Extensive faulting is observed in sediments containing high concentrations of methane hydrate off the southeastern coast of the United States. Faults that break the sea floor show evidence of both extension and shortening; mud diapirs are also present. The zone of recent faulting apparently extends from the ocean floor down to the base of gas-hydrate stability. We infer that the faulting resulted from excess pore pressure in gas trapped beneath the gas hydrate-bearing layer and/or weakening and mobilization of sediments in the region just below the gas-hydrate stability zone. In addition to the zone of surface faults, we identified two buried zones of faulting, that may have similar origins. Subsurface faulted zones appear to act as gas traps.
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Faulting of Gas-Hydrate-Bearing Marine Sediments — Contribution to Permeability


Abstract
Extensive faulting is observed in sediments containing high concentrations of methane hydrate off the southeastern coast of the United States. Faults that break the sea floor show evidence of both extension and shortening; mud diapirs are also present. The zone of recent faulting apparently extends from the ocean floor down to the base of gas-hydrate stability. We infer that the faulting resulted from excess pore pressure in gas trapped beneath the gas-hydrate-bearing layer and/or weakening and mobilization of sediments in the region just below the gas-hydrate stability zone. In addition to the zone of surface faults, we identified two buried zones of faulting, that may have similar origins. Subsurface faulted zones appear to act as gas traps.

Introduction
Methane hydrate in continental margin settings, especially in passive margins, commonly occurs in hemipelagic clay/silts. These deposits appear to have some of the highest concentrations of hydrate, but they also have low permeability, presenting an impediment to extraction of hydrate-derived gas. Recently, seismic profiling by the U.S. Geological Survey and drilling by the Ocean Drilling Program (ODP) have been carried out on the Blake Ridge off the coast of the southeastern United States, a location having high gas-hydrate concentrations. Extensive faulting is noted in these deposits, probably partly associated with gas-hydrate processes. The faulting may create zones of high permeability that could act as reservoirs for exploitation, or that might contain shallow gas deposits that could represent drilling hazards.

Methods
Most of the profiles shown in this paper were collected with seismic systems designed to image the gas-hydrate zone and the region directly below it (1.5-2.0 s below the sea floor). They are part of a set of 4-km-spaced seismic profiles that cover a 4,800 square-kilometer area on the crest of the Blake Ridge. Moderately small, pneumatic seismic-sound sources provided adequate power to penetrate below the region of gas-hydrate stability, while still maintaining the best possible resolution. Sources used were a 160-cubic inch (2.62-liter) airgun or a generator/injector (GI) gun, in which the generator chamber (which generates the primary signal) was 105 cubic inches (1.72 liters), and the injector chamber (which controls bubble pulsing) was also 105 cubic inches. Swept-frequency ("chirp", 2 to 7 kHz) subbottom-reflection data were obtained from a deep-towed multisensor system; they provide data on near-surface sediments (upper 60 m).

Blake Ridge
The Blake Ridge (Fig. 1) is a broad, generally smooth sedimentary accretionary ridge — a deep-sea sediment drift deposit — that is accreting at the site of interaction of major ocean currents. Deposition on its southern flank and erosion on its northern flank have resulted in slow southward migration of the feature. The ridge is considered to be the area where gas hydrate may be most concentrated on the United States Atlantic margin. The surface of the ridge is generally smooth except for minor differential erosion features on its northern (eroding) flank, but, at the crest of the ridge at about 31° 50'N to 32°N, a complex topographic depression covers an area of about 33 by 22 km (Fig. 2).

Faults
Shallow Faults. Seismic-reflection profiles clearly show that the complex topographic depression is a faulted structural collapse (Fig. 3). Faulting took place in a surface layer of sediment about 0.5 to 0.6 s thick (about 400 to 500 m). Seismic profiles indicate that these faults consistently extend from the sea floor to near the base of the gas-hydrate stability zone. The base of the gas-hydrate stability zone is assumed to be identified by the Bottom Simulating Reflection (BSR, note...
4.4 to 5.0 s at the southwest end of line 92-11. This comparable strong reflections near the top of the faulted yet be completely sealed to form a gas trap. Rather, it may This is marked by disruptions at depths of about 4.4 to 4.9 s present gas-hydrate stability zone in the area, just as with the extent of the faults appears to be about 0.5-0.6 s (from about' southwestern flank of the ridge and actually seems to form a gas trap. Line 92-11 is a profile from this locality (Fig. 6; and 7) the top of the faulted zone is marked with squares and the BSR is marked with circles. Indications of free gas exist at the top of the faulted zone both beneath the BSR at ODP site 994, and above the BSR to the southwest on the ridge flank (Figs. 6 and 7). Vertical seismic profiles at the ODP 994 well indicate velocities of about 1750 - 1800 m/s through the lower part of the hydrate zone and such velocities continue downward beneath the hydrate zone to the strong reflections at the top of the interpreted faulted zone. Below the reflection, velocities drop to about 1500 m/s. strongly suggesting presence of free gas. Further southwest, where the top of the faulted zone rises into the gas-hydrate stable zone, the reflection shows apparent phase reversals compared to the sea floor, indicating an acoustic impedance inversion, which again is most easily explained by low velocity produced by free gas. Therefore, as a preliminary interpretation, we suggest that the strong reflection at the top of the faulted zone may represent a gas trap extending across much of the Blake Ridge.

