Large-scale elongated gas blowouts along the U.S. Atlantic margin

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[1] In May 2000 we surveyed a series of en echelon, asymmetric depressions along the outer shelf off Virginia and North Carolina using high-resolution chirp and side-scan sonar. The features, which are elongated parallel to the shelf edge and have steep landward walls, are ~4 km long, 1 km wide, and up to 50 m deep. On the basis of internal stratal geometry interpreted from chirp profiles, the depressions do not appear to result from simple, down-to-the-east, normal displacement along deep-seated faults or structure. Rather, the depressions seem to have been excavated primarily by gas expulsion, creating large-scale asymmetric gas escape structures that have been termed "gas blowouts." Gas appears to have been trapped beneath a shelf edge delta that is a few tens of meters thick and exhibits internal soft sediment deformation suggestive of progressive downslope (seaward) creep. These new data suggest the blowouts occurred when thin-skinned deformation and creep of the surficial deltaic sediment layers combined with updip/upslope gas migration, ultimately leading to gas pressure in excess of the overburden. The location of the expulsion craters along the shelf edge and their elongated, asymmetric shapes strongly suggests a causal relation between the downslope creep of the delta and the expulsion event. We suggest a positive feedback between upward migration of gas-rich fluids through the low-stand delta and the downslope creep processes. While the complex interplay between differential permeability, overpressure, and upslope fluid migration remains poorly understood, we suggest such interactions may play an important role in controlling slope stability. *INDEX TERMS:* 3022 Marine Geology and Geophysics: Marine sediments—processes and transport; 8105 Tectonophysics: Continental margins and sedimentary basins (1212); 8045 Structural Geology: Role of fluids; *KEYWORDS:* pockmarks, fluid expulsion, creep

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1. Introduction

[2] Seafloor pockmarks and trapped gas have been observed along many continental margins [*Josenhans et al.*, 1978; *Hovland et al.*, 1984; *Hovland and Judd*, 1988; *Yun et al.*, 1997; *Vogt et al.*, 1999]. These features are indicators of past or present fluid migration. Pockmarks are usually circular depressions ranging in size from several to hundreds of meters with depths on the order of centimeters to tens of meters, but they exhibit marked variability in size and shape as a result of different excavation histories [*Hovland et al.*, 2002]. For example, elongated pockmarks or depressions, where one axis is much greater than the other, occur along slopes or in areas where the seafloor is affected by strong currents [*Hovland et al.*, 2002]. In addition to asymmetry, areas exhibiting linear pockmark trends are commonly associated with a structural control on their formation.

[3] Shallow gas associated with pockmarks along continental margins can be either thermogenic or biogenic in origin [*Hovland and Judd*, 1988; *Kvenvolden*, 1993]. If the source is thermogenic, deep-seated faults are required to allow upward migration of the gas to charge shallow regions. If the gas is biogenic, it can be produced in situ by methanogenesis of organic material. Gas of either origin also may be derived from gas hydrate dissociation at water depths >500 m, with subsequent upslope migration. Until recently, most of the hydrate dissociation discussion focused on depressurization by sea level falls during glacial periods and the effect of the resulting release of overpressurized gas-charged fluids on slope stability. Consequently, gas hydrate dissociation on passive margins was thought to occur during the Last Glacial Maximum (LGM) [*Paull et*

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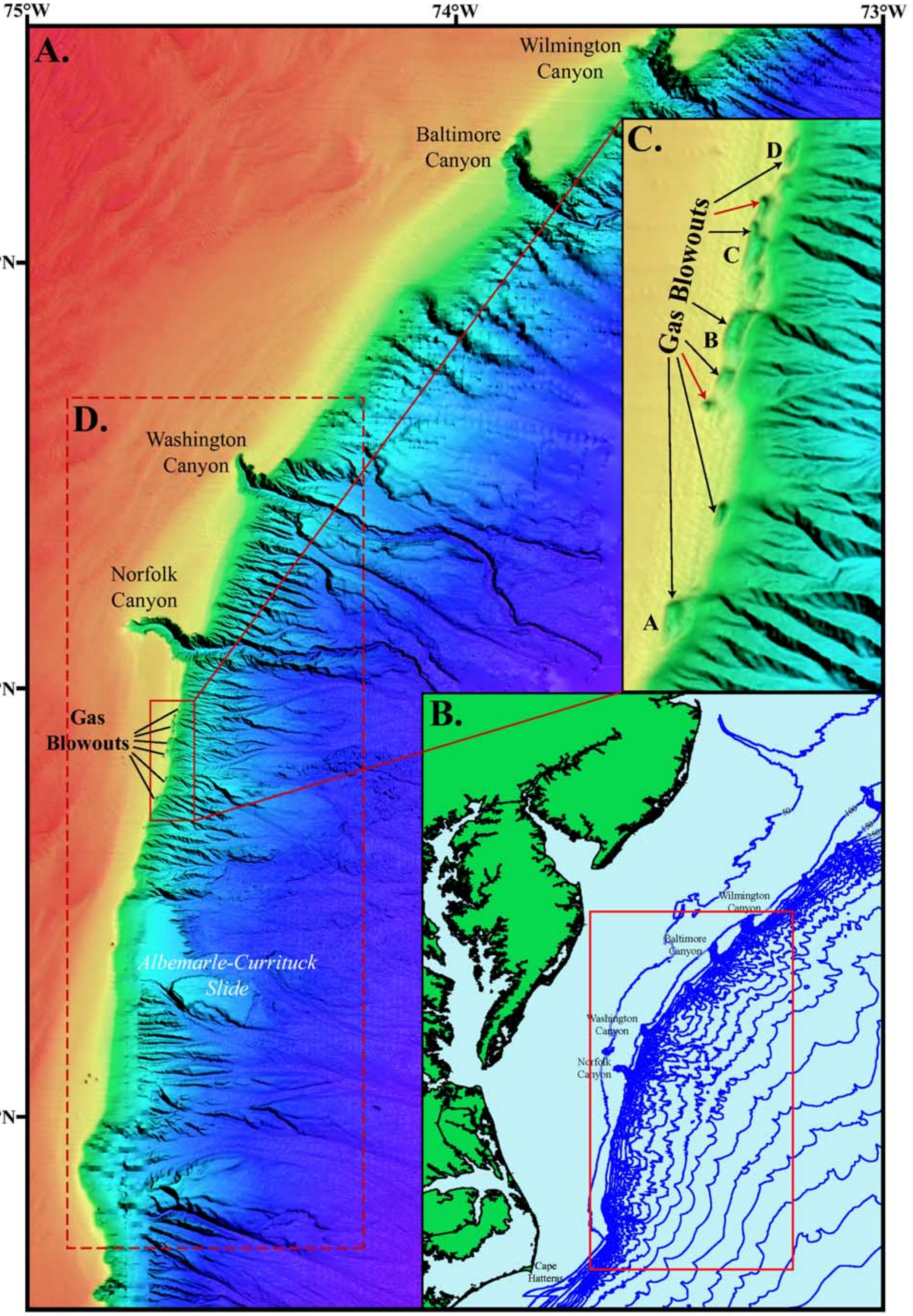


75°W
74°W
73°W
38°N
37°N
36°N
A.
Wilmington Canyon
Baltimore Canyon
D.
Washington Canyon
Norfolk Canyon
Gas Blowouts
Albemarle-Currituck Slide
C.
Gas Blowouts
A
B
C
D
B.
Wilmington Canyon
Baltimore Canyon
Washington Canyon
Norfolk Canyon
Cape Hatteras

Figure 1

al., 1996]. While methane release by depressurizing gas hydrate could occur during sea level falls, hydrate dissociation might also occur during interglacials/interstadials owing to secular warming of bottom waters [*Bratton*, 1999; *Driscoll et al.*, 2000; *Kennett et al.*, 2000; *Mienert et al.*, 2002; *Vogt and Jung*, 2002]. Thus, while there is general agreement that gas hydrate dissociation can provide overpressurized, gas-charged pore fluids that would promote slope instability on continental margins, there is no consensus on whether the mechanism happens preferentially during glacial or interglacial intervals.

