BOTTOM CHARACTER MAP OF THE NORTHERN BLAKE PLATEAU

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INTRODUCTION

This map shows the bottom character of the Florida-Hatteras shelf, slope, and northern Blake Plateau off Georgia and South Carolina based primarily on the integration of acoustic echo character with sampling information, submersible observations and other seismic data such as side scan sonar and deeper penetrating seismic reflection profiles. The utility of continuous 3.5 kHz echogram records in studying the sedimentary processes that affect the deep sea floor is well established (for references and a discussion of the use of these techniques on the US Atlantic margin see Clay and Rona, 1964; Bryan and Markl, 1966; Heezen and others, 1966; Hollister, 1967; Embley and Jacobi, 1977; Damuth and others, 1979; Mullins and others, 1979; Damuth, 1980; Embley, 1980; 1986; Laine, Damuth, and Jacobi, 1986; Pratson and Laine, 1989). The use of the technique in studying the sedimentary processes affecting shallower water is less established. In as much as echo character is a sensitive indicator of lithology, morphology, and induration of the shallowest sediments, variations in echo character are likely to be good indicators in differences in physical properties such as the density and velocity of the sea floor.

The principles and methods of echo character mapping have been described in detail by Damuth (1980). The parameters generally classified include seafloor morphology or roughness, the presence or absence of hyperbolic returns, the distinctness of the echo return of the seafloor, the prolongation of the subbottom echo, and whether other reflectors are visible in the subbottom and their orientation and clarity. All of the echo characteristics appear to have geologic meaning: bottom roughness can be of any scale, such as that of submarine canyons on the continental slope or that caused by furrows or bedforms such as ripples and sediment waves on the sea floor; echo prolongation can be related to sediment parameters such as the relative abundance of coarse bedded terrigenous sediment (silt, sand, gravel) in the upper few meters of the sea floor (Damuth and Hayes, 1977).

The accuracy and usefulness of the echo sounder interpretation is increased when combined with other information such as bathymetric data, bottom cores and photographs, sidescan sonar records (both short, mid-range (SeaMarc), and long-range (GLORIA) techniques), and deeper-penetrating lower-frequency seismic records. This additional information is necessary because echo character is not unique to any sea floor process without knowledge of environment. For instance, echo character classifications developed for the deep sea do not apply to the northern Blake Plateau region. Although Laine and others (1986) show the northern Blake Plateau on their compilation (their Plate 7) as nearly all characterized as indistinct (surface) echo with prolonged subbottom return and no subbottom reflectors (their echo type IIA, "apparently the result of sound-pulse reflections from laterally discontinuous beds"), I have found that this particular echo type is probably caused by few-meter thick veneer of sand over phosphorite pavement on the Blake Plateau. A second illustration of different causes of similar echo character types is shown on fig. 1A, an echo type characterized as a generally distinct sharp echo reflected by uneven mounds separated by notches and slope breaks interspersed with indistinct hyperbolic echos. This echo type is identical to Pratson and Laine (1989) echo type IVB, interpreted in the deep sea as produced by coarse mass-wasting debris covered locally with fine sediment. On the Blake Plateau this echo character is characteristic of current-eroded topography developed on Oligocene sediments in 250 m water depth. All that can be said with certainty in both cases is that the sea floor is very rough and the surficial sediments are compacted. These illustrations show that many of the echo types on the Blake Plateau are similar to those defined in the literature based on deep-sea echo character, but the processes that formed the echo character are different. Because of this, I have not used the published classifications of previous workers on my map, although I occasionally refer to the published number or letter designation assigned to a particular style of echo character as a comparison.

GENERAL GEOLOGY OF THE MAPPED AREA

The following discussion briefly outlines the general geology. The three major provinces of the study area are the Florida-Hatteras Shelf; Florida-Hatteras Slope; and the Blake Plateau which can be subdivided into the topographically flat southern Blake Plateau, the current-facing and topographically rough Charleston Bump, and the smooth-floored northern Blake Plateau. This discussion is for background only and is not intended to be comprehensive.

FLORIDA-HATTERAS SHELF

Most of the mapped area between the coastline and lat 79° W. is underlain by the Florida-Hatteras Shelf where water depths are generally shallower than 60 m. Bottom topography of the shelf is generally smooth and flat, marked mainly by gently undulating sand ridges or waves. Declivity is a fraction of a degree.

The surficial sediment of the Florida-Hatteras shelf is composed dominantly of sand that forms a thin veneer (generally 2 m or less) over older sedimentary rocks. The sand cover is well sorted and reworked by benthic infauna. In places older sediments (Miocene, Pliocene, or Pleistocene in age, also dominantly sands, clays and limestones) crop out. Although patchiness occurs, near-shore sediments tend to be fine-grained terrigenous sand, middle and outer-shelf sediments tend to be coarser-grained sand and there is an offshore increase in the carbonate component (Pilkey and others, 1980). Off Georgia, the Quaternary (Pleistocene and Holocene) sand cover is somewhat thicker, averaging about 10 m over the shelf and reaching more than 100 m in a progradational buildout at the continental slope (Edsall, 1978; Paull and Dillon, 1980; Popenoe, 1991). The sand cover thins northward off South Carolina where Miocene (Coosawhatchee Formation) and Pliocene (Duplin Formation) clay and sand underlie the shelf surface at shallow depth. These older sediments crop out at places to form ledges known as hardgrounds where indurated rocks create relief. The shelf edge on many of our crossings is marked by a *Lithothamnion* (algae cemented) ridge known as the shelf-edge reef or ridge (fig. 1B).

THE UPPER FLORIDA-HATTERAS SLOPE

The Florida-Hatteras slope forms the transition between the shallow Florida-Hatteras shelf (<60 m water depth) and the deeper Blake Plateau (250 to 1100 m depth). Slope sediments generally consist of fine-grained sands of Quaternary age on the upper slope. The sand is well-sorted because the Florida Current (Gulf Stream) has winnowed away much of the finer component. The upper slope generally forms a smoothly sloping surface of about 1.5° declivity with little or no relief.

THE LOWER FLORIDA-HATTERAS SLOPE

On the lower Florida-Hatteras slope phosphatic sediments of middle Miocene age are at or near the surface and the slope is considerably rougher than its shallower part and usually slightly steeper. Submersible dives to the lower slope (Milliman and others, 1967; Popenoe, unpublished observations from the Johnson SeaLink in July, 1992) show that the lower slope is characterized by a bottom that is variably phosphatic gravel, deep-water coral mounds or coral rubble, or glauconitic sand. The transition from the upper slope, underlain by Quaternary sand, to the lower slope, underlain by phosphatic Miocene sandy silts and clays, is relatively sharp and can be recognized on bathymetric charts (National Ocean Survey 1976; 1978a; 1978d) by a distinct change in bottom roughness. Much of the roughness is due to deep-water coral mounds that apparently originally gained a foothold by attachment to phosphatic gravel winnowed by the Gulf Stream from the Miocene sediments. No canyons or mass wasting features are apparent.

THE BLAKE PLATEAU

On the Blake Plateau there are three major bathymetric and depositional provinces; the flat-surfaced and deeper southern Blake Plateau that overlies the Blake Plateau Basin; the rougher, shallower, current-facing south flank of the Charleston Bump, a bathymetrically shallower area that overlies a corner of the Carolina Platform that projects onto the Blake Plateau (Dillon and Popenoe, 1988; Klitgord and others, 1988); and the smoother and shallower northern Blake Plateau, down-current of the bathymetric rise.

The southern Blake Plateau

Gulf Stream currents acting on the bottom of the deeper (800-1000 m), flat, southern part of the Blake Plateau are less intense. Drill holes (Charm and others, 1969; Schlee and Gerard, 1965; Schlee, 1977) and cores (Kaneps, 1979) show that the bottom is comprised of well-winnowed and sorted, medium- to coarse-grained foraminiferal sand at the surface that grades downward into a clayey ooze at depth. The thickest accumulations of post-Miocene sediments occur on the outer Blake Plateau, east of the axis of the Gulf Stream. Northward, currents intensify at the foot of the Charleston Bump as the Gulf Stream currents are diverted eastward by the shoaling bathymetry to the north, and post-Miocene sediments have been scoured away.

The south flank of the Charleston Bump

In the central part of the mapped area the Charleston Bump forms a landward shallowing ramp that creates a bathymetric barrier to Gulf Stream flow. Because of intensification of Gulf Stream bottom currents caused by constriction, the bottom on the current-facing flank of the Charleston Bump is scoured down to erosion-resistant, indurated strata of Paleogene (Paleocene, Eocene, and lower Oligocene) and Upper Cretaceous age. These rocks are capped by a nearly continuous lag of phosphorite gravel winnowed from formerly present phosphatic Miocene sediments. In most areas these gravels are now cemented into an impenetrable pavement that has been impregnated and coated by a manganese rind precipitated over millions of years from the sea water (Manheim and others, 1980).

Erosion of the older rocks on the Charleston Bump is controlled by composition. The late Cretaceous rocks, where exposed by scour, are calcareous siltstones equivalent to the onshore PeeDee and Black Creek Formations found in the Cape Fear region of North Carolina (Sohl and Owens, 1991). In the offshore these rocks form a prodeltaic outbuilding (slope facies) of terrigenous clastics into the Blake Plateau Basin and Carolina Trough from the Cape Fear area. Within the Blake Plateau Basin the composition of the unit changes to dominantly calcareous marl deposited in deeper water, but these marls are now buried and not exposed. The late Cretaceous sequence is extremely resistant to erosion and where Cretaceous strata are near the sea floor, they are exposed by erosion but not deeply dissected. Our submersible observations within the area of Cretaceous outcrop indicate that phosphorite pavement and a thin veneer of calcareous sand form the surface in most areas, and exposures of bedrock are common in scour depressions.

This contrasts with the erodability of the Paleogene sequence. Paleogene rocks are dominantly moderately- to well-indurated calcarenites containing stringers of siliceous limestone and chert that ring when hit with a hammer and that break with a conchoidal fracture (Schlee and Gerard, 1965). They are interlayered with soft ooze having the consistency of ice-cream. It is the indurated strata, however, that form the eroded surface beneath the phosphorite pavement cover because softer sediments were scoured away prior to deposition of the pavements. Phosphorite pavement up to a meter thick is nearly ubiquitous in areas of Paleogene subcrop (figs. 2, 3, 4).

Erosion of the Paleogene strata was strongly controlled by the layering. On the current-facing south flank of the Charleston Bump erosion has been checked by the harder layers so that much of the topography follows a smooth paleo-depositional surface that is breached only by scattered scour holes. At places, distinct layers have been stripped from this surface causing a step-like break in bottom profile where erosion has proceeded to an underlying hard layer. The layering forms ledges and overhangs in large scour holes that breach the bottom (fig. 5). Some hard layers are sufficiently thick and indurated to project as much as 10 m from cliff faces (Popenoe and Manheim, 1991).

On the periphery of the highly scoured area of the Charleston Bump, preserved by less-intense scour, deep-water calcarenitic ooze of Miocene age overlies the Paleogene carbonates. The ooze is faintly mottled to massive, and unconsolidated to partly compacted (Schlee, 1977). On intensely scoured areas of the plateau, as stated previously, soft Miocene sediments that were formerly present have been scoured away leaving a phosphorite lag gravel that has been cemented into pavement (Manheim and others, 1980; Popenoe and Manheim, 1991).

North of the Charleston Bump

North of the Charleston Bump the surficial sediments are well sorted and winnowed foraminiferal sands that are 50% to over 75% carbonate (Hathaway, 1971). These sands have accumulated on the downcurrent, or lee side, of the Charleston Bump where bottom currents are less strong due to diversion of the Gulf Stream by the shoal bathymetry to the south. Late Oligocene- and late Miocene-age sands and foraminiferal oozes crop out near the highest parts of the Bump near lat 32°50′ N., lon 77°30′ W. and cause bottom roughness at the base of the Florida-Hatteras slope on the inner Blake Plateau from the resistance of these older units to bottom scour. This roughness is apparent on the echo-sounder records and is illustrated on the Richardson Hills and Cape Fear bathymetric maps (National Ocean Survey, 1978c; 1978e). Farther offshore and downcurrent the bottom consists of partly indurated and well-winnowed sand of Pliocene age. These scoured areas become covered northward by smoother sands of Pleistocene and Holocene age. Just north of the mapped area at lat 33°10′ N., long 77° W. a large sand wave field demonstrates the presents of strong northward-flowing currents acting on the bottom (fig. 6).

CORAL MOUNDS

Along the inner Blake Plateau and in a belt crossing the northern Blake Plateau near lat 32° N., coral mounds make up much of the bottom. The mounds, which are particularly developed in areas of rugged topography, are seen on seismic records as hyperbolae with transparent cores. The mounds, which range in size from less than a meter to over 100 m high, are built of sticky pelagic ooze held within a framework of coral debris and other materials (Stetson and others, 1962; Mullins and others, 1981). The tops of the mounds are capped by living deep-water ahermatypic coral thickets (fig. 7). Stetson and others, (1962) proposed that the thicket-like structure of the coral, mainly *Dendrophyllia profunda* and *Lophelia prolifera,* forms a baffle that traps mud and other organic debris causing the mounds to build upward. Living coral thickets occupy mainly the top surface of the mound. Our submersible dives on the mounds (Popenoe, unpublished observations from the Johnson SeaLink, July, 1992) show that the mounds are steep-sided with slope angles of up to 45° or more and have sharp, pinnacle-like tops. The mounds were easily penetrated by push cores and the holes visibly collapsed on removal of the core, causing a turbidity plume in the water column demonstrating their soft, unconsolidated nature.

Coral mounds are rare south of lat 31° 45′ except on the inner Blake Plateau, probably because the currents are too strong to allow the trapping of hemipelagic material that infill the coral structure to build mounds. Much of the area where coral mounds are not common is characterized by solitary corals and sponges that are attached to pavement and project through the thin sand veneer (fig. 3). These corals, which do not appear to be mound-builders, show visible abrasion from the drifting sand indicating that they are ephemeral in this environment.

CONSTRUCTION OF THE BOTTOM CHARACTER MAP

My bottom character map is not a true echo character map, as it is based in part on a knowledge of surficial and shallow subsurface stratigraphy as it relates to 3.5 kHz echo character. The map was constructed based on the interpretation of 3.5 kHz echo sounder profiles, and on a seismic-stratigraphic interpretation from deeper-penetrating single channel and sparker seismic reflection records. Both published (National Ocean Survey, 1969; 1976; 1978a-e) and unpublished bathymetry (Popenoe, in press) were also used to guide in drawing echo-type boundaries between tracklines. In addition, east of lat 79° W., the GLORIA sidescan sonar image of the northern Blake Plateau (EEZ-SCAN 87 Scientific Staff, 1991) was used to guide in drawing boundaries since the GLORIA record also presents an acoustic picture of the sea floor and shallow subbottom. The distribution of tracklines on which 3.5 kHz profiles were recorded and examined to construct the map are shown on the map. These data were from the R.V. Fay cruises 17 and

18 (McGinnis and Locker, 1976; Dillon, 1976), R.V. Iselin, 1979 cruise 3 (Popenoe, 1980), and the 1987 R.V. Farnella cruises including legs 1 and 5 (EEZ-SCAN 87 Scientific Staff, 1991). Locations of figures discussed in the text are also shown.

