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Geological interpretation of a low-backscatter anomaly found on the New Jersey continental margin

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ABSTRACT

An enigmatic low-backscatter, acoustic anomaly occurs on the New Jersey continental margin between Hudson and Wilmington Canyon channels. The presence of the low-backscatter anomaly, as seen with 6.5- and 12-kHz data, indicates a change in the physical properties of the seafloor or near sub-surface. Analyses of seafloor and sub-surface acoustic data with previously collected sediment cores suggest the low-backscatter feature corresponds to an outcrop of older strata uncovered by erosion and non-deposition by the Western Boundary Undercurrent (WBUC). The decrease in backscatter strength is enhanced by the presence of gas in the sub-surface sediments found in the buried Chesapeake Drift.

1. Introduction

Improvements in sonar technologies over the last several decades have greatly increased the resolution and spatial accuracy of seafloor imaging. Multibeam echo-sounders (MBES) provide data at a scale of 100 m horizontal resolution in the deep sea of both seafloor bathymetry and acoustic backscatter. The high-resolution of these data helps to identify features that were previously unresolved along continental margins and allows more detailed analysis on seafloor morphology and sediment distribution. This information can be used to better interpret the geological processes that have shaped the margins.

Bathymetric surveys conducted in 2004, 2005 and 2008 by the Center for Coastal and Ocean Mapping (CCOM) at the University of New Hampshire mapped the U.S. Atlantic continental margin using a 12-kHz MBES (Gardner, 2004; Cartwright and Gardner, 2005; Gardner et al., 2006; Calder and Gardner, 2008) (Fig. 1). The MBES data were used to generate 100 m cell size bathymetry and co-registered acoustic-backscatter grids of the seafloor. Along with the MBES data, high-resolution 3.5-kHz CHIRP subbottom profiles were collected that imaged as much as 60 m of the shallow stratigraphy. These data provide a three-dimensional, quantitative view of the geomorphology of the U.S. Atlantic margin, showing submarine canyon-channel systems, seamounts, escarpments and sediment drifts, etc. The seafloor features resolved in the high-resolution MBES data set present an opportunity to better interpret the geological processes that have shaped the present seafloor on the U.S. Atlantic margin.

The focus of this study is on the mid-Atlantic margin offshore New Jersey (referred to here as the New Jersey continental margin). Here, we interpret the origins of a better resolved low-backscatter feature using MBES data and CHIRP subbottom profiles collected in 2004 and 2005 combined with previously collected GLORIA sidescan-sonar data, seismic-reflection data and sediment cores. We suggest that the low-backscatter feature is an area of older sediments that have been exposed by the Western Boundary Undercurrent. We also speculate that the decrease in acoustic backscatter results from the presence of sub-surface gas within the sediments.

2. Geological setting

The U.S. Atlantic continental margin is composed of a thick Jurassic to Quaternary sequence (greater than 15 km thick in some areas) (Poag, 1992). Its evolution is described in detail by numerous authors (Rona, 1969; Hollister and Heezen, 1972; Embley, 1980; Bulfinch et al., 1982; Mountain and Tucholke, 1985; Poag, 1985; McCave and Tucholke, 1986; Mountain, 1987; McMaster et al., 1989; Pratson and Laine, 1989; Poag, 1992; Mountain et al., 1994; McHugh et al., 2002; Chaytor et al., 2007; Twitchell et al., 2009). The Quaternary margin sequences are strongly influenced by glacial deposits in the northern Atlantic margin and hemipelagic sediment (Poag, 1992).

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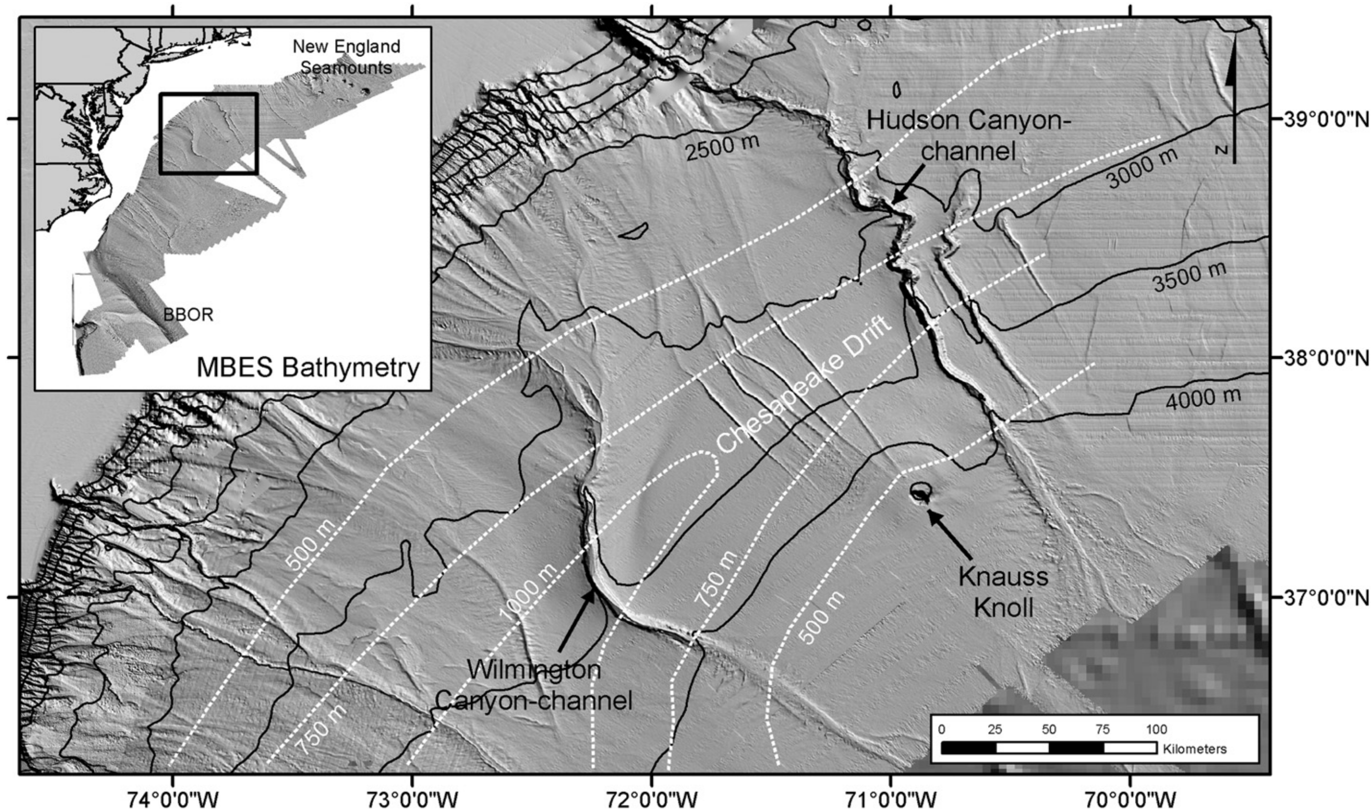

Fig. 1. Map showing multibeam bathymetry data collected on the U.S. mid-Atlantic continental margin in 2004, 2005 and 2008 with the location of the Chesapeake Drift (shown as white-dashed isopachs from Mountain and Tucholke, 1985) superimposed over bathymetry data. Background bathymetry is National Geophysical Data Center NOAA ETOPO2 satellite bathymetry data and the Coastal Relief Model. Bathymetric contours are shown in black (500 m intervals). MBES data are available at http://www.ccom.unh.edu and ETOPO2 data can be found at http://www.ngdc.noaa.gov/.

