Geo-Marine Letters (1993) 13: 145–152

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Evidence for gas accumulation associated with diapirism and gas hydrates at the head of the Cape Fear Slide

Received: 19 October 1992 / Revision received: 22 March 1993

Abstract Single-channel seismic reflection profiles show evidence for areas of significant gas accumulation at the head of the Cape Fear Slide on the continental rise off North Carolina. Gas accumulation appears to occur beneath a gas hydrate seal in landward-dipping strata and in domed strata associated with diapirism. In addition, gas venting may have occurred near diapirs located at the head of the slide.

Introduction

Gas hydrate is a crystalline solid that forms from natural gas and water under conditions of low temperature, high pressure, and gas saturation, and is stable in marine sediments on continental slopes and rises in water depths greater than approximately 500 m (Dillon and Paull 1983; Sloan 1989; Miller et al. 1991). Large volumes of gas may be stored in gas hydrate layers. Approximately 170 ft^3 of gas at STP will form 1 ft^3 of gas hydrate (Makogan 1981). The formation of gas hydrate in the sediment drastically reduces its permeability, enabling it to act as an efficient gas seal (Dillon et al. 1980), and it has been inferred that free gas is often trapped beneath gas hydrate-cemented sediment (Tucholke et al. 1977; Shipley et al. 1979; Dillon et al. 1980; Carpenter 1981; McIver 1982; Dillon and Paull 1983; Miller et al. 1991; Lee et al. 1992).

The Cape Fear Slide is a large mass movement located on the continental rise off North Carolina in an area of pervasive gas hydrate formation (Dillon et al. 1980; Paull and Dillon 1981) (Fig. 1). Single-channel seismic reflection profiles at the head of the Cape Fear Slide have revealed bright spots beneath the base of the gas hydrate, which may indicate large accumulations of gas trapped beneath a gas hydrate seal.

Geologic setting

The Cape Fear Slide complex is the largest mass movement feature that has been mapped on the US Atlantic Margin. The slide is located off the Carolinas on the continental rise in approximately 2300–5500 m water depth, and debris from the slide extends downslope for over 300 km (Popenoe 1982; Cashman and Popenoe 1985; EEZ-Scan 87 1991) (Fig. 1). The head of the Cape Fear Slide occurs near 76°W, 33°N. A string of salt-cored diapirs aligned with the East Coast Magnetic Anomaly rises from Jurassic rift sediments along the eastern edge of the Carolina Trough intersecting the head of the Cape Fear Slide (Grow et al. 1979; Dillon et al. 1982; Cashman and Popenoe 1985) (Fig. 1).

Bathymetry from 3.5 kHz seismic reflection profiles and mid-range side-scan sonar imagery reveal that the head of the Cape Fear Slide is characterized by a main slump scarp that partially surrounds a large, breached diapir (Cashman and Popenoe 1985; Schmuck et al. 1992a, b; Popenoe et al. 1993) (Figs. 2 and 3). The main slump scarp is irregularly shaped and ranges from 20 to 100 m in height. It runs contour-parallel for over 30 km in approximately 2400 m water depth before turning oblique to the slope at its northern end. Secondary scarps are located upslope from the main slump scarp and are smaller in height and less continuous. The secondary scarps are believed to be the surface expression of fault-bounded, rotated blocks (Cashman and Popenoe 1985). Five piercement diapirs were located at the head of the Cape Fear Slide (Fig. 3) using 20- to 560-$in.^3$ airgun single-channel seismic reflection profiles.

The most prominent diapir is a large, breached diapir (diapir B, Fig. 3) located approximately 10 km downslope from the main slump scarp in the center of the area (Dillon

