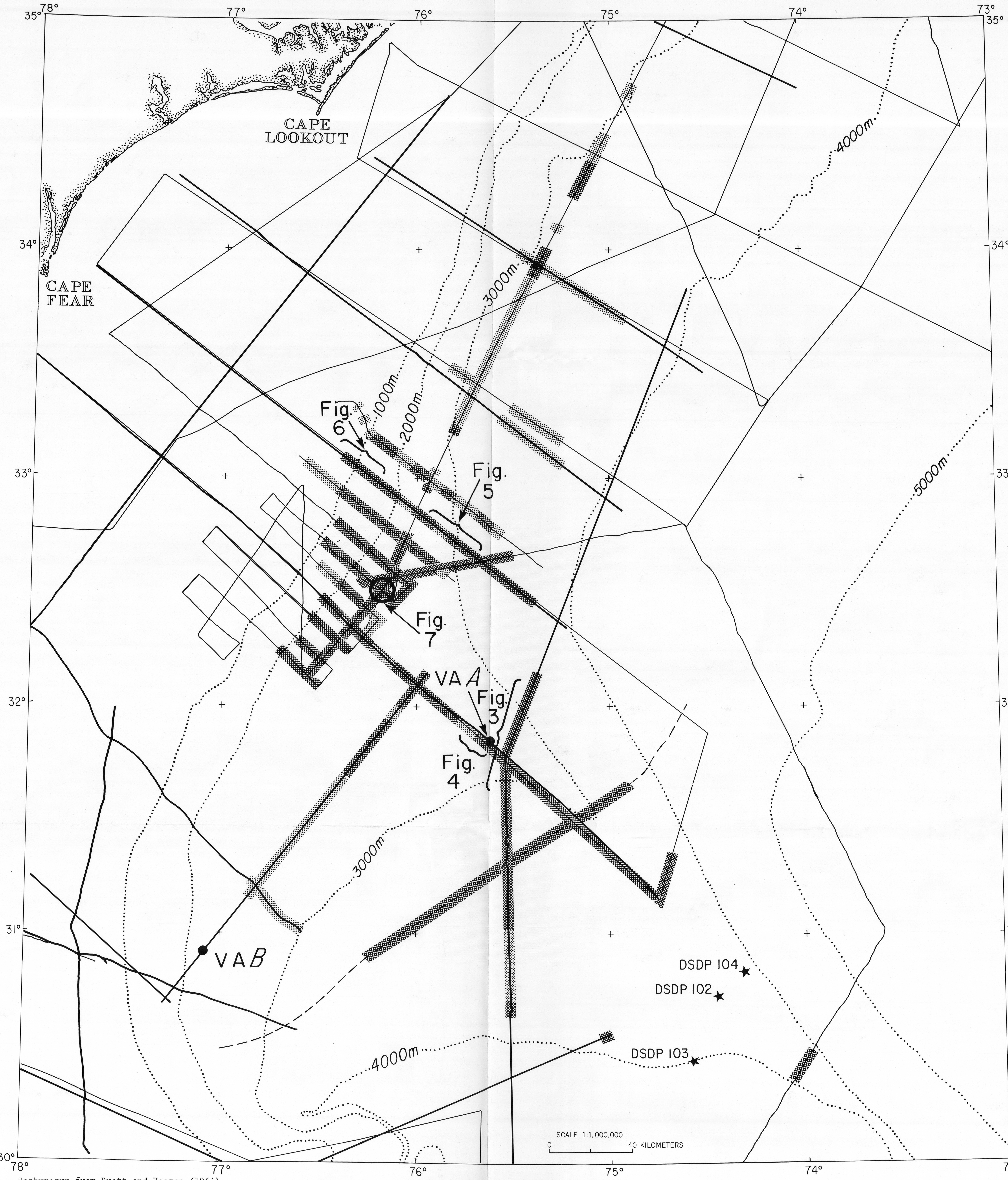

Bathymetry from Pratt and Heezen (1964)
Universal Transverse Mercator projection

Figure 1.—Trackline locations of the seismic-reflection profiles collected in the Blake Ridge region by or for the USGS. The dashed line shows where data were collected by the University of Texas (Shipley and others, 1978). Heavier tracklines indicate collection of multichannel data, and lighter lines indicate collection of single-channel data. The bold pattern overlying some trackline segments shows where the BSR is strong and of high amplitude; the lighter pattern shows areas where the reflection is of low amplitude and identification of the BSR is more tentative. Brackets indicate sections of profiles shown in figures 3 through 7; bracket lengths represent profile-section lengths only approximately. VA *A* and VA *B* mark locations of velocity analyses *A* and *B* discussed in figure 8.