The margin sequence has been modified by periods of intense gravity-driven processes (turbidity currents, debris flows, slumps and slides), as well as deep-sea geostrophic circulation. Large canyon-channel systems, such as Wilmington and the Hudson Canyon-channels (Fig. 1) have cut into the slope and shelf area in the New Jersey margin and have delivered large volumes of clastic sediments to the lower margin regions (Tucholke and Laine, 1982; Locker, 1989; Chaytor et al., 2007; Twitchell et al., 2009). These canyon-channel systems are thought to have formed largely throughout the glacial episodes of the Quaternary (although some are thought to be as old as Eocene) as a result of high volumes of sediment input and downslope sediment transport by turbidity currents. Numerous debris flows have also been mapped on the middle Atlantic margin and have played an important role in transporting sediment downslope (Damuth, 1980; Embley and Jacobi, 1986; McHugh et al., 2002; Gardner, 2004; Chaytor et al., 2007; Twitchell et al., 2009).

Studies also indicate the importance of the Western Boundary Undercurrent (WBUC) in reworking margin sediments and the construction of sediment drifts (Schneider et al., 1967; Bulfinch et al., 1982; Bulfinch and Ledbetter, 1984; Stow and Holbrook, 1984; Ledbetter and Balsam, 1985). The WBUC is a geostrophic current that flows southwest along the western boundary of the North Atlantic Ocean basin. The WBUC possesses a section of intensified flow rates known as the high-velocity 'core.' This section of the WBUC has varied in water depth over the last 25 ka (Bulfinch et al., 1982). Sediment grain size and magnetic alignment in mineral grains found in sediment cores collected along the New Jersey margin suggest that the upper boundary of the high-velocity core of the WBUC resides at the 4440 ± 20 m isobaths today and extends to water depths of approximately 5200 m (Bulfinch et al., 1982). However, sediment-core data show that the high-velocity core of the WBUC was close to the 4000-m isobath between 17 and 7 ka (Ledbetter and Balsam, 1985).

The WBUC formed a large sediment drift offshore New Jersey, referred to as the Chesapeake Drift (Mountain and Tucholke, 1985) (Fig. 1). Now buried, it was constructed during the Middle Miocene through the Pliocene (Locker, 1989). Studies suggest that the drift contains sub-surface gas that originated from buried organic material found in the sediments (Tucholke et al., 1977; Mountain and Tucholke, 1985; Dillon et al., 1995; Dillon and Max, 2000; Butman et al., 2006).

3. Data and methods

Geophysical data analyzed for this study include bathymetry and acoustic backscatter from a Kongsberg Maritime EM121A 12-kHz multibeam echo sounder (MBES), CHIRP subbottom profiles from an ODEC Bathy2000 system, USGS 6.5-kHz GLORIA sidescan-sonar data (Paskevich et al., 2010) and Lamont-Doherty Earth Observatory (LDEO) airgun (25-in^3) single-channel seismic-reflection profile V2114 (Fig. 2) (Tucholke et al., 1977). The MBES and CHIRP data were collected aboard the USNS *Henson* and the USNS *Pathfinder* in 2004 and 2005, respectively, (Gardner, 2004; Cartwright and Gardner, 2005). The MBES data were gridded at 100 m cell size.

MBES bathymetry data were processed using the University of New Brunswick-Ocean Mapping Group's *SwathEd* software. 'Bad' bathymetric soundings were flagged in the raw MBES data and not included in bathymetry grids (Gardner, 2004; Cartwright and Gardner, 2005). MBES backscatter data were processed using *Geocoder* version 3.2 level 2 software (Fonseca and Calder, 2005). Radiometric and geometric corrections were applied to the backscatter data to account for acoustic losses through the water column, incident angle of the

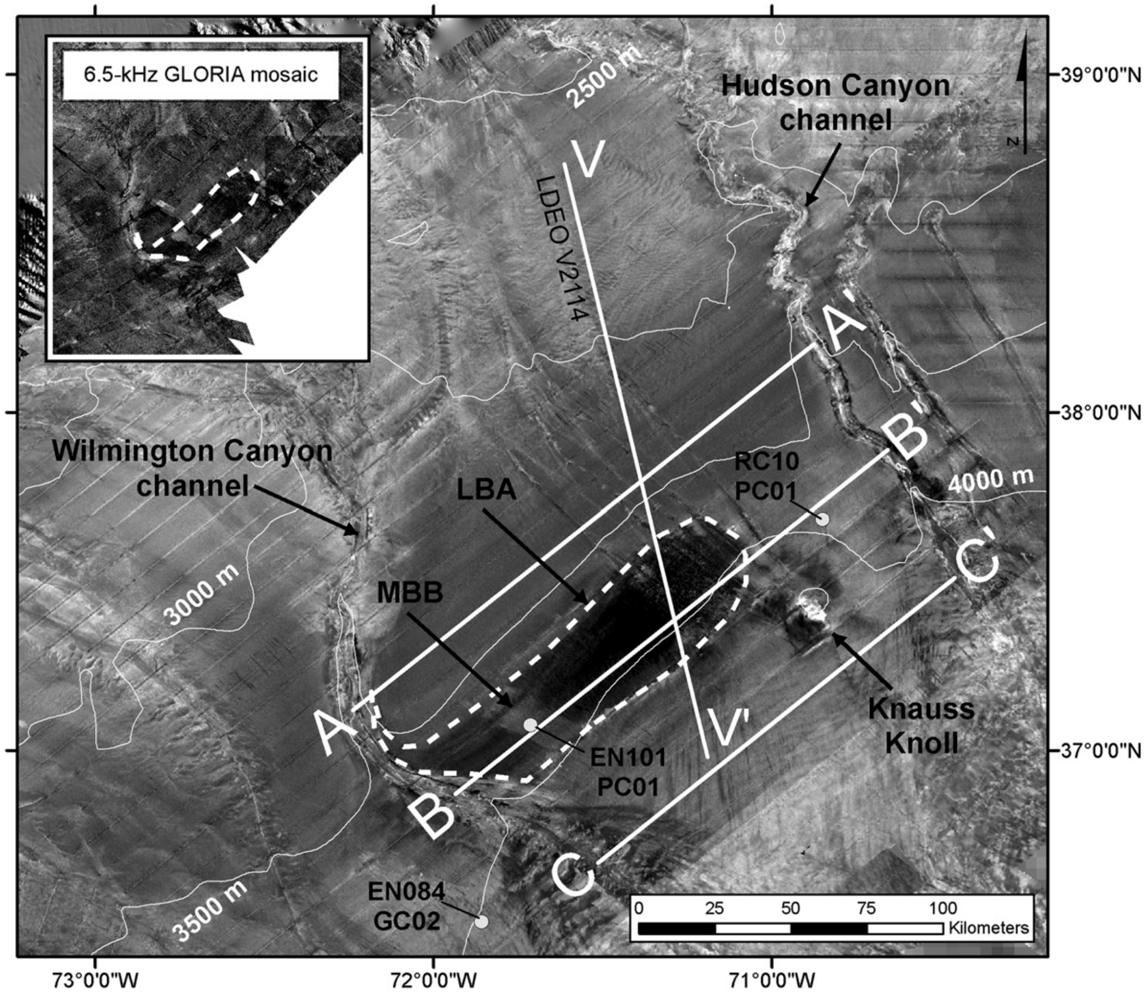

Fig. 2. Map showing multibeam backscatter intensity collected on the New Jersey continental margin (low backscatter intensity = dark and high backscatter = light) and the locations of the low-backscatter anomaly (LBA) (in white-dashed line) and medium-backscatter bridge (MBB). The map also shows the locations of sediment cores, CHIRP lines and the single-channel seismic profile analyzed for this study (single-channel seismic data found at www.geomapapp.org). Inset map shows corresponding location of GLORIA data (found at www.usgs.gov).

acoustic beams on the seafloor and the signal-strength effects of the local seafloor slope (Fonseca and Mayer, 2007). The *Geocoder*-corrected backscatter data were mosaicked to produce a 100 m cell size resolution image projected in Universal Transverse Mercator (UTM) (zone 19 N) coordinate system. Individual beam averages were used to compute backscatter intensity in decibels (dB).