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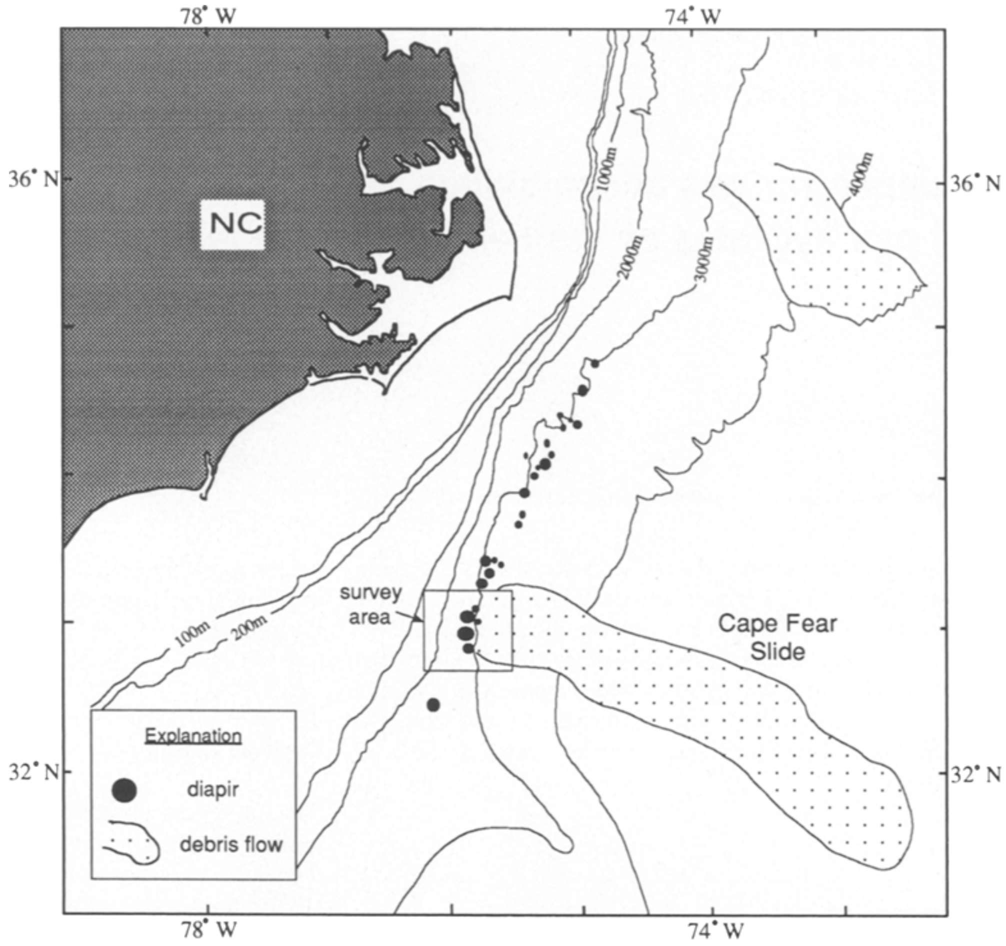
Fig. 1. Map showing the location of the study area at the head of the Cape Fear Slide



