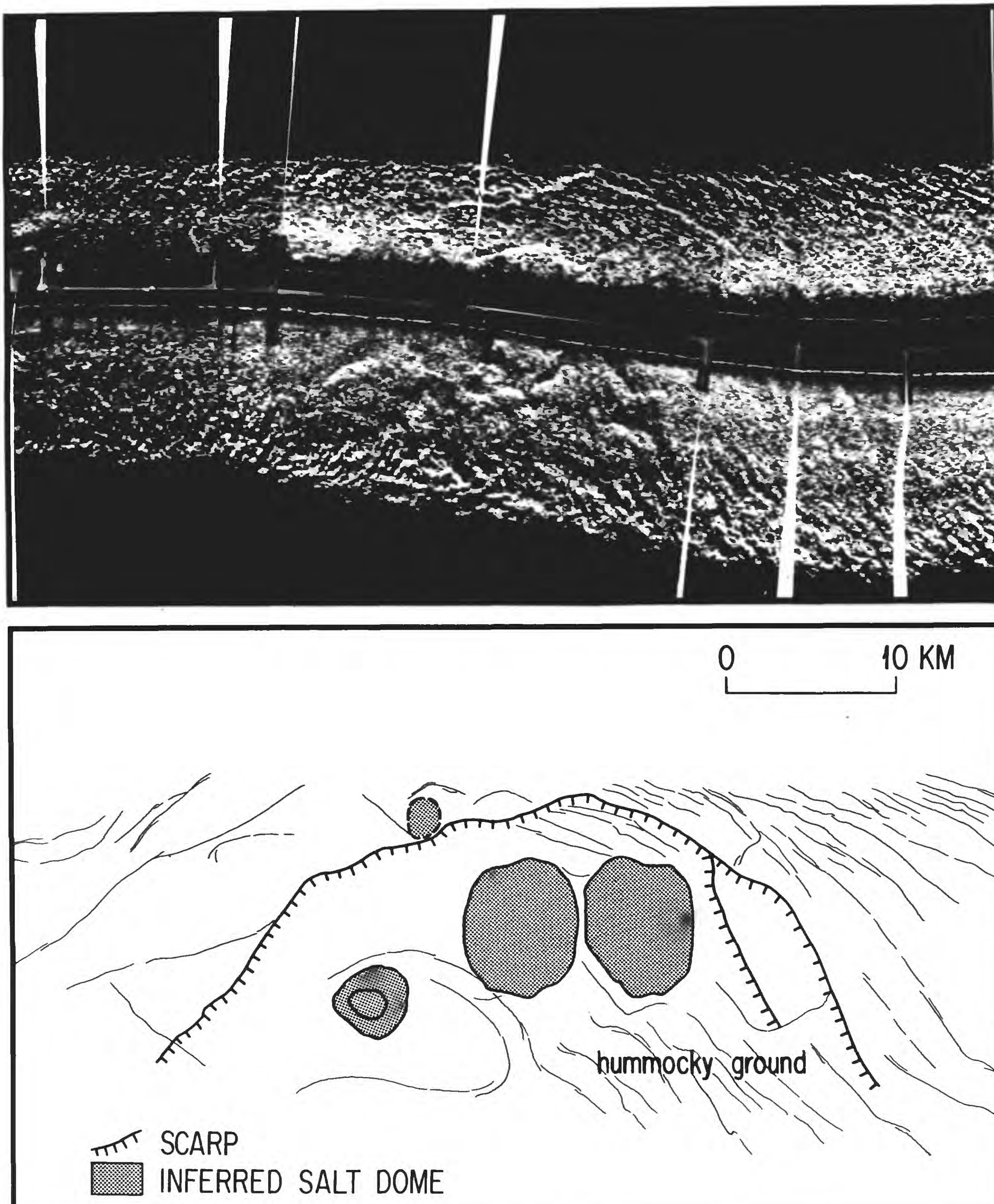


Figure 17. Interpreted mid-range sidescan-sonar image showing a part of the slump scarp shown in figures 14, 15, and 16. The upper picture shows the actual image, and the drawing shows the complex relationship of the large scarp (heavy hachured line) to slide tracks furrowed into the bottom downslope of the scarp (lighter hachured lines). The breaks depict scarps, and the hachures point toward lower bottom. The bottom below the main scarp (60-80 m high) is furrowed by slide tracks (5-10 m deep) which extend downslope. Elevated areas between adjacent tracks separate individual slide paths. Details of this picture are discussed in figures 18 and 19.