A search of existing samples in the region (Sweeney, 2008) found that 3 cores (EN101–PC01, EN084–GC02 and RC10–PC01) were collected near the study area (Fig. 2). Core information is summarized in Table 1. The cores were photographed and sediment compositions were determined at 5 to 10 cm intervals from smear slides. Mixed species of planktonic foraminifera (*Globorotalia menardii, Globoquandrina dutertrei, Globigerinoides ruber, Globigerinoider sacculifer, Sphaeroidinella dehiscens* and *Orbulina universa)* were selected from core depths of 10, 300, 345 and 355 cm from core EN101–PC01 for accelerator mass spectrometry (AMS)-radiocarbon dating. Age analyses were conducted at the National Ocean Science Accelerator Mass Spectrometry (NOSAMS) facility at Woods Hole Oceanographic Institution. Reservoir corrections were applied to these sample ages using the calibration data set provided by *CALIB* version 6.0 (Stuiver and Braziunas, 1993; Reimer et al., 2004, 2009) (Table 2).

Table 1
Summary table of core samples analyzed for this study.

Core ID	Length (cm)	Type	Latitude N	Longitude W	Water Depth (m)
EN084–GC02	280	gravity	36.2700	71.8683	4052
EN101–PC01	800	piston	37.0750	71.7133	3617
RC10–PC01	1059	piston	37.6830	70.8500	3911

4. Results

4.1. Multibeam bathymetry

The low-backscatter anomaly (LBA) is located on a section of relatively steep (average gradient ~0.7°) seafloor between Hudson and Wilmington Canyon channels (Fig. 3A and B). Average gradients immediately upslope from the LBA (between the 2500 and 3000 m isobaths) and downslope from the feature (beyond the 4100 m isobath) are ~0.2°. Mountain (1987) identified this region as the location of the buried Chesapeake Drift. The deeper section of seafloor has been referred to as the seaward flank of the buried Chesapeake Drift (Mountain and Tucholke, 1985; Mountain, 1987; Pratson and Laine, 1989).

The MBES bathymetry data show five small channels located between Wilmington and Hudson Canyon channels that begin upslope from the LBA (Fig. 3A and C). These small channels are most distinct

Table 2
AMS-radiocarbon age results showing ^{14}C Age, Fraction Modern (F modern or Fm) and δ^{13}C.

Accession numbers	Depth (cm)	δ^{13}C	F Modern	Fm Error	^{14}C Age	Age Error	ΔR	ΔR Uncertainty	Age Range with 1 σ	Age Range with 2 σ
OC-66063	10	1.61	0.3997	0.0024	7370	45	145	52	7761–7615 cal BP	7838–7563 cal BP
OS-66061	300	1.19	0.0031	0.0004	46500	1200	145	52	50001–48050 cal BP	50001–46645 cal BP
OS-66051	345	1	0.0037	0.0003	45100	610	145	52	48536–46753 cal BP	49376–46196 cal BP
OS-66054	355	0.92	0.01	0.0004	37000	310	145	52	41778–41255 cal BP	42038–41000 cal BP

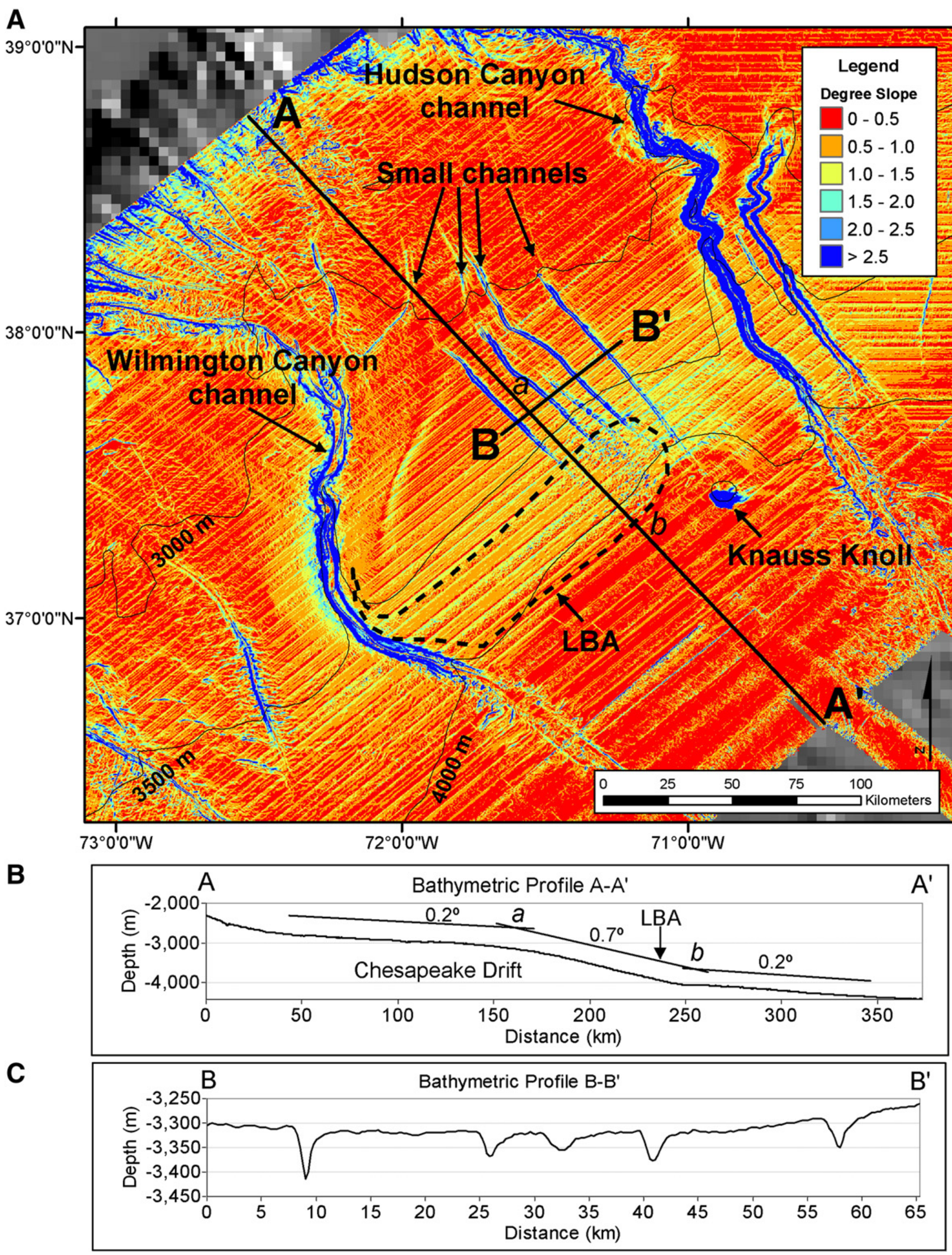

Fig. 3. (A) Map showing a slope map on the New Jersey continental margin near the LBA (outlined in black dashed line). Lower slope gradients shown in red and steeper slopes shown in blue. (B) Bathymetric profile AA' across the continental margin perpendicular to bottom contours showing the location of the LBA. (C) Bathymetric profile BB' across the margin parallel to bottom contours showing small channels.

on the section of seafloor with steeper (average ~0.7°) gradients. The three western-most small channels appear to terminate within an area of rough seafloor near the 4000 m isobath (Fig. 4). The rough area consists of bathymetric depressions that measure as much as 2 km wide and 25 m deep. Similar bathymetric depressions are also observed along the channel floors.