3.5 kHz echo character was examined on all profiles and was noted along tracklines. Prominent breaks in the bottom, scarps seen on seismic records and on the GLORIA image, and deep-water coral mounds were also recorded. Subcrop geology (Edsall, 1978; Paull and Dillon, 1980; Paull and others, 1980; Pinet and Popenoe, 1985; Popenoe, 1991) was used to guide in drawing boundaries. The map is an attempt to present acoustic provinces that reflect sea floor morphology, shallow subsurface geology, and acoustic provinces of the Blake Plateau and Florida-Hatteras shelf and slope. Although much of the bottom of the Blake Plateau is capped with a pavement of cemented phosphorite and phosphorite-manganese gravel (Manheim and others, 1980) that is as much as a meter thick, this pavement sits on sediments of variable induration, which influences the shallow velocity structure.

CLASSIFICATION AND DISTRIBUTION OF ECHO TYPES

FLORIDA-HATTERAS SHELF AND UPPER FLORIDA-HATTERAS SLOPE

Essentially all of the Florida-Hatteras shelf and the upper slope are characterized by the Laine and others (1986) echo type IB. This echo type displays a distinct, strong bottom echo with discontinuous or little subbottom return (echo character "A" on Plate 1). Laine and others (1986) state that this echo type is the most common for the consolidated sediments of continental shelves where distinct sharp surface echos are observed with little subbottom penetration. Because compact sand makes up the bottom, most of the sound energy is reflected or attenuated, and acoustic penetration is limited to a few meters.

There are three types of type IB echos observed, but these have not been separated on my map, chiefly because the profiles recorded by the R.V Fay cruises were not always uniform, causing adjacent lines to differ slightly in character. The most common echo type, demonstrated by figure 8A, is characterized by a smoothly undulating shelf surface, a sharp bottom echo and discontinuous subsurface echos with subbottom penetration of about 15 m. This echo type varies on the inner shelf where cut-and-fill channeling is commonly seen, particularly on coast-parallel tracklines. A second variation, demonstrated by figure 1B, is a less-sharp surface echo and a semi-prolonged subbottom return with no internal reflections. A third variation, demonstrated by figure 8B and seen mainly on the outer shelf and upper slope, is a strong surface echo with no subbottom return.

Noted in a few areas of the shelf are crossings of more rugged bottom relief caused by *Lithothamnion* hardgrounds or outcropping older strata (fig. 1). Only prominent, high-relief (>3 m) hardground areas, mainly the shelf-edge reef, are shown on my map.

I was unable to trace the location of these features between tracklines by using published bathymetric charts and the GLORIA image was not collected at these shallow depths.

LOWER FLORIDA-HATTERAS SLOPE

The middle to lower Florida-Hatteras slope, where Miocene rocks are near the surface, has an irregular "bumpy" texture (figures 9A, 9B) due mainly to coral mounds that have gained an attachment to the phosphatic lag gravels winnowed from the Miocene sediments (echo character "B" on Plate 1). The mounds are all sizes on the lower slope, ranging from less than 1 m to over 30 m high. They are alligned along slope forming ridges and troughs, some in excess of 1 km in length (Milliman and others, 1967).

BLAKE PLATEAU

The echo character from the post-Miocene sediments well south of the Charleston Bump on the Blake Plateau is similar to those of the continental shelf but with fewer discontinuous subbottom reflectors (echo type "A"). These sediments are easily recognized on 3.5 kHz records by a smooth, sharp bottom echo with a few reflectors in the subbottom (fig. 10A) to somewhat fuzzy (fig. 10B) sea floor echo with a semi-prolonged subbottom echo. Like shelf sands, these sands are well-compacted and winnowed. Post-Miocene sands occur mainly south of lat 30°30′ N. (Fig. 10B) and north lat of 32° N (fig. 10A). They also occur within a large, north-northeast striking, shallow scour depression (now partly filled with Miocene and post Miocene sediments) that crosses the outer part of the northern Blake Plateau between about lat 31°45′N., long 77°50′W. and lat 31°45′N., long 77°30′W. (fig. 10C).

On the southern part of the map a textural change in bottom composition is apparent from 3.5 kHz echo character which shows a change from a sharp bottom return with a prolonged echo on the south central part of the mapped area to a somewhat fuzzy bottom return with a prolonged echo in the southeast quadrant of the map. The change probably reflects an increase in pelagic ooze toward the outer part of the Blake Plateau.

Miocene sediments are characterized by a bumpy, irregular-surfaced bottom (figures 11A, 11B, 11C) with a semi-prolonged echo on 3.5 kHz echo sounder profiles. This texture probably results from scattered accumulations of phosphorite pavement rubble lying on the sea floor as well as small deep-water coral mounds. The boundaries of the Miocene sediments are also easily traced on the GLORIA image by the contrast of their intermediate-brightness gray tone with the brighter or darker tones of other units. The intermediately-bright return from Miocene sediments on the GLORIA image probably results both from greater induration than post-Miocene sands and from the rough surface texture of the unit that causes high backscatter of the sidescan-sonar signal. The sea floor over Miocene sediments does not have a well-developed pavement layer at the surface. Both the echo-character and the GLORIA sidescan sonar character of the Miocene sediments is distinct, allowing us to map their distribution in detail.

Oligocene foraminiferal calcarenites and limestones crop out on the crest of the Charleston Bump that have a distinct echo character because of the mesa-like erosional topography of the sea floor (figures 12A, 12B). The Oligocene sediments are characterized by a strong return from the bottom and no subbottom penetration or by hyperbolic echos (fig. 1A). Our submersible dives in this area (Popenoe, observations from the Delta submersible in July, 1990) found a bottom that is composed of fragmented phosphorite slabs lying on hard limestone layers whose surfaces were highly phosphatized. The unit is distinct on the James Island bathymetric chart (National Ocean Survey, 1969) because numerous small ridges and depressions with an east-west grain make up the sea floor. Sampling of the unit was difficult because of phosphatization, but two samples of clayey calcarenite of a plastic consistency, made up entirely of foraminiferal tests of early Oligocene age, were recovered from tilefish burrows during our dives. Attempts to piston core in this area failed to recover any bedrock and resulted in numerous bent pipes or smashed core cutters (M.W. Ayers, unpublished cruise report, Eastward cruise E-2E-78, Duke University; Ayers and Pilkey, 1981).

There are four echo types that are characteristic of the highly-scoured south-facing flank of the Charleston Bump. The typical bottom return for phosphorite pavement where it overlies hard strata (silicic limestone?) on the smooth surfaced part of the Bump (fig. 13) is a sharp, continuous echo having a second reflection that follows bathymetry. There are no other subbottom reflections. The double reflection is probably caused by the return of the entire outgoing pulse chirp by the extremely hard sea floor. Since most of the 3.5-kHz energy is returned by the sea floor, almost no energy can penetrate the bottom to reflect off deeper horizons. A "fuzzy" or less distinct sea floor combined with the double reflection or prolonged subbottom echo (figs. 14, 15) is interpreted to indicate extensive coral and sponge growth on the pavement and a thicker veneer of sand over the pavement. Both of these echo types characterize the sea floor on the less-dissected south flank of the Charleston Bump.

On the bottom character map I have divided the Paleogene section into two echo-character units, based primarily on the smoothness of the seafloor. Smooth sea floor, breached only by occasional scour holes is characteristic of much of the southern flank of the Charleston Bump. It is my belief that this unit probably constitutes the highest shallow velocity unit of the map, since the unit reflects both a relatively thick and unbroken capping of phosphorite pavement at the surface that lies directly over a relatively thick continuous layer of indurated strata, probably silicic limestone. My second unit reflects greater dissection of the Paleogene units by bottom current scour. This scoured unit is characterized by a rugged and dissected bottom that forms scarps, buttes, and mesas. Although phosphorite pavement also caps this eroded surface, the pavement is more likely to be fragmented by undercutting, and the subbottom is not a coherent continuous layer but is formed by the breaching of many layers.

Where the bottom is highly eroded the echo character is typically a strong bottom return with a more prolonged subbottom echo (fig. 16A, 16B). On most 3.5 kHz profiles a wispy second reflection that follows the seafloor is usually evident. Submersible dives in the area of 16A indicate that most of the erosion of the sea floor occurred prior to the formation of the phosphorite pavements, since unbroken phosphorite pavements are found in the bottoms of the largest scour depressions (Popenoe and Manheim, in preparation). The sea floor over the highly eroded areas appears to be very hard and the sand veneer is probably underlain by pavement in most areas. As stated earlier, this unit is mapped separately on the bottom character map.

In areas of rugged topography on the inner Blake Plateau coral mounds are so large and numerous that the detailed configuration of the sea floor is obscured on 3.5 kHz records by hyperbolic echos (fig. 16C).

Because of the change in composition and erosional character between the Cretaceous sequence and the overlying Paleogene rocks, I have classified areas of Cretaceous outcrop on the Bottom Character Map as a distinct echo-character unit. Figures 17A and 17B demonstrate the echo character of this unit, that of a strong bottom return with a slightly prolonged subbottom echo. Both profiles show coral mounds.

Figure 18 demonstrates the hyperbolic, rough bottom with a strong surface return and a semi-prolonged subsurface echo associated with an area near the top of the Blake Escarpment that is characterized on the GLORIA sidescan sonar image as an area of circular bottom features. One possible explanation for these features is that they represent the top of an ancient reef now exposed by scour.

REFERENCES CITED

Ayers, M.W., and Pilkey, O.H., 1981, Piston cores and surficial sediment investigations of the Florida-Hatteras Slope and inner Blake Plateau; in Popenoe, Peter, Environmental geologic studies on the southeastern Atlantic Outer Continental Shelf: U.S. Geological Survey Open-File Report 81-582-A, p. 5-1 to 5-89.

Bryan, G.M., and Markl, R.G., 1966, Microtopography of the Blake-Bahama region: Lamont Geological Observatory Technical Report no. 8, CU 8-66-NObsr 85077, 44 p.

Charm, W.B., Nesteroff, W.D., and Valdes, Sylvia, 1969, Detailed stratigraphic description of the JOIDES cores on the continental margin off Florida: U.S. Geological Survey Professional Paper 581-D, 13 p.

Clay, C.S., and Rona, P.A., 1964, On the existence of bottom corrugations in the Blake-Bahama Basin: Journal of Geophysical Research, v. 69, p. 231-234.

Damuth, J.E., 1980, Use of High-frequency (3.5 kHz) echograms in the study of near-bottom sedimentation processes in the deep sea; a review: Marine Geology v. 38, p. 51-75.

Damuth, J.E., and Hayes, D.E., 1977, Echo character of the east Brazilian continental margin and its relationship to sedimentary processes: Marine Geology, v. 24, p. M73-M95.

Damuth, J.E., Tucholke, B.E., and Coffin, M.F., 1979, Bottom processes on the Nova Scotian continental rise revealed by 3.5 kHz echo character (abs.): EOS, Transactions, American Geophysical Union, v. 60, p. 855.

Dillon, W.P., 1976, Cruise report, R/V FAY 017, June 20-29, 1976: Unpublished USGS cruise report, Woods Hole, MA, 5 p.

Dillon, W.P., and Popenoe, P., 1988, The Blake Plateau Basin and Carolina Trough, in R.E. Sheridan and J.A. Grow, eds., The Geology of North America Volume I-2, The Atlantic Continental Margin: U.S.: Geological Society of America DNAG Series, p. 291-328.

Edsall, D.W., 1978, Southeast Georgia Embayment high-resolution seismic-reflection survey: U.S. Geological Survey Open-File Report 78-800, 90 p.

Embley, R.W., 1980, The role of mass transport in the distribution and character of deep ocean sediments with special reference to the North Atlantic: Marine Geology, v. 38, p. 23-50.

Embley, R.W., and Jacobi, Robert, 1977, Distribution and morphology of large sediment slides and slumps on Atlantic continental margins: Marine Geotechnology, v. 2, p. 205-228.

Embley R.W., and Jacobi, Robert, 1986, Mass wasting in the western North Atlantic, in Vogt, P.R., and Tucholke, B.E., eds., The Geology of North America, Vol. M, The Western North Atlantic Region: Geological Society of America, Boulder, Colo., p. 479-490.

EEZ-SCAN 87 Scientific Staff, 1991, Atlas of the U.S. United States Exclusive Economic Zone--Atlantic Continental Margin: U.S. Geological Survey Miscellaneous Investigation Series I-2054, 174 p.

Hathaway, J.C., 1971, Data file, Continental Margin Program, Atlantic coast of the United States: Woods Hole Oceanographic Institution Technical Report reference no. 71-15, 696 p.

Heezen B.C., Hollister, C.D., and Ruddiman, W.F., 1966, Shaping the continental rise by deep geostrophic contour currents: Science, v. 152, p. 502-508.

Hollister, C.D., 1967, Sediment distribution and deep circulation in the western North Atlantic [Ph.D. thesis]: Columbia University, 369 p.

Kaneps, A.G., 1979, Gulf Stream, velocity fluctuations during the late Cenozoic: Science, v. 204, p. 297-301.

Klitgord, K.D., Hutchinson, D.R., and Schouten, Hans, 1988, The U.S. Atlantic continental margin; structural and tectonic framework, in Sheridan, R.E., and Grow, eds., The Geology of North America, Vol. I-2, The Atlantic Continental Margin, U.S.: The Geological Society of America, Boulder, Colo., p. 19-55.

Laine, E.P., Damuth, J.E., and Jacobi, Robert, 1986, Surficial sedimentary processes revealed by echo-character mapping in the western North Atlantic Ocean, in Vogt, P.R., and Tucholke, B.R., eds., The Geology of North America, Vol. M, The Western North Atlantic Region: Geological Society of America, Boulder, Colo., p. 427-436.

Manheim, F.T., Pratt, R.M., and McFarlin, P.F., 1980, Composition and origin of phosphorite deposits of the Blake Plateau: in Bentor, Y.K., ed., Marine Phosphorites: Society of Economic Paleontologists and Mineralogists Special Publication no. 29, p. 117-137.

McGinniss, L.D., and Locker, S.D., 1976, Cruise report, FAY 018:

unpublished USGS cruise report, Woods Hole, MA, 14 p.