We have not identified the BSR in water depths greater than 3750 m, which is consistent with the observation that the BSR on the Blake Ridge is rarely or never deeper than 5.6 s, two-way travel time (Markl and others, 1970). However, the strength of the BSR tends to fade laterally, so the limits of the BSR are often determined subjectively.

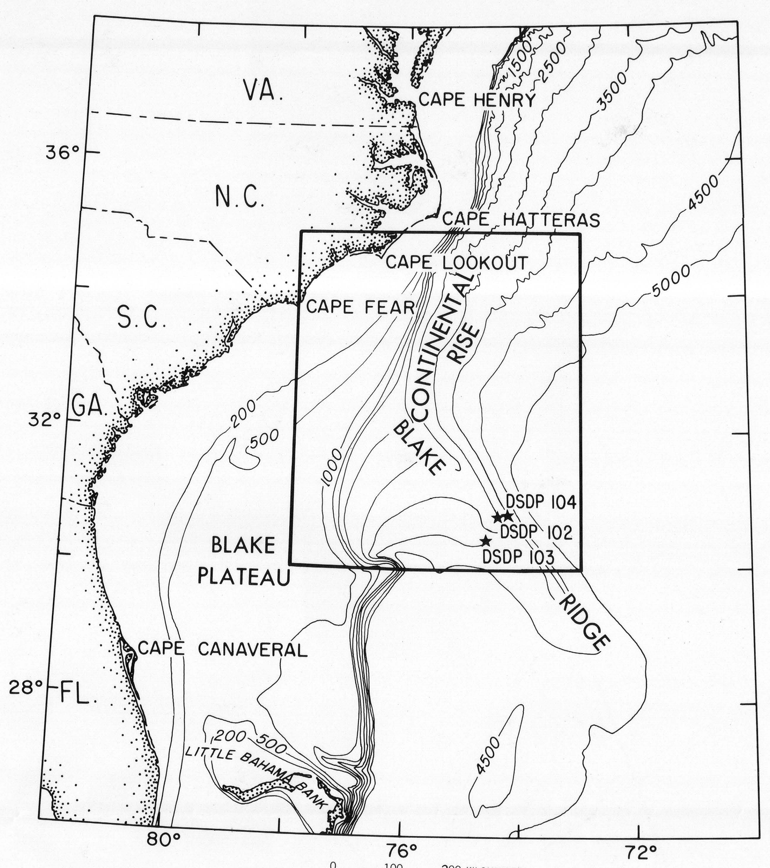

Figure 2.—Bathymetric index map showing the region off the southeastern United States. Box indicates study area of this report, shown in figure 1. Locations of Deep Sea Drilling Project (DSDP) wells on the Blake Ridge are indicated by stars and identified by number. Bathymetric contours, in meters, are from King (1969).