4.2. Multibeam backscatter

The MBES acoustic-backscatter data indicate an anomalous, low-backscatter region that covers an area of 2,750 km^2, with dimensions ~110 km across parallel to bathymetric contours and ~40 km across perpendicular to bathymetric contours. This feature, referred to as the low-backscatter anomaly, represents a relative decrease of ~10 dB in backscatter strength compared to the surrounding seafloor (Fig. 2). The LBA is located near the 4000 m isobath between Hudson and Wilmington Canyon channels and downslope from several small channels near Knauss Knoll (Lowrie and Heezen, 1967). The LBA was mapped in four separate lines over a span of several days and has boundaries that do not correlate with the edges of the MBES swaths. Although less distinct, the LBA is also resolved in U.S. Geological Survey (USGS) 6.5-kHz GLORIA sidescan-sonar data (Fig. 2). The presence of the LBA across several survey lines of the 2004 and 2005 MBES backscatter data as well as in the GLORIA data demonstrates that the LBA is a real seafloor feature and not a data artifact.

MBES backscatter values (all backscatter values are referenced to 12-kHz frequency unless otherwise stated) from the New Jersey margin range from −51 to −25 dB. Backscatter was subdivided into low (−51 to −42 dB), medium (−42 to −34 dB) and high (−34 to −25 dB) zones. The MBES backscatter data show predominantly high backscatter strength with a mottled texture on the gently dipping (0.2°) seafloor region between the 2500 m and the 3000 m isobaths in the area between Hudson and Wilmington Canyon channels (Fig. 2). The multibeam backscatter data show that the seafloor region with relatively low slope gradients (0.2°) beyond the 4000-m isobath has medium backscatter strength with a linear-streaky backscatter texture (Fig. 2).

Steeper (0.7°) seafloor immediately downslope from the 3000 m isobath has a homogenous backscatter texture and medium backscatter strength. The low-backscatter anomaly is located on this section of relatively steeper seafloor (Fig. 2).

A feature of medium-backscatter strength, referred to as the medium-backscatter bridge (MBB), crosses the LBA near Wilmington Canyon channel (Fig. 2). The MBB is approximately 10 km wide along slope and extends downslope across the width of the LBA.

4.3. CHIRP profiles

Three CHIRP subbottom profiles collected near and across the LBA are shown in Fig. 5. CHIRP profile A-A' was collected upslope from the LBA across seafloor of medium backscatter strength and homogeneous texture (Fig. 2). The profile shows good penetration and indicates conformable, well-stratified horizontal subbottom reflectors (Fig. 5A). CHIRP profile B-B' crosses through the LBA and shows weakly-stratified, outcropping subbottom reflectors (Fig. 5B). This profile shows an acoustically transparent, lens-shaped subbottom feature that disrupts horizontal sub-surface reflectors beneath the MBB. CHIRP profile C-C' was collected in medium-backscatter seafloor with variable streaky and rilled backscatter texture downslope from the LBA. The profile shows horizontal, well-stratified, continuous reflectors with strong bottom returns (Fig. 5C).

4.4. LDEO single-channel seismic-reflection profile

Seismic profile V-V' (Fig. 6) is a section of Lamont–Doherty Earth Observatory single-channel airgun seismic-reflection profile V2114 that crosses the LBA with a north–south orientation. Stratified,

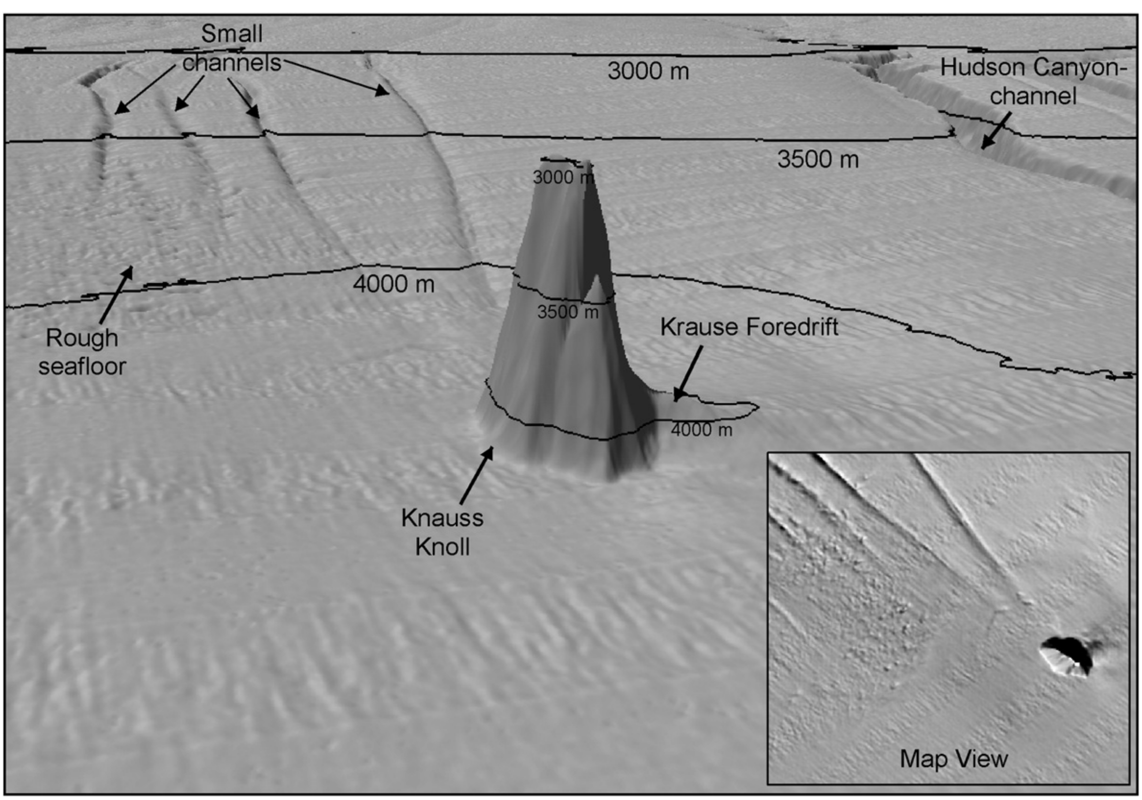

Fig. 4. Perspective image of MBES bathymetry showing Knauss Knoll, Krause Foredrift and rough seafloor found downslope from the small channels. View is looking northwest with vertical exaggeration = 10×. Inset image is map view of Knauss Knoll area.