Growth Faults. The faults considered so far seem to exist in layers that are about the thickness of the gas-hydrate stability zone. In contrast, other faults appear to extend over greater vertical distances and, as they seem to be growth faults (having decreasing throw upward), seem to have been more or less continuously active for a long period (Fig. 8). These faults probably just result from compaction of the sedimentary deposits of the Blake Ridge.

Summary and Conclusions Faulting is common in an area of extensive gas-hydrate development off the coast of the southeastern United States. The most recent (shallowest) faults show significant extensional and compressional effects and evidence of mud diapirism all restricted to the depth range of gas-hydrate stability, which extends from the sea floor down to the bottom simulating reflection (BSR). The BSR marks gas that has accumulated at the base of the hydrate stable zone. At least one older episode of faulting seems to be restricted to an equivalent (400-500 m) thickness of sediments. We infer that the faulting and collapse of near-surface strata within the zone of gas-hydrate stability is caused by generation of overpressures beneath the gas-hydrate stable zone and/or by formation of a weakened, mobilized layer just beneath the gas-hydrate stable zone due to presence of trapped high concentrations of fluids. A specific sedimentary interval of hydrate stability will persist only for a short time before the sea floor of the Blake Ridge accretes and the entire gas-hydrate stability zone moves upward as the isotherm that controls its base moves upward. Therefore we conclude that the faulting in these fairly thin (~500 m) intervals occurred in a geologically brief time interval. Growth faults that extend through thicker zones were active for longer times.

At some places, gas seems to be trapped by permeability variations associated with faulting both below and within the zone of gas-hydrate stability, whereas, at other sites, gas seems to be escaping at the sea floor. Both phenomena require that free gas exist within the zone of gas-hydrate stability, but at the temperature/pressure conditions anticipated in the gas-hydrate stability zone, gas bubbles in the presence of water.
would form hydrate. For gas to enter the zone from below, or exist in it, or pass through it to escape at the sea floor, the gas must find channels where no water is present (perhaps locally sealed off by gas hydrate) or where the temperature is sufficiently warm to prevent hydrate formation (perhaps due to passage of warm fluids from greater depth). Chemical changes and thermodynamic phenomena can also affect the stability of hydrate, but it is difficult to imagine one that would allow gas to exist well within the stability zone for gas hydrate on the Blake Ridge (away from salt diapirs). The zones of higher permeability associated with faults may provide sites where gas might be produced and, by pressure reduction, gas from adjacent hydrate might be accessed.

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References

Fig. 1—Location of survey area on the Blake Ridge off the southeastern United States. Dots indicate Ocean Drilling Program and Deep Sea Drilling Project drill site. Square indicates location of Fig. 2.

Fig. 2—Detailed bathymetry of the central part of the study area. Map was generated from available echo-sounder profiles. Locations are indicated for seismic profiles shown in this paper. Region of rough topography at the crest of the ridge from approximately 31°50'N to 32°N was formed by extensive faulting.
Fig. 3—Airgun seismic line 8 across the crest of the Blake Ridge showing structure of the collapse depression between shotpoints 1500 and 900. Location in Fig. 2.
Fig. 4—High-resolution, chirp (swept frequency) profile showing fault scarps with inferred vents at their bases. Location shown in Fig. 2.
Fig. 5—Generator-injector gun seismic line 2B showing buried faults at depth of about 4.4-4.9 s between shotpoints 400-900. The weak BSR in this area compared to the much stronger BSR to the left (at about 0.5 s below the sea floor) indicates that there is much less gas trapped beneath the hydrate zone; the gas may have escaped up faults between shotpoints 500 and 600.
Fig. 6—Line drawing interpretation of airgun seismic line 92-11. Note that the strong reflection near the top of the faulted section (marked with squares) extends from below the base of gas hydrate stability/BSR (marked with circles) to above it on moving from the crest of the Blake Ridge to the southwestern flank.

Fig. 7—Part of seismic line 92-11. Location of this photograph is shown by brackets in Fig. 6. Circle marks BSR and square marks strong reflection near top of faulted section as in Fig. 6.
Fig.—8—Part of seismic line 11 showing apparent growth faults.