Milliman, J.D., Manheim, F.T., Pratt, R.M., and Zarudski, F.K., 1967, Alvin dives on the continental margin off the southeastern United States, July 2-13, 1967: Woods Hole Oceanographic Institute Technical Report reference no. 67-80, 64 p.

Mullins, H.T., Bordman, M.R., and Neumann, A.C., 1979, Echo character of off-platform carbonates: Marine Geology, v. 32, p. 251-268.

Mullins, H.T., Newton, C.R., Heath, Kathryn, and Vanburen, H.M., 1981, Modern deep-water coral mounds north of little Bahama Bank: criteria for recognition of deep-water coral bioherms in the rock record: Journal of Sedimentary Petrology, v. 51, p. 999-1013.

National Ocean Survey, 1969, James Island, South Carolina: Topographic Bathymetric Map NI 17-12, scale 1:250,000.

National Ocean Survey, 1976, Jacksonville, Bathymetric Map NH 17-5, scale 1:250,000.

National Ocean Survey, 1978a, Hoyt Hills: Bathymetric Map NH 17-3, scale 1:250,000.

National Ocean Survey, 1978b, Harrington Hill: Bathymetric Map NH 18-1, scale 1:250,000.

National Ocean Survey, 1978c, Richardson Hills, Bathymetric Map NI 18-10, scale 1:250,000.

National Ocean Survey, 1978d, Stetson Mesa, Bathymetric Map NH 17-6, scale 1:250,000.

National Ocean Survey 1978e, Cape Fear, Bathymetric Map NI 18-7, scale 1:250,000.

Paull, C.K., and Dillon, W.P., 1980, Structure, stratigraphy and geologic history of the Florida-Hatteras Shelf and inner Blake Plateau: American Association of Petroleum Geologists Bulletin v. 64, p. 339-358.

Paull, C.K., Popenoe, Peter, Dillon, W.P., and McCarthy, S.M., 1980, Geologic subcrop map of the Florida-Hatteras shelf, slope, and inner Blake Plateau: U.S. Geological Survey Miscellaneous Field Investigation Map MF-1171, scale 1:500,000.

Pilkey, O.H., Keer, Fred, and Keer, Stephanie, 1980, Surficial sediments of the U.S. Atlantic southeastern United States continental shelf, in Popenoe, Peter, ed., Environmental studies, southeastern United States Atlantic continental shelf: U. S. Geological Survey Open-File Report 80-146, p. 5-1 to 5-40.

Pinet, P.R., and Popenoe, P., 1985, Shallow seismic stratigraphy and post-Albian geologic history of the northern and central Blake Plateau: Geological Society of America Bulletin v. 96, no. 5, p. 627-638.

Popenoe, Peter, 1980, Single-channel seismic-reflection profiles collected on the northern Blake Plateau, 29 September to 19 October, 1978: U.S. Geological Survey Open-file Report 80-1265, 4 p.

Popenoe, Peter, 1991, Maps and cross sections depicting the shallow seismic stratigraphy of the continental shelf and slope off Georgia from interpretation of high-resolution seismic-reflection data: U.S. Geological Survey Open-File Report 91-97, 35 p.

Popenoe, Peter, in press, Geology, bathymetry, and sea floor character of the northern Blake Plateau: U.S. Geological Survey Miscellaneous Investigations Series map MF 94- , 4 sheets.

Popenoe, Peter, and Manheim, F.T., 1991, Phosphorite deposits of the Blake Plateau as observed from the NR-1 submarine and DELTA submersible, in U.S.G.S. Research on Mineral Resources - 1991: U.S. Geological Survey Circular 1062, p. 61-63.

Pratson, L.F., and Laine, E.P., 1989, The relative importance of gravity-induced versus current-controlled sedimentation during the Quaternary along the mideast U.S. Outer Continental Margin revealed by 3.5 kHz echo character: Marine Geology, v. 89, p. 87-126.

Schlee, J.S., 1977, Stratigraphy and Tertiary development of the continental margin east of Florida: U.S. Geological Survey Professional Paper 581-F, 25 p.

Schlee, J.S., and Gerard, R., 1965, Cruise Report and preliminary core log, M/V CALDRILL I--17 April to 17 May, 1965: J.O.I.D.E.S Blake Panel Report, NSF Grant GP-4233, unpublished, 64 p.

Sohl, N.F., and Owens, J.P., 1991, Cretaceous stratigraphy of the Carolina Coastal Plain, in Horton, J.W., and Zullo, V.A., The Geology of the Carolinas: The University of Tennessee Press, Knoxville, p. 191-220.

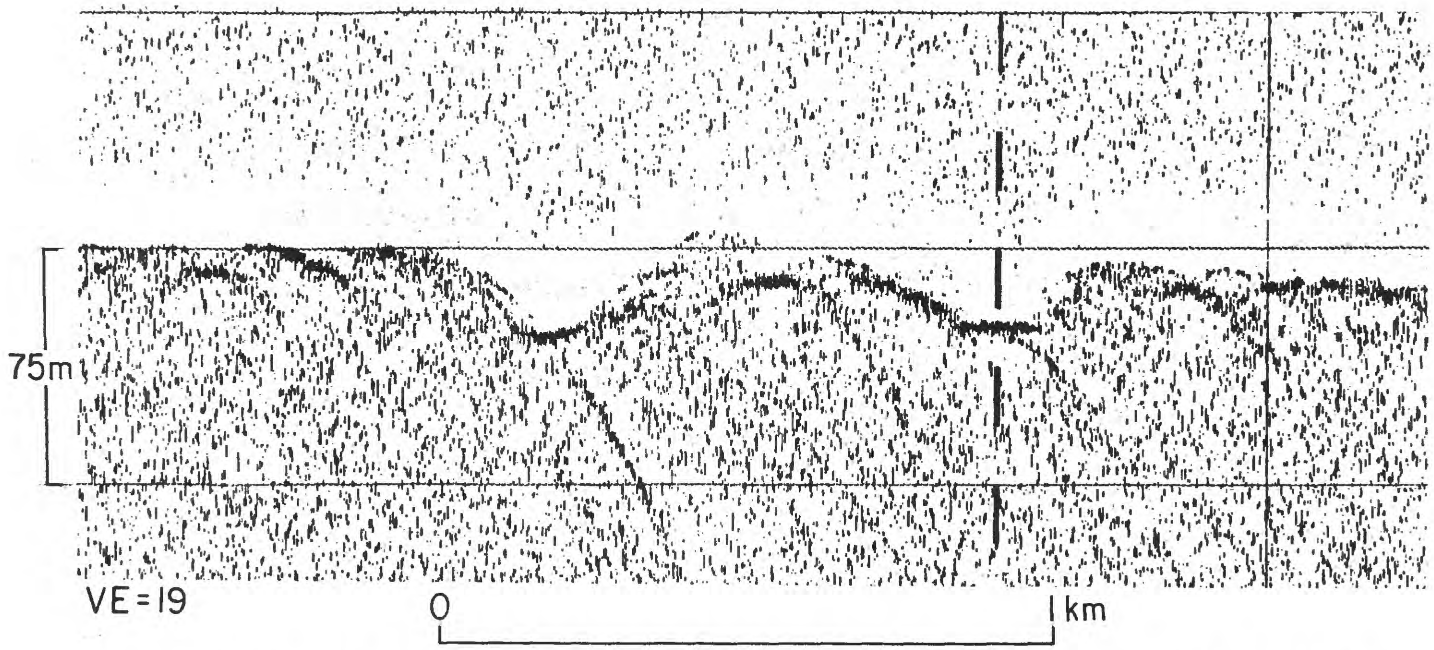


Figure 1A. Echo character of current-eroded bottom in 250 m water depth at the crest of the Charleston Bump. This echo character of uneven mounds separated by notches and slope breaks is identical to Pratson and Laine (1989) echo character IVB, characteristic of the rough bottom produced by mass wasting debris on the continental rise. This echo character is caused by a rough seafloor, but is not diagnostic of the process that formed that surface.

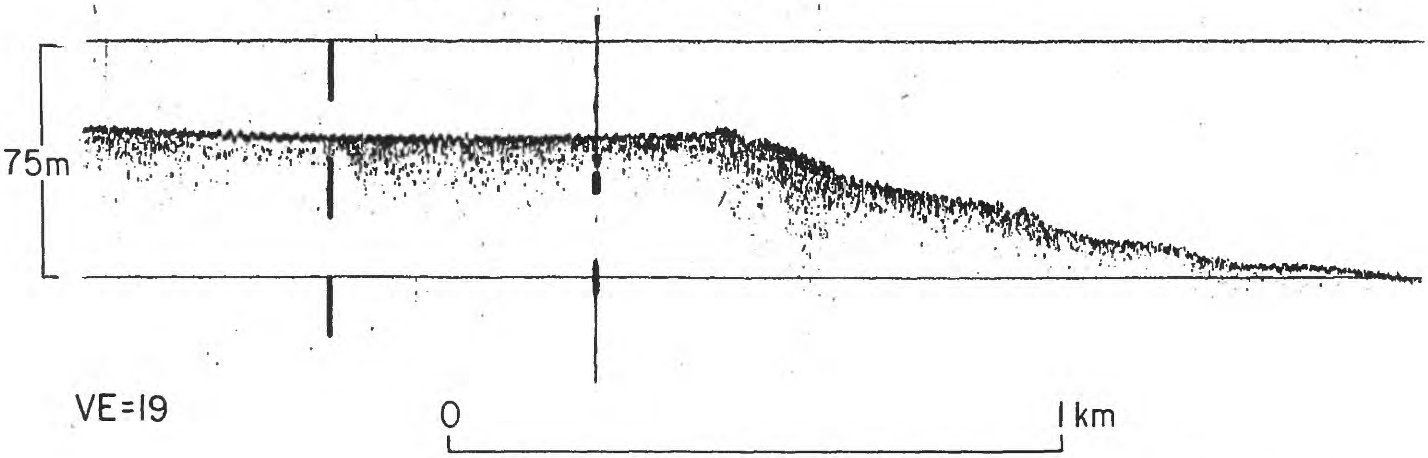


Figure 1B. 3.5 kHz echo sounder record across the shelf-edge ridge or reef.

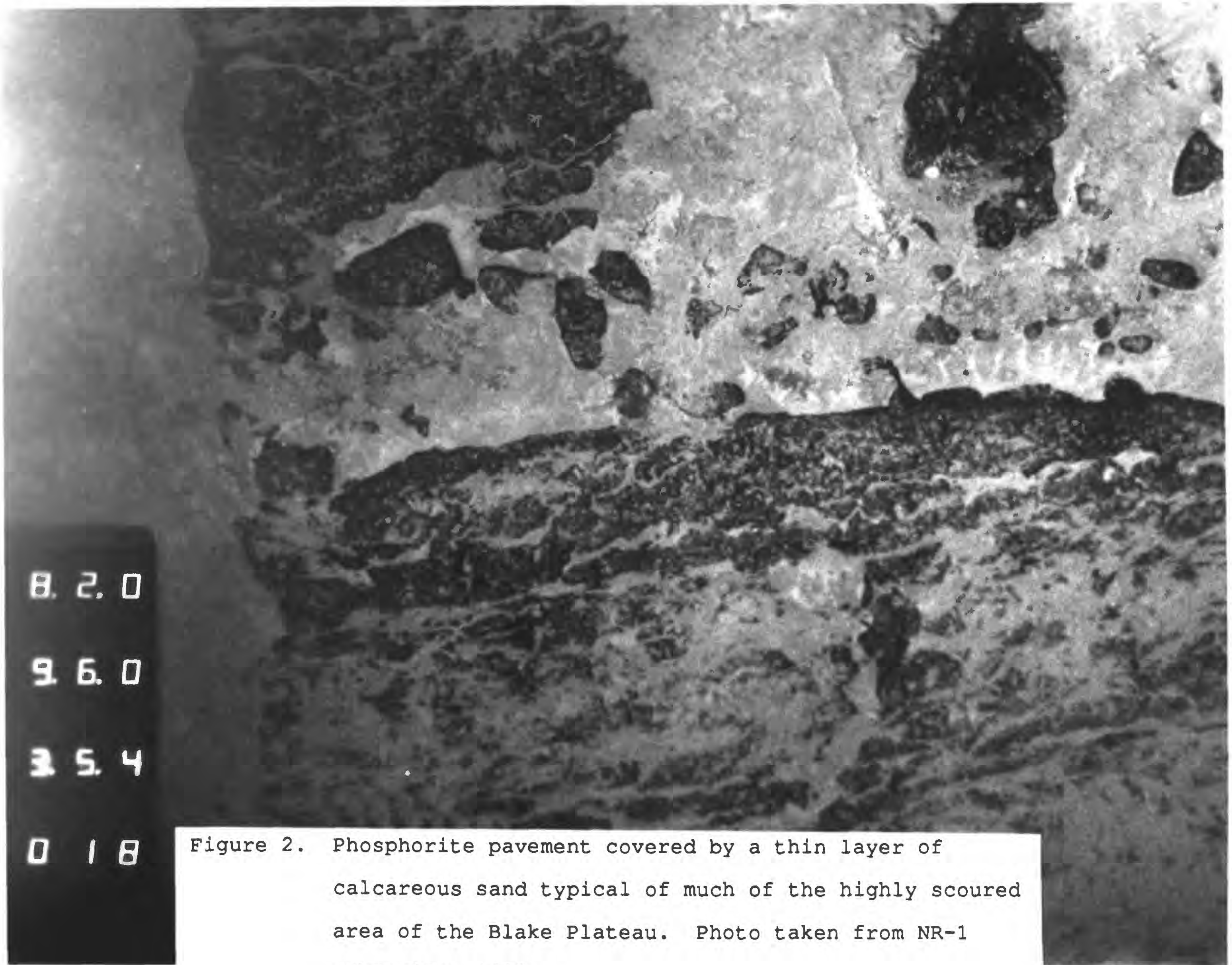


Figure 2. Phosphorite pavement covered by a thin layer of calcareous sand typical of much of the highly scoured area of the Blake Plateau. Photo taken from NR-1 submarine, 1990.

Figure 3. Deep-water coral and sponge covered sea floor on the south-facing flank of the Charleston Bump. The coral is attached to phosphorite pavement that underlies a thin veneer of drifting carbonate sand. Photo with permission of Barbara Hecker, Lamont-Doherty Geolgic Observatory.