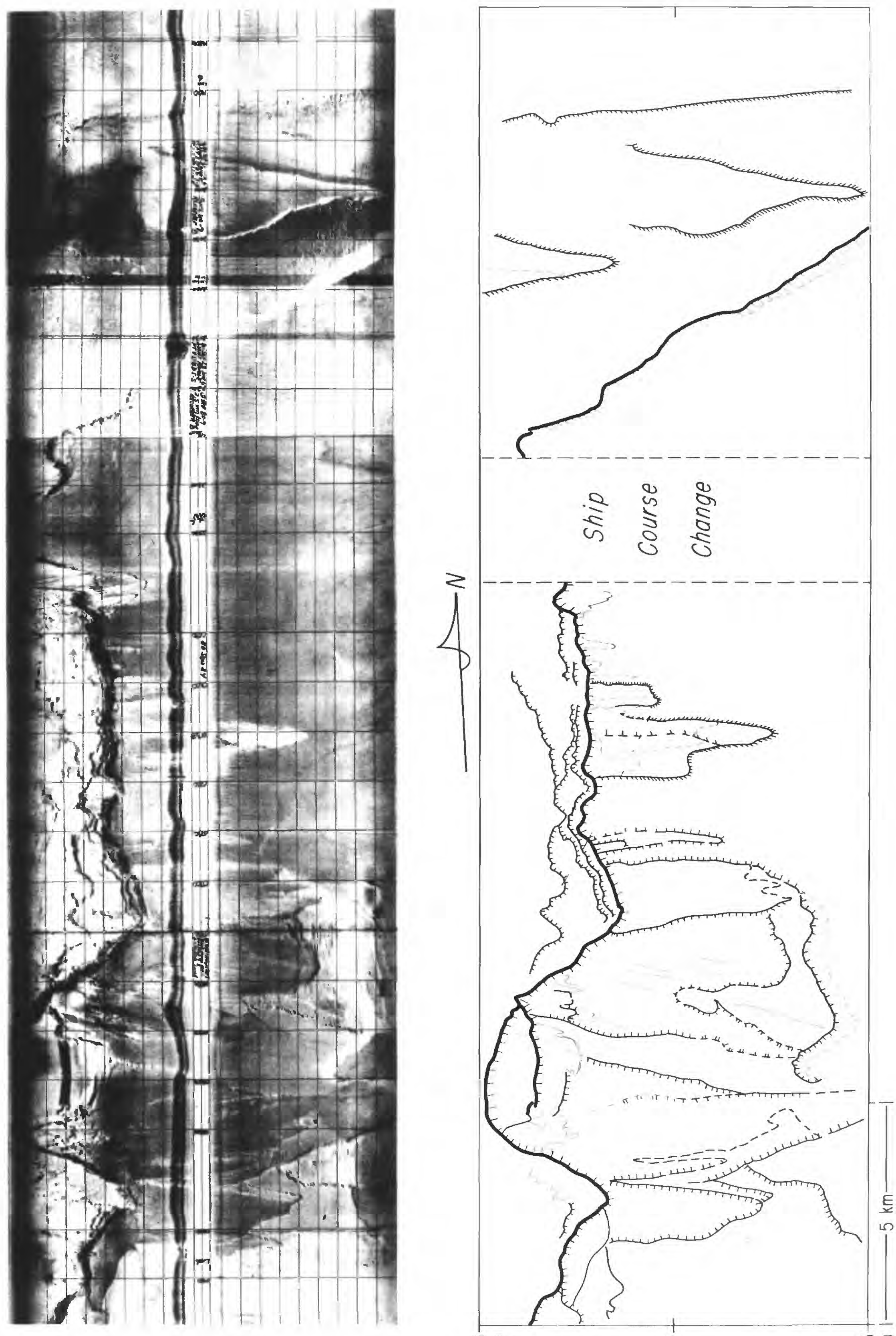

N
Ship
Course
Change
2.5 km
0
2.5 km
5 km

Figure 18. A part of the slant-range corrected mid-range sidescan-sonar image shown in figure 17. The slump-scarp face (a) exposes truncated bedding (d). Downslope of the scarp, slide tracks (b) are furrowed as much as 10 m into the bottom, and elevated "mesas" (c) and rubble trains (e) are left between tracks.

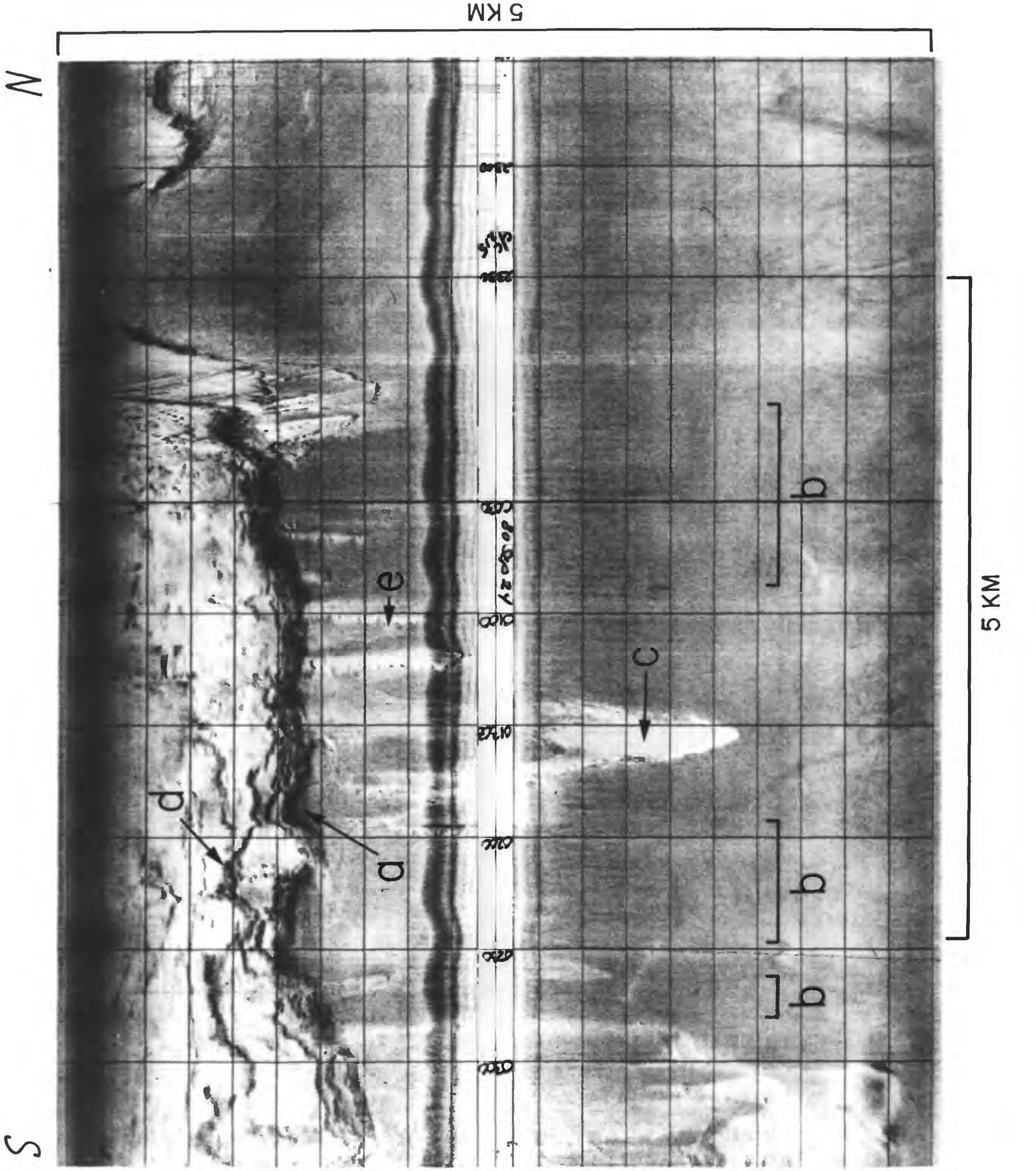


Figure 18

Figure 19. Detail of a part of the mid-range sidescan-sonar record shown in figure 17. This image shows the northern part of the main slump area where the main scarp (a) trends diagonally upslope. Smaller slumps have furrowed tracks into the bottom which diverge downslope (b) leaving remnant areas of high bottom (c). Rough bottom (d) probably reflects rubble left from the descending slump block. The smooth featureless slope (e) on the north side of the image is typical of the Continental Slope along most of our mid-range sidescan-sonar traverse in this area.