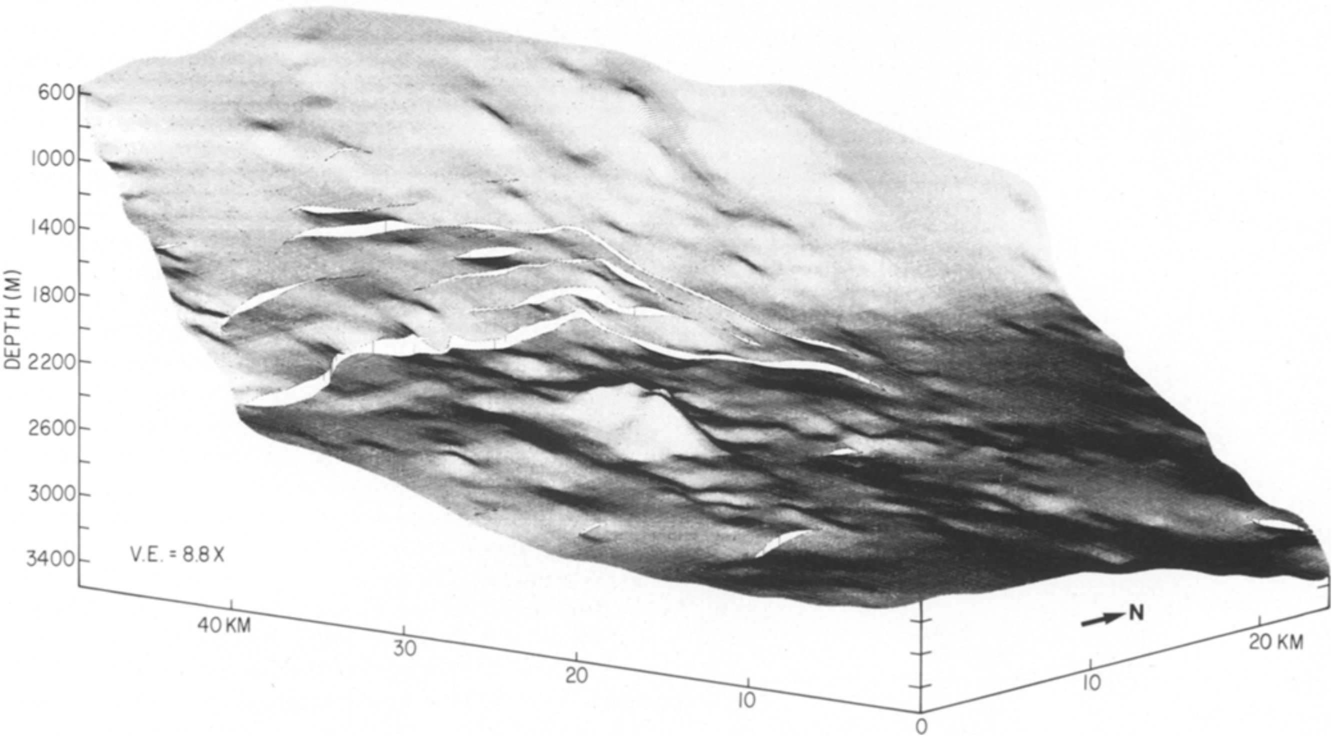


Fig. 2. A three-dimensional view looking northwest of the bathymetry in the study area at the head of the Cape Fear Slide. The bathymetric data was digitized from 3.5-kHz single-channel seismic reflection profiles collected by the Department of Geology at the University of North Carolina-Chapel Hill and corrected using side-scan sonar imagery collected by the US Geological Survey Branch of Atlantic Marine Geology. The large, breached diapir is visable in the center of the image partially surrounded by scarps located further upslope

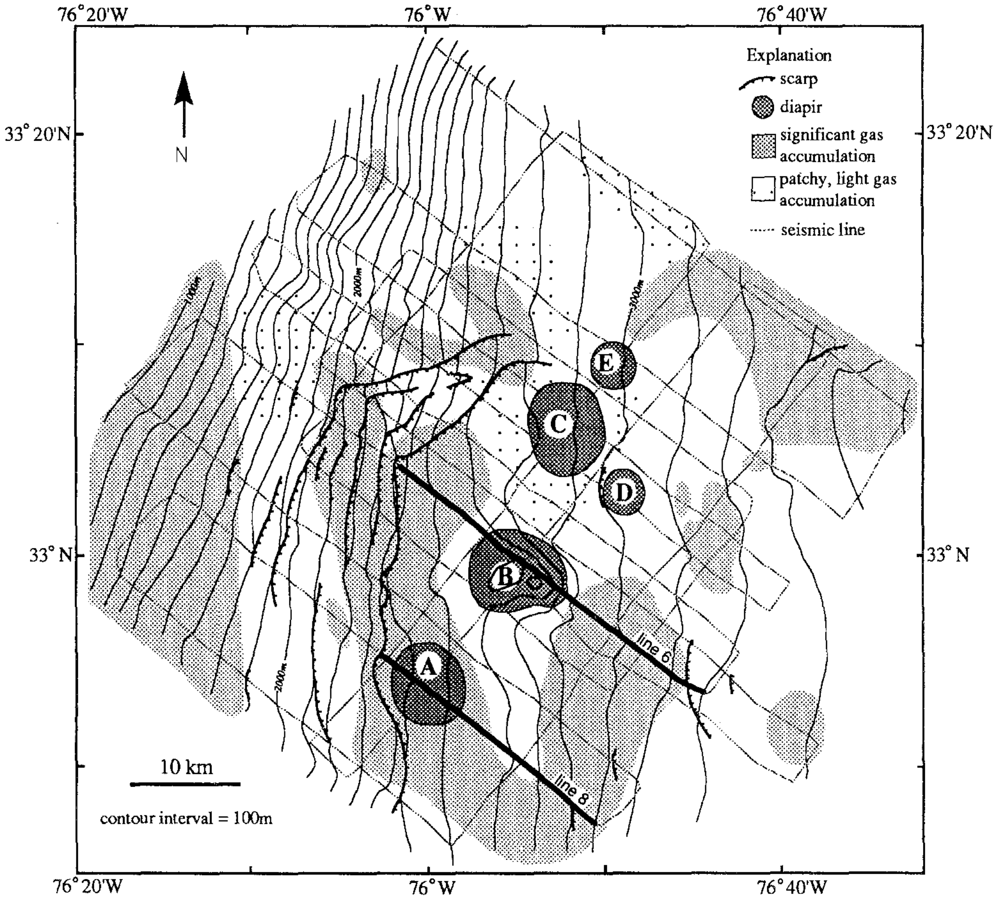


Fig. 3. A map of the head of the Cape Fear Slide showing locations of diapirs in the area. Contour interval is 100 m. Diapir B is the breached diapir visible at the center of Fig. 2. The amount of gas accumulation is inferred from the reflection character of single-channel seismic reflection profiles