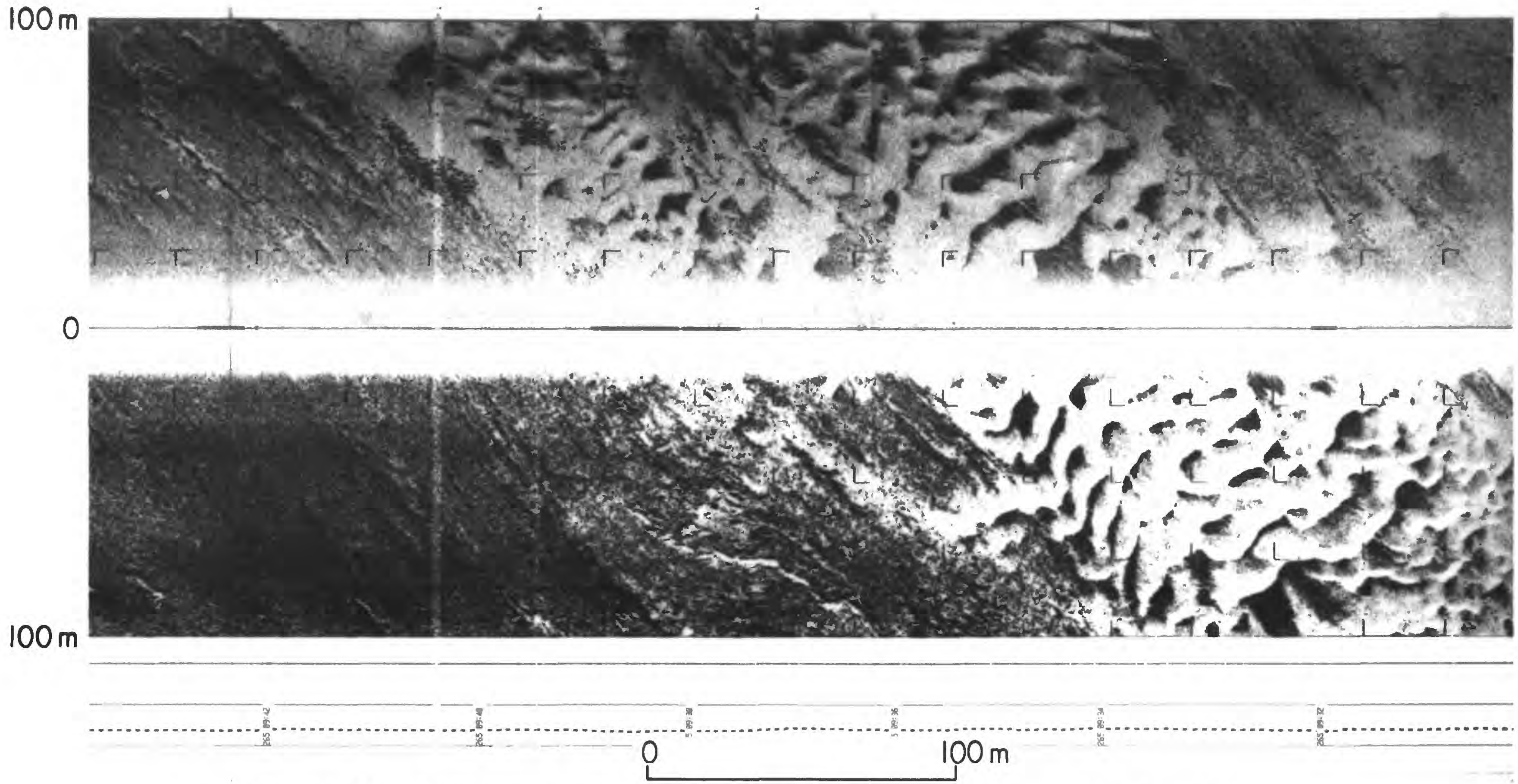


Figure 4. Sidescan sonar record showing continuous phosphorite pavement (dark, textured return on left side of record) being crossed by a large sand wave field (light, linear features on right side of record). South Facing flank of Charleston Bump.

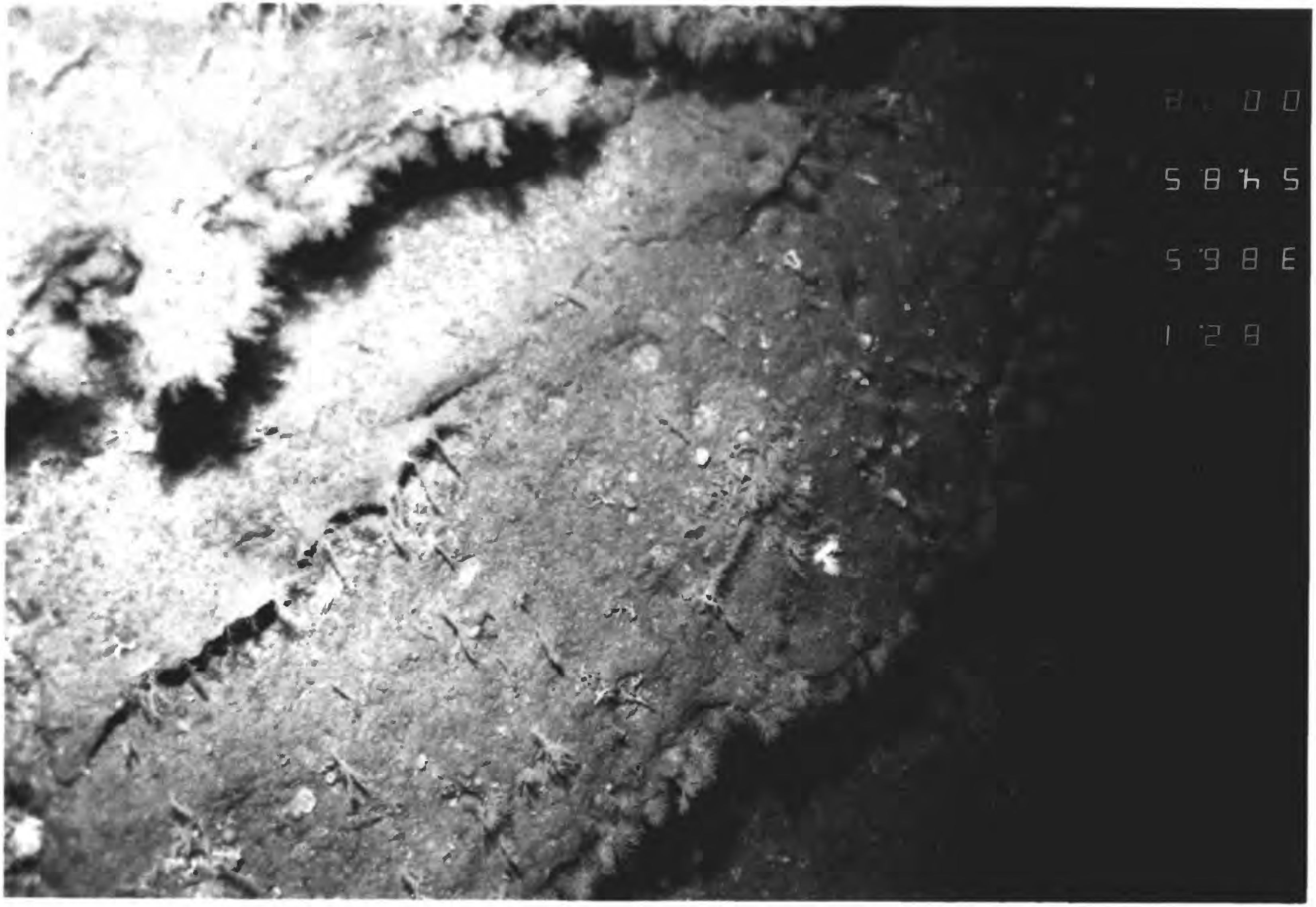


Figure 5. Outcropping Paleogene age strata on the wall of a scour depression. Photo taken from the NR-1 submarine, 1990.

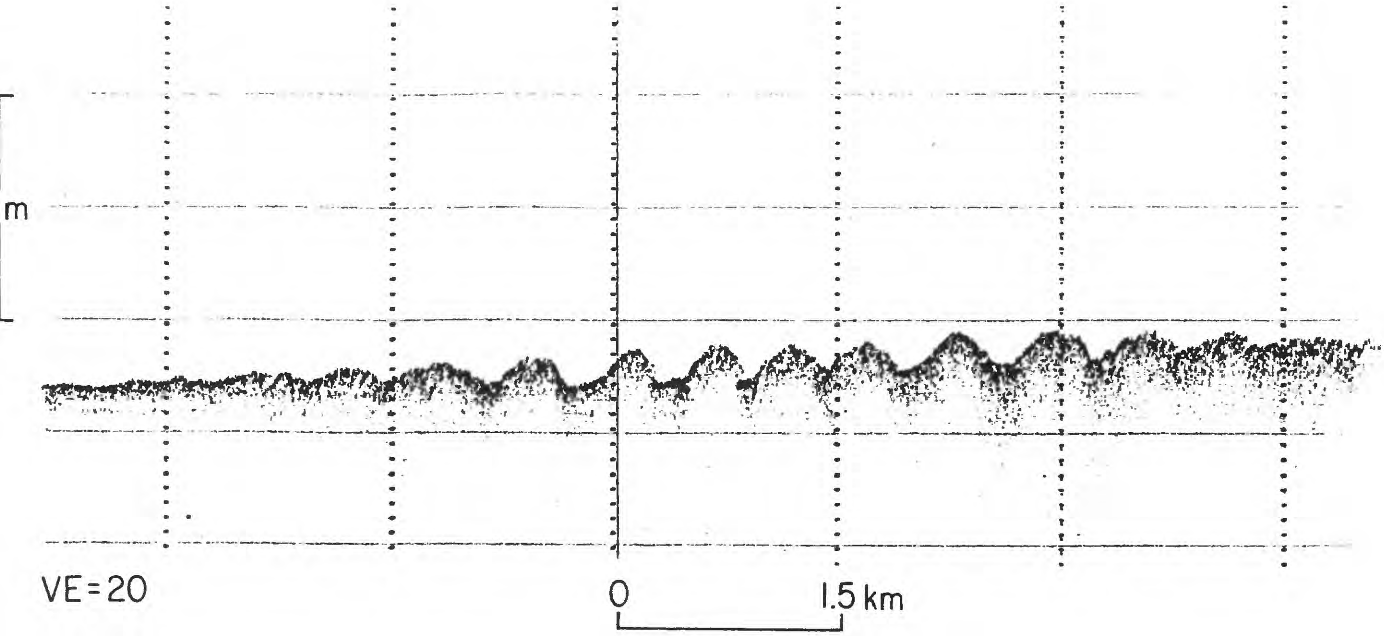


Figure 6. A large sand wave field in 320 m of water on the Blake Plateau just north of the Charleston Bump. The steep face on the north side of these sand waves indicates they result from north-flowing currents acting on the bottom.

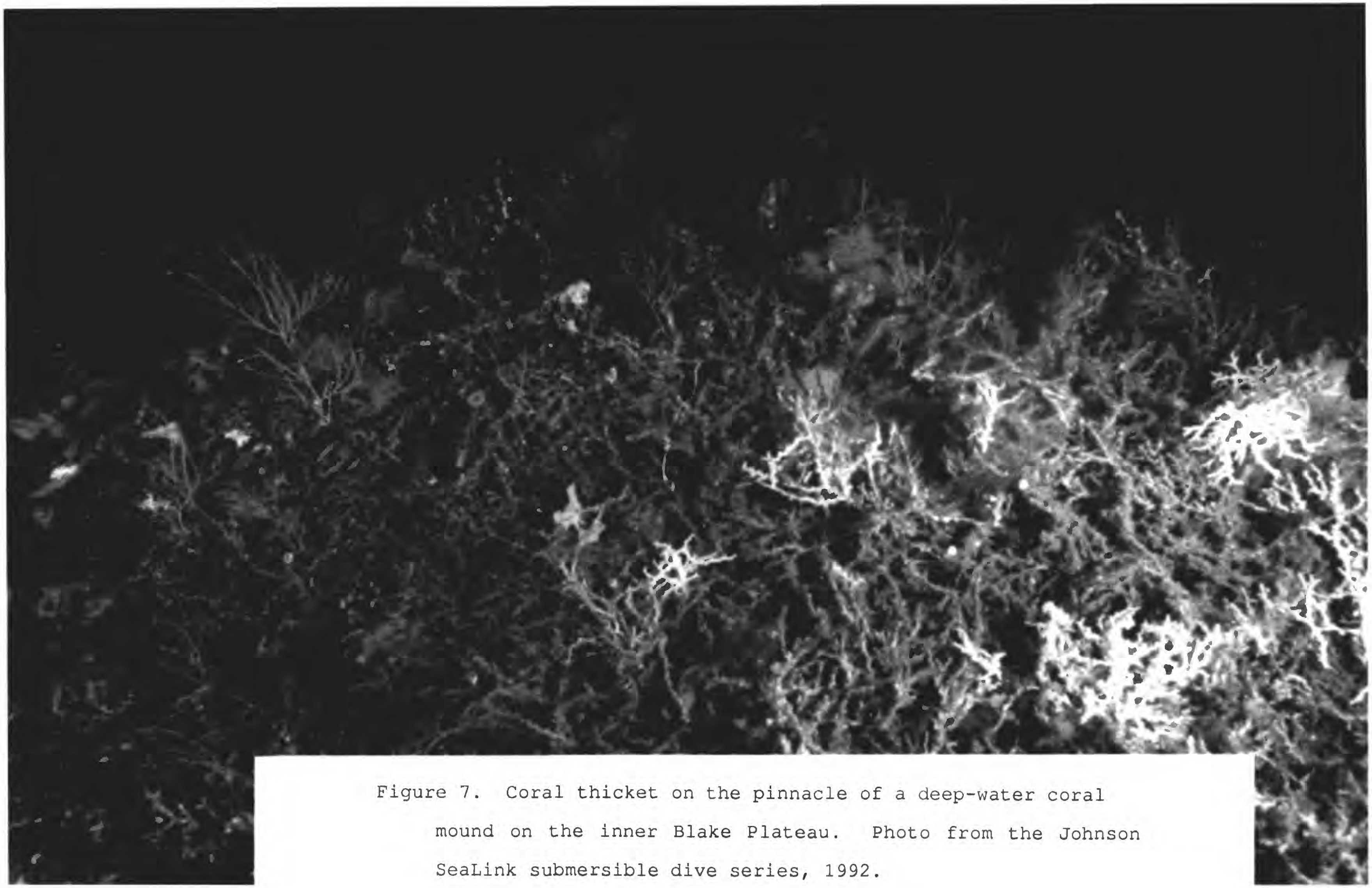


Figure 7. Coral thicket on the pinnacle of a deep-water coral mound on the inner Blake Plateau. Photo from the Johnson SeaLink submersible dive series, 1992.