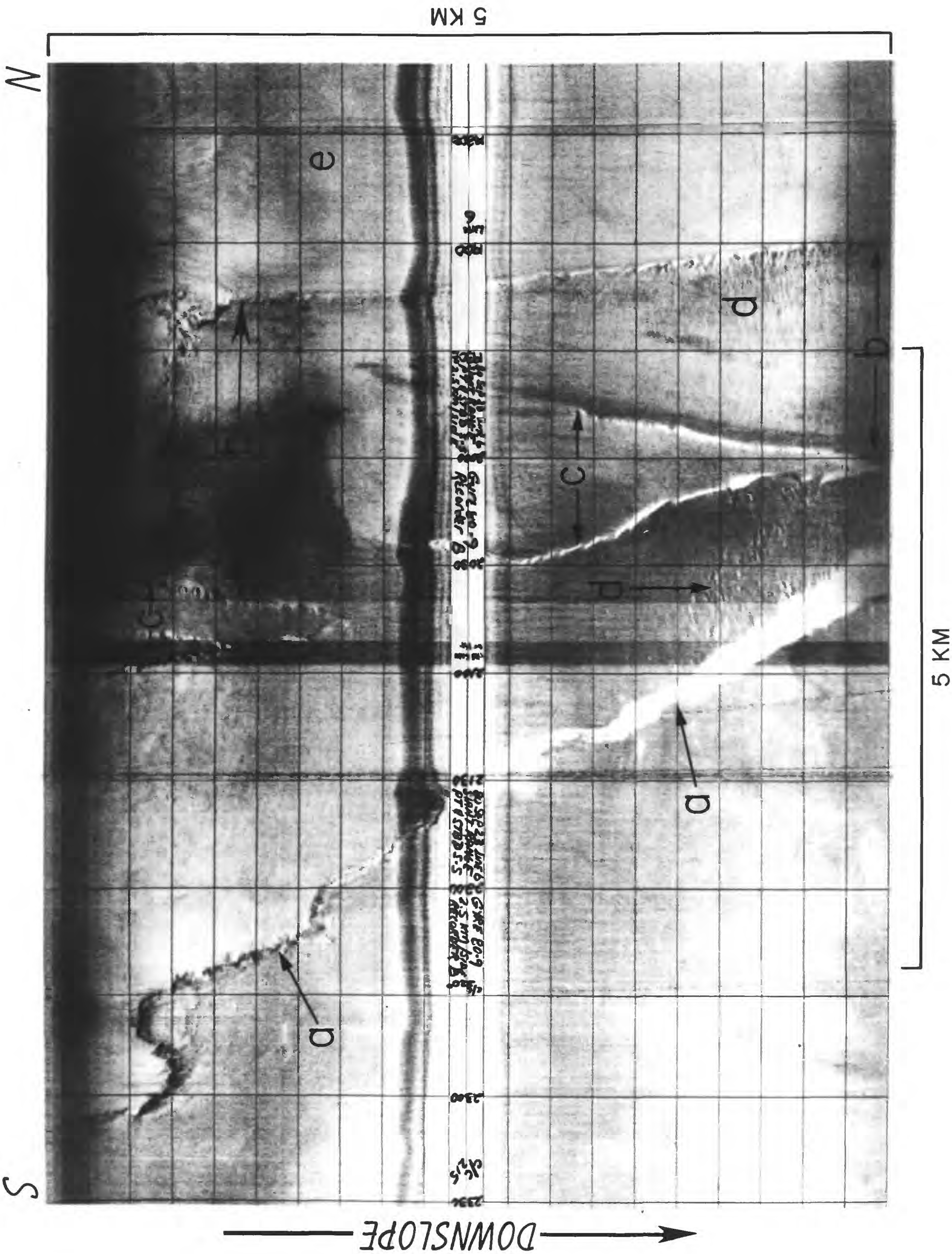


Figure 19

Figure 20. Seismic-reflection record (3.5 kHz) of the area of the slope shown in figure 15 which shows the detail of the upper beds over the rotational slump-fault traces. The bottom is dimpled and offset by the rotational slump faults, indicating that these faults are active. The upper layers of sediment on the slope are thicker within slump-fault traces, indicating that these slumps have been moving downslope during deposition of these layers. Note the fault that dimples the bottom about 2 km above the slump scarp. This active feature suggests that a block 2 km deep, 80 m high, and of unknown length, is slowly failing.

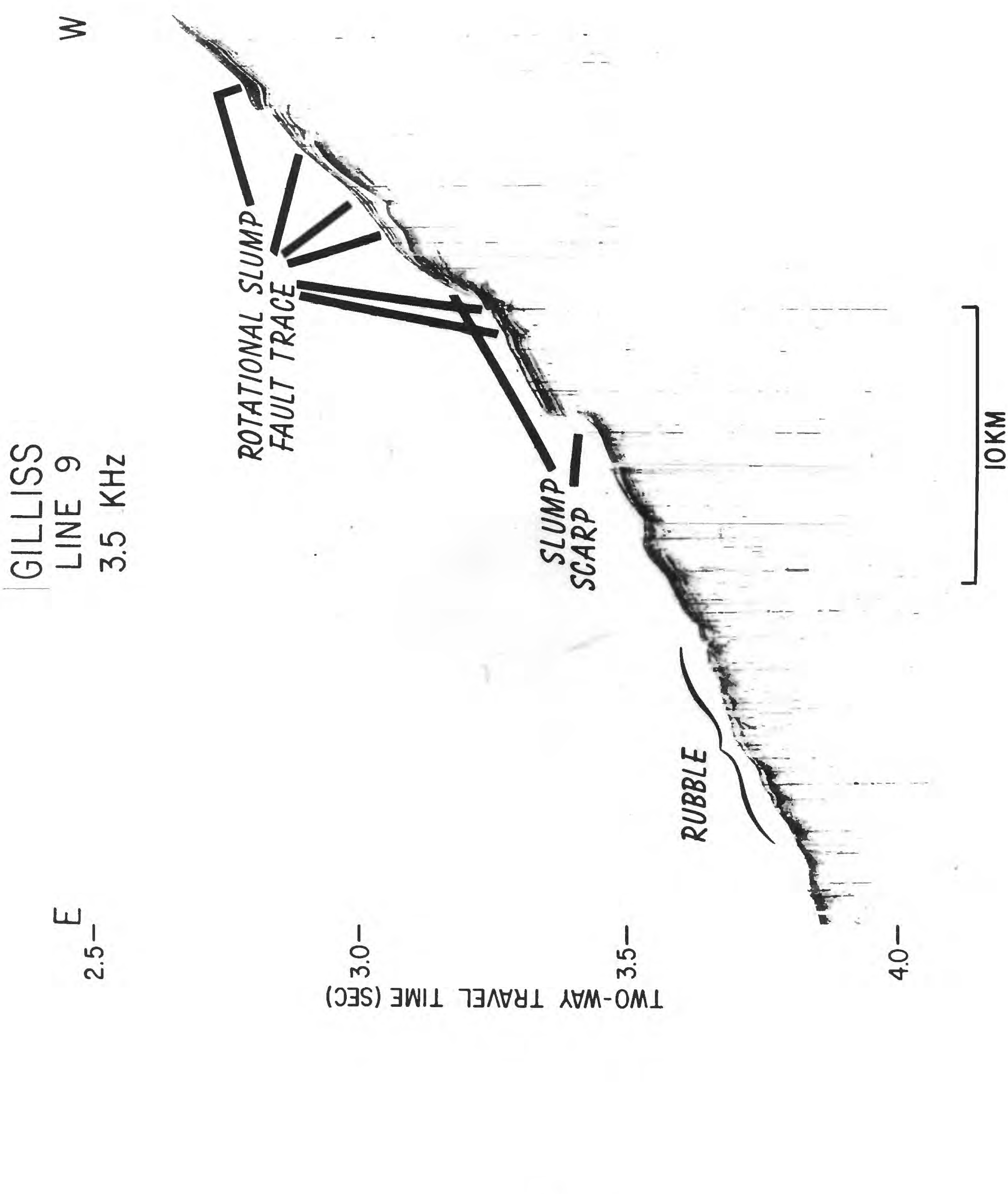

GILLISS
LINE 9
3.5 KHz
E
W
ROTATIONAL SLUMP
FAULT TRACE
SLUMP
SCARP
RUBBLE
10KM
2.5
3.0
3.5
4.0
TWO-WAY TRAVEL TIME (SEC)