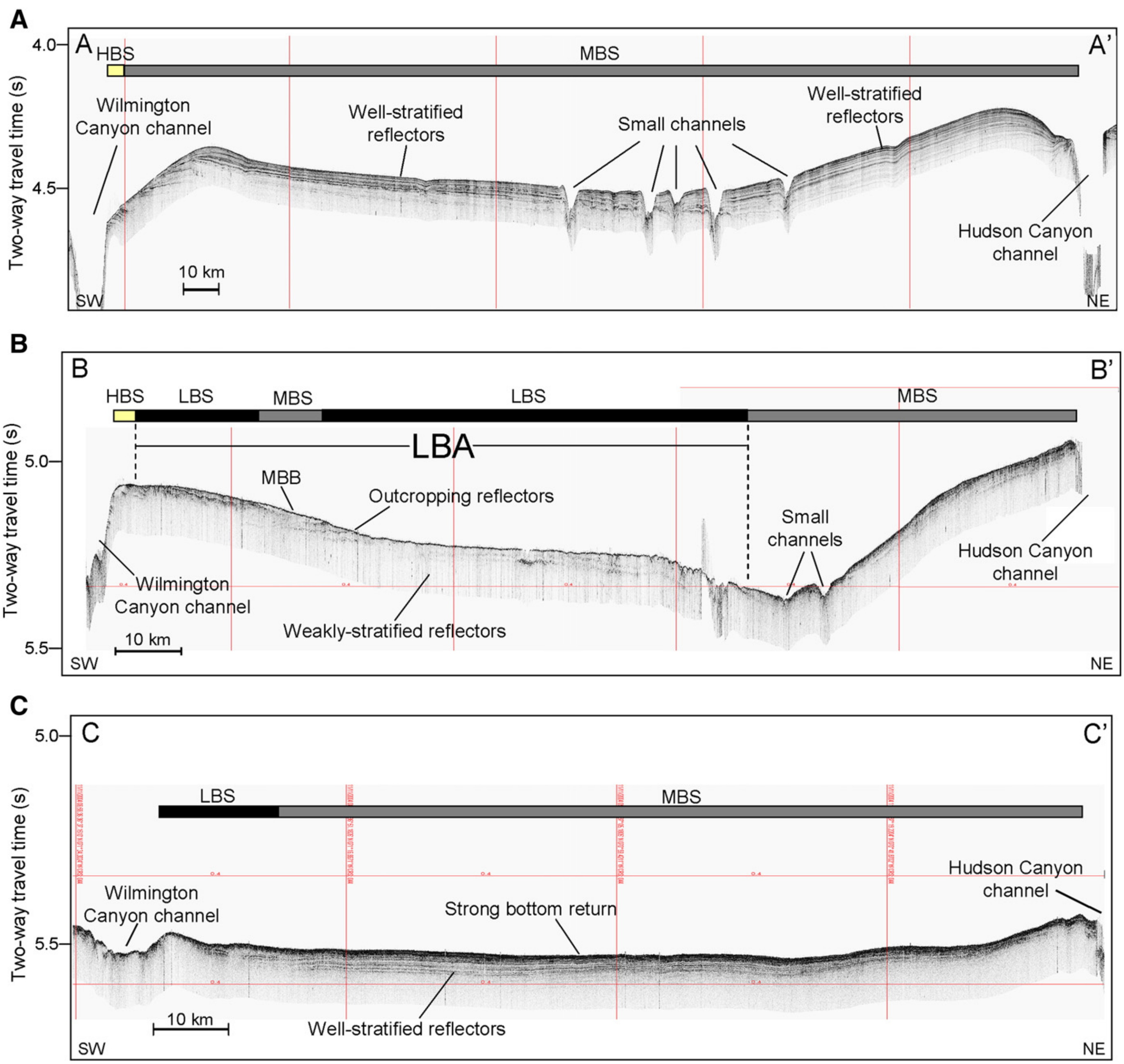

Fig. 5. (A) CHIRP profile AA' between Wilmington and Hudson canyon channels showing well-stratified reflectors upslope from the LBA. (B) CHIRP profile BB' showing weakly stratified and outcropping reflectors across the LBA. MBB shown as acoustically transparent, les-shaped subbottom feature (C) CHIRP profile CC' showing well-stratified reflectors downslope from the LBA.

high-amplitude seismic reflectors correlate to the high-backscatter and homogenous medium-backscatter seafloor upslope from the LBA (Fig. 2). The well-stratified seismic reflectors are underlain by a section of low-amplitude seismic reflectors that appear to outcrop at the seafloor within the LBA. Downslope from the LBA, a high-amplitude well-stratified, wedge-shaped seismic sequence overlies a weakly laminated, low-amplitude section. The wedge corresponds to the relatively flat (~0.2° average gradient), medium-backscatter seafloor. The seismic-reflection profile also shows a bottom-simulating reflector (BSR), previously identified by Tucholke et al. (1977), that is located in the sub-surface upslope from the LBA. In the marine slope environment, BSRs found in seismic-reflection profiles often result from the acoustic impedance contrast created by a zone of free gas trapped beneath gas free sediments that often contain gas hydrate (Mackay et al., 1994).

4.5. Sediment core samples

Core RC10–PC01 was collected at 3911 m water depth in medium backscatter-strength seafloor between the LBA and Hudson Canyon channel (Fig. 2). The CHIRP data across this area show laminated acoustic stratigraphy with strong bottom returns. Visual observations and smear-slide analyses of the core show that the sediment is composed of foraminifera-bearing silty clay with several thin silt layers mainly composed of quartz grains. Average grain-size analyses of the top 100 cm of the core range between 4.8 and 6.9 phi (coarse to

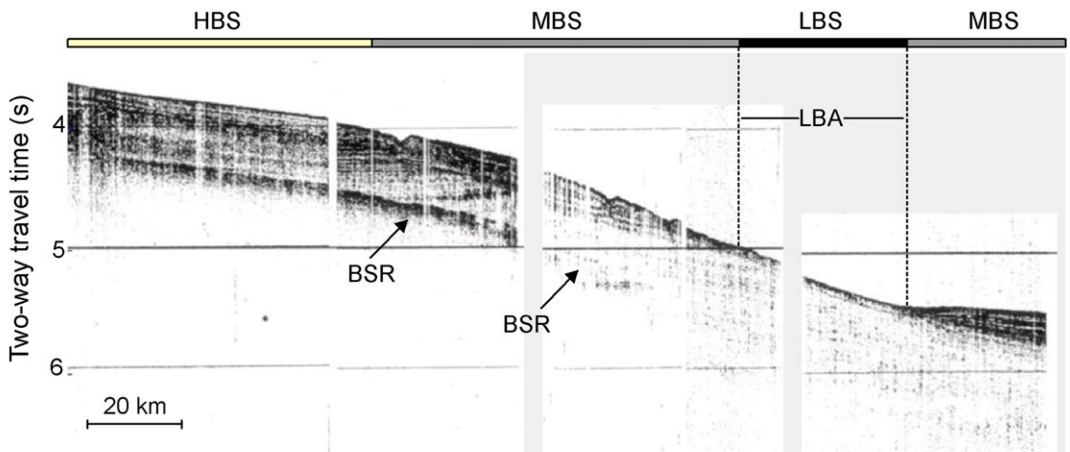

Fig. 6. Single-channel seismic data (V2112) across the LBA showing a well-defined bottom-simulating reflector (BSR) in the sub-surface, upslope from the LBA.

fine silt) and are consistent with the visual observations. Piston core EN101–PC01 was collected at a water depth of 3817 m within the MBB (Fig. 2). Grain-size analyses show that average grain sizes within the core range between 5.7 and 7.8 phi (medium to very fine silt) (Fig. 7A). The CHIRP profiles indicate that the core was collected within the lens-shaped sub-surface feature (Fig. 7B). Visual observations of the core indicate the sediment is predominantly a mottled olive-gray foraminifera-bearing silty clay with authigenic carbonate nodules. This core has sections with uniform grain sizes interspersed with sections with successions of thin coarser silt intervals. Smear-slide analyses indicate that the coarse intervals are composed of silt-size siliciclastic grains, whereas the homogeneous sediment between coarse layers is composed of foraminifera-rich calcareous nannoplankton silty clay. The radiocarbon ages in Fig. 7 show sediments from this core are Pleistocene to Holocene; however, the ages measured at 300 and 345 cm core depth show an age inversion relative to the sediment age measured in the 355 cm sample (Fig. 7).