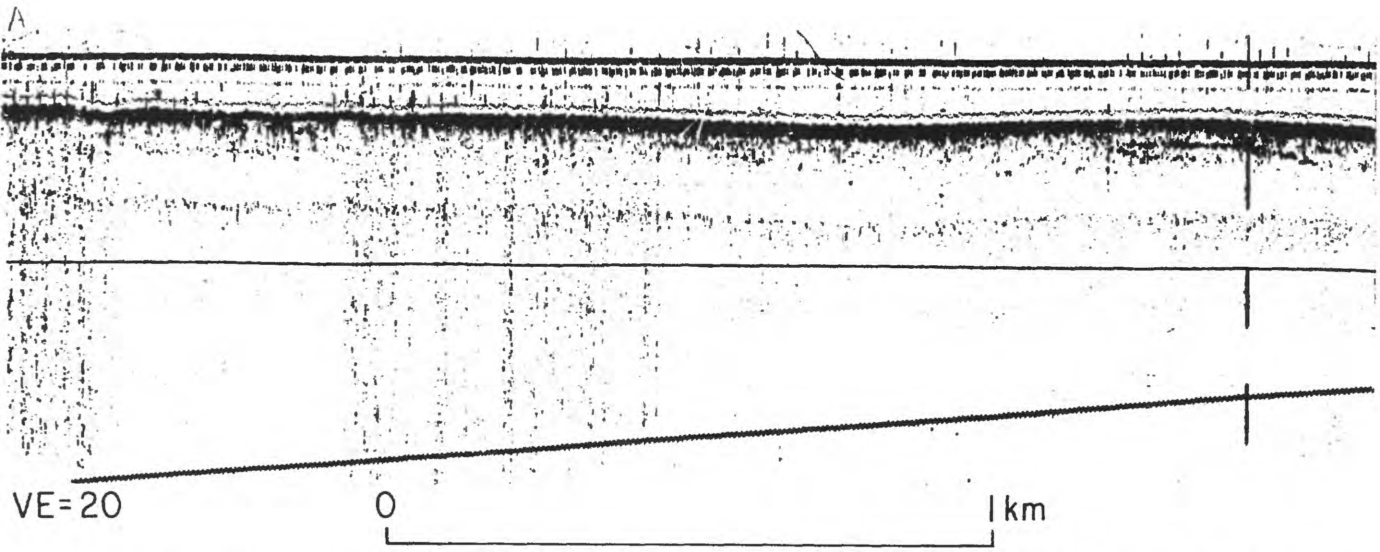


Figure 8A. The most common echo character type (Laine and others, type 1B) observed over the Florida-Hatteras shelf. The shelf surface is typically smoothly undulating and sharp. Subbottom penetration is typically 15 m or less and characterized by discontinuous reflectors or cut-and-fill channeling.

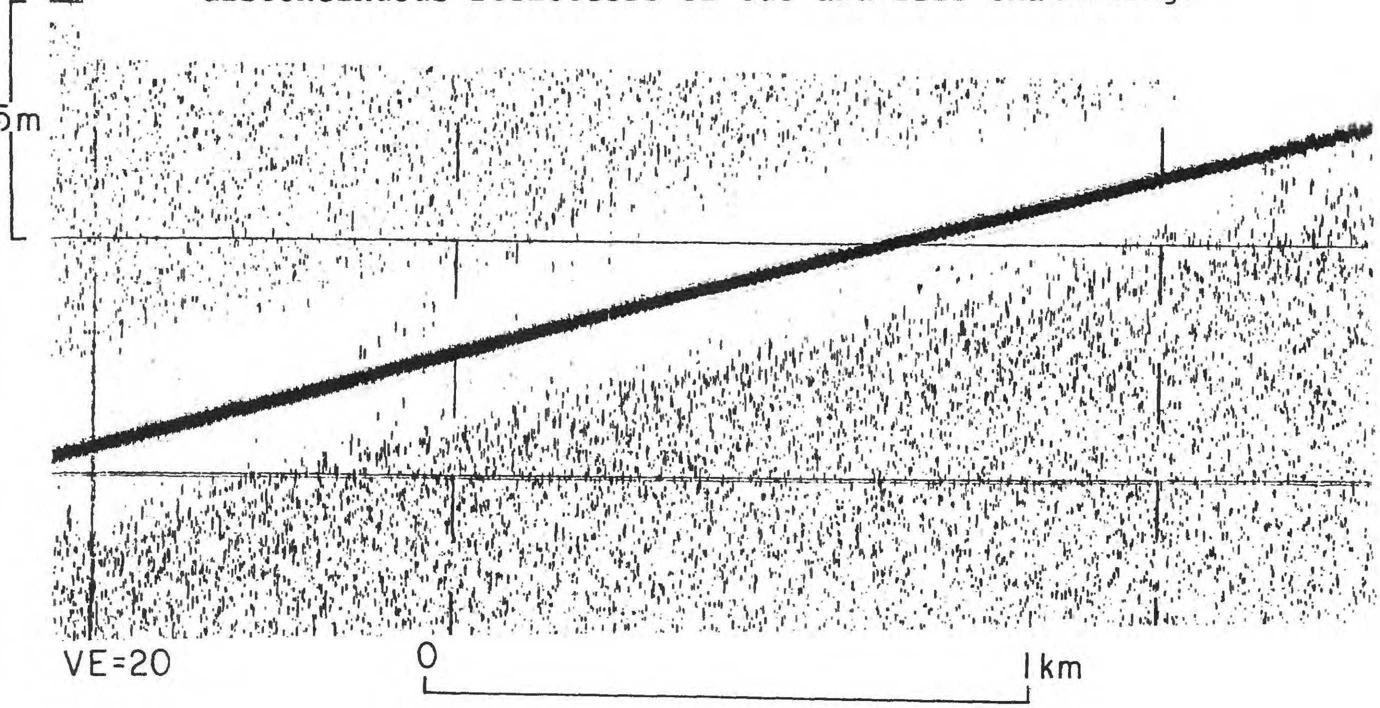


Figure 8B. Sharp, single echo with no subbottom reflectors characteristic of the outer Florida-Hatteras shelf and upper slope.

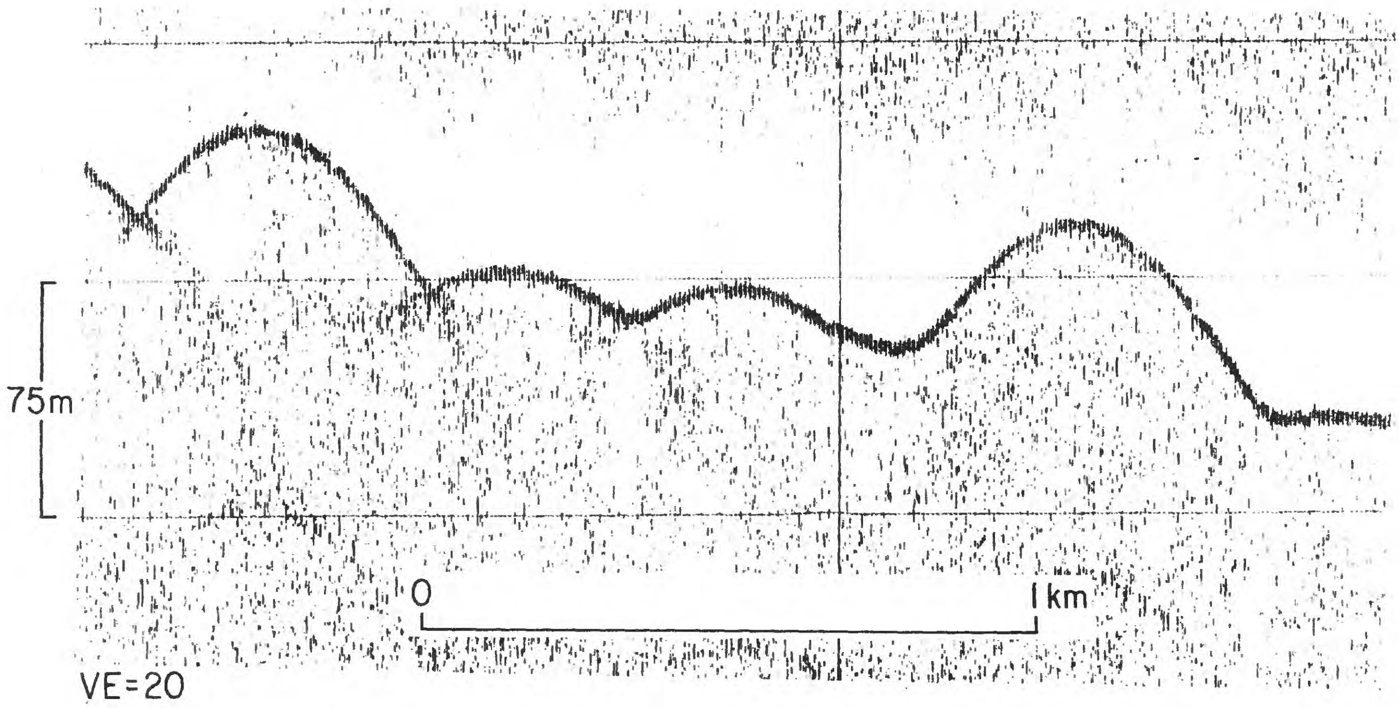


Figure 9A. Large deep-water coral mounds that typify the top of the Miocene outcrop area on the Florida-Hatteras slope.

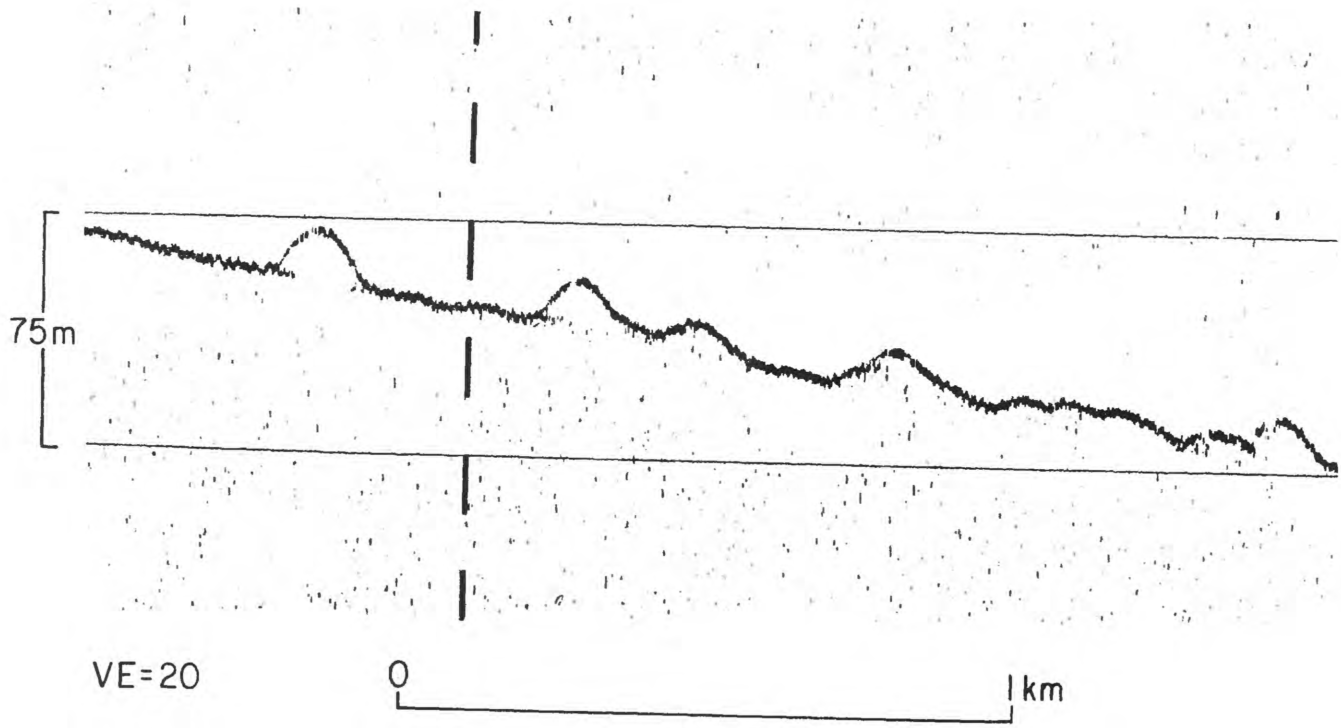


Figure 9B. Bumpy echo character of the lower Florida-Hatteras slope where Miocene sediments are the subsurface strata. Relief appears to be due to both erosion and to deep-water coral mounds.

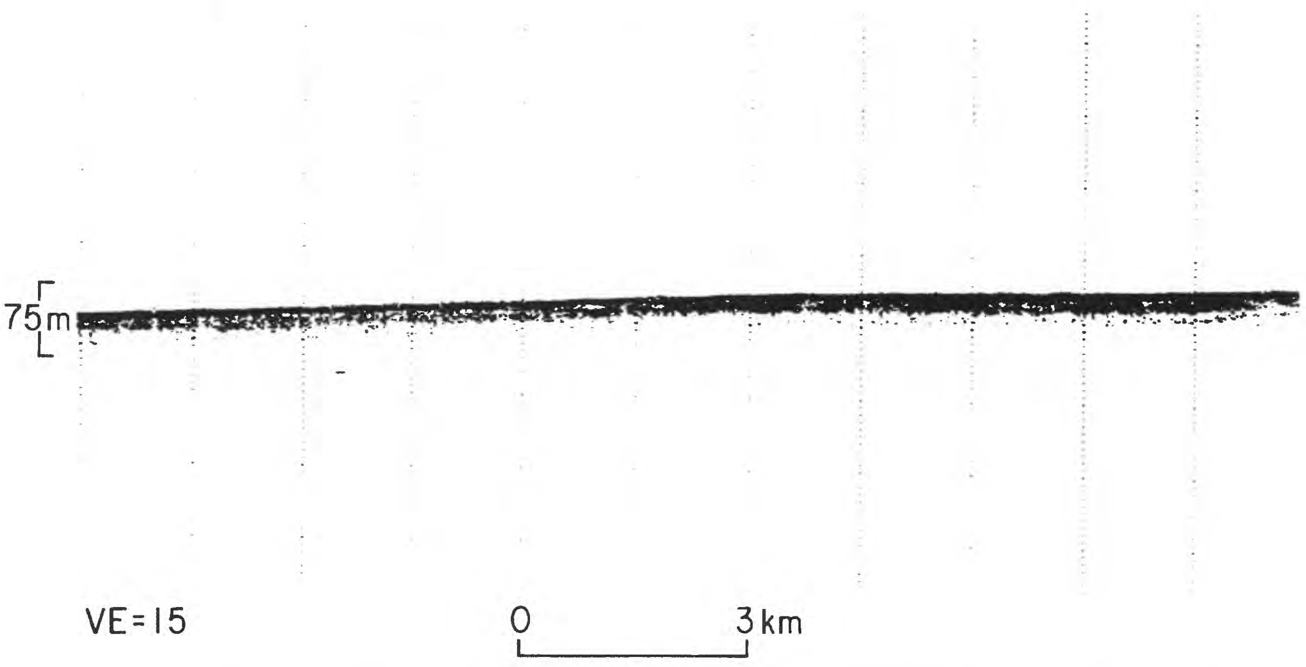


Figure 10A. Smooth bottom return with discontinuous reflectors and poor bottom penetration characteristic of post-Miocene sand north of the highly scoured Charleston Bump area.