Figure 20

Figure 21. Seismic-reflection profiles GYRE line 10 (A-A′ upper) and GYRE line 9 (B-B′ lower) showing profiles of the slope near lat. 36°30′N., long. 74°30′W. Figure 22 shows the location of these profiles and local slope bathymetry. The upper profile (A-A′) is characteristic of the slope in this area; the surface is deeply mantled by Pleistocene deposits and dissected by submarine canyons. Older, truncated, smoothly dipping units underlie the Pleistocene cover of the upper slope and a strong-reflecting unit parallel to the sea floor underlies the lower slope and upper rise. In contrast, the lower profile (B-B′) shows a smooth slope, along which are two steep scarps. Neither the slope or upper rise show a mantling of Pleistocene material or submarine canyons. The lack of Pleistocene sediments and canyons and the presence of steep scarps as shown on profile B-B′ all suggest that a major slump has taken place in this area. The areal extent of the slump feature is shown on figure 22 by the bathymetry, which suggests that two large arcuate areas of the slope have slumped and thus been removed. Vertical exaggeration is approximately five times.

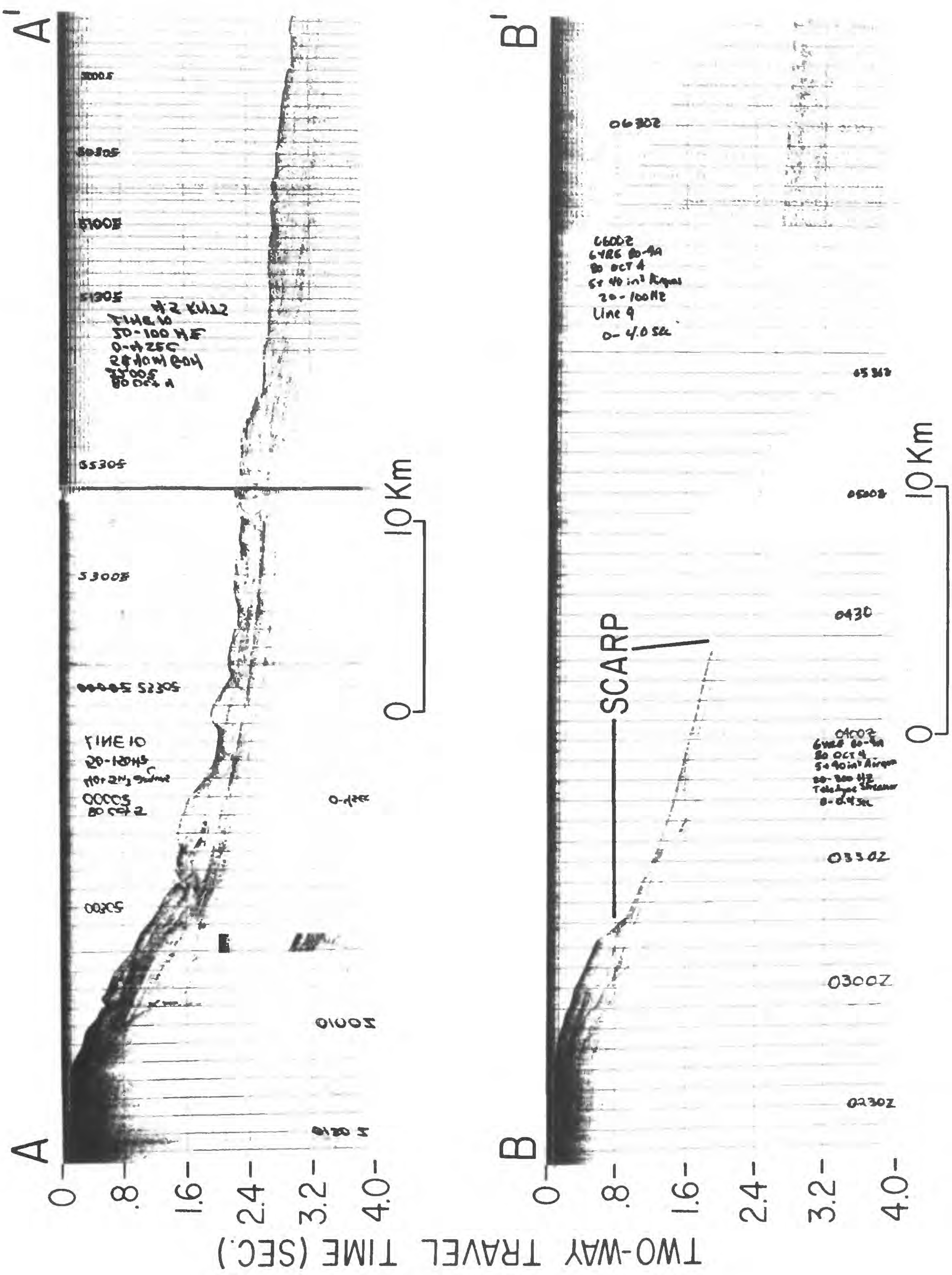


Figure 21

Figure 22. Bathymetric map of a part of the Continental Slope just south of the offshore extension of the Virginia-North Carolina border including locations of the profiles shown in figure 21. This bathymetry is taken from the 1:250,000 scale NOS topographic-bathymetric map of the Currituck Sound quadrangle. Line A-A′ corresponds to GYRE line 10 on figure 21, which crosses the slope in an area dissected by submarine canyons. Line B-B′ corresponds to GYRE line 9, which crosses a smooth section of Continental Slope. The steepened slope areas on profile B-B′ are scarps associated with slump faults. Hachured lines outline areas of probable slumping.