[4] Side-scan and subbottom data acquired during the May 2000 CH1000 survey aboard the R/V *Cape Hatteras* imaged a series of large asymmetric depressions along the U.S. mid-Atlantic margin (Figures 1 and 2). The en echelon depressions, located at ~100 m water depth, are ~4 km long, 1 km wide, and up to 50 m deep. The location of these features near the shelf break, their elongation parallel to the shelf edge, and their steeper inner or landward walls, as well as proximity to the large, late Pleistocene Albemarle-Currituck slide to the south, led *Driscoll et al.* [2000] to suggest these features might represent incipient large-scale failure of the outer shelf/upper slope. The asymmetric cross-sectional morphology of the depressions identified from the NOAA 3″ bathymetry suggested the features may have originated through a small amount of down-to-the-east normal slip [*Driscoll et al.*, 2000]. The data presented here indicate that the origin of the depressions is more complex and suggest gas escape plays an important role.

[5] Here we describe in detail the morphology of the depressions in relation to their position on the shelf edge and the surrounding stratigraphy. We propose these are gas blowout features and their formation is directly related to release of shallowly trapped gas. This study area (Figure 1) provides an ideal opportunity to examine the interplay between downslope creep of shelf edge sediments, differential slope permeability, and the upslope migration of gas-charged pore water. We also seek to determine if the blowouts represent an early phase of slope instability and to examine whether their formation, involving several interacting factors (e.g., gas accumulation, deformation of under-compacted sediment, and fluid flow), might provide new insights to the triggering mechanisms of slope failure.

2. Data Acquisition

[6] The CH1000 side-scan and chirp sonar survey covered the outer shelf region from Cape Hatteras to the Norfolk Canyon (Figure 2). Sonar data were acquired using the Scripps Institution of Oceanography subbottom sidescan (SUBSCAN) system, which is based on components manufactured by EdgeTech. The system includes the following: (1) a DF1000 dual-frequency (100 and 500 kHz) side-scan instrument and (2) an X-Star chirp subbottom reflection sonar with submeter vertical resolution. The two sonar instruments were towed in tandem arrangement at depths from several to a few tens of meters above the seafloor. Data were acquired at a ship speed of ~4–5 knots. Towfish navigation was obtained by monitoring fish depth and the winch cable payout in relation to topside differential global positioning service (DGPS) receivers. The CH1000 cruise track (Figure 2) was designed to provide the following: (1) detailed dip line coverage (200 m line spacing) from the outer shelf to the upper slope across the northern blowouts B and C, (2) detailed strike line coverage (200 m line spacing) of the blowouts, and (3) regional reconnaissance dip lines at 2 km spacing from the Norfolk Canyon to the Albemarle-Currituck slide. Subbottom reflection profiles were acquired using a 1–5.5 kHz chirp signal with a 50 ms sweep. Side-scan data were obtained on swaths extending out ~200 m either side of the towfish, providing ~100% overlap on dip and strike lines over the northern blowouts (Figure 2, inset).

[7] The chirp subbottom data were processed using the SIOSEIS [*Henkart*, 2003] and Seismic Unix [*Cohen and Stockwell*, 1999] seismic processing software packages. The side-scan data were processed using Xsonar [*Danforth*, 1997]. We constructed three mosaics of the 100 kHz side-scan data using the following: (1) all the dip lines, (2) the west looking portions of the strike line data, and (3) the east looking portions of the strike line data. Three-dimensional perspective images were created using *Interactive Visualization Systems* [2004] Fledermaus.

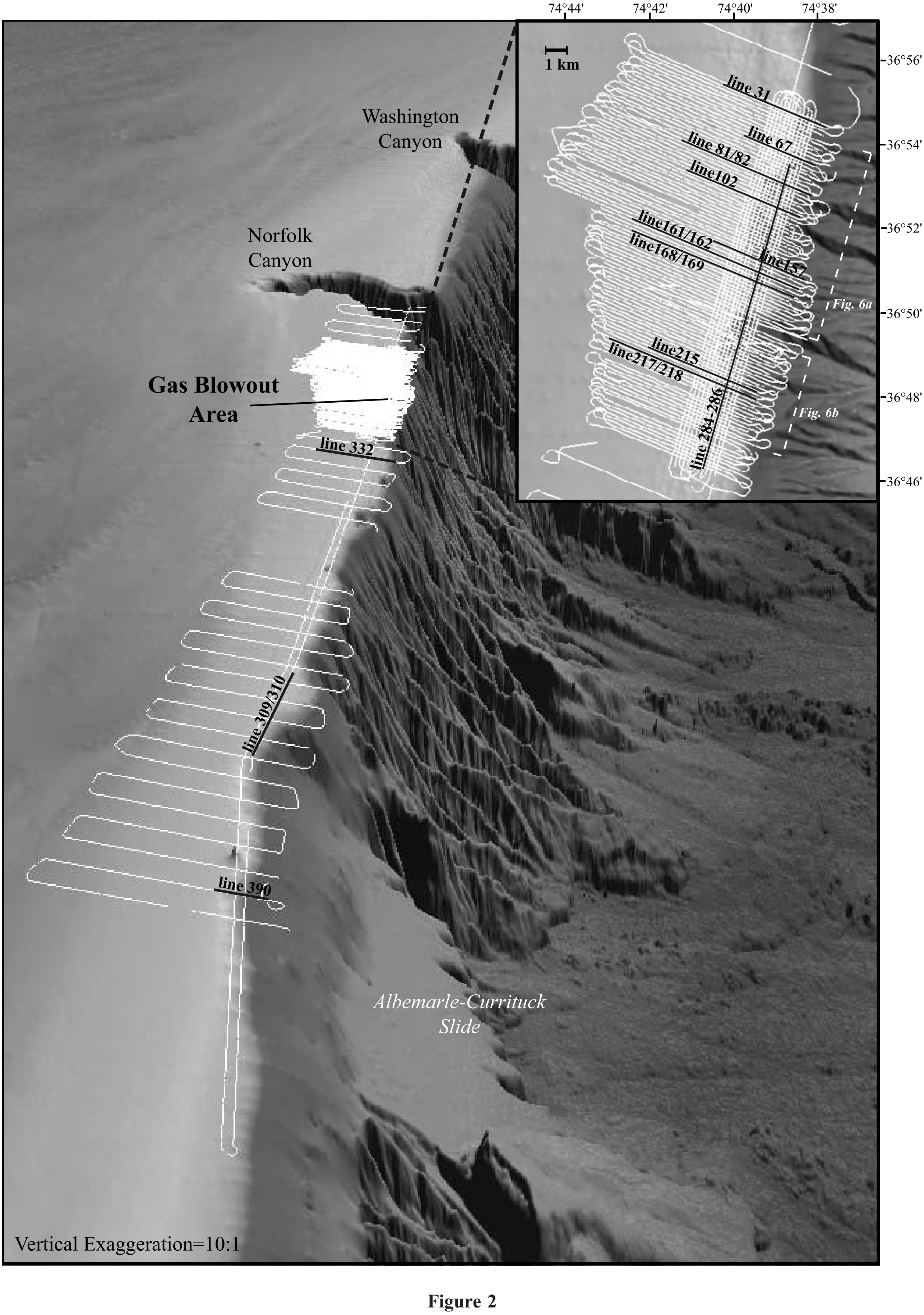
3. Results

3.1. Morphology of Shelf Edge Depressions

[8] The shelf edge depressions are located on the outermost shelf, in ~100 m of water, between the Norfolk Canyon to the north and the Albemarle-Currituck submarine slide to the south (Figures 1 and 2). Both the bathymetry and the subbottom data show a varying cross-sectional asymmetry across the depressions (Figures 3 and 4). The slope of the landward walls is generally very steep, while the seaward walls show a more irregular morphology, ranging from gentle and relatively flat to somewhat steep (Figures 3 and 4). North and south of the main area of large, elongated depressions are several smaller, more circular craters (Figure 1c). Throughout most of the region the depressions are a sufficient distance landward from the shelf edge, so that there is a distinctive seaward wall. However, in regions where the depression is very close to the shelf edge, the seaward wall appears as more of a collapse structure, where the outermost portion of the shelf has moved a short distance downslope, creating an open-sided feature (e.g., Figure 3a, line 67).