5. Discussion

The cause of the LBA is not immediately evident from the backscatter data alone because backscatter is controlled by several parameters that are dependent upon the frequency of the sonar being used and the angle of incidence between the acoustic pulse and the seafloor (Jackson et al., 1986; de Moustier and Alexandrou, 1991; Gardner et al., 1991; Fonseca et al., 2002). These parameters are 1)

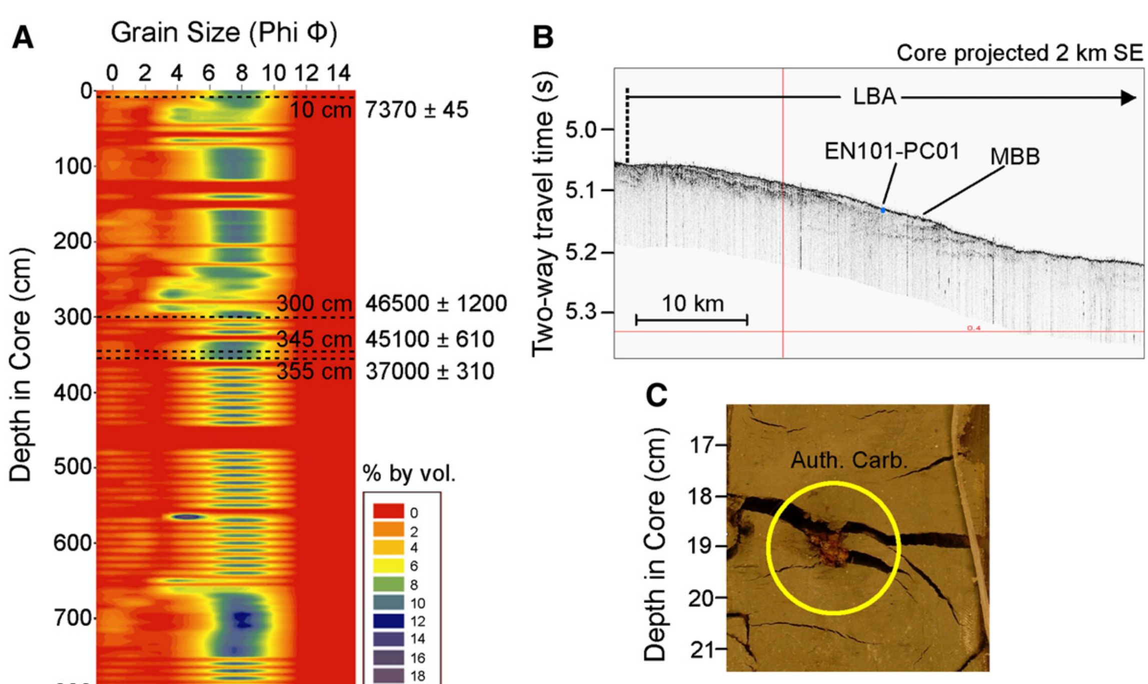

Fig. 7. (A) Image showing results from grain-size analysis conducted on core EN101–PC01. Plot depicts grain size (*Φ*) as percent by volume (*x*-axis) and sample depth (cm) (*y*-axis) within the core. (B) Location of sediment core EN101–PC01 projected onto CHIRP profile BB' showing its location in the MBB. (C) Photograph showing authigenic carbonate nodule found in sediment core EN101–PC01.

interface backscatter due to seafloor surface roughness and acoustic hardness (impedance) and 2) volume backscatter due to inhomogeneities found in the upper few meters of the sediment volume caused by discrete objects such as shells, gas bubbles, burrows or subsurface sediment layers (Hamilton, 1970; Jackson et al., 1986; Gardner et al., 1991; Fonseca et al., 2002). Although these complexities make it difficult to interpret the geoacoustic cause of the LBA from the sonar data alone, understanding the local geological processes can provide clues to its origins.

The presence of seafloor channels shown in the MBES bathymetry and CHIRP data documents that downslope sediment transport has occurred. The CHIRP profiles and sediment core data that correspond to the MBB also provide evidence of downslope sediment transport. Studies have ground-truthed and interpreted similar lens-shaped masses of acoustically incoherent sub-surface units in 3.5-kHz subbottom records from other areas as debris-flow deposits (i.e. Embley and Jacobi, 1986). The AMS-radiocarbon age inversions found in core EN101–PC01 at depths 300 and 345 cm relative to 355 cm suggest disruption in sediment deposition.

Studies have also suggested that the WBUC has greatly influenced the seafloor in the vicinity of the LBA (Schneider et al., 1967; Ledbetter and Balsam, 1985; Mountain and Tucholke, 1985; Stapleton, 1987; Locker, 1989; Pratson and Laine, 1989). Pratson and Laine (1989) proposed that the morphology of the seafloor near the LBA has generated accelerated speeds of the WBUC and caused erosion and non-deposition of sediments that resulted in an erosional surface. Locker (1989) called this region of the seafloor a "bypass" area, whereby sediment gravity flows have passed across the LBA region with little deposition because of the locally steeper slopes. Additionally, Locker (1989) and Schlee and Robb (1991) suggested that confinement of downslope sediment flows within Hudson and Wilmington Canyon channels has caused sediment to bypass the LBA region.

Compass-oriented bottom photographs analyzed by Schneider et al. (1967) show evidence of swift southwest-flowing currents near the LBA zone. They reported near tranquil deep-sea current conditions near the 3100 m isobath. However, bottom photographs near the 3400 m isobath indicate sediment streamers and bottom fauna deflected to the southwest and at the 4200 m isobath bottom photos show noticeably sediment-laden "murky" water near the seafloor (Schneider et al., 1967). Krause Drift at the base of Knauss Knoll (Lowrie and Heezen, 1967) also suggests that the WBUC has played a significant role in sediment transport processes on this section of the margin.

One interpretation of the origin of the LBA is that it is a sediment drift deposit that formed by the interaction between turbidity currents that flowed downslope through the small channels and the southwest-flowing WBUC. In this interpretation, fine sediments from the channelized flows were transported downslope towards the LBA and would have been intercepted, carried and deposited by the WBUC across the slope as a sediment drift. However, CHIRP profiles that cross the LBA do not indicate the presence of a distinguishable corresponding sediment depocenter and there are no associated changes in bathymetry in the LBA zone shown in the multibeam data. CHIRP and airgun profiles instead show seismic reflectors that outcrop within the bounds of the LBA, suggesting an eroded surface. Given the high-resolution of the CHIRP profiles and the large size of the LBA, it seems unlikely that a drift deposit would not be resolved in subbottom and MBES data.