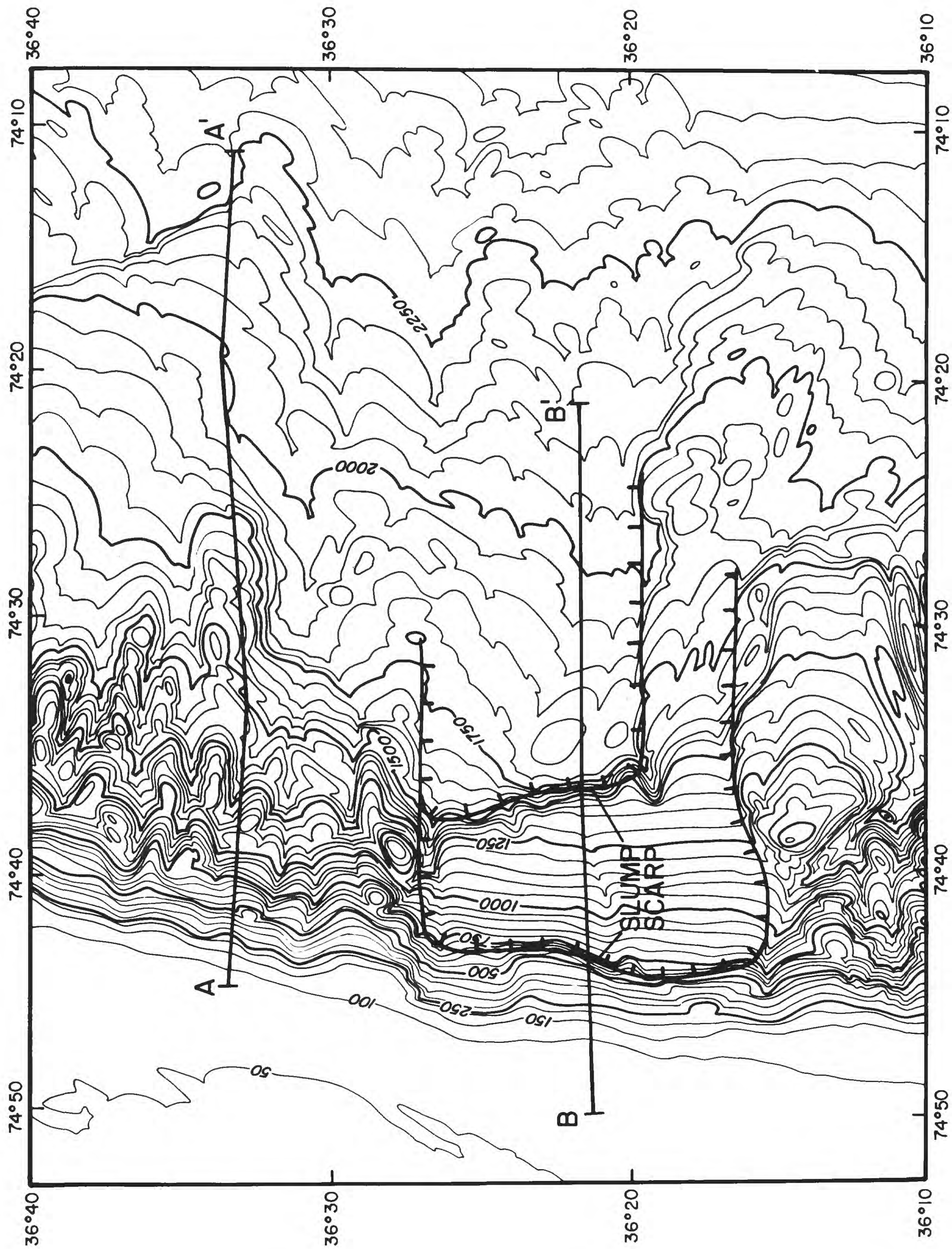

36°40
36°30
36°20
36°10
74°10
74°20
74°30
74°40
74°50
A
A'
B
B'
SLUMP
SCARP
50
100
150
250
500
750
1000
1250
1500
1750
2000
2250

Figure 22

Abyssal Plain. Canyons are extensive on the upper slope within the nominated blocks of Lease Sale 56 in the Manteo quadrangle where relief between ridges and canyons ranges is as much as 700-800 m. Relief decreases downslope.

Because of their complexity, the geomorphic patterns of the canyons are not discernible from widely spaced seismic-reflection records without very closely spaced data (<0.5 km). However, mid-range sidescan sonar (GYRE 80-9 leg 1, Popenoe and others, 1981a) show closely spaced canyons, sharp divides, and rounded thalwegs on the upper slope (fig. 23). In some areas, undissected slope occurs between canyons (figs. 24, 25). Sides of canyons are incised by many small tributaries and chutes, and bottoms are both straight (fig. 23) or slightly meandering (figs. 24, 25) with bend at tributary chute intersections. The geomorphic pattern of the upper slope canyon tributaries is best described as pinnate, reflecting the steep slopes ($\sim 12^{\circ}$) on which they have formed.

The canyons appear to be the product of mass wasting and slumping, maintained by headwall and sidewall erosion. Debris channeled down the thalweg apparently undercuts side walls and facilitates further slumping. Turbidity currents may play a small part in canyon formation and maintenance, but the dominant process appears to be mass wasting. For example, figure 25 shows a sidescan-sonar image of a canyon cut into a relatively smooth slope in which a downslope tributary to the main canyon has started to pirate the main canyon by upslope headwall erosion. This midslope erosion could be accomplished only by mass wasting, as turbidity from the shelf would be funneled down the main canyon and would not feed the tributary canyon. Submersible dives have confirmed the presence of small slumps within canyons further north (Grow, 1981). The sharpness of the divides between canyons and the general "crispness" of canyon systems suggests that the slumping process is active at the present time.

The canyons are cut almost exclusively into Pleistocene sediments and expose older rocks in their axes, therefore, they are late Pleistocene to Holocene events.

Clathrates and accompanying trapped gas

Plate 1 defines the updip and downdip limit of a frozen gas hydrate layer (clathrate) that has been detected in seismic-reflection records from the slope and upper rise off North Carolina (Shipley and others, 1979; Dillon and others, 1980; Paull and Dillon, 1980, 1981; Popenoe and others, 1981b). A gas hydrate is an icelike crystalline lattice of water molecules in which gas molecules become trapped. It forms in the marine environment under the low temperatures and high pressures of deep water; its lower phase boundary occurs about 0.4 to 0.6 seconds (two-way travel time) subbottom, where the gas hydrate becomes unstable owing to the geothermal gradient (Tucholke and others, 1977). Beneath this phase boundary, which can be detected seismically by a bottom-simulating reflector, "bright spots" or amplitude anomalies often are visible in seismic records; the "bright spots" are caused by the large impedence contrast between free gas, which is trapped beneath the frozen layer, and water. Such "bright spots" are visible on figures 14, 15, and 26, and are ubiquitous on much of our data on the lower slope and upper rise.