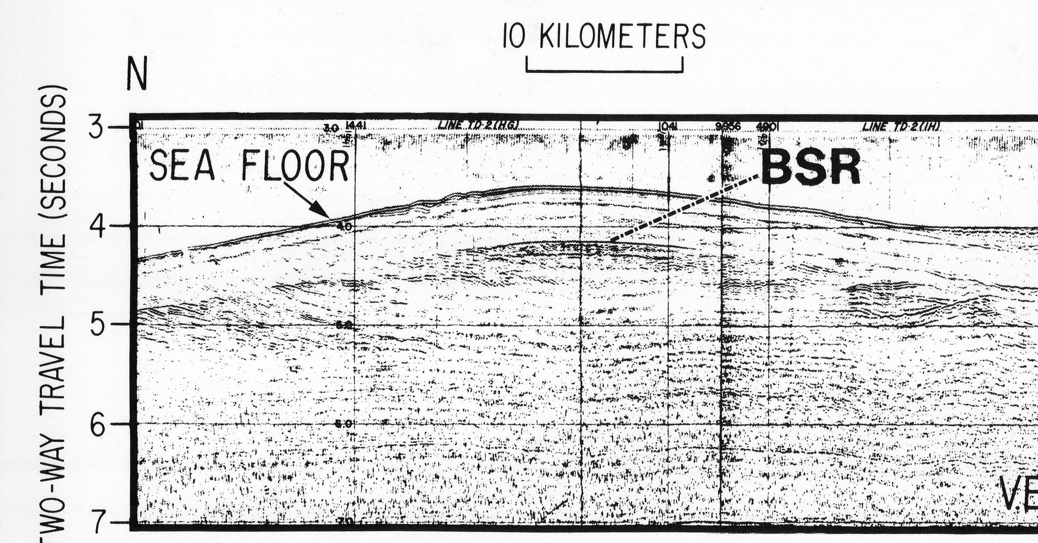

Figure 3.—Section of the near-trace monitor record from a multichannel profile across the crest of the Blake Ridge. Location of the profile is shown in figure 1. The BSR clearly parallels the ridge crest and intersects bedding planes. In this section, closure exists at the crest of the Blake Ridge. The BSR character varies as the intensity of the reflection increases toward the ridge crest. The strength of the BSR may be due in part to the character of the sedimentary beds in which it occurs, for its response is symmetrical on both sides of the ridge crest within the same unit. On the flanks of the ridge high-amplitude returns occur not only along the BSR but also on reflectors that dip away from the BSR, perhaps indicating that these units are porous and have gas trapped within them by the clathrate seal. V. E., vertical exaggeration.

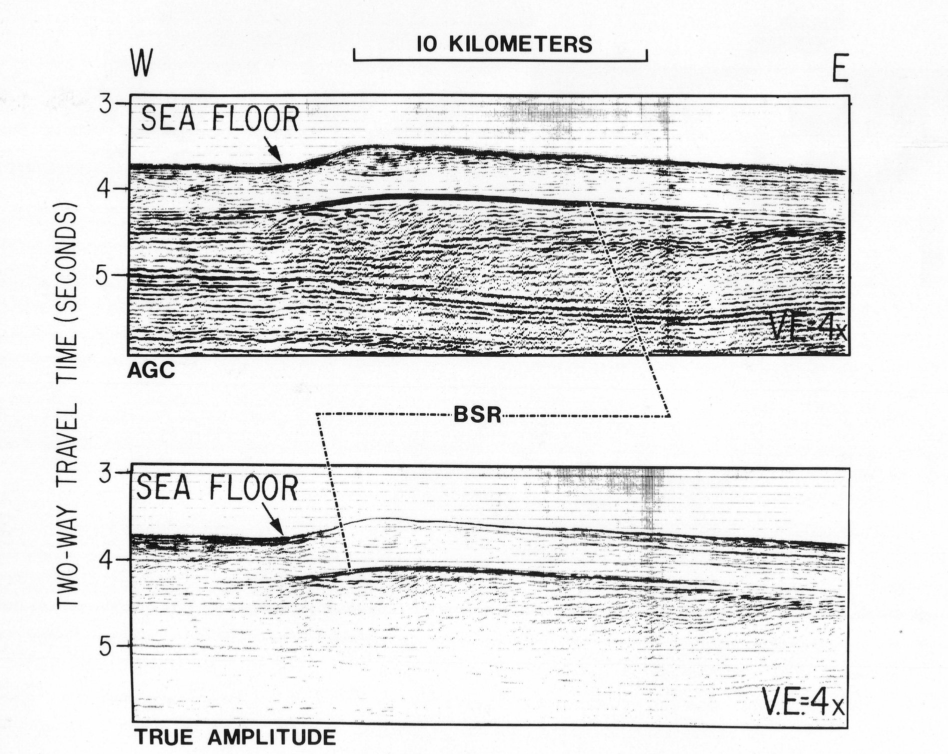

Figure 4.—Two displays of the same section of a CDP profile. Location is shown in figure 1. Both sets of data are 48-channel records with 36-fold processing. The lower section is a true-amplitude display; the upper section has automatic gain control (AGC) applied. The BSR closely follows the sea bottom and is strong on the east side of the profile, but its presence becomes questionable toward the west where it fades. The change in the character of the seismic units above and below the BSR is clear in both displays. The unit above the BSR is essentially acoustically transparent, whereas stronger returns appear beneath the BSR. V. E., vertical exaggeration.