et al. 1982; Cashman and Popenoe 1985; Schmuck et al. 1992a, b; Popenoe et al. 1993) (Figs. 2–4). The diapir rises about 100 m above the sea floor on its landward flank and over 250 m above the sea floor on its seaward flank and has a lobate shape with an irregular crest consisting of peaks and depressions. The diapir is approximately 8 km in diameter and its highest point is at a water depth of 2526 m. Ten kilometers north of the breached diapir is a diapir complex in the shallow subsurface consisting of one large diapir and two smaller diapirs (diapirs C, D, E; Fig. 3). The large diapir (diapir C) is about 8 km in diameter while the two smaller diapirs, located less than 1 km off to the southeast (diapir D) and northeast (diapir E) of the large diapir, are less than 5 km in diameter. Another large, subsurface diapir (diapir A) is located 10 km to the southwest of the breached diapir and is nearly 8 km in diameter (Figs. 3 and 5). It can be inferred from a broad depression in the bathymetry seaward of the main slump scarp that a large section of the rise strata is missing at the head of the slide (Figs. 2 and 3) and that the breached diapir has been at least partially exhumed by the mass movement (Schmuck et al. 1992a, b).

Gas hydrates

The head of the Cape Fear Slide occurs in an area of extensive gas hydrate formation denoted by the presence of a bottom-simulating reflection (BSR) (Paull and Dillon 1981). Bottom-simulating reflections are seismic reflections that mimic the sea floor topography and correspond to a reflector formed by an acoustic impedance contrast between higher-velocity hydrate-cemented sediment and non-hydrate-cemented lower-velocity sediment at the base of the gas hydrate stability zone. Several authors have suggested that the presence of free gas beneath the base of the gas hydrate is responsible for the large acoustic impedance contrast necessary to form the BSR (Tucholke et al. 1977; Shipley et al. 1979; Dillon et al. 1980; Miller et al. 1991). Dillon et al. (1980) calculated velocities from multichannel seismic reflection profiles collected over the Blake Outer Ridge and found a velocity inversion between sediments above and below the BSR. Sediments above the BSR in the zone of hydrate formation had velocities greater than 2.5 km/sec, while velocities below the BSR had very low velocities, probably lower than the speed of sound in water (1.5 km/sec). The authors concluded that free gas bubbles must be trapped in the interstitial water below the base of the gas hydrate in order to obtain such low velocities. In addition, Miller et al. (1991) proposed that the presence of a BSR is a function of the amount of free gas trapped beneath the base of the gas hydrate-cemented sediment and that, if insufficient gas is trapped, the BSR is either patchy or absent. It follows that in an area where the BSR is patchy or absent, the sediment may still contain gas hydrates, but may not have enough free gas trapped beneath the hydrate to produce a bottom-simulating reflec-