Figure 23. Mid-range sidescan-sonar image showing a section of the upper Continental Slope near lat. 35°30′N., long. 74°45′W. that is dissected by steep-walled submarine canyons. This image is reverse printed so that reflecting surfaces are white and shadows are dark. Because the image is uncorrected for slant range, a profile of the bottom (marked "BOTTOM" on photo) is shown on both sides of the center line. The image is taken along slope and looks upslope at the top of the picture and downslope on the lower half of the picture. The canyons, which have as much as 500 m of relief between ridges and thalwegs, have rounded bottoms; divides between canyons are sharp crested. The slope is almost totally dissected by canyons that run straight downslope and have few tributary canyons (compare with fig. 24) but many tributary chutes.

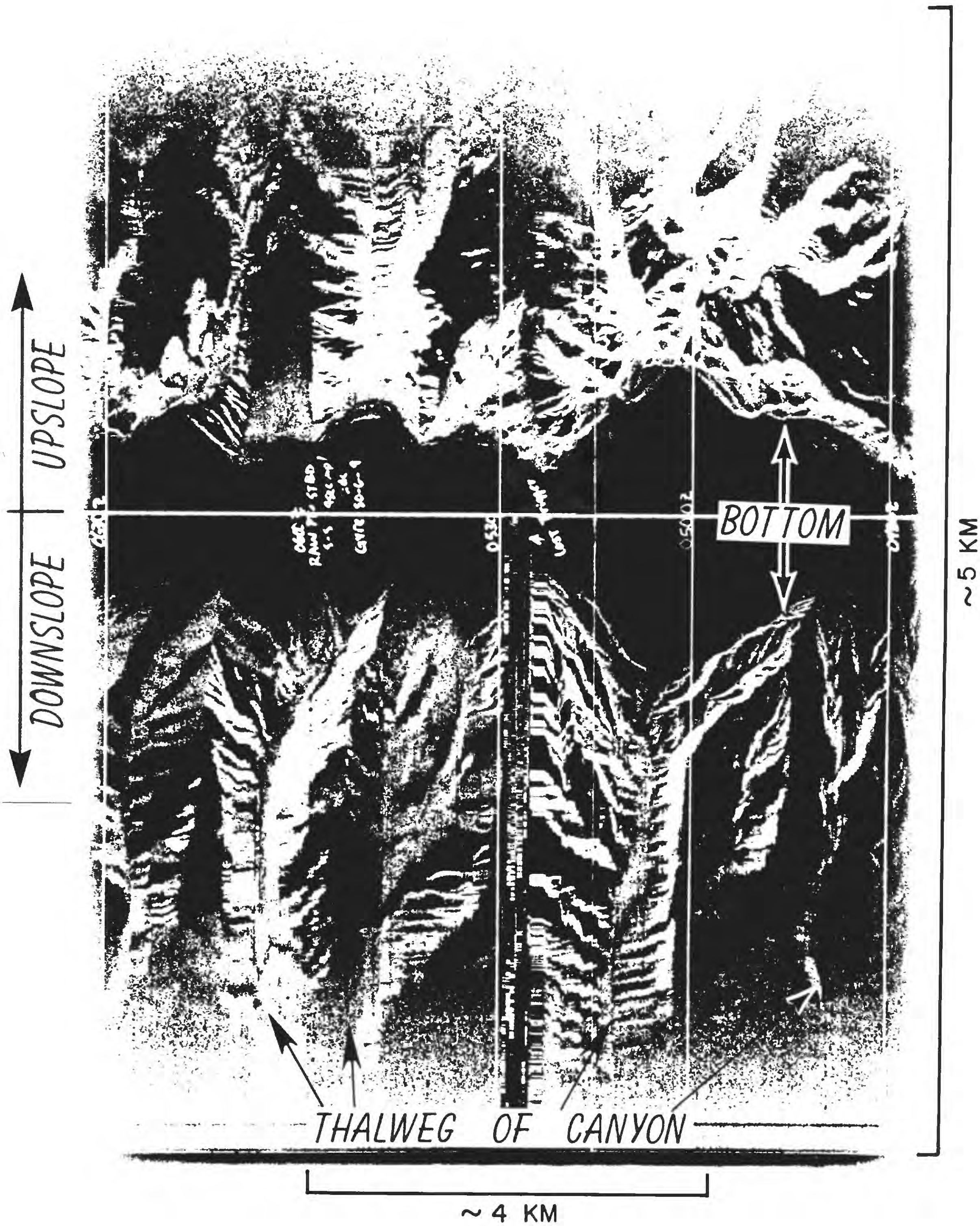

UPSLOPE
DOWNSLOPE
BOTTOM
THALWEG OF CANYON
~5 KM
~4 KM

Figure 24. Slant-range corrected mid-range sidescan sonar image of a submarine canyon near lat. 35°30′N., long. 74°45′W. This image shows the side downslope from the detector. Reflecting slopes (facing the detector) are dark, and shadows are light. The axis (a) of this canyon is not straight (as are the canyons shown in fig. 24) but bends at intersections of tributary canyons or chutes (b). Between canyons in this area are remnants of undissected slope (c).