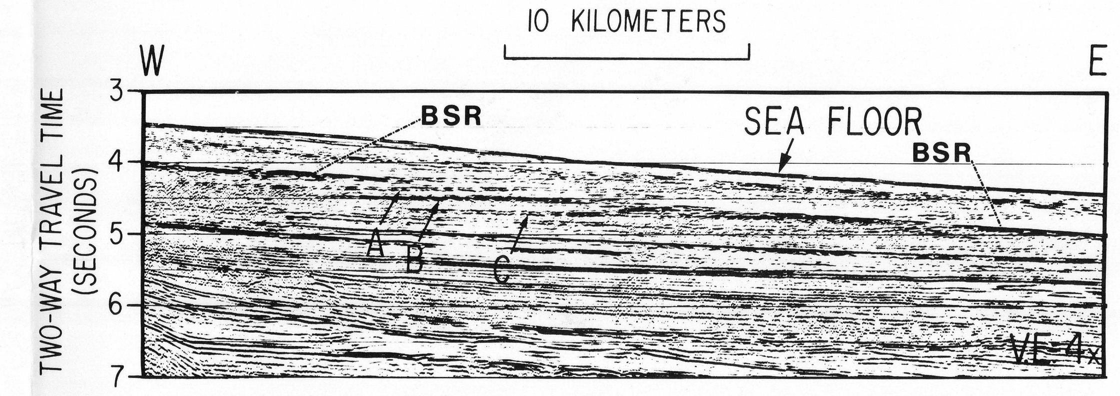

Figure 5.—Part of a CDP profile, the location of which is shown in figure 1. AGC was applied. The BSR is strong and distinct on the left and right sides of the profile, but it is weak in the middle, where the true dip of reflections is landward. Horizons A, B, and C are believed to be sedimentary beds that have a true dip toward land. These horizons appear to pass through the BSR but show weaker reflections above the BSR than below it. Free gas may be trapped within the beds sealed against the near-bottom zone of gas-hydrate-cemented sediment. V. E., vertical exaggeration.

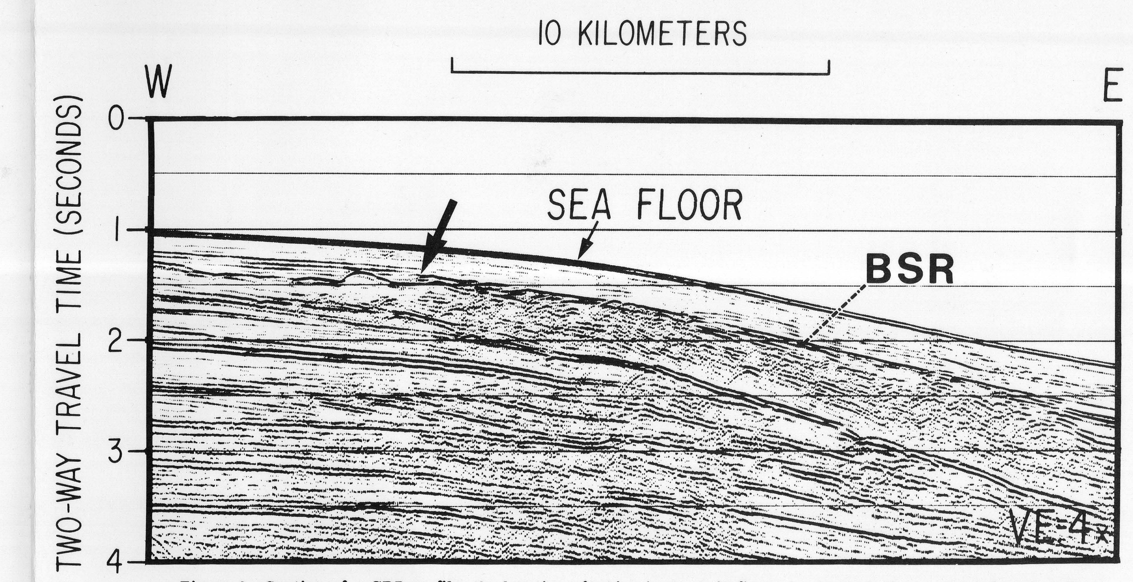

Figure 6.—Section of a CDP profile, the location of which is shown in figure 1. Arrow indicates the inferred updip limit of the BSR. This limit occurs where the thick Tertiary section that makes up the Blake Ridge thins to an abbreviated Tertiary section on the Blake Plateau. V. E., vertical exaggeration.