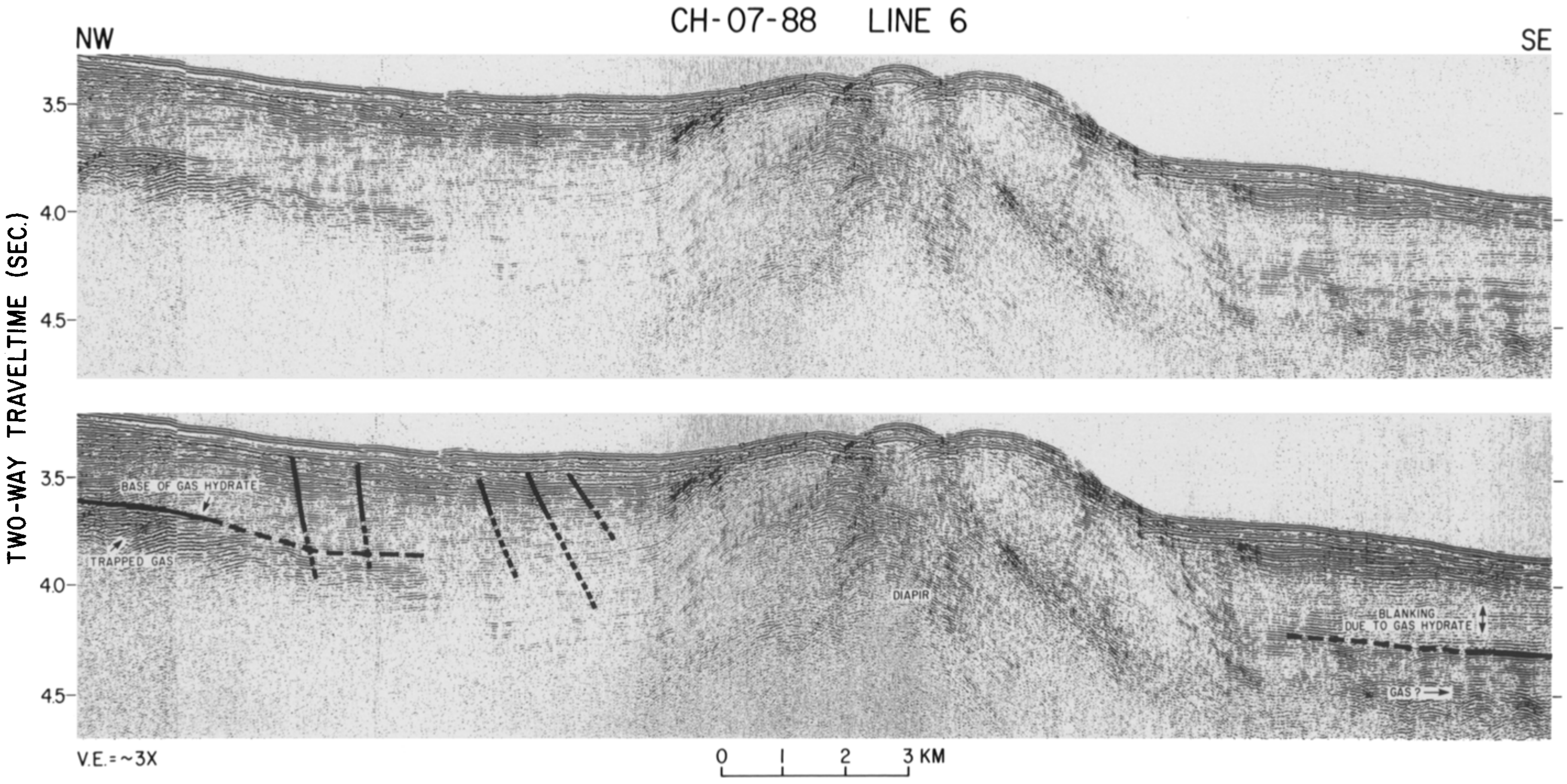


Fig. 4. A 20-in.^{3} airgun single-channel seismic reflection profile across the breached diapir (Department of Geology, University of North Carolina-Chapel Hill: Cruise CH-07-88, line # 6). The base of the gas hydrate is visible across most of the profile denoted by a series of terminations of high-amplitude reflections believed to indicate trapped gas. Reverse-dip strata upslope from the diapir are crosscut by the base of the gas hydrate forming a gas trap. Faults located upslope from the diapir may continue below the base of the gas hydrate into the zone of high-amplitude reflections. Blanking above BSR may be caused by the cementation of the sediment by gas hydrate.