[9] Many of the chirp profiles show evidence of thinly laminated, recent sediment several meters thick infilling the underlying depression surface (Figure 3). Sediment deposited within the depressions and on the sloping walls modifies the overall morphology of the features such that the greater the sediment infill, the smoother the features appear. Both the chirp and side-scan sonar data show evidence of southerly

Figure 1. (a) En echelon, large-scale, elongated depressions offshore of Virginia and North Carolina between the Norfolk Canyon and the Albemarle-Currituck slide. Bathymetry is from the NOAA 3″ grid. The shelf edge depressions are interpreted as ‘‘gas blowout’’ features and will hereinafter be referred to as such. (b) Location map. (c) Enlargement of gas blowout features. Individual blowouts are labeled A–D. Red arrows indicate the smaller, more circular blowout features. (d) Location of Figure 2.



74°44'
74°42'
74°40'
74°38'
36°56'
36°54'
36°52'
36°50'
36°48'
36°46'
1 km
line 31
line 67
line 81/82
line102
line161/162
line168/169
line157
Fig. 6a
line215
line217/218
Fig. 6b
line 284-286
Washington Canyon
Norfolk Canyon
Gas Blowout Area
line 332
line 309/310
line 390
Albemarle-Currituck Slide
Vertical Exaggeration=10:1

Figure 2

transport of the recent sediment (Figures 3b and 5b). The strike lines shown in Figure 3b (e.g., line 286/285) display small, southward prograding clinoforms along the northern margins of the depressions, with minimal recent sediment buildup on the southern end. The side-scan data have regions of high backscatter on the shelf directly landward of the shelf edge depressions (Figure 5b) that appear to be mobile sediment bed forms. The linear features or ridges are asymmetric, with a sharp northern boundary and diffuse southern face of the bed form (Figure 5b). In addition, trailing high-backscatter patterns are observed on the southern side of the features (Figure 5b).

3.2. Stratal Geometry of Shelf Edge Deposit

[10] The several outer kilometers of the margin in the shelf edge depression region are covered by a well-stratified sediment wedge that appears to be a shelf edge delta (e.g., Figure 4a, inset). The strata imaged in the dip profiles show evidence of a seaward dipping sequence perched on the edge of the margin (Figure 3a, e.g., lines 161/162). Several short gravity cores (<15 cm long) taken during the CH1000 survey revealed that the surface sediment is poorly sorted, consisting of gravels and silty clays. The stiff, cohesive nature of the sediments prevented the acquisition of longer cores. Thus the deeper sediments were not sampled, and therefore their age remains unconstrained.

[11] Strata in the seaward dipping wedge are not continuous and are disrupted at several length scales. The strata have small-scale "apparent folds," or undulations, with highly variable layer thicknesses (Figure 4c, inset). These features are of short wavelength and are difficult to correlate laterally across adjacent profiles 200 m apart (Figure 6). There is no systematic relationship between the apparent folds and the walls of the shelf edge depressions.

3.3. Seismic Signature of Gas-Charged Sediments

[12] Trapped gas is recognized in seismic data as bright, high-amplitude reflections that obscure deeper returns [*Hovland and Judd*, 1988]. This reflection character of gas is observed in the shelf edge deposit (Figures 3, 4, and 6). In addition to this particular reflection signature commonly associated with gas, acoustically transparent "wipeout" zones that disrupt the stratigraphy are observed (e.g., Figure 3a). Disturbance of stratigraphic laminations has been identified in other gas-prone regions and has been related to the passage of gas or fluid through the sediment (e.g., "columnar disturbances" described by *Hovland and Judd* [1988]). The acoustic wipeout zones occur in the landward walls, in the seaward walls, and beneath the shelf edge craters (Figures 3 and 4). Inboard of the laminated strata, a blotchy, unstratified acoustic character is observed in the surface sediments, which appears to be a large, composite acoustic wipeout zone.

[13] Bright reflections associated with trapped gas in the chirp data are often observed immediately below the steep, landward sides of depressions B and C (e.g., Figure 3a, lines 161/162 and 31, and Figure 4b, inset). The strike line side-scan data show lineated zones of very high backscatter a few hundred meters long, parallel or subparallel to outcropping shelf edge strata along the inner crater walls (Figure 5a, inset). These high-backscatter zones correlate spatially with bright reflections associated with gas accumulation in the chirp profiles. The same zones can be identified in both the east and west looking swaths (Figure 5a, inset), indicating that these patches are reflectivity changes resulting from seabed roughness or changes in seafloor composition rather than large-scale seafloor slope variations.

3.4. Spatial Relation Between Trapped Gas and the Shelf Edge Delta

[14] The sonar data show evidence for extensive amounts of gas at shallow depths along the outer shelf between Cape Hatteras and the Norfolk Canyon. There is a strong spatial correlation between trapped gas on the outer shelf, the shelf edge depressions, and finely laminated deltaic strata. Landward of this deposit, gas appears to be freely venting through the seafloor, and no large depressions are observed. This same spatial correlation is observed in the Albemarle-Currituck slide region, where numerous gas pockets are observed, both trapped and freely venting. The chirp profiles across the upper slide region have evidence of internal deformation in layered strata along the shelf edge and are associated with bright reflections attributed to trapped gas (Figure 7a). Additionally, there is a prominent dome-shaped feature in the topography (Figure 7b). The center of the dome is characterized by high backscatter and generally mottled acoustic signature; however, there are some steeply dipping reflections beneath the middle of the dome.

4. Discussion

4.1. Origin of Shelf Edge Depressions, or Gas Blowout Features

[15] Prior to surveying the region, it seemed plausible that the shelf edge depressions might have been controlled by normal faulting with collapse and rollover of the hanging wall into the fault trace [*Driscoll et al.*, 2000]. However, the chirp reflection profiles show no evidence of large normal faults. The highly layered stratigraphy of the outer shelf provides clear marker horizons from which we can discern the lack of offset. Downslope creep along bedding planes is the only type of mass movement that can be identified from the chirp reflection data.

[16] Trapped gas is evident in chirp reflection profiles across our study area and appears to have a strong spatial correlation with a thin (few tens of meters) wedge of stratified sediment draped across the outermost shelf/upper slope. Gas also appears to be present (possibly venting) along the landward walls of the shelf edge depressions. The lack of large normal faults, along with observations of soft sediment deformation of the layered strata and the abundance of gas, led us to conclude that these are gas escape features, or gas blowouts, created during expulsion episodes.

4.2. Morphology and Age of Gas Blowouts

[17] Strings of pockmarks are expected to nucleate along zones of weakness in the upper sediments [*Hovland et al.*, 2002]. In the blowout region it appears that gravitational

Figure 2. Survey ship track coverage superposed on NOAA 3$''$ gridded bathymetry in three-dimensional perspective view. Profile line numbers shown in Figures 3, 4, and 7 are labeled. See Figure 1 for location.