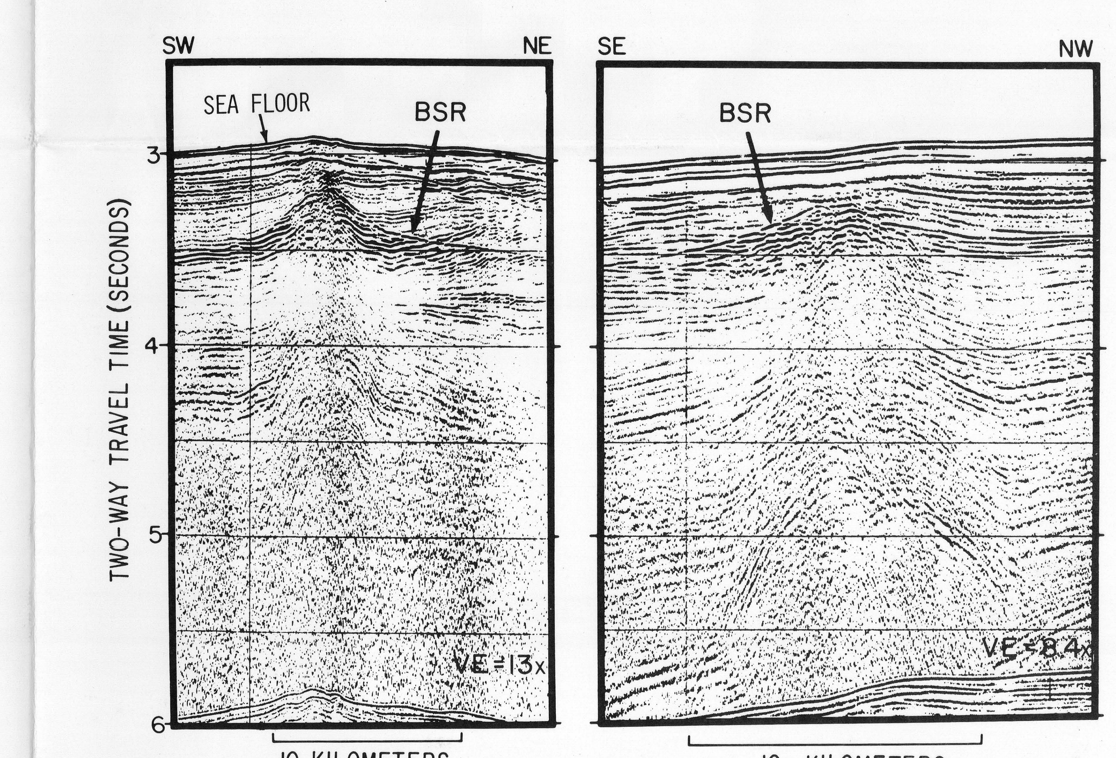

Figure 7.—Two single-channel seismic-reflection profiles that cross perpendicular to each other at the crest of a diapir (Grow and others, 1979). Location of the profiles is shown in figure 1. The BSR rises around the diapirs and crosses other reflections at a high angle. V. E., vertical exaggeration.