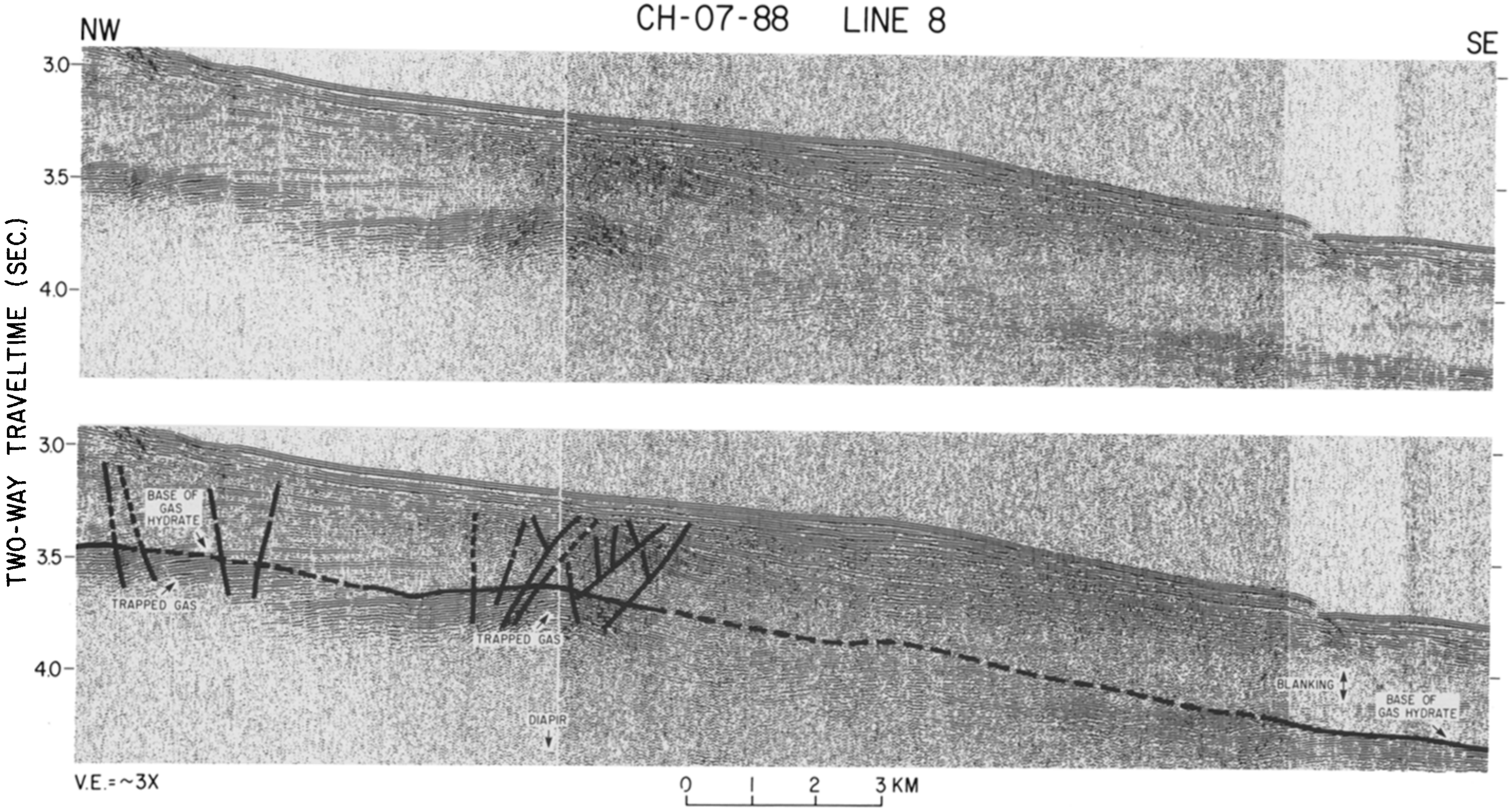


Fig. 5. A 20-in.^{3} airgun single-channel seismic reflection profile across the breached diapir (Department of Geology, University of North Carolina-Chapel Hill: Cruise CH-07-88, line # 8). A diapir in the subsurface (diapir A in Fig. 3) has caused doming of the surrounding strata and the base of the gas hydrate to retreat upward forming a localized high and consequent gas trap. Several extensional faults occur above and upslope from the diapir and extend below the base of the gas hydrate into the zone of high-amplitude reflections.

tion. In addition, the character of the BSR is dependent on the frequency of the seismic source used. When comparing low-frequency (560-in.^{3} airgun) seismic reflection profiles with high-frequency ones (5-in.^{3} airgun), from the same cruise over the Blake Outer Ridge (USGS Gillis-79-05), it has been observed that the BSR changes from a single, strong, high-amplitude reflection to a series of high-amplitude reflections (W. P. Dillon, personal communications 1993). Above the BSR in the gas hydrate stability zone, a reduction in the amplitude of seismic reflections, known as blanking on seismic profiles, often occurs. Blanking may be due to the filling of the pore space by hydrate, which would cause changes in the acoustic character of the sediments (Shipley et al. 1979; Dillon et al. 1980; Lee et al. 1992).