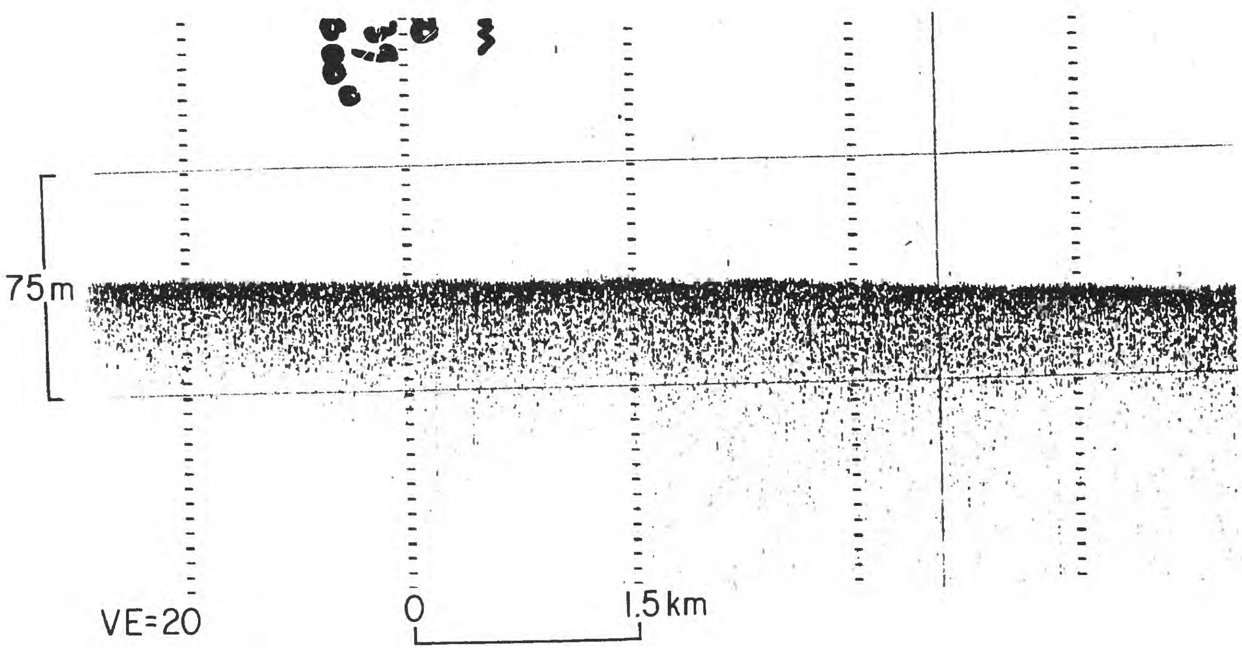


Figure 10B. Smooth to somewhat fuzzy bottom return with a semi-prolonged subbottom echo characteristic of post-Miocene sediments in 850 m of water south of the Charleston Bump.

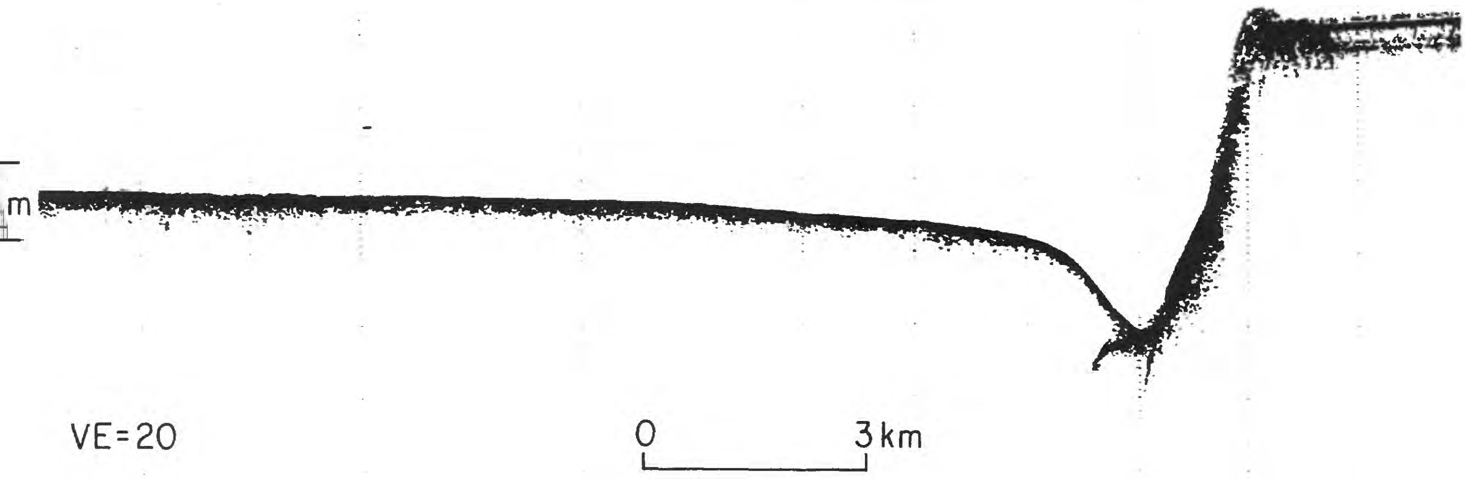
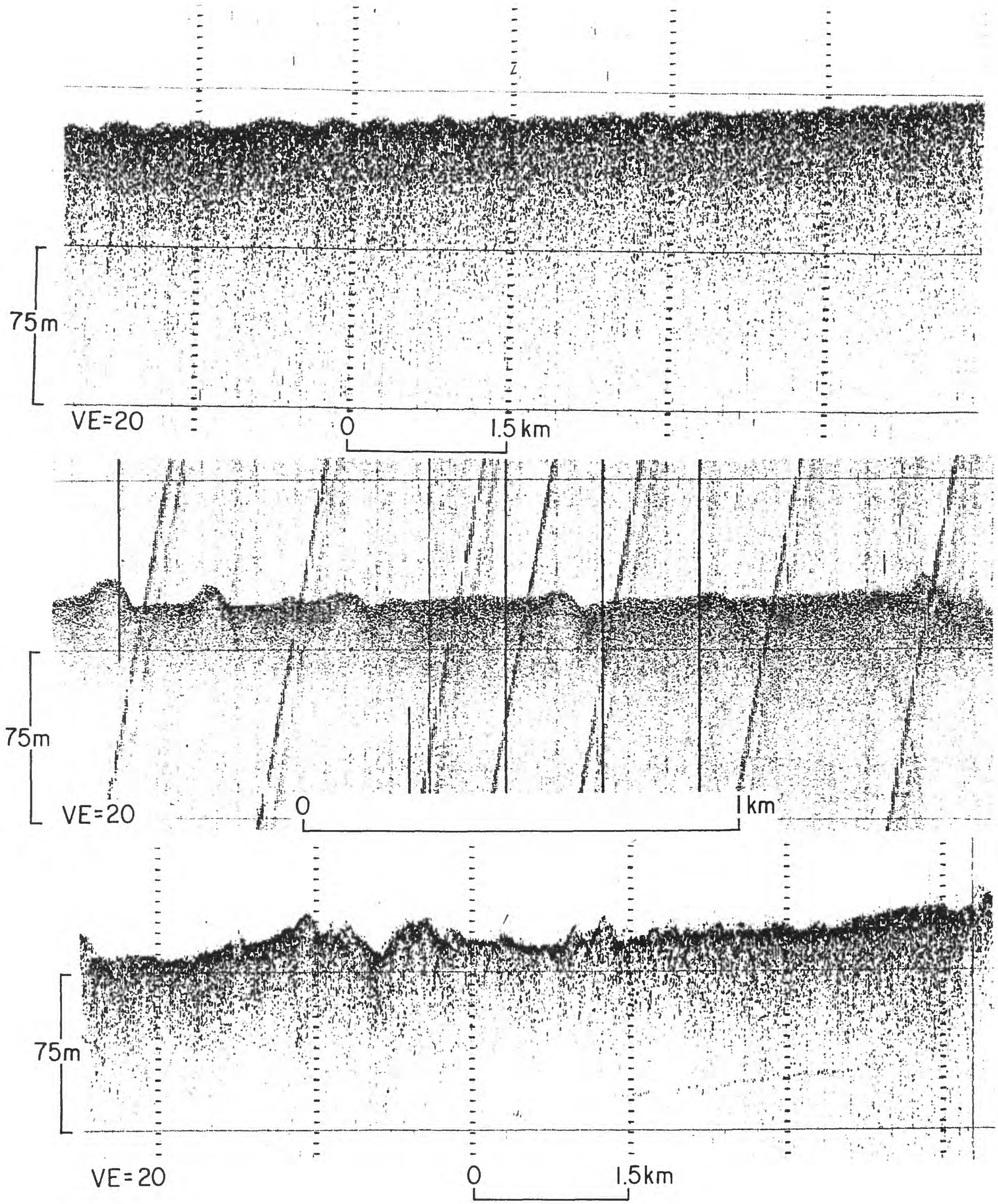


Figure 10C. Smooth sand bottom with semi-prolonged echo within a large scour depression. The cliff on the right (south) side of this profile is capped by phosphorite pavement that produces a characteristic double echo.



Figures 11A, B, and C. Three variations of bumpy-textured bottoms with semi-prolonged echos charactistic of outcropping Miocene strata south of the Charleston Bump.

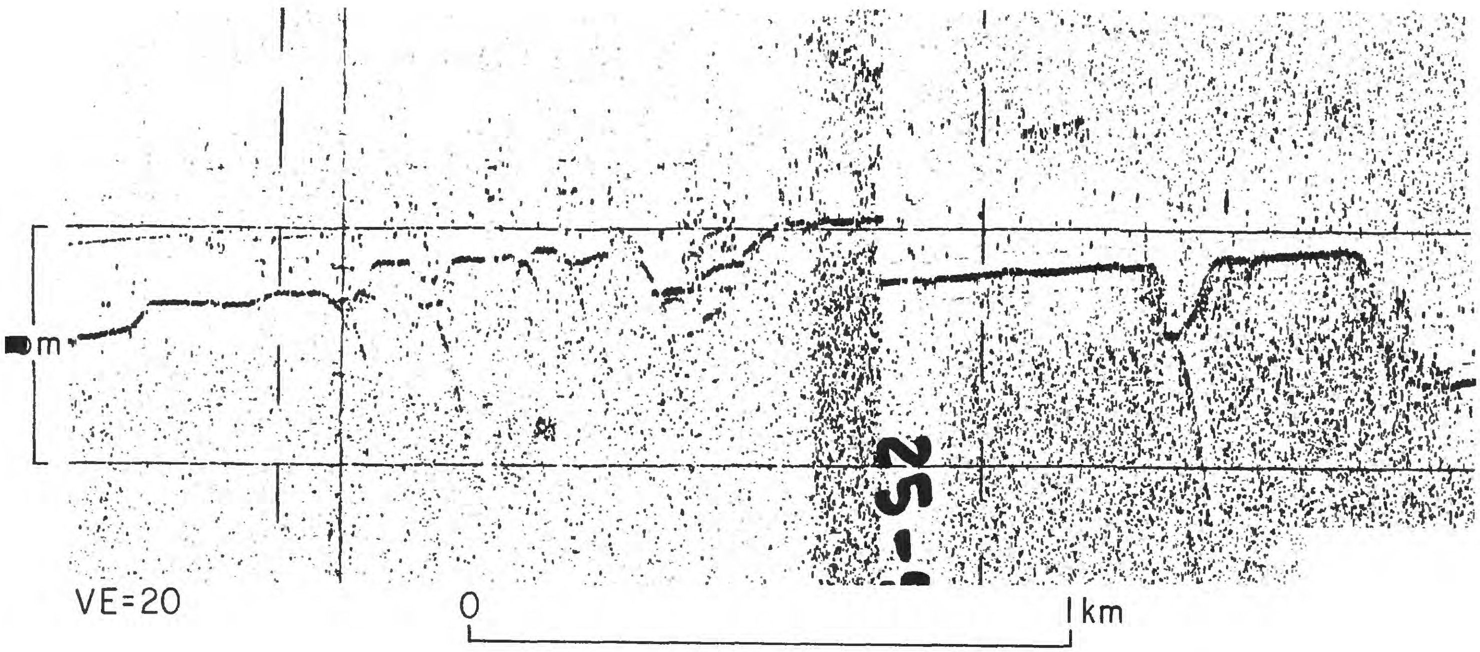


Figure 12A. Mesa-like topography caused by erosion of Oligocene strata in 350 m of water on the inner Blake Plateau. The unit is characterized by a sharp bottom return and no subbottom echo.

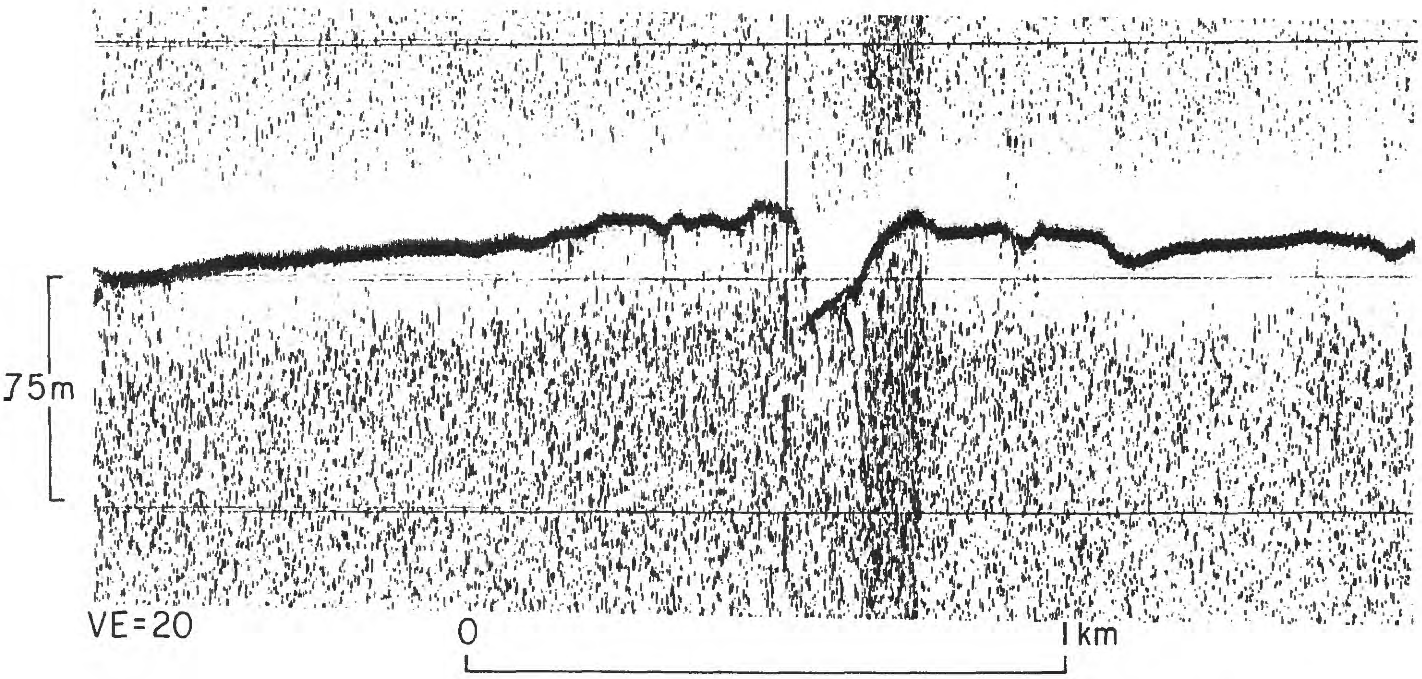


Figure 12B. Current eroded Oligocene strata in 250 m of water near the crest of the Charleston Bump.