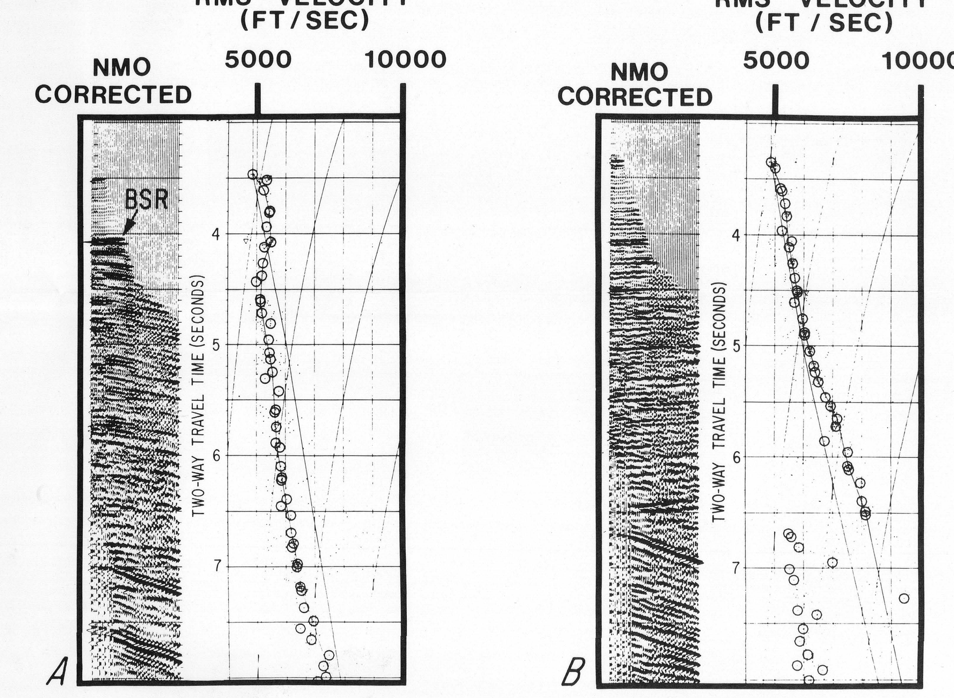

Figure 8.—Sections of two velocity analyses (VA), both from 48-channel CDP data collected and processed by Geophysical Services, Inc. Locations of the two VA's are indicated in figure 1. The root-mean-square (RMS) velocity functions are best indicated by the line that most closely fits the points of high coherence. The left side of each VA shows the traces of the shot after being corrected for normal moveout (NMO) using the velocity function shown to its right. The BSR is strong in the area of VA *A*. The RMS velocity function in *A* shows an inversion just below 4 seconds, at the time-depth of the BSR. This velocity inversion is typical of areas where the BSR is strong. By comparison, *B* is a VA that comes from an area where the BSR has not been identified and shows a normal RMS velocity function, constantly increasing as depth increases.

A strong reflection parallel to the sea floor has been observed in seismic-reflection profiles in the Blake Ridge area off the southeastern United States. This reflection occurs at a subbottom depth of 400 to 700 m, in water depths of 750 to 3750 m. Because the reflection parallels the sea floor, it is known as a bottom-simulating reflection (BSR). It is independent of reflections that represent sedimentary strata, and in places it crosses such reflections.

This report illustrates the appearance and distribution of the BSR in selected seismic-reflection profiles collected by the U.S. Geological Survey (USGS) (figs. 1,3 through 8). The USGS has collected more than 10,000 km of multi-channel common-depth-point (CDP) seismic-reflection profiles and 15,000 km of single-channel seismic-reflection profiles off the East Coast of the United States south of Cape Hatteras. Many of these reflection profiles were obtained on the Blake Ridge and on the Continental Rise north of it—the only area off the southeastern United States where the BSR is known to occur (figs. 1, 2). Presence of the BSR in profiles off the southeastern United States has also been noted by Markl and others (1970), California University (1972), Tucholke and others (1977), and Shipley and others (1979).

Bottom-simulating reflections probably result from the contrast between an upper, high-velocity zone of gas-hydrate-cemented sediment, and a zone in which no such cementation occurs and in which seismic velocities are lower. The strength of the seismic return can be enhanced by free gas bubbles below the boundary, which can further reduce the seismic velocities (Stoll and others, 1971). A gas hydrate, also known as a clathrate, is a solid formed by the crystallization of water molecules in a lattice in which small gas molecules such as methane (CH_4), ethane (C_2H_6), and hydrogen sulfide (H_2S) become trapped. Gas hydrates are stable under the temperature and pressure conditions found in the deep ocean (Claypool and Kaplan, 1974; Miller, 1974), and they appear to form where the water and sediment are saturated with gas. Because gas hydrates are stable under conditions of high pressure and low temperature, and because sediment temperature increases with greater depth in accordance with the geothermal gradient, gas hydrates cannot form below a certain depth. The base of the gas hydrate zone follows a temperature-pressure surface that represents the maximum depth at which the gas hydrate is stable. For example, the BSR is observed to dome up around diapirs (fig. 7), which are interpreted to be salt domes by Grow and others (1979). It seems likely that such doming of the BSR is caused by the presence and shape of these diapirs, for several reasons. First, because salt is a good thermal conductor, heat flow through the diapirs presumably is greater than heat flow in the surrounding sediments, and thus the temperature in or near the salt domes would be too high for gas hydrate formation. Second, salt itself is an inhibitor of clathrate formation (Tucholke and others, 1977). There is no identified upper boundary to the gas hydrate zone; presumably it extends upward as far as the sediment is saturated.