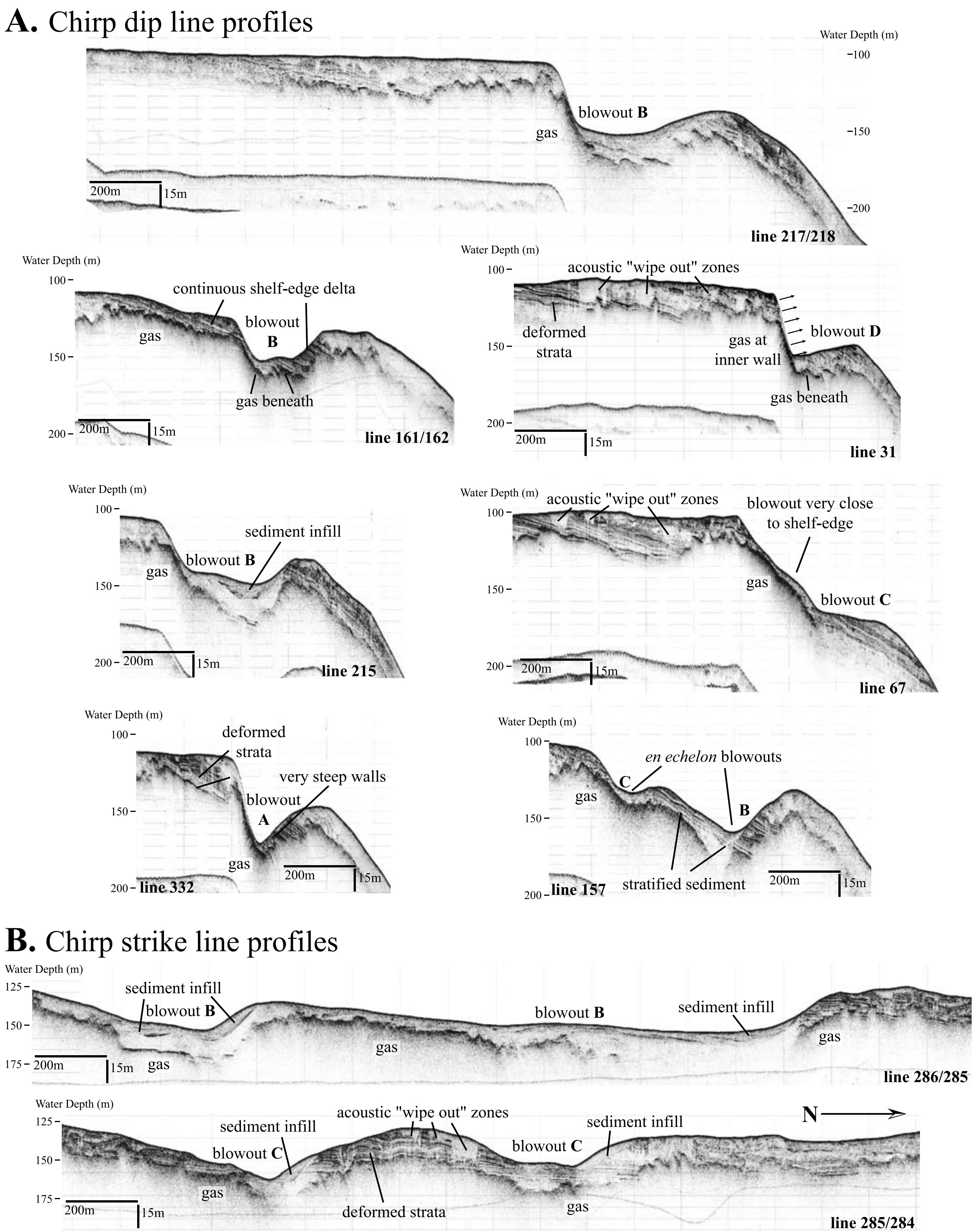

A. Chirp dip line profiles
Water Depth (m)
100
150
200
blowout B
gas
200m
15m
line 217/218
continuous shelf-edge delta
blowout B
gas
gas beneath
line 161/162
acoustic "wipe out" zones
deformed strata
gas at inner wall
blowout D
gas beneath
line 31
sediment infill
blowout B
gas
line 215
acoustic "wipe out" zones
blowout very close to shelf-edge
gas
blowout C
line 67
deformed strata
very steep walls
blowout A
gas
line 332
en echelon blowouts
C
B
gas
stratified sediment
line 157
B. Chirp strike line profiles
125
150
175
sediment infill
blowout B
gas
blowout B
sediment infill
gas
line 286/285
acoustic "wipe out" zones
sediment infill
blowout C
blowout C
sediment infill
N
gas
deformed strata
gas
line 285/284

Figure 3

forces have created tensional stress within the shelf edge delta sediments, as evidenced in the downslope creep of these strata. The en echelon pattern of the blowout features also points to a tensional stress regime within the upper sediments and fluid flow focusing along weaknesses in the deltaic strata. While this might seem to indicate that the shelf edge region would be dominated by extensional faulting, many of the dip seismic crossings of depressions (Figure 3, lines 161/162 and 157; Figure 4, line 168/169) show no evidence for large down-to-the-east normal offset.

[18] The morphology of the seaward wall changes with proximity to the shelf/slope break. Where the blowout is coincident with the shelf/slope break, the seaward wall appears to have collapsed. The morphology here is different than the seaward walls where the blowouts are set slightly inboard of the shelf/slope break in that the collapsed walls are less steep, with minimal to no landward dip (e.g., Figure 3a, line 67).

[19] Variability in size and shape is observed along the series of blowouts, with a number of small, more circular depressions superposed on the larger depressions (Figure 1c). It is unclear whether the smaller (up to $\sim$1 km in diameter), more circular blowouts broaden and link together to form elongated features through time or are formed subsequently as a result of continued fluid venting.

[20] The chirp subbottom data show evidence of recent sediment infill in the blowout depressions in the form of southward prograding clinoforms, with thicknesses reaching up to $\sim$5 m (Figure 3b, line 286/285). The southern transport direction is consistent with the current flow direction inferred from the asymmetric bed forms observed in the side-scan data (Figure 5b). Reworking and erosion of the shelf edge delta and transgressive deposits by Gulf Stream outer shelf return flow currents might be the source of the mobile sediment. Given the patchiness of the sediment deposits, it is difficult to infer an accumulation rate for the region. On the basis of the locations of the gas blowouts and the overlying sediment infill the best available age estimate for the blowouts is that they postdate the last major period of lower sea level, i.e., the Last Glacial Maximum, and predate the southward prograding clinoforms in the craters. While it is possible the shelf edge delta was deposited during Oxygen Isotope Stage 4 or 3, prior to the LGM (Isotope Stage 2), the lack of evidence for subaerial exposure, including the absence of channels developed in the seaward dipping wedge, suggests it was deposited subsequent to the LGM.

4.3. Downslope Creep and Gas Migration

[21] The location of the blowout depressions along the shelf edge and their highly elongated, asymmetric shapes suggests a causal link between the downslope creep of the deltaic sediments and fluid expulsion. The strata imaged by the chirp profiles display several criteria diagnostic of soft sediment deformation and creep features (Figure 4c): thickening and thinning of chaotic or transparent layers, segmentation and rotation of originally contiguous sections, and homoclinal contacts emphasizing contrasts between transparent and reflective intervals [*O'Leary and Laine*, 1996].

[22] We believe these deltaic stratal patterns do not result from primary depositional processes, such as sediment waves [*Schwehr et al.*, 2002]. Rather, we suggest the apparent fold patterns have formed by downslope creep processes that have progressively deformed the shelf edge/upper slope sediments since their deposition. Such sedimentary deformation would have been facilitated by the following: (1) deposition of the low-stand delta across the outermost shelf and upper slope, providing a clear downslope gradient; (2) likely relatively rapid deposition (compared to interglacial/interstadial sedimentation at the same location), perhaps leading to under compaction within the wedge; and (3) the presence of clay layers within the sequence or at the base, which would provide possible décollement surfaces, facilitating downslope sliding.

[23] We surmise that downslope creep within the lowstand wedge is linked to gas release through the shelf edge seafloor in the following way: Clay-rich layers in the lowstand delta and underlying high-stand deposits are an effective seal to the vertical movement of gas. However, sandy layers within and below the delta would allow gas-charged fluids to migrate up section and updip along bedding planes. At some point the buoyancy of the gas-charged fluids would exceed the confining pressure of the overburden, resulting in expulsion of gas-charged fluid and sediment to form the observed excavations. This scenario is illustrated schematically in Figure 8.

4.4. Gas Distribution

[24] Chirp and side-scan data suggest gas-rich fluids have continued to accumulate and discharge through the floors of the excavations, particularly along the landward walls and beneath the blowouts, after the primary gas expulsion episode (Figure 3a, lines 161/162 and 31, and Figure 4c). Authigenic carbonate precipitation occurs in areas where gas-charged fluid venting is active or has been recently active [e.g., *Hovland and Judd*, 1988]. Such seepage sites have been found on almost all active margins and on many passive margins [*Naehr et al.*, 2000]. We suggest the high-amplitude backscatter observed along the bedding plane outcrop in the inner wall of blowout C represents authigenic carbonate precipitation on the seafloor (Figure 5a, inset), which is consistent with observations from Hydrate Ridge, a gas discharge site on the Oregon-Washington margin [*Johnson et al.*, 2003]. Similar high-backscatter returns in side-scan data have been observed over Hydrate Ridge, and

Figure 3. (a) Dip chirp subbottom profiles. (See Figure 2 for location.) The depressions have steep landward walls with high-backscatter gas prominent at the face of this wall. The internally deformed wedge of stratified sediment perched at the shelf edge has been locally removed by the gas blowout processes. Stratified sediment is also locally disturbed by gas "wipeout" zones. (b) Strike chirp subbottom profile. (See Figure 2 for location.) Strike line profiles show characteristics similar to the dip line profiles, including high-backscatter gas, internally deformed, stratified sediment, and gas wipeout zones. Additionally, small prograding clinoforms are shown in the sediment infill along the northern walls of the blowout depressions.