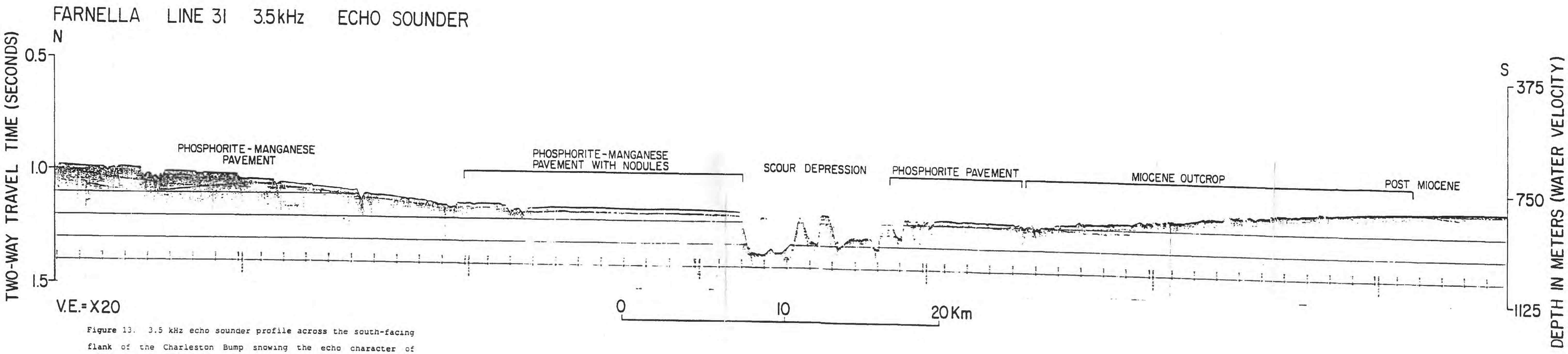


Figure 13. 3.5 kHz echo sounder profile across the south-facing flank of the Charleston Bump showing the echo character of phosphorite and phosphorite-manganese pavement as well as Miocene and post-Miocene sediments. The Pavement areas are characterized by a strong double echo with a semi-prolonged to no subbottom echos.

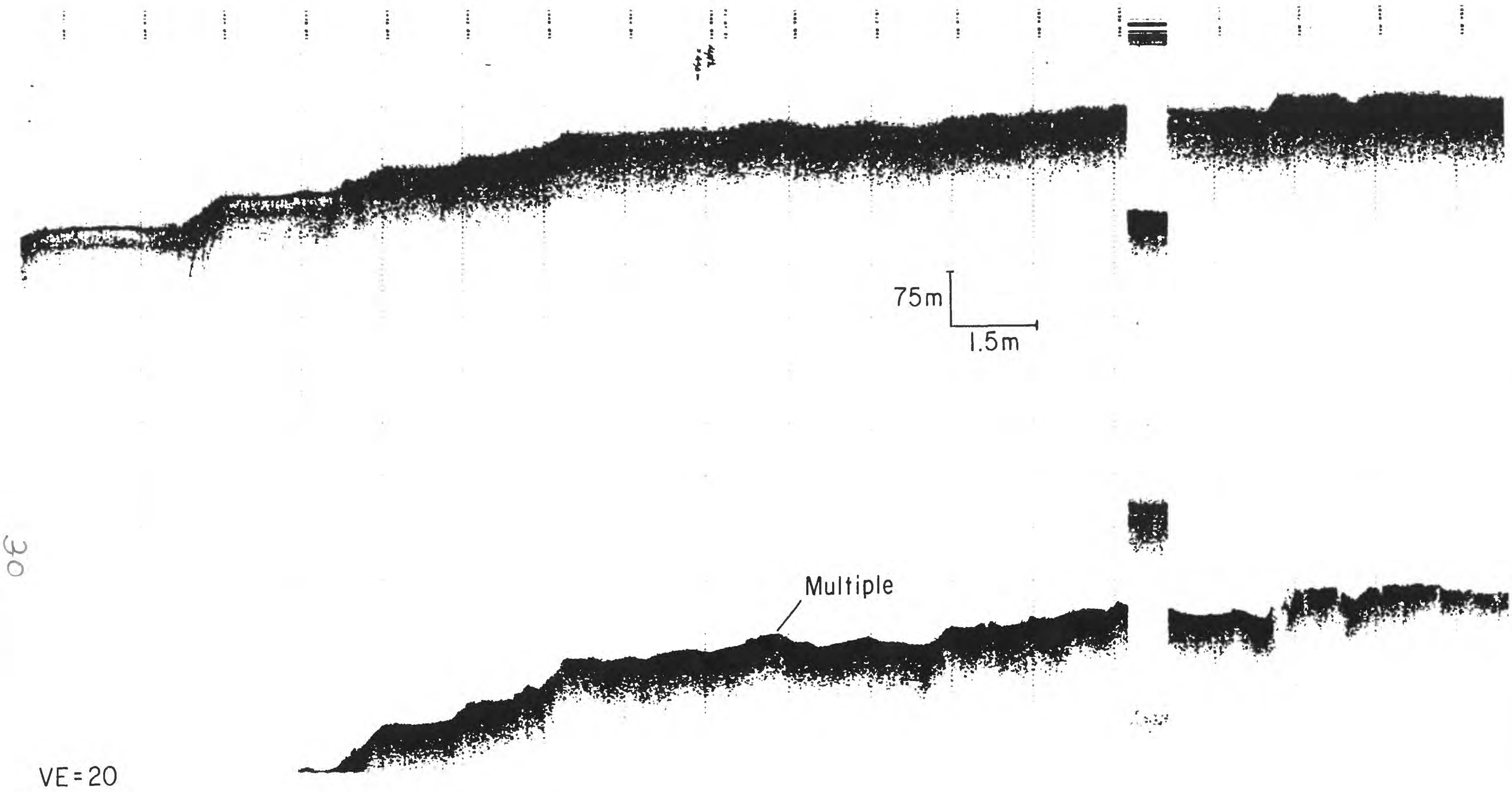


Figure 14. "Fuzzy", indistinct seafloor, double echo, little or moderately-prolonged subbottom echo, and a strong bottom multiple. The interpretation of this profile is that the bottom is phosphorite pavement, in places covered by coral and sponge growth and a veneer of sand. The pavement overlies eroded Paleogene siliceous limestone.

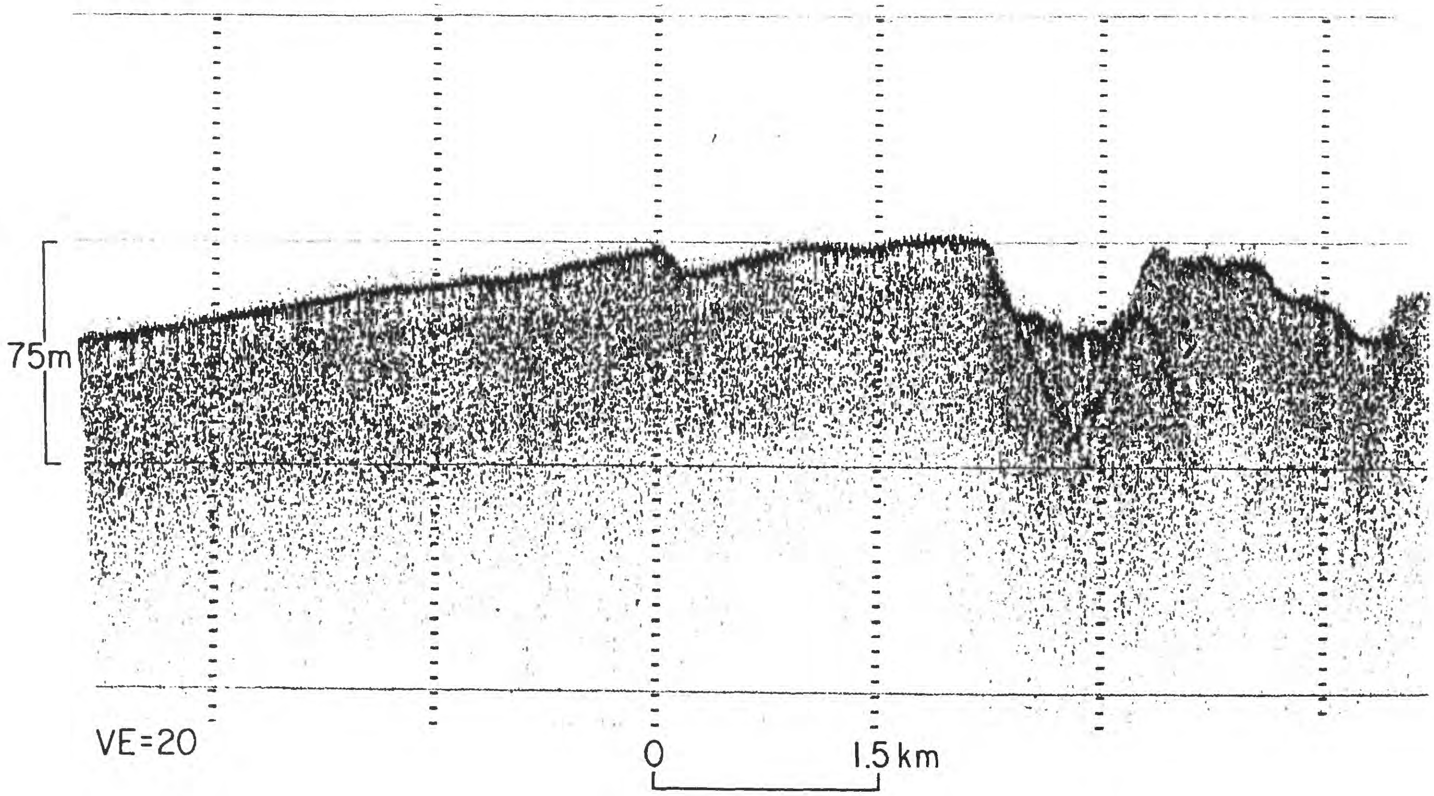


Figure 15. Somewhat fuzzy, strong, bottom return with a weak double echo and a prolonged subbottom return. This type of return is characteristic of a bottom that is covered by coral, sponges, and a thin veneer of sand as shown on fig. 3.

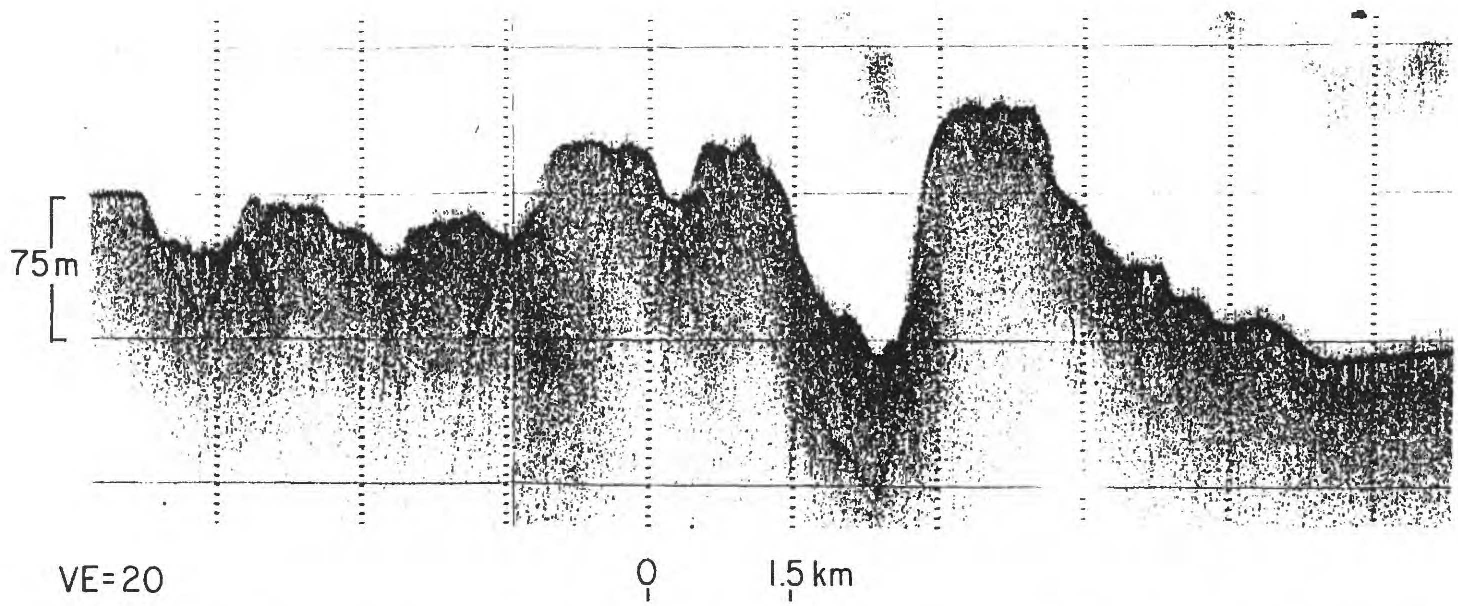


Figure 16A. Highly eroded bottom characterized by a strong bottom return and a prolonged subbottom echo. This profile typifies the rugged and rough sea floor of erosion-breached areas of the Charleston Bump.