The BSR closely parallels the sediment-water interface and shows crosscutting relationships with other reflections that presumably are related to the bedding planes (figs. 3-7). The character of seismic reflections from the units above and below the BSR differs, especially where the BSR is strong. The unit above the BSR is usually acoustically transparent, having very weak or essentially no seismic reflections, whereas reflections from beneath the BSR are usually strong and closely spaced. The change in reflection character across the BSR is clearly visible on both true-amplitude and gain-ranging-amplification displays (fig. 4). The subbottom depth of the BSR varies as a function of the overlying water depth. In the vicinity of the Blake Ridge, the shallowest observation of the BSR was in water 750 m deep, where the BSR was an additional 0.2 s (two-way travel time) beneath the sea floor. Our deepest observation of the BSR was in water 3750 m deep, where the BSR occurred an additional 0.6 s (two-way travel time) below the sea bottom. This variation reflects pressure-temperature relations.

The BSR is frequently of a high amplitude, producing a "bright spot" (Savit, 1974) that indicates a strong acoustic-impedance contrast and, therefore, large changes in density and (or) seismic velocity at this boundary (fig. 4). Interval velocities determined from velocity analyses (fig. 8) of seismic profiles show that the boundary does mark a large velocity inversion.

The very low seismic velocities observed beneath the BSR (fig 8*A*) also support the interpretation that the BSR reflects the base of a gas hydrate zone. These low velocities, which are less than that of sea water, are interpreted to result from the presence of free gas bubbles trapped beneath the gas-hydrate-cemented zone. Bubbles amounting to only a small percentage of the interstitial water volume can produce low velocities (Brandt, 1960; Levin, 1962). The contrast of high-velocity gas-hydrate-cemented sediment with low-velocity gas-filled sediment would account for the large acoustic-impedance change and large reflectivity at this boundary (Stoll and others, 1971).

According to California University (1972), an abrupt decrease in drilling rate was observed during drilling on the Blake Ridge, near what they presumed was the depth of the BSR. Their calculated depth to the BSR was based on an assumed sediment velocity of less than 2.0 km/s, which is less than that expected in a gas-hydrate-cemented zone (Stoll and others, 1971). This suggests that the BSR was deeper than the depth penetrated in these wells. Abundant siderite was found near the bottom of hole 102, and hole 104 ended in a hard ankerite nodule, both possibly indicating a diagenetic boundary. Although a reflection could be produced by a thin cemented layer such as a diagenetic boundary, the velocity structures we observed require a considerable thickness of high-velocity material above the reflector and low-velocity material below it, and thus cannot be explained as a result of a thin layer of authigenic minerals. Therefore we conclude that the BSR results primarily from velocity contrasts at the base of a gas hydrate zone.

Areas of major surface erosion appear to correlate with areas where the BSR is weak or broken. In these places the geothermal gradient would be depressed and therefore would cause a downward migration of the gas hydrate stability field, which could proceed below and out of the zone where the sediment is uniformly saturated with biogenic gas. In contrast, the gas hydrate stability field in areas of deposition would migrate upward in the sediment. This migration would cause once-stable gas hydrates to decompose, thus providing additional free gas which would rise and assure gas saturation in the sediment above the new phase boundary. The breakdown of hydrates releases large amounts of gas because water in the hydrate form can contain more than 50 times the volume of gas it could hold in its liquid phase. (Cieslewicz, 1971).

Deep-Sea Drilling Project (DSDP) holes 102, 103, and 104 (fig. 1) have demonstrated that gas is present in large quantities in the Blake Ridge sediments. Cores from these drill holes released large amounts of gas for several hours after exposure on the deck of the drilling ship. This slow release of gas is consistent with the breakdown of gas hydrates. The gas was predominantly methane and contained traces of ethane and hydrogen sulfide (California University, 1972).