Sediment failure was considered as a possible cause for sediment removal across the LBA feature. However, no evidence of a slope failure deposit or sediment scarp is seen in the MBES or CHIRP data downslope from the LBA. A feature resembling the medium-backscatter bridge might be expected if a landslide had caused an erosion scar. The MBES and CHIRP data do not indicate evidence of downslope sediment failure below the LBA. Additionally, a corresponding scarp could not be identified in MBES data or CHIRP profiles in the LBA zone. Therefore, we suggest that the LBA formed as the result of WBUC erosion and sediment bypass, similar to conclusions of Locker (1989) and Pratson and Laine (1989) for this area. The MBB appears to be a debris flow that was deposited across the exposed outcrop.

Without further sediment sampling investigations, we can only speculate on the sediment composition within the LBA. We would expect the sediment to have a high water content to cause low acoustic impedance or to be stratigraphically homogenous to cause a low volume-backscatter component. If the LBA does in fact correspond to a window of older, exposed strata, then this seems counterintuitive: exposed, older sediments would likely have a lower water content due to compaction and the surface would likely be rough from the process of erosion. However, the significant decrease in backscatter may also be caused by the presence of subsurface gas in the sediments. Sub-surface gas is thought to exist within the Chesapeake Drift that underlies the area (Tucholke et al., 1977; Mountain and Tucholke, 1985; Dillon et al., 1995; Dillon and Max, 2000; Butman et al., 2006). Evidence for sediment gas near the LBA may be reflected by the rough seafloor shown in the MBES data (downslope from the smaller channels). These bathymetric depressions could be gas expulsion features, similar to pockmarks. Authigenic carbonate nodules found in core EN101–PC01 also suggest the presence of sediment gas. Authigenic carbonates have been found in seafloor environments such as gas seeps where fluids are enriched in methane (Bohrmann and Torres, 2006) and in known gas-hydrate zones such as Blake Ridge (Rodriguez et al., 2000).

Under the appropriate conditions, the presence of gas in marine sediments can lower the overall sediment density and reduce the sediment sound speed, causing a lower acoustic impedance contrast between the sediments and overlying water (Anderson and Hampton, 1980; Fonseca et al., 2002). If this is the case at the LBA, it may be that the LBA is an exposure of sediments that form the seaward flank of the Chesapeake Drift.

6. Conclusions

High-resolution bathymetry and backscatter data acquired by multibeam echo-sounders provide the opportunity to refine interpretations on the geological processes that influence continental margin evolution. Multibeam sonar backscatter data and CHIRP subbottom profiles collected from the U.S. Atlantic continental margin show an anomalous low-backscatter feature on the lower New Jersey continental margin. This feature has not been clearly mapped in previous seafloor studies, but is visible in GLORIA images. This low-backscatter anomaly corresponds to an area of outcropping sediment shown in 3.5-kHz CHIRP profiles because of erosion by WBUC combined with sediment bypass due to the local seafloor bathymetry. The exposure could be composed of sediments containing gas that form the Chesapeake Drift.

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References

Anderson, A.L., Hampton, L.D., 1980. Acoustics of gas-bearing sediments. I. Background. Journal of the Acoustical Society of America 67, 1865–1889.

Bohrmann, G., Torres, M.E., 2006. Gas Hydrates in Marine Sediments. In: Schulz, Horst D., Zabel, Matthius (Eds.), Marine Geochemistry. Springer, Berlin Heidelberg, New York, pp. 481–512.

Bulfinch, D.L., Ledbetter, M.T., 1984. Deep western boundary undercurrent delineated by sediment texture at the base of the North Atlantic continental rise. Geo-Marine Letters 3, 31–36.

Bulfinch, D.L., Ledbetter, M.T., Ellwood, Brooks B., Balsam, William L., 1982. The high-velocity core of the western boundary undercurrent at the base of the U.S. continental rise. Science 215, 970–973.

Butman, B., Twitchell, D.C., Rona, P.A., Tucholke, B.E., Middleton, T.J., Robb, J.M., 2006. Seafloor Topography and Backscatter Intensity of the Hudson Canyon Region Offshore New York and New Jersey. U.S. Geological Survey Open File Report 2004–1441.

Calder, B.R., Gardner, J.V., 2008. U.S. Law of the Sea Cruise to Map the Foot of the Slope of the Northeast U.S. Atlantic Continental Margin: Leg 6. University of New Hampshire — Center for Coastal and Ocean Mapping/Joint Hydrographic Center, Durham, NH . (131 pp. http://www.ccom-jhc.unh.edu/index.php?p=42|52|57&page=law_of_the_sea.php).

Cartwright, D., Gardner, J.V., 2005. U.S. Law of the Sea Cruise to Map the Foot of the Slope and 2500-m Isobath of the Northeast US Atlantic Continental Margin: Legs 4 and 5. University of New Hampshire - Center for Coastal & Ocean Mapping/Joint Hydrographic Center, Durham, NH . (Rept. 27 pp. http://www.ccom-jhc.unh.edu/index.php?p=42|52|57&page=law_of_the_sea.php).

Chaytor, J.D., Twitchell, D.C., Ten Brink, U.S., Buczkowski, B.J., Andrews, B.D., 2007. Revisiting submarine mass movements along the U.S. Atlantic continental margin: implications for the tsunami hazards. In: Lykousis, V., Sakellariou, D., Locat, J. (Eds.), Submarine Mass Movements and Their Consequences, pp. 395–403.

Damuth, J.E., 1980. Use of high-frequency (3.5–12 kHz) echograms in the study of near-bottom sedimentation processes in the deep-sea: a review. Marine Geology 38, 51–75.

de Moustier, C., Alexandrou, D., 1991. Angular dependence of 12-kHz seafloor acoustic backscatter. Journal of the Acoustical Society of America 90, 522–531.

Dillon, W.P., Max, M.D., 2000. The U.S. Atlantic Continental Margin; the Best-Known Gas Hydrate Locality. In: Max, M.D. (Ed.), Natural Gas Hydrate in Oceanic and Permafrost Environemtents. Kluwer Academic Publishers, Netherlands, pp. 157–170.

Dillon, W.P., Fehlhaber, K., Coleman, D.F., Lee, M.W., Hutchinson, D.R., 1995. Maps showing gas-hydrate distribution off the east coast of the United States. U.S. Geological Survey Miscellaneous Field Studies Map MF-2268.

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 38, 23–50.

Embley, R.M., Jacobi, R., 1986. Mass wasting in the western North Atlantic. In: Vogt, P.R., Tucholke, B.E. (Eds.), The Geology of North America, Volume M, The Western North Atlantic Region. Geological Society of America, pp. 479–490.

Fonseca, L., Calder, B., 2005. Geocoder: An efficient backscatter map constructor: U.S. Hydrographic Conference. San Diego, CA, March 29–31. Conference Proceeding.

Fonseca, L., Mayer, L., 2007. Remote estimation of surficial seafloor properties through the application angular range analysis to multibeam sonar data. Marine Geophysical Research 28, 119–126.

Fonseca, L., Mayer, L., Orange, D., Driscoll, N., 2002. The high-frequency backscattering angular response of gassy sediments: model/data comparison from the Eel River Margin, California. Journal of the Acoustical Society of America 111, 2621–2631.

Gardner, J.V., 2004. U.S. Law of the Sea cruise to map the foot of the slope and 2500-m isobath of the Northeast US Atlantic continental margin CRUISES H04-1, 2 and 3. Center for Coastal & Ocean Mapping/Joint Hydrographic Center, Durham, NH, Rept. (61 pp. http://www.ccom-jhc.unh.edu/index.php?p=42|52|57&page=law_of_the_sea.php).