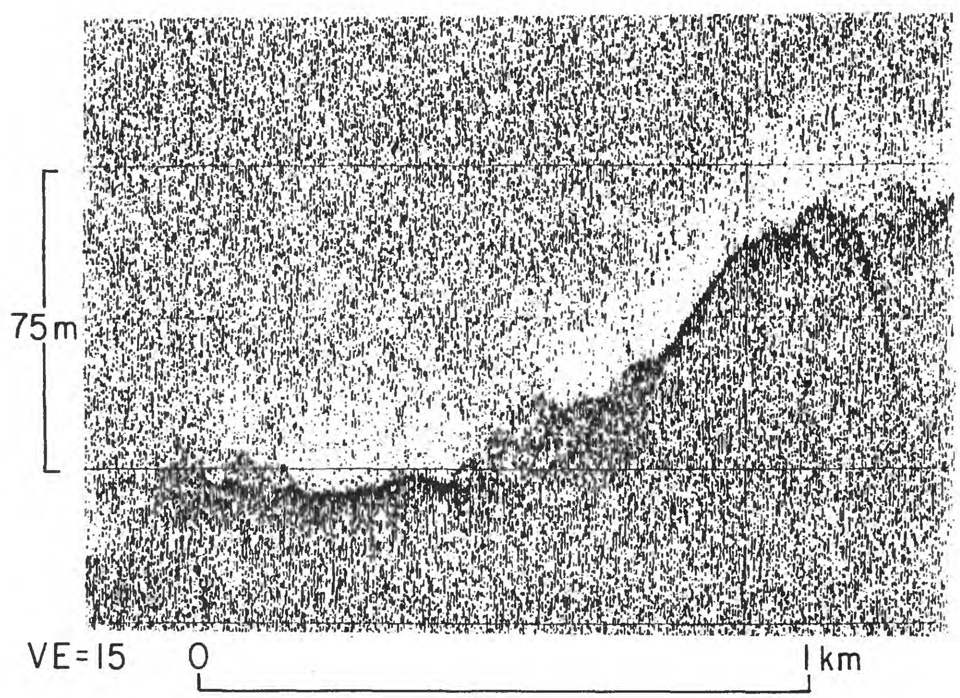


Figure 16B. Highly eroded sea floor, as above, but with scattered coral mounds.

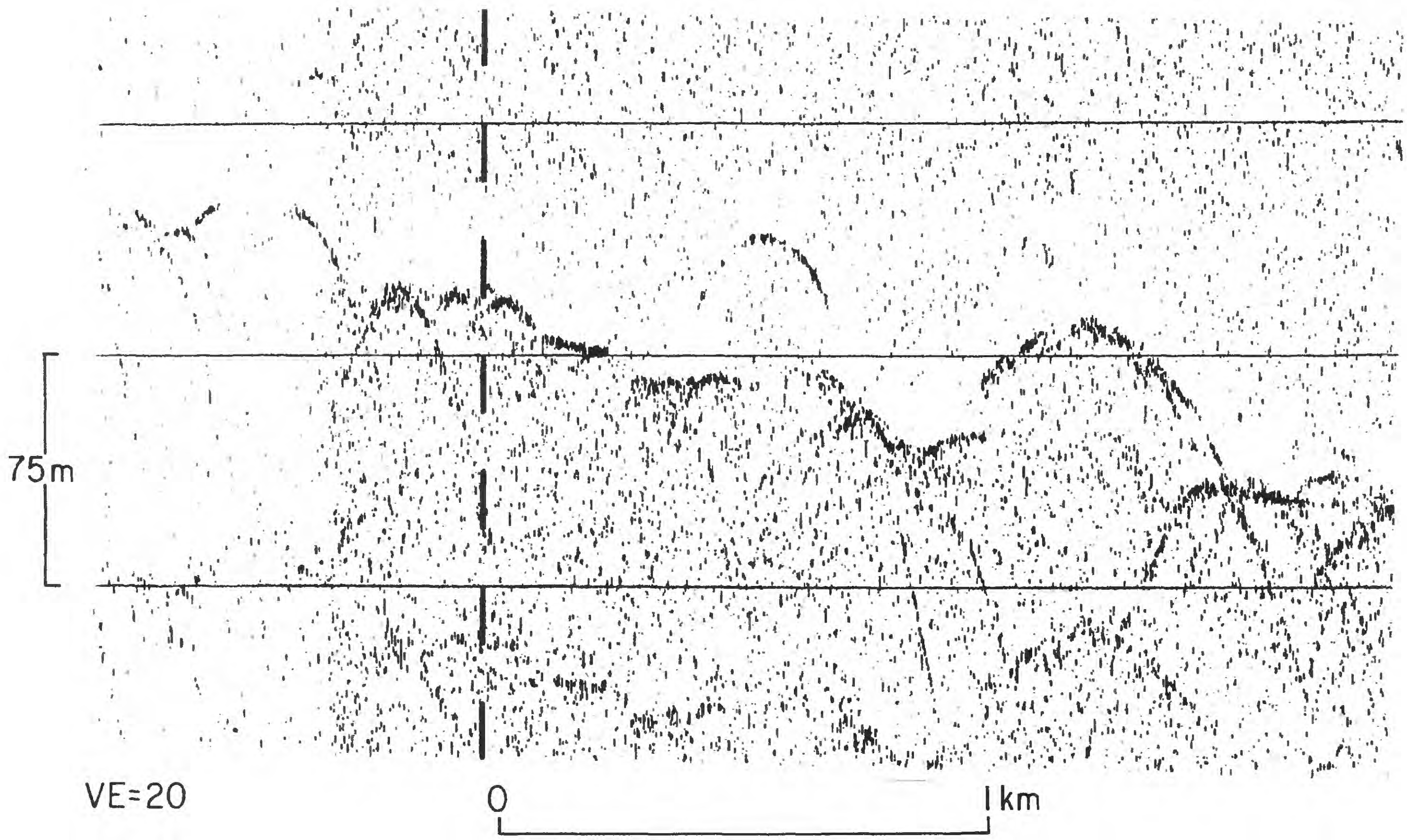


Figure 16C. Extensive cover of coral mounds producing overlapping hyperbolic echos on a rugged, highly eroded sea floor.

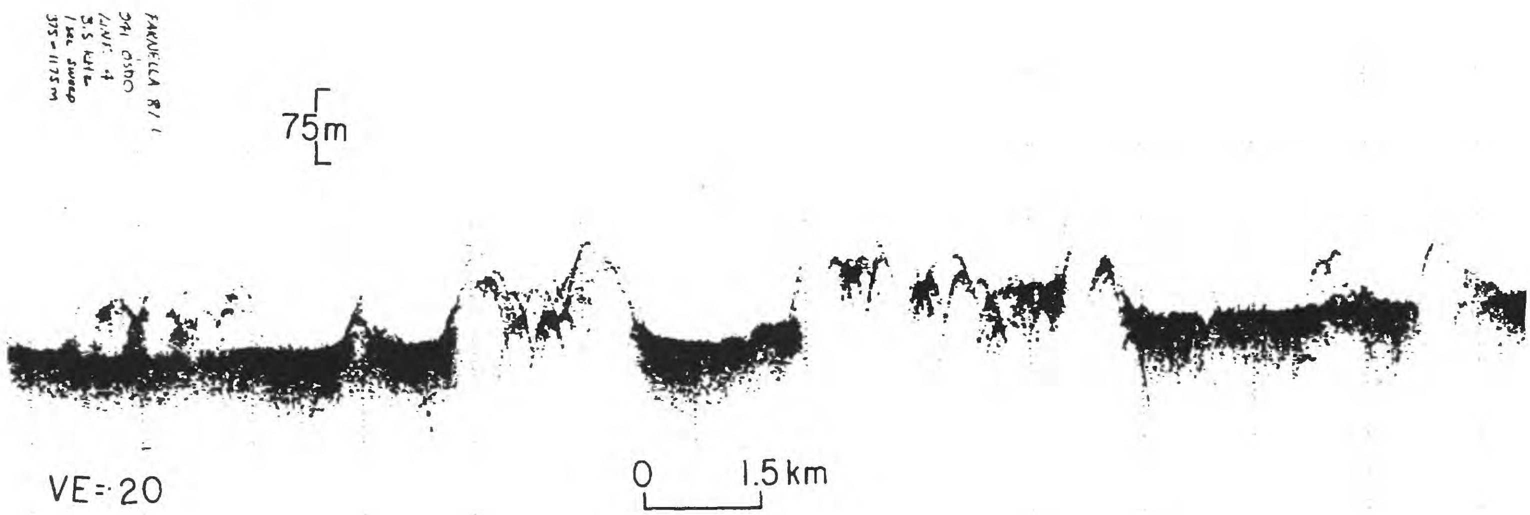


Figure 17A. Hyperbolic echos with transparent inner structure on a relatively low-relief sea floor with a moderately prolonged subbottom echo. This profile shows extensive coral mounds developed over the Cretaceous outcrop area on the south-facing flank of the Charleston Bump.

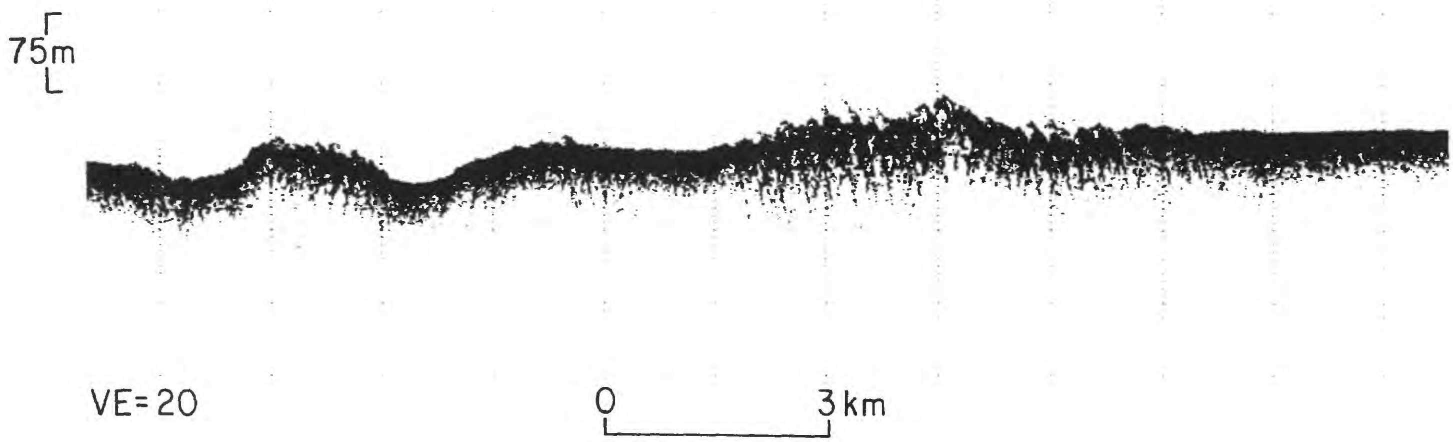


Figure 17B. Strong bottom return with a moderately-prolonged subbottom echo and scattered, patchy hyperbolic returns on a generally smooth to low-relief sea floor. The interpretation of this record is that the bottom is underlain by Cretaceous calcareous siltstone with a scattered broken pavement and a thin veneer of sand.

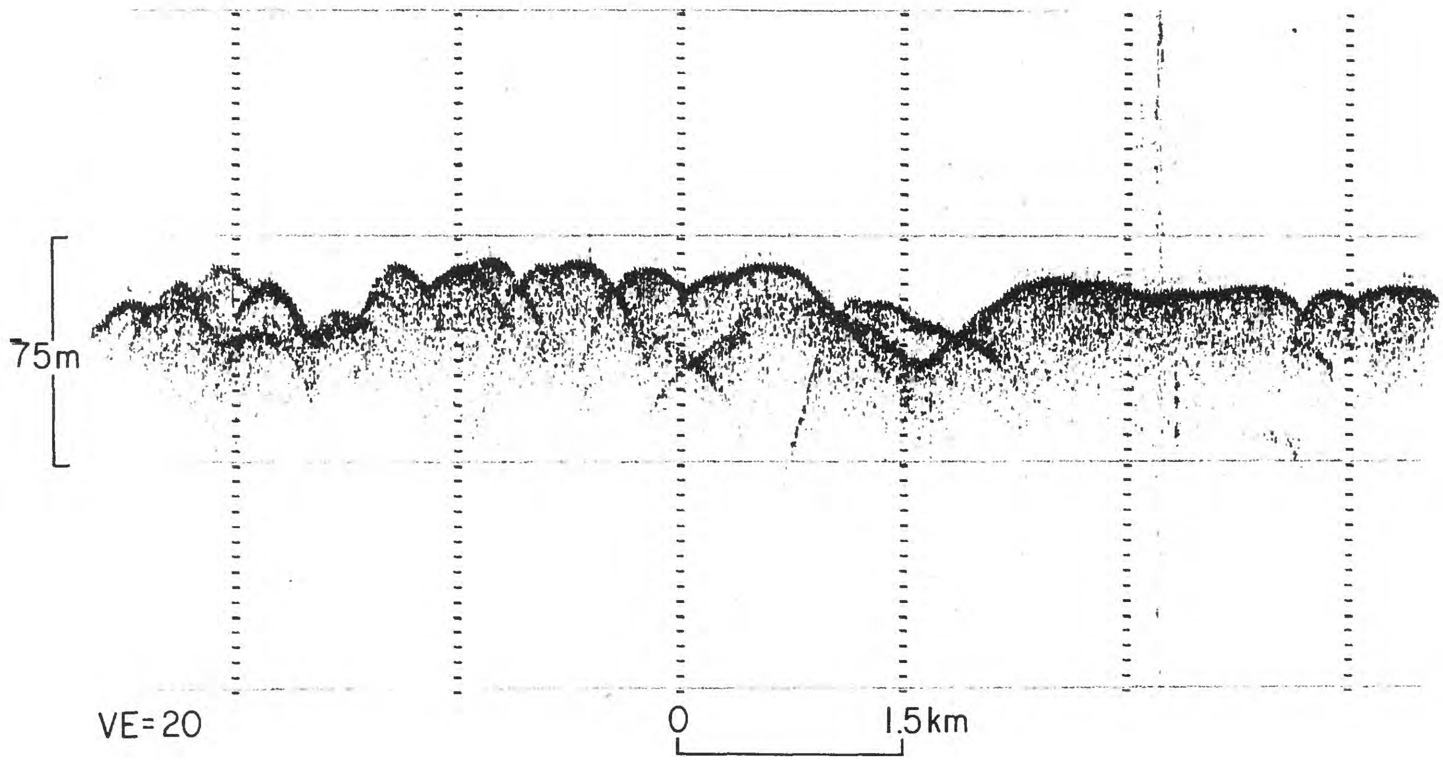


Figure 18. Hyperbolic echos from an area near the top of the Blake Escarpment characterized on the GLORIA sidescan sonar image as an area of circular features, possibly the top of an ancient reef.