Large gas reservoirs may exist in places where there is a significant amount of closure on the BSR surface. For example, the Blake Ridge is sealed along both its flanks by a gas hydrate zone (fig. 3). A tremendous amount of free gas could be trapped beneath this structure, for there are thousands of cubic kilometers of closure formed by the BSR surface and updip beds.

The gas hydrate zone itself also represents a potential resource if technology can be devised to retrieve the gas from it. The great concentration of gas theoretically could be released by adding the necessary heat of decrystallization. The amount of heat necessary to break down a gas hydrate is equal to 5 to 30 percent of the energy available in the gas released (G. Holder, oral commun., 1979), and therefore a net energy gain could be realized.

REFERENCES CITED

Brandt, H., 1960, Factors affecting compressional wave velocity in unconsolidated marine sand sediments: Journal of the Acoustical Society of America, v. 32, no. 2, p. 171-179.
California University, Scripps Institution of Oceanography, La Jolla, 1972, Initial Reports of the Deep Sea Drilling Project, Volume XI: * * * Washington, D.C., National Science Foundation, 1077 p.
Cieslewicz, W. J., 1971, Some technical problems and developments in Soviet petroleum and gas production: Mines Magazine, v. 61, no. 11, p. 12-16.
Claypool, G. E., and Kaplan, I. R., 1974, The origin and distribution of methane in marine sediments, *in* Kaplan, I. R., ed., Natural gases in marine sediments: Marine Science, v. 3, p. 99-139.
Grow, J. A., Dillon, W. P., Popenoe, Peter, and Sheridan, R. E., 1979, Diapirs along the Continental Slope southeast of Cape Hatteras [abs.]: Southeastern section of the Geological Society of America, 28th Annual Meeting, v. 11, no. 4, p. 181.
King, P. B, 1969, Tectonic map of North America: U.S. Geological Survey, scale 1:5,000,000.
Levin, F. K., 1962, The seismic properties of Lake Maracaibo: Geophysics, v. 37, p. 35-47.
Markl, R. G., Bryan, G. M., and Ewing, J. I., 1970, Structure of the Blake-Bahama outer ridge: Journal of Geophysical Research, v. 75, no. 24, p. 4539-4555.
Miller, S. L., 1974, The nature and occurrence of clathrate hydrates, *in* Kaplan, I. R., ed., Natural gases in marine sediments: Marine Science, v. 3, p. 151-177.
Pratt, R. M., and Heezen, B. C., 1964, Topography of the Blake Plateau: Deep-Sea Research, v. 11, no. 5, p. 721-728.
Savit, C. H., 1974, Bright spot in the energy picture: Ocean Industry, v. 9, no. 2, p. 60-65.
Shipley, T. H., Buffler, R. T., and Watkins, J. S., 1978, Seismic stratigraphy and geologic history of Blake Plateau and adjacent western Atlantic continental margin: American Association of Petroleum Geologists Bulletin, v. 62, no. 5, p. 792-812.
Shipley, T. H., Houston, M. H., Buffler, R. T., Shaub, F. J., McMillen, K. J., Ladd, J. W., and Worzel, J. L., 1979, Seismic evidence for widespread possible gas hydrate horizons on continental slopes and rises: American Association of Petroleum Geologists Bulletin, v. 63, no. 12, p. 2204-2213.
Stoll, R. D., Ewing, J. I., and Bryan, G. M., 1971, Anomalous wave velocities in sediments containing gas hydrates: Journal of Geophysical Research, v. 76, no. 8, p. 2090-2094.
Tucholke, B. E., Bryan, G. M., and Ewing, J. I., 1977, Gas-hydrate horizons detected in seismic-profiler data from the Western North Atlantic: American Association of Petroleum Geologists Bulletin, v. 61, no. 5, p. 698-707.

Units of Measurement

International System (SI or metric) units of measurement herein are used in preference to Customary (English) units. Some conversion factors are given below.

Multiply	By	To obtain
kilometers (km)	0.6214	miles (mi)
kilometers	0.540	nautical miles (nmi)
nautical miles	1.1508	miles

APPEARANCE AND DISTRIBUTION OF THE GAS HYDRATE REFLECTION IN THE BLAKE RIDGE REGION, OFFSHORE SOUTHEASTERN UNITED STATES

By
Charles K. Paull and William P. Dillon

1981

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