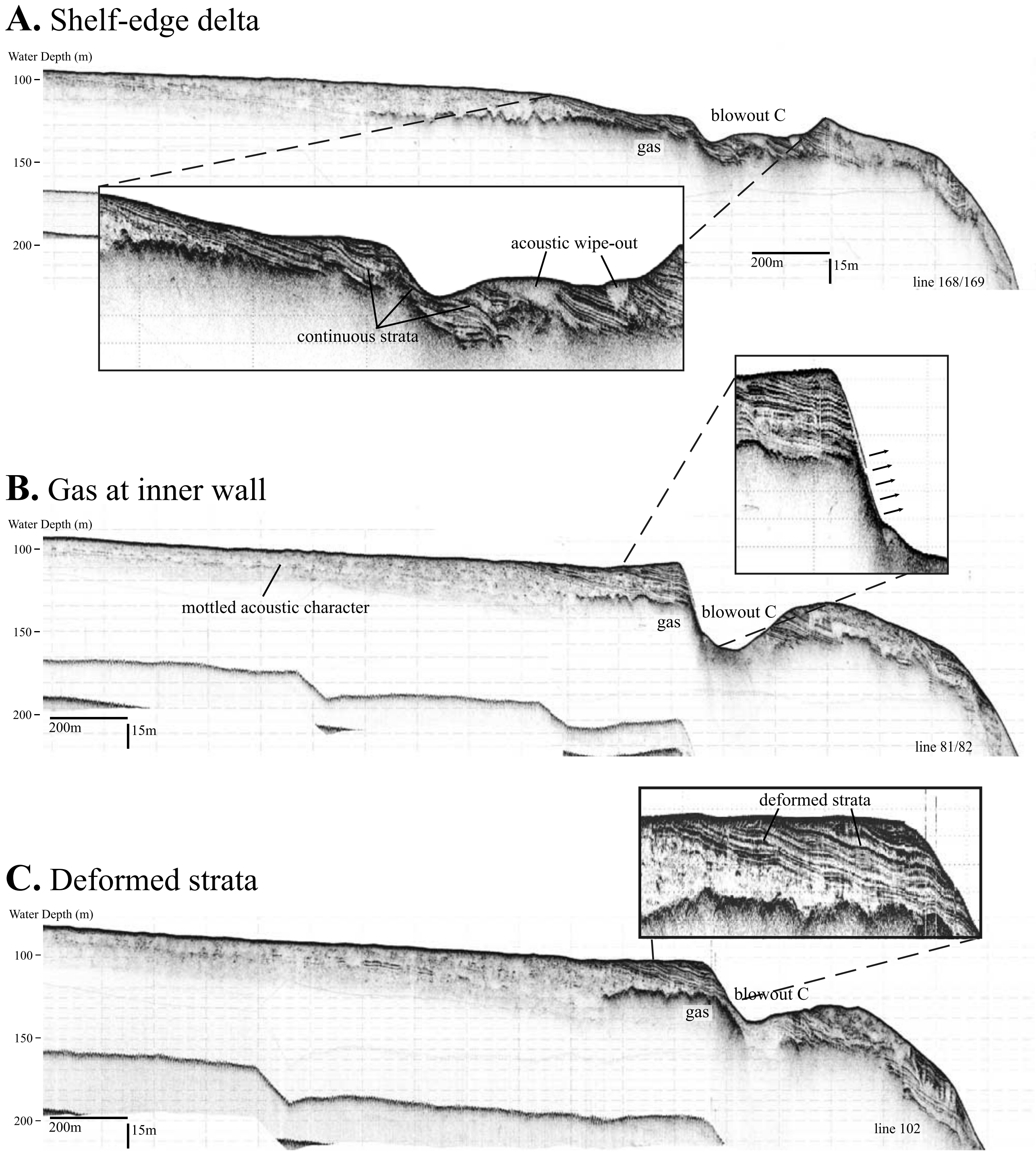
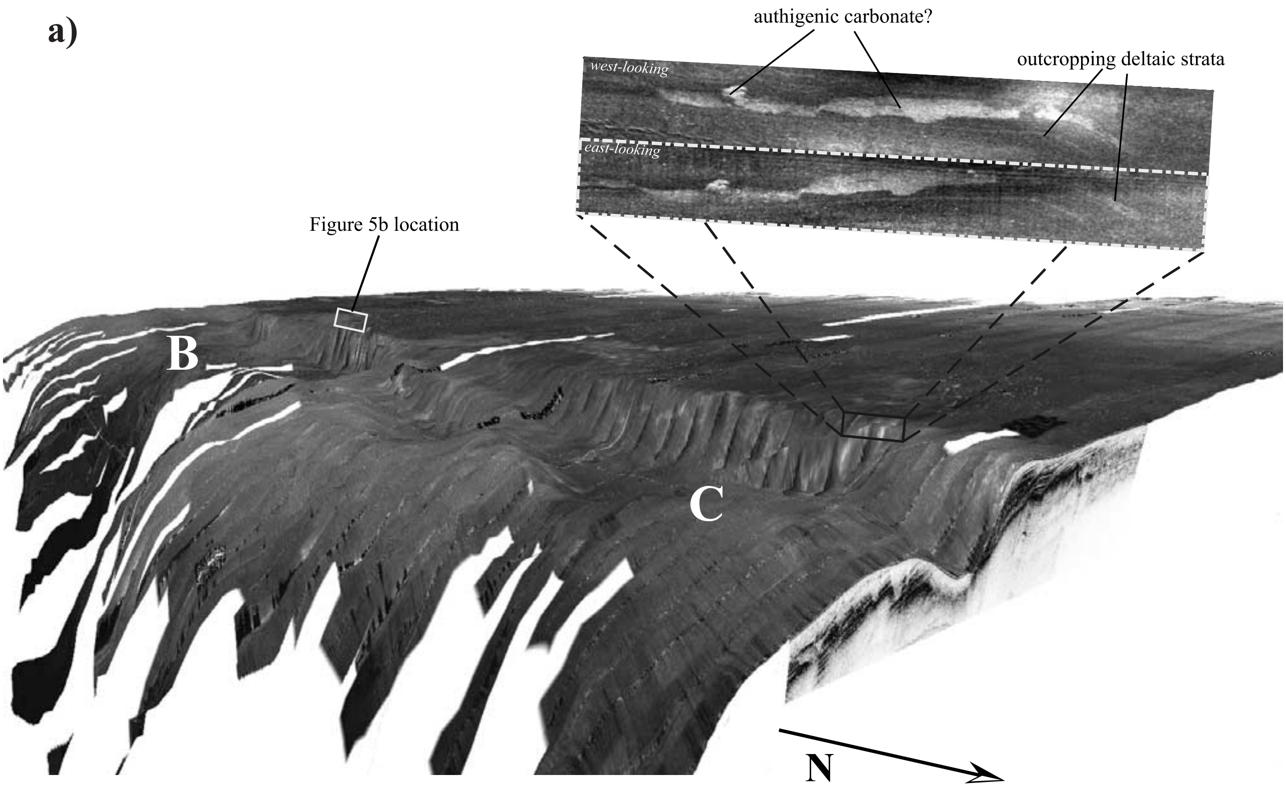


Figure 4. (a) Stratified sediment wedge interpreted as a shelf edge delta, continuous across the blowout area. (b) Highly reflective gas at the steep, landward wall of the blowout, showing possible evidence of continued gas-charged fluid seepage. (c) Internal deformation of the stratified sediment as a result of downslope creep.

the high backscatter coincides with the occurrence of authigenic carbonates observed from manned submersibles, remotely operated vehicles, camera tows, and cores.