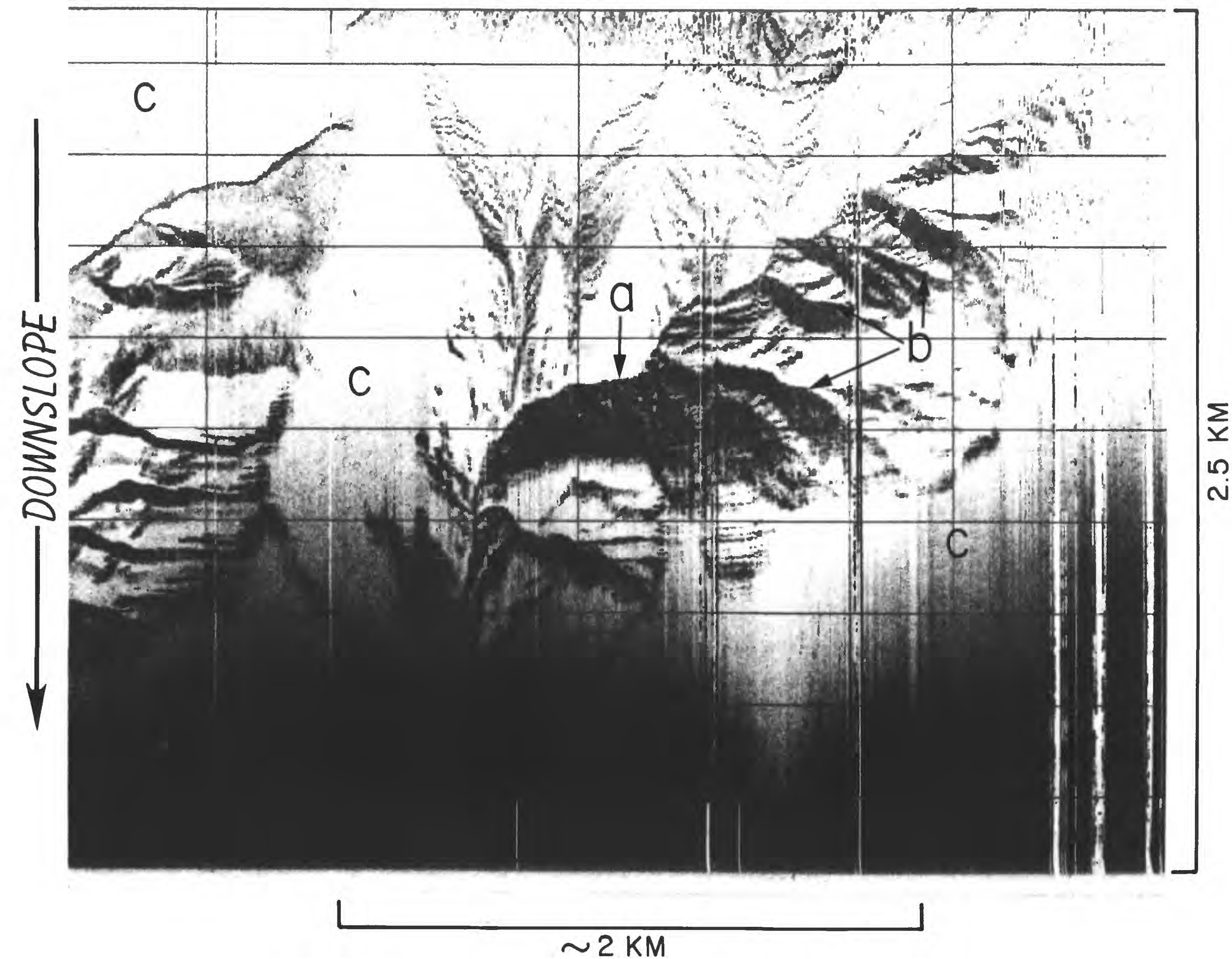
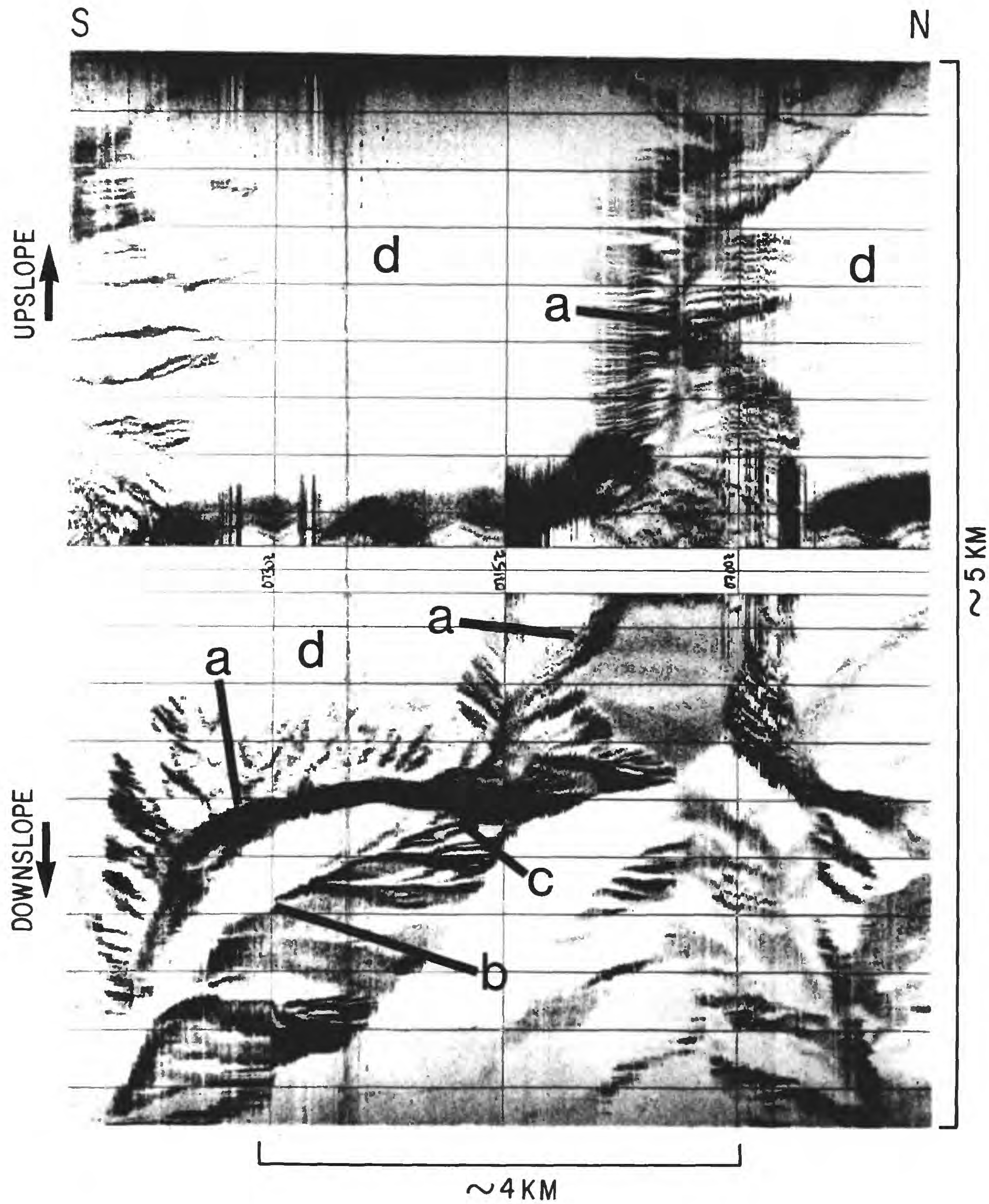


Figure 24

Figure 25. Slant-range corrected mid-range sidescan-sonar image showing a submarine canyon near lat. 35°30′N., long. 74°45′W. In this image, surfaces facing the detector (center line) are dark, and shadow zones are light. The main canyon (a) crosses the profile in a downslope direction with a slight jog to the south. Headwall erosion of a tributary canyon (b) is beginning to erode the divide between the two canyons at "c." Undissected slope (d) occurs on both sides of this canyon.


S
N
UPSLOPE
DOWNSLOPE
d
d
a
a
a
d
c
b
~5 KM
~4 KM

The clathrate layer probably does not pose a threat to drilling operations unless shallow gas (methane, ethane, carbon dioxide, hydrogen sulfide, etc.) is trapped beneath it. The penetration of shallow gas pockets beneath permafrost off Mackenzie Delta, Alaska, has led to the loss of several drill rigs (Peter Day, Phillips Petroleum Company, personal communication, 1980), and this danger may also exist with gas pockets trapped beneath clathrate. Very little is known of the dangers posed by gas pockets beneath clathrates because these frozen layers are in water depths that are beyond the present limits of exploration and production technology. As exploration proceeds into greater water depths, these shallow gas pockets may prove to be a primary hazard.