Gardner, J.V., Field, M.E., Lee, H., Edwards, B.E., Masson, D.G., Kenyon, N., Kidd, R.B., 1991. Ground-truthing 6.5-kHz sidescan sonar sonographs: what are we really imaging? Journal of Geophysical Research 96, 5955–5974.

Gardner, J.V., Mayer, L.A., Armstrong, A., 2006. Mapping supports potential submission to U.N. Law of the Sea. EOS. Transactions of the American Geophysical Union 87, 157–160.

Hamilton, E.L., 1970. Reflection Coefficients and Bottom Losses at Normal Incidence Computed from Pacific Sediment Properties. Geophysics 35, 995–1004.

Hollister, C.D., Heezen, B.C., 1972. Geological Effects of Ocean Bottom Currents: Western North Atlantic. In: Gordon, A.L. (Ed.), Studies in Physical Oceanography, vol. 2. Gordon and Breach, New York, pp. 37–66.

Jackson, D.R., Winebrenner, D.P., Ishimaru, A., 1986. Application of the composite roughness model to high-frequency bottom backscattering. Journal of the Acoustical Society of America 79, 1410–1422.

Ledbetter, M.T., Balsam, W.L., 1985. Paleoceanography of the Deep Western Boundary Undercurrent on the North American continental margin for the past 25,000 yr. Journal of Geology 13, 181–184.

Locker, S.D., 1989. Cenozoic Depositional History of the Middle U.S. Atlantic Continental Rise. Ph.D. Thesis. Univ. Rhode Island, Kingston, R.I. 180 pp.

Lowrie, A., Heezen, B.C., 1967. Knoll and sediment drift near Hudson Canyon. Science 157, 1552–1553.

Mackay, M.E., Jarrard, R.D., Westbrook, G.K., Hyndman, R.D., 1994. Origin of bottom-simulating reflectors: geophysical evidence from Cascadia accretionary prism. Journal of Geology 22, 459–462.

McCave, I.N., Tucholke, B.E., 1986. Deep current-controlled sedimentation in the western North Atlantic. In: Vogt, P.R., Tucholke, B.E. (Eds.), The Geology of North America, Volume M, The Western North Atlantic Region. Geological Society of America, pp. 451–468.

McHugh, C.M.G., Damuth, J.E., Mountain, G.S., 2002. Cenozoic mass-transport facies and their correlation with sea-level change, New Jersey continental margin. Marine Geology 184, 295–334.

McMaster, R.L., Locker, S.D., Laine, E.P., 1989. The Early Neogene continental rise off the Eastern United States. Marine Geology 87, 137–163.

Mountain, G.S., 1987. Underway Geophysics during Leg 95. In: Poag, C.W., Watts, A.B., et al. (Eds.), Initial Reports of the Deep Sea Drilling Project, 95. U.S. Govt. Printing Office, Washington, pp. 601–631.

Mountain, G.S., Tucholke, B.E., 1985. Mesozoic and Cenozoic Geology of the U.S. Atlantic Continental Slope and Rise. In: Poag, C.W. (Ed.), Geologic Evolution of the United States Atlantic Margin. Van Nostrand Reinhold, New York, pp. 293–341.

Mountain, G.S., Miller, K.G., Blum, Leg 150 Shipboard Scientific Party, 1994. Proceedings of the Ocean Drilling Program, Initial reports, 150. Ocean Drilling Program, College Station, Texas (885 pp.).

Paskevich, V.F., Wong, F.L., O'Malley, J.J., Stevenson, A.J., Gutmacher, C.E., 2010. GLORIA sidescan-sonar imagery for parts of the U.S. Exclusive Economic Zone and adjacent areas. U.S. Geological Survey Open-File Report 2010–1332. [http://pubs.usgs.gov/of/2010/1332/].

Poag, C.W., 1985. Cenozoic and Upper Cretaceous Sedimentary Facies and Depositional Systems of the New Jersey Slope and Rise. In: Poag, C.W. (Ed.), Geological Evolution of the United States Atlantic Margin. Van Nostrand Reinhold Co., New York, pp. 343–365.

Poag, C.W., 1992. U.S. Middle Atlantic Continental Rise: Provenance, dispersal, and deposition of Jurassic to Quaternary sediments. In: Poag, C. Wylie, de Graciansky, Pierre Charles (Eds.), Geological evolution of Atlantic continental rises. Van Nostrand Reinhold Co., New York, pp. 100–156.

Pratson, L.F., 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 89, 87–126.

Reimer, P.J., Baillie, M.G., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Manning, E., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. INTCAL04 terrestrial radiocarbon age calibration, 0–26 Cal kyr BP. Radiocarbon 46, 1029–1058.

Reimer, P.J., Baillie, M.G., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Manning, E., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. IntCal09 and Marine09 Radiocarbon Age Calibration Curves, 0–50000 Years cal BP. Radiocarbon 51, 1111–1150.

Rodriguez, N.M., Paull, C.K., Borowski, W.S., 2000. Zonation of authigenic carbonates within gas-hydrate bearing sedimentary sections on the Blake Ridge: offshore southeastern North America. In: Rodriguez, N.M., Paull, C.K., and Borowski, W.S., 2000. Zonation of authigenic carbonates within gas hydrate-bearing sedimentary sections on the Blake Ridge: offshore southeastern North America. In Paull, C.K., Matsumoto, R., Wallace, P.J., and Dillon, W.P. (Eds.), Proc. ODP, Sci. Results, 164. College Station, TX (Ocean Drilling Program), pp. 301–312. http://dx.doi.org/10.2973/odp.proc.sr.164.227.2000.

Rona, P.A., 1969. Middle Atlantic continental slope of United States: deposition and erosion. American Association of Petroleum Geologists Bulletin 53, 1453–1465.

Schlee, J.S., Robb, J.M., 1991. Submarine processes of the middle Atlantic continental rise based on GLORIA imagery. Geological Society of America Bulletin 103, 1090–1103.

Schneider, E.D., Fox, P.J., Hollister, C.D., Needham, H.D., Heezen, B., 1967. Further evidence of contour currents in the western North Atlantic. Earth and Planetary Science Letters 2, 351–359.

Stapleton, D.C., 1987. Geotechnical properties of marine sediments from the Low Level Waste Disposal Project Study areas: Northwest Atlantic. M.S. Thesis, Univ. Rhode Island, Kingston, R.I.

Stow, D.A.V., Holbrook, J.A., 1984. North Atlantic contourites: an overview. Geological Society, London Special Publications 15, 245–256.

Stuiver, M., Braziunas, T.F., 1993. Modeling atmospheric ^{14}C influences and ^{14}C ages of marine samples back to 10,000 BC. Radiocarbon 35, 137–189.

Sweeney, E.M., 2008. Geological interpretations of a low-backscatter anomaly found in 12-kHz multibeam data on the New Jersey continental margin. M.S. Thesis, Univ. New Hampshire, Durham, New Hampshire.

Tucholke, B., Laine, E.P., 1982. Neogene and Quaternary development of the lower continental rise off the central U.S. east coast. In: Watkins, J.S., Drake, C.L. (Eds.), Studies in continental margin geology.American Association of Petroleum Geologists Memoir 34, 295–305.

Tucholke, B.E., Bryan, G.M., Ewing, J.I., 1977. Gas-hydrate horizons detected in seismic-profiler data from the western North Atlantic. American Association of Petroleum Geologists Bulletin 61, 698–707.

Twitchell, D.C., Chaytor, J.D., ten Brink, U.S., Buczkowski, B., 2009. Morphology of late Quaternary submarine landslides along the U.S. Atlantic continental margin. Marine Geology 264, 4–15.