[25] Although the shelf edge delta appears to provide a relatively impermeable capping layer for gas, allowing gas to build up below this layer, there is large lateral variability, and the seal is not entirely impermeable. Throughout the midshelf region where the delta is absent, gas appears to be discharging freely through the seafloor, creating a mottled seismic character in the surface sediments (e.g., Figure 4b). There are numerous acoustic wipeout zones throughout the delta section, indicating disturbance of the sedimentary laminations by gas discharge in some places (e.g., Figure 3, lines 31 and 67, and Figures 4a and 7). The timing of the

a)


authigenic carbonate?
outcropping deltaic strata
west-looking
east-looking
Figure 5b location
B
C
N

b)

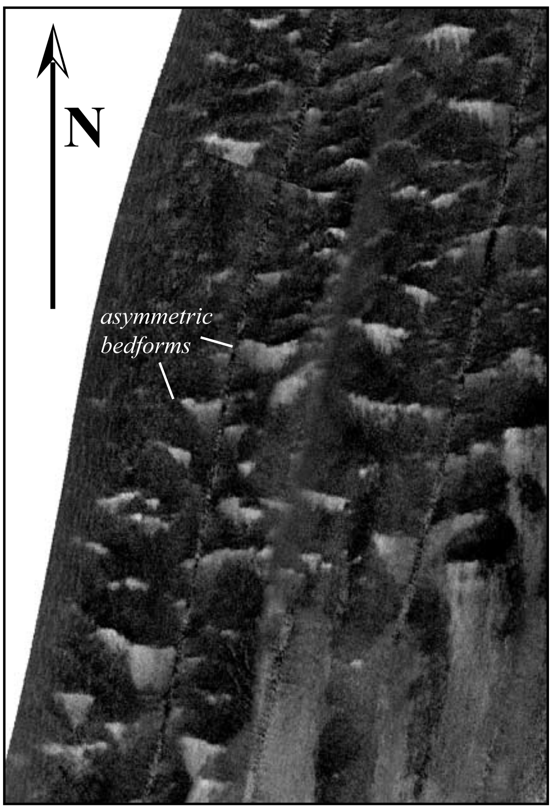

N
asymmetric
bedforms

Figure 5

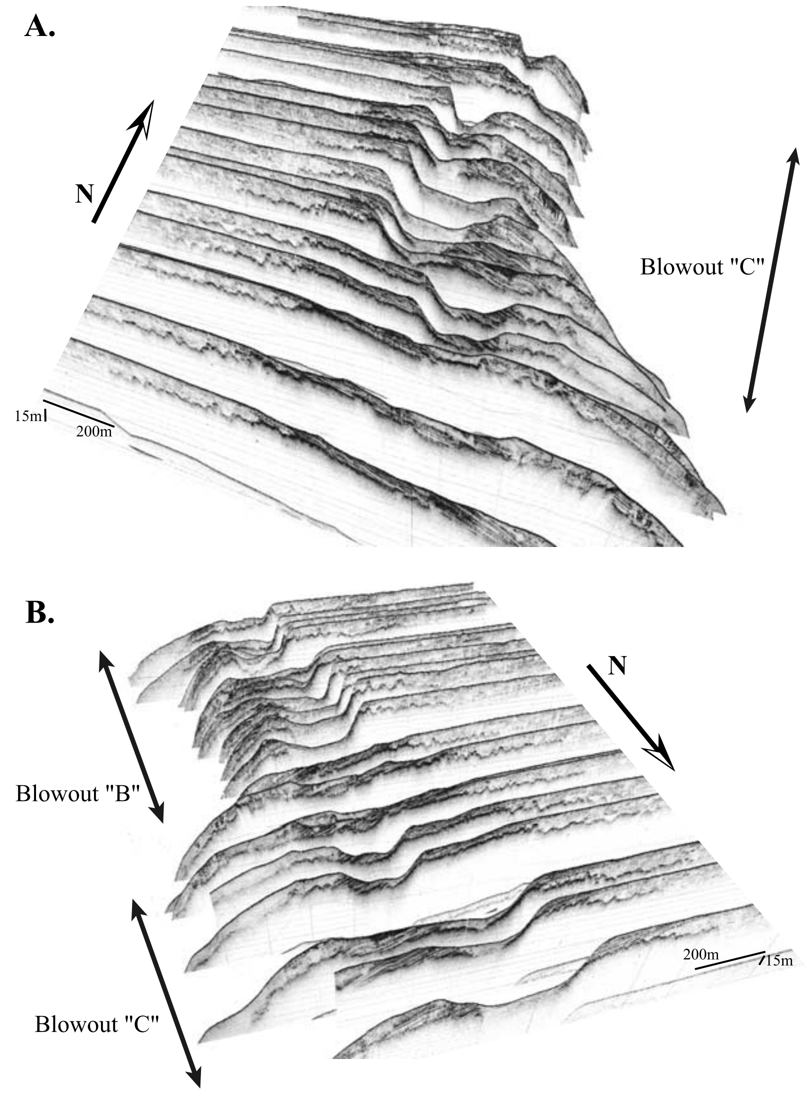


Figure 6. (a and b) Chirp subbottom profiles coregistered with bathymetry and displayed in a three-dimensional perspective. The blowout features display a distinct en echelon pattern. A strong correlation between trapped gas and the shelf edge delta is apparent throughout the region. The deformed strata are difficult to trace laterally between profiles, and the deformation and gas make it difficult to observe the character of the deeper stratigraphy along the margin.

acoustic wipeout zones is not constrained relative to the formation of the blowouts.

[26] In addition to spatial variability in gas distribution, differences in acoustic character of gas-charged sediments are observed in the shelf edge delta. For example, concentrated gas beneath an impermeable layer results in a high-amplitude reflector with acoustic blanking below. Density and sound velocity in gas-charged sediments is much lower than in gas-free sediments, creating a large acoustic impedance change that reflects a high proportion of incident

Figure 5. (a) Dip line side-scan mosaic draped over the NOAA 3″ bathymetric grid, showing location of the strike images above. The chirp subbottom profile on the right has been coregistered with the dip line mosaic. Blowouts B and C are labeled (see Figure 1). Figure 5a inset shows the following backscatter images from the strike line mosaics: (top) west looking and (bottom) east looking from the inner wall of blowout C in the vicinity of chirp profile 81/82 (Figure 4b). West (shallower water) is at the top. Lighter shades correspond to higher backscatter. Low-stand delta bedding outcrop along the blowout inner wall is clearly imaged. The slightly lobate high-backscatter zone appears to obscure the outcropping bedding on the downslope side. This relation is consistent with precipitation of carbonate crusts from continued gas-rich discharge after formation of the blowouts. (b) Portion of strike side-scan mosaic. Asymmetric bed forms discussed in the text are labeled. These are interpreted as sand ridges, and the asymmetric nature of the bed form appears to indicate southward sediment transport in the blowout region.