High-resolution (20-in.^{3} airgun) single-channel seismic reflection profiles from the head of the Cape Fear Slide show high-amplitude reflections occurring approximately 0.4–0.6 s below the sea floor that are often landward-dipping (Figs. 4 and 5). These reflections terminate updip at a depth that corresponds with the observed location of a BSR in this area (Dillon et al. 1980; Paull and Dillon 1981; Dillon and Paull 1983; Lee et al. 1992). Carpenter (1981) noticed the same phenomenon in the area and concluded that the reflections were bright spots that indicated free gas trapped beneath the base of the gas hydrate. We infer the same in this case: that the high-amplitude reflections are bright spots that indicate gas trapped by a gas hydrate seal. Several faults associated with rotated blocks and doming due to diapirism continue below the base of the gas hydrate-cemented sediment into the area of free gas accumulation. Blanking of seismic reflections is prevalent in the zone of gas hydrate stability near the diapirs at the head of the slide. The blanking often occurs above patchy or absent high-amplitude reflections located beneath the base of the gas hydrate-cemented sediment, indicating the presence of gas hydrate but little trapped gas (Fig. 4).

Gas accumulation

Dillon et al. (1980) described the geometries necessary for trapping gas beneath the base of the gas hydrate-cemented sediment. Gas may be trapped in landward-dipping strata or in bowed strata that are crosscut and capped at their updip ends by the base of the gas hydrate-cemented sediment. Gas may also be trapped by doming of the gas hydrate-cemented sediment due to diapirism. The thermal conductivity of a salt diapir is greater than that of the surrounding sediment, resulting in a local increase in heat flow away from the diapir and a compression of the isotherms above it (MacLeod 1982). Increased heat flow from a salt diapir and the migration of salt ions into the surrounding sediment cause the base of the gas hydrate to retreat away from the diapir, creating a dome in the base of the hydrate-cemented sediment (Dillon et al. 1980; Macleod 1982). This process, in conjunction with the doming of the surrounding strata by the diapir, forms a trap for gas released by disintegrating gas hydrate above the diapir and gas migrating updip from strata surrounding the diapir.

Gas at the head of the Cape Fear Slide is trapped by such means as described above. We have divided areas of inferred trapped gas into *significant* and *patchy* zones on the basis of the character of the high-amplitude reflections that occur beneath the base of the gas hydrate-cemented sediment in airgun single-channel seismic reflection profiles. Strong, continuous, and well-developed high-amplitude reflections in which the set of reflections have a thickness of 0.2 s (two-way travel time) or greater are described as significant, whereas weak and discontinuous high-amplitude reflections are described as patchy. Transitions from significant to patchy areas of gas accumulation or areas void of gas accumulation are generally gradational, but may be abrupt. Significant gas accumulation beneath a gas hydrate seal occurs in three areas: (1) along the upper rise in the western corner of the study area in landward-dipping strata, (2) in a discontinuous band around the diapirs in rotated strata and strata that have been deformed due to diapirism, and (3) above diapir A in domed strata. Patchy gas accumulation occurs around the diapirs located to the north of the breached diapir (diapirs C, D, E) and in an area on the upper rise (Fig. 3). In general, gas appears to be trapped by a gas hydrate seal around the diapirs in a broad structural arch formed by diapirism and upslope from the diapirs in an area of landward-dipping, rotated strata.

Possible gas venting

Numerous faults occur at the head of the Cape Fear Slide, which continue below the base of the gas hydrate into the zone of free gas (Fig. 5). These faults may provide conduits for gas escape to the surface (Prior et al. 1989; Neurauter and Bryant 1990). However, the release of the gas along fault zones could only occur during active phases, as gas moving along fault planes at this depth would eventually reform into gas hydrate inhibiting further gas escape. Several diapirs along the East Coast Magnetic Anomaly have been shown to have gas trapped above them by a gas hydrate seal (Schmuck et al. 1992a, b). Diapir A (Figs. 3 and 5) is an excellent example of this sort of gas trap. The apparent lack of gas accumulation around the large, breached diapir (diapir B) at the head of the Cape Fear Slide and the patchy gas around diapirs to the north (diapirs C, D, E) suggest that gas that was once trapped above the diapirs by a gas hydrate seal may have escaped (Fig. 6).

We speculate that the accumulation and venting of gas around the diapirs at the head of the slide may have proceeded as follows:

1. As a diapir migrated through the subsurface, the overlying strata bowed upward and the base of the gas hydrate receded locally above it, forming a gas