CONTINENTAL RISE

The Continental Rise overlies the deepest part of the Carolina trough. The Cretaceous paleoshelf edge (Dillon and others, 1981) and the salt diapirs beneath the rise (pl. 1, fig. 26) offer potential structural traps for petroleum or gas. Though few data are available on geologic hazards to or limits on exploration in these water depths, the primary drilling or production hazards probably include shallow gas pockets beneath clathrates and the possibility of debris flows from upslope. Limits on exploration or production would include strong currents from the Western Boundary undercurrent, filled channels, scour, and shallow faults associated with salt tectonism (pl. 1). Plate 1 outlines an area of highly disturbed sediments and shallow structures associated with the salt diapirism (for an example, see figs. 15, 16, and 26).

The potential hazard of debris flows on the rise from upslope mass wasting is supported by long-range sidescan-sonar (GLORIA) records from the mid-Atlantic region, which show large lobate areas in which the bottom is pushed into ridges 10 to 20 m high below Wilmington canyon, 20 km east of the base of the slope (B.A. McGregor, personal communication, 1981). These ridges, investigated by dives with the submersible ALVIN (B.A. McGregor, personal communication, 1981) were found to be the result of deformed and upturned clay having near-vertical bedding; the deformation is no doubt due to gravity tectonism.

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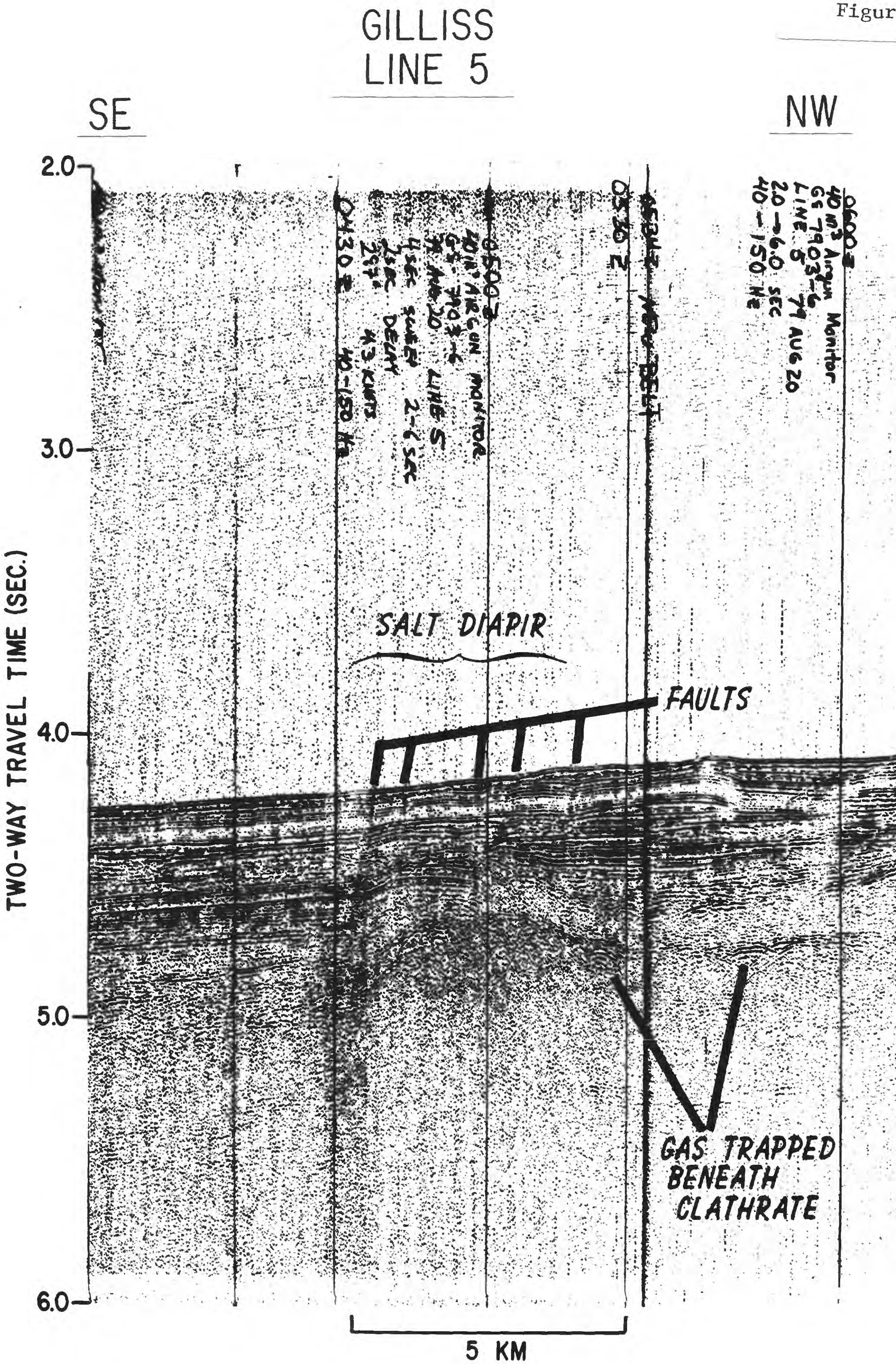
The investigations reported herein are an element of a broader environmental assessment program administered by the U.S. Bureau of Land Management (BLM) and related to the petroleum exploration and development of the Atlantic Continental margin. This report concerns one study element of the FY 79-80 program detailed in two Memoranda of Understanding (MOU AA551-MU9-8 and MOU AA551-MU0-16) between the Geological Survey (USGS) and BLM. The seismic-reflection data on which the report draws were obtained by cruises carried out in FY 76-80, manned by personnel of the USGS Woods Hole office, and funded jointly by the USGS and BLM. The long-range sidescan-sonar data (GLORIA) were obtained on a cruise carried out as a cooperative between the USGS and the British Institute of Oceanographic Sciences (IOS) of Wormley, Surrey, England. The mid-range sidescan-sonar data were obtained with a sidescan-sonar system developed by the Lamont-Doherty Geological Observatory (LDGO) of Columbia University, Palisades, NY, which was used on a cooperative cruise instigated and funded by BLM and manned by USGS and LDGO personnel.

Figure 26. Seismic-reflection record showing the top of a near-surface salt diapir near lat. 34°07´N., long. 75°15´W. Sediments over the diapir are fractured by faults, and the diapir slightly uplifts the sea floor. Note the "bright spots" caused by free gas trapped beneath the clathrate layer.

Figure 26


GILLISS
LINE 5
SE
NW
2.0
3.0
4.0
5.0
6.0
TWO-WAY TRAVEL TIME (SEC.)
SALT DIAPIR
FAULTS
GAS TRAPPED
BENEATH
CLATHRATE
5 KM

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