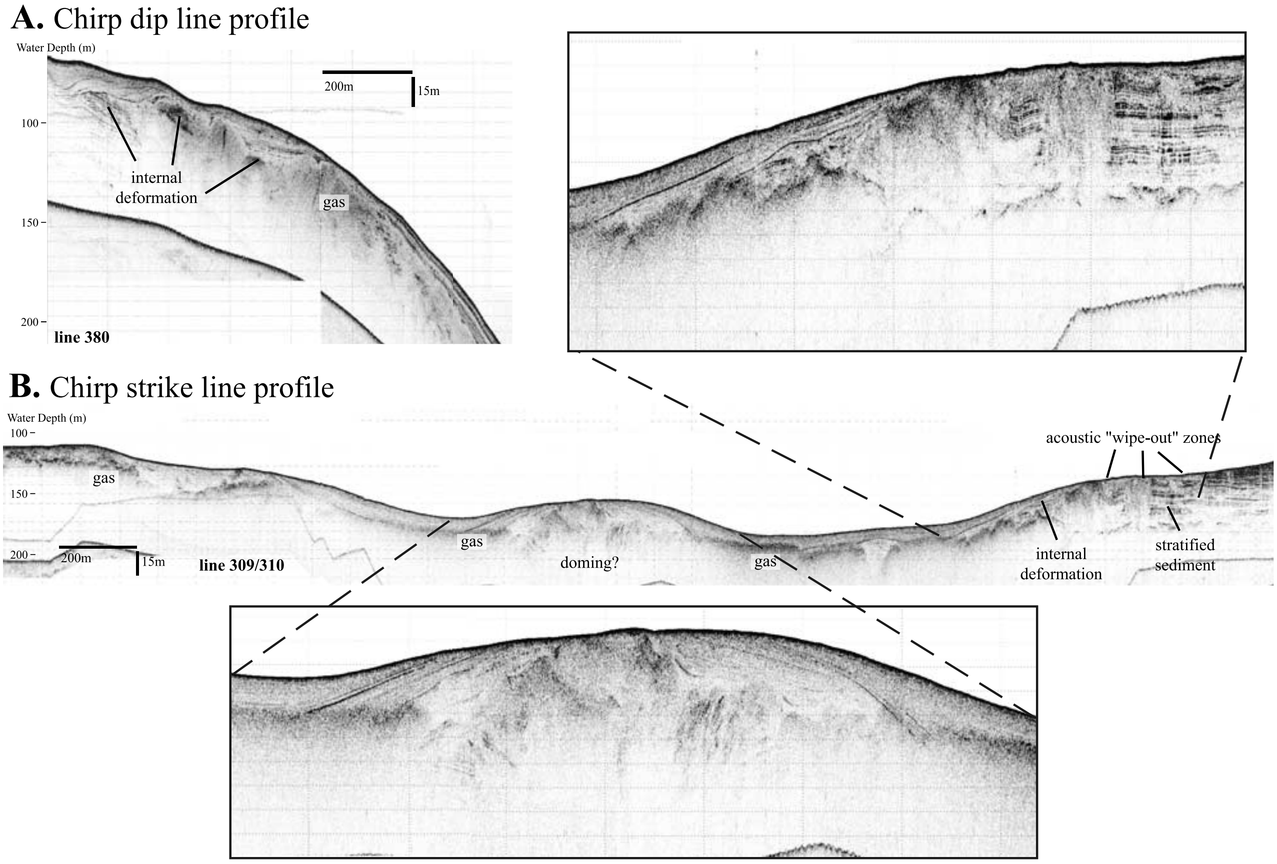


Figure 7. (a) Dip and (b) strike chirp subbottom profiles from the Albemarle-Currituck slide area. Similar to the gas blowout region, this area shows internally deformed, stratified sediments, highly reflective trapped gas, and gas wipeout zones. Additionally, there is a large dome-like feature showing possible evidence of uplift by gas-charged fluids.

acoustic energy [*Hovland and Judd*, 1988]. When gas rises through the overlying sediments, a very different, more transparent, acoustic character results [*Hovland and Judd*, 1988; *O'Leary and Laine*, 1996]. Previous researchers noticed that this acoustic character could be confused with filled erosional channels [*Hovland and Judd*, 1988]. However, there is no stratigraphic expression of sediment infill, and the acoustically transparent zones are very difficult to trace laterally from line to line, implying these features are not part of a drainage network (Figure 6). Our preferred interpretation is that gas expulsion physically disturbs the internal stratigraphic layering of the sediments, and therefore the impedance contrast, resulting in a zone with reduced acoustic reflectivity [*Hovland and Judd*, 1988; *O'Leary and Laine*, 1996].

4.5. Origin of the Gas

[27] Thermogenic gas in Upper Jurassic–Lower Cretaceous rocks was discovered in exploratory drilling of the Baltimore Canyon Trough at ~3700–4700 m depth [*Mattick and Libby-French*, 1988]. However, we surmise that it would be difficult for the thermogenic gas to migrate up section through various permeability barriers to the shallow depths observed in the chirp profiles unless there were permeable pathways created by tectonic activity (faults and fractures) extending from deep gas reservoirs to the near surface. The chirp reflection data suggest such fracture pathways are not present.

[28] We therefore assume that the gas is biogenic in origin, produced either in situ by bacterial decay of organic carbon in marine sediments or by decomposition of gas hydrate deeper on the margin and subsequent updip/upslope migration of the released gas to the blowout sites on the outer shelf. It is difficult to distinguish between these two possible origins. A biological origin of the gas would involve local methanogenesis by microbial reduction of CO_2 or acetate derived from organic carbon in the sediments [*Wellsbury and Parkes*, 2000]. A supply of organic carbon (greater than ~0.5 wt % of the sediment [e.g., *Kennicutt et al.*, 1993]) would be needed, plus burial rapid enough to prevent oxidation of the organic matter in the sulphate reduction zone of the shallow subseafloor environment. Ocean Drilling Program work off New Jersey encountered abundant gas in the under-compacted/overpressurized Pleistocene section of the upper slope [*Shipboard Scientific Party*, 1998]. The Pliocene-Pleistocene shelf edge succession there appears to be composed of stacked marine deltaic wedges deposited rapidly during glacials, with intervening thin, hemipelagic muds deposited during sea level transgressions and highstands [*Dugan and Flemings*, 2000], indicating that favorable conditions are present for biogenic methane production.

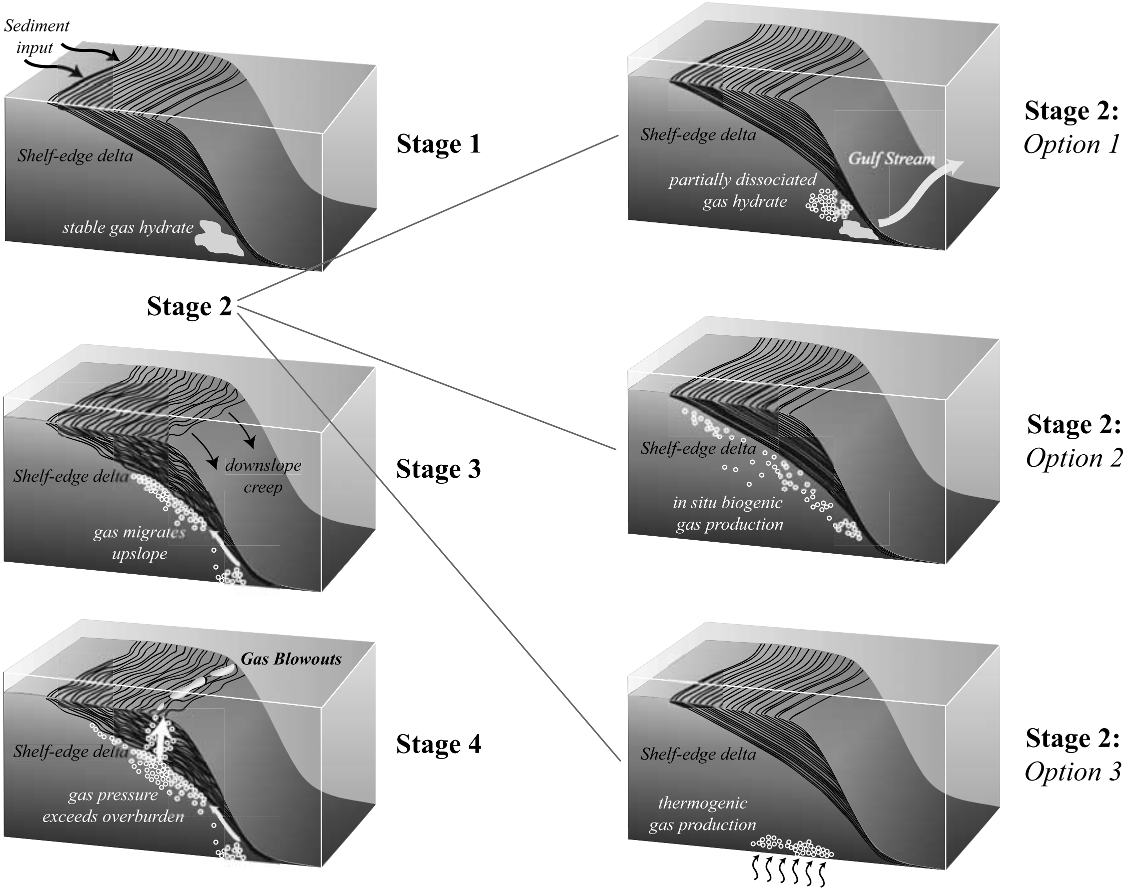


Figure 8. Schematic outlining the proposed gas blowout process. In stage 1, there is a buildup of shelf edge delta during period of lowered sea level, presumably glacial-interglacial transition; stable gas hydrate is present at depth on the upper slope. In stage 2, gas accumulation on the shelf/slope has three possible origins. In option 1, gas is produced from hydrate dissociation. Postglacial introduction of warm Gulf Stream bottom water across the top of the gas hydrate stability zone lower on the slope dissociates hydrates at ~500 m water depth. In option 2, biogenic gas is produced in situ from organic carbon in the sediments. In option 3, thermogenic gas is produced at depth. In stage 3 the shelf edge strata creep downslope, and gas migrates upslope. Biogenic gas, however, may be produced at multiple depths along the slope, including directly beneath the shelf edge delta, and would not require upslope migration. In stage 4, gas accumulates sufficient pressure to exceed the overburden and is expelled through the overlying sediments, creating the gas blowout craters.