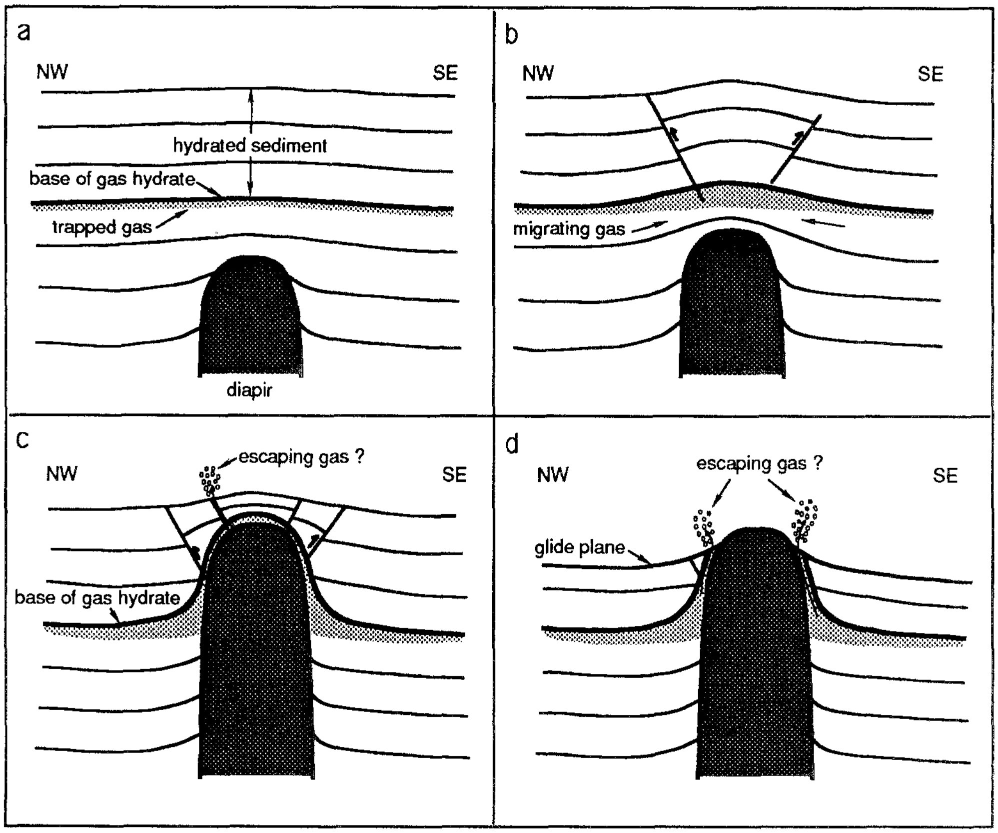


Fig. 6a–d. An illustration showing the inferred progression of a diapir through the subsurface and the consequent accumulation and release of gas. As the diapir penetrates upsection, the strata dome above it (**a**). Further penetration of the diapir causes extensional faulting above the diapir and the base of the gas hydrate to recede locally above the diapir. Gas collects beneath a hydrate seal (**b**). As the diapir nears the sea floor, gas may vent to the surface along active fault planes (**c**), or may escape to the surface due to the rupturing of the gas hydrate seal by mass movement (**d**)

trap. Much of the trapped gas was derived from the breakdown of hydrate above the diapir as well as gas that may have migrated from the surrounding area (Fig. 6a, b). At this time, extensional faults developed above the diapir and may have extended through the base of the gas hydrate (Fig. 6b).

2. Continued progression of the diapir caused an increase in faulting and the base of the gas hydrate to recede farther (Fig. 6c).
3. At this point, gas may have escaped along active fault planes to the surface (Hedberg 1974; Prior et al. 1989; Neurauter and Bryant 1990), or
4. the gas may have escaped due to the mass movement excavating the diapir and removing the hydrate seal (Fig. 6d).

Another possibility is that escaping gas from around the diapirs may have initiated the Cape Fear Slide. The mechanism that would have caused this is unclear. The slide may have been triggered by an explosive eruption of gas from beneath a gas hydrate seal along fault planes to the surface.

Summary

It can be inferred that significant gas accumulation appears to occur beneath gas hydrate seals in conjunction with landward-dipping and domed strata at the head of the Cape Fear Slide. The gas is trapped in an area on the upper rise in landward-dipping strata and on the lower rise in domed strata above diapirs. Several faults formed due to mass movement and diapirism extend below the base of the gas hydrate-cemented sediment and may act as conduits for gas escape. The absence of significant gas accumulation around shallow diapirs at the head of the slide suggests that gas escaped that was trapped around the diapirs. The gas may have vented along fault planes to the surface or may have been released due to the rupturing of the gas hydrate seal by mass movement.

Acknowledgments Thanks to Peter Popenoe and Bill Dillon of the USGS for their insights and help in locating useful seismic and side-scan sonar data. Thanks also to Tom O'Brien for help in digitally processing seismic data and Jeff Zwinakis for excellent drafting.

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