Evidence for extensive methane venting on the southeastern U.S. Atlantic margin

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ABSTRACT
We present the first evidence for widespread seabed methane venting along the southeastern United States Atlantic margin beyond the well-known Blake Ridge diapir seep. Recent ship- and autonomous underwater vehicle (AUV)-collected data resolve multiple water-column anomalies (>1000 m height) and extensive new chemosynthetic seep communities at the Blake Ridge and Cape Fear diapirs. These results indicate that multiple, highly localized fluid conduits punctuate the areaally extensive Blake Ridge gas hydrate province, and enable the delivery of significant amounts of methane to the water column. Thus, there appears to be an abundance of seabed fluid flux not previously ascribed to the Atlantic margin of the United States.

INTRODUCTION
Extensive reservoirs of gas hydrate and associated free gas exist within the sediments of continental margins. The rapid release of methane from dissociating gas hydrates has been invoked as a potential trigger for climate change, submarine slope failures, and seafloor collapse (Carpenter, 1981; Kvenvolden, 1993), and more gradual release may play a role in the global carbon cycle (Archer et al., 2009). In addition, sites of seabed fluid escape can foster isolated chemosynthetic ecosystems. Understanding the factors that govern the distribution of such communities has been a scientific pursuit since the discovery of the first cold seep (Paull et al., 1984). Despite the potential significance of seabed methane escape, our knowledge of the frequency and intensity of active seabed fluid flux is constrained by a limited number of deep-sea observations (Hovland et al., 2012).

Seafloor methane venting occurs most often in faulted petroleum basins (e.g., the Gulf of Mexico and the Black Sea) and on active margins (e.g., Cascadia). Those settings have large, deep reservoirs of subsurface methane and/or abundant conduits that facilitate methane escape to the seafloor (Chen and Cathles, 2005). In contrast, passive-margin sediments that are not coincident with thermogenic basins are typically characterized by the slow upward advection of dissolved methane, which mostly oxidizes before reaching the seafloor (Borowski et al., 1999). An exception is passive margins punctuated by diapirs (Paull et al., 1995). The Blake Ridge diapir seep (BRD seep), drilled as Site 996 during Ocean Drilling Program (ODP) Leg 164, is a locus of methane venting within the most areally extensive and best-characterized gas hydrate province on the Atlantic margin of the United States (Fig. 1). The BRD is the southernmost in a line of mostly buried, salt-cored diapirs that extends northeastward from the BRD along the seaward side of the Carolina Trough (Dillon et al., 1982). Salt diapirism leads to the formation of accommodating faults, the warming of sediments, and fluid mobilization, but repeated surveys at the Blake Ridge and Cape Fear diapirs have verified active fluid expulsion only at ODP Site 996 (e.g., Hornbach et al., 2005; Paull et al., 1996; Van Dover et al., 2003). Settings like the Atlantic margin of the United States have therefore been judged as unlikely locations for seabed fluid flow.

BACKGROUND
The Blake Ridge gas hydrate province extends from the Carolina Rise southward and eastward under the Blake Ridge sediment drift deposit on the southeastern Atlantic margin of the United States (Dillon et al., 1982; Paull et al., 1995). Bottom-simulating reflections (BSRs), which are negative-polarity reflections produced by the impedance contrast between hydrate-bearing sediments and underlying gas-charged sediments, mark the base of the gas hydrate stability zone (GHSZ) in some, but not all, marine gas hydrate settings. The Blake Ridge province has a widespread BSR and a GHSZ that reaches a thicknesses of ~465 m at ODP Site 997 (Paull et al., 1996). While no BSR has been imaged at the Cape Fear diapir (CFD), seismic evidence and heat flow data suggest a GHSZ thickness of up to 400 m there (Dillon et al., 1982; Ruppel et al., 1995). Beneath the BRD seep, the BSR is upwarped over the high-thermal-conductivity core of the salt diaper, and the BSR completely disappears where a dendritic fault network capable of advecting fluids at 20–400 m/y, coalesces downward into larger faults that perturb the GHSZ (Hornbach et al., 2005, 2007b; Taylor et al., 2000). Water-column bubbles, chemosynthetic communities, and pore-water geochemistry provide evidence for modern fluid escape at the BRD seep, and authigenic carbonate at 30 m to 50 m below the seafloor indicates that the seep has persisted since at least the early
Pleistocene (Paull et al., 1996, 1995; Van Dover et al., 2003). Results from Deep Sea Drilling Project (DSDP) Leg 76 and ODP Leg 164 gave no indications of thermogenic hydrocarbons underlying the area (Gradstein and Sheridan, 1983; Paull et al., 1996).

METHODS

In July 2012, the NOAA (U.S. National Oceanic and Atmospheric Administration) ship Okeanos Explorer collected 3500 km² of swath bathymetry and coincident water-column and sub-bottom imagery using an EM302 (30 kHz) multibeam and a 3.5 kHz Knudsen 3260 sub-bottom profiler. Near the Blake Ridge and Cape Fear diapirs, ship tracklines were spaced 40 m and 400 m apart, respectively. Conductivity, temperature, and depth (CTD) casts were performed over each diapir using a Seabird SBE 911 Plus, and 11 AUV Sentry dives were conducted at the two diapirs. Sentry was instrumented with a Reson 7125 multibeam sonar (400 kHz) and a high-dynamic-range (12-bit) 1024 × 1024 pixel digital still camera, along with other sensors. Sentry flew 20 m above the seafloor with 60 m line spacing to gather ~120% multibeam coverage. During photo collection, Sentry flew 5 m above the seafloor at 0.80 m/s with 5 m line spacing and took photos every 3.5 s or 7 s.

RESULTS

Water-column anomalies (WCAs) were identified at the BRD seep, at five additional locations near the BRD seep (~1.5 km north and 0.3 km south of ODP Site 996), and at the CFD (Figs. 2 and 3; Table 1) based on multibeam data that imaged high reflectivity in coherent, plume-like features emanating from the seafloor. Over 11 days in varying weather conditions, these distinct WCAs were imaged consistently in multiple passes, implying persistence over this period. The six WCAs identified at the BRD were detectable more than 1000 m above the seafloor. The tallest WCA (1330 m high) emanates from the seafloor within 10 m of ODP Site 996. The CFD WCA extends 1160 m above the seafloor. The WCAs drift eastward as they rise in the water column, likely due to prevailing currents in the area.

Sentry multibeam data resolve zones of irregular seafloor relief (1–4 m high) at the base of the WCA at both diapirs (Figs. 2 and 3). Mounds and pockmarks (1–75 m in diameter) occur in four discrete clusters within the vicinity of the BRD, but are scattered across the generally rougher seafloor surrounding the CFD. Photos resolve fields of debris that are blanketed in sediment.

Bottom photos also reveal the presence of chemosynthetic benthic communities where the WCAs originate at the seafloor (Figs. 2 and 3). Microbial mats and clams (Vesicomya cf. venusta) occur at both the BRD and CFD, while mussels (Bathymodiolus heckeri) were found only at the BRD. At the BRD, dense, concentric clusters (ranging from 0.0278 km² to 0.108 km²) of live adult and juvenile mussels were observed, commonly surrounded by dead mussels. Clams occurred in either scattered or dense patches, sometimes at the periphery of mussel beds (Wagner et al., 2013). At the CFD clam beds, bacterial mats and bubbles were observed in three patches ranging between 0.0005 km² and 0.0160 km² in area.

At the BRD, Chirp data show zones of lower reflectivity in the shallow sediments (Fig. 2). Where previously recognized near the BRD, these seismic anomalies have been attributed either to gas charging of sediments or cementation by gas hydrate or authigenic carbonate (Hornbach et al., 2007b). The WCAs originate from seafloor sites located directly above some of the low-reflectivity zones, implying a possibly continuous fluid-flow pathway from sub-seafloor to the water column. Similar pathways are not identifiable in the generally lower-quality Chirp data collected at
the CFD because widespread seafloor diffractions obscure coherent reflectors in the shallow subsurface (Fig. 3).

DISCUSSION

Distribution and Character of Seabed Fluid Flux
The abundance of chemosynthetic communities and WCAs indicates that seabed methane escape is regionally extensive over a larger spatial scale than previously realized. For example, previous studies observed fluid escape only over a pockmark at the BRD seep (0.0325 km²) (Paul et al., 1995; Van Dover et al., 2003), while our data show that fluids are escaping from 0.197 km² of seafloor spaced over 0.583 km² of the BRD, approximately six times the previous estimate. This investigation expands the previously known area of chemosynthetic communities at the BRD by a comparable amount and confirms that their distribution follows the meandering shallow fractures above the BRD (Fig. 2). For the CFD, our results document the first observed chemosynthetic communities, which occupy an area of 0.023 km².

Chemosynthetic