[29] Our preferred hypothesis, however, is that gas in this region is related to the dissociation of gas hydrates during the late Pleistocene/Holocene. According to the pressure-temperature stability field for methane hydrate and modern bottom water temperatures [e.g., *Kvenvolden*, 1993] the base of the hydrate stability zone today would intersect the seafloor at ~650 m on the upper continental slope of the mid-Atlantic margin [*Dillon and Max*, 2000]. Thus there should be no gas hydrate present in the sediments directly underlying the shelf edge blowouts. Gas hydrate might have extended to shallower depths along the margin earlier during glacial cycles depending on the relationship between sea level and bottom water temperature, but the stability zone would still have been much deeper on the slope than the blowout region [cf. *Vogt and Jung*, 2002].

[30] The stratigraphic relationship of the blowouts with the shelf edge delta deposits indicates the blowout features occurred since the LGM. We propose that secular warming of bottom waters, caused by the reorganization of water masses during climate fluctuations, may be an important mechanism to dissociate gas hydrates at depth [e.g., *Bratton*, 1999; *Driscoll et al.*, 2000; *Kennett et al.*, 2000; *Mienert et al.*, 2002; *Vogt and Jung*, 2002]. *Vogt and Jung* [2002] showed that thermal conduction could melt 10–100 m of hydrate in the hydrate stability zone of the upper continental slope within a few thousand years after a rise in bottom water temperatures. Temperature fluctuations of slope water on the order of 2.5°C have been documented in the western North Atlantic since the last glaciation [*Dwyer et al.*, 2000]. For the U.S. mid-Atlantic margin, postglacial introduction of warm Gulf Stream waters might have released gas trapped in hydrates along the upper slope, allowing free gas to migrate upward to the outer shelf region. Gas then either would be trapped by the deltaic strata or would escape through other areas of more permeable shelf sediments.

4.6. Relationship Between Gas and Slope Instability

[31] Both free and hydrate-trapped gas have been recognized previously along the Blake Ridge section of the southern North Carolina margin, and gas has been implicated in triggering the Cape Fear and Cape Lookout landslides on the continental slope [*Popenoe and Dillon*, 1996]. Though our study area is to the north of these known gas-prone regions, the seismic reflection profiles provide evidence for an extensive amount of gas along the outer shelf from Cape Hatteras to the Norfolk Canyon, including the Albemarle-Currituck slide area. Throughout the shelf edge region, gas appears to be both trapped beneath the finely laminated, clay-rich, capping layer and freely venting in areas where this layer appears to be absent. We suggest the distribution of slides along the U.S. Atlantic margin may coincide with the distribution of low-stand deltaic sediments, a correlation commonly explained by rapid sedimentation, under compaction, and oversteepening of the shelf edge [e.g., *Embley and Jacobi*, 1977]. In the Cape Hatteras to Norfolk Canyon section of the margin we observe an association between shelf edge delta deposits and trapped gas. The blowout features described here indicate that gas may play a more important role in controlling slope stability in this region than previously recognized. Additionally, similar evidence of shallow gas accumulation is identified in the large, late Pleistocene Albemarle-Currituck slide region ($\sim$100 km^3 in area [*Prior et al.*, 1986; *Driscoll et al.*, 2000]), indicating that gas may also have played a role in triggering this slide (Figure 7, line 309/310).

[32] While the origin of gas in the blowout region remains unknown, we propose a two-phase shelf/slope destabilization model, based on the assumption that the gas is derived from hydrate dissociation at depth. The conceptual model builds on previous understanding regarding slope failure and feedbacks on hydrate stability [*Paull et al.*, 1996, 2000]. In the *Paull et al.* [1996, 2000] model, lowered sea level (e.g., during glacial periods) triggers hydrate dissociation and subsequent slope failure. Unloading due to slope failure lowers the overburden, causing further hydrate dissociation that, in turn, may lead to additional slope failure. In this scenario, because of the positive feedback between unloading and hydrate dissociation, small failures could evolve into larger failures [*Paull et al.*, 1996, 2000]. The model presented here is an example of how the interplay between hydrate melting and climate fluctuations can lead to slope instability during interglacial periods.

[33] In our model for this process the first stage is temperature dependent, and the second stage is pressure dependent. Following the LGM, a series of events brought relatively warmer Gulf Stream waters westward into contact with the continental slope of the western Atlantic margin [*Boyle and Keigwin*, 1987; *Dwyer et al.*, 2000]. The introduction of warmer bottom water facilitates the initial gas release by shifting the top of the gas hydrate stability zone deeper, melting any hydrates above the new threshold. The free gas migrates upslope, building up significant overpressure where it is trapped by shelf edge delta sediments. Downslope creep of the deltaic strata in response to gravitational forces and continued updip/upslope fluid migration account for gas blowouts similar to the ones described in detail here. These features represent the initiation of slope failure in the upper few tens of meters of sediment. Removal of the upper strata would then cause further hydrate destabilization downslope through the effects of depressurization.

4.7. Implications for Stability of the U.S. East Coast Margin

[34] The association of shallow, trapped gas with shelf edge delta deposits appears to be the key link in forming the blowout features observed in our study area. However, the question remains as to whether this situation has occurred or will occur along other parts of the margin. Our side-scan and chirp sonar data indicate an extensive amount of shallow gas present along a large section of the margin, much of which coincides with shelf edge delta deposits. The region encompassing the Albemarle-Currituck slide, which received sediment from the Albemarle River during the Pleistocene [*Bunn and McGregor*, 1980], displays several intriguing features indicating that this area may represent the precondition for a gas blowout. In the case of existing gas blowouts to the north we have found evidence that well-laminated, internally deformed strata may provide a sufficient trapping mechanism for shallow gas, such that gas pressure can accumulate and eventually exceed the overburden. Similar evidence of shallow, trapped gas beneath layered strata is also found in the Albemarle-Currituck slide region. While gas blowouts are not found here, there is a prominent topographic dome on the shelf edge, which suggests trapped gas may be exerting pressure on the overlying sediments and causing the doming. The evidence is not conclusive, yet it raises the possibility that a gas blowout scenario might have been the triggering mechanism for the Albemarle-Currituck slide.

5. Conclusions

[35] The outermost shelf offshore of Virginia/North Carolina displays a series of en echelon, elongated depressions that we interpret from seismic and backscatter evidence as asymmetric gas blowouts or pockmarks [e.g., *Hovland and Judd*, 1988]. Our chirp seismic data delineate a wedge of stratified sediment draped across the shelf edge. This sediment wedge appears to be a low-stand delta deposit that was most likely deposited since the LGM. The deltaic strata show evidence of internal deformation indicative of active downslope creep. There is no evidence of large normal faulting or other structural control on the stratal geometry. There appears to be a strong spatial correlation between trapped, shallow gas and the shelf edge delta deposit. Gravitational forces have caused tensional stress within the shelf edge delta sediments, producing soft sediment deformation features consistent with downslope creep. The en echelon pattern of the blowout features also points to a tensional stress regime within the surficial sediments. Updip/upslope fluid migration most likely occurs in sandy layers beneath and within the shelf edge delta. The buoyancy of the gas-charged fluids eventually should exceed the confining pressure of the overburden, resulting in expulsion of gas-charged fluid and sediment to form the observed excavations. The precise age of the blowouts remains unknown, although they postdate the formation of the shelf edge delta, which is presumably after the LGM. The origin of the gas remains unknown; however,

post-LGM formation of the blowout features suggests secular warming of bottom waters and methane hydrate dissociation. The processes described here indicate gas may play a more important role in shelf/slope stability than previously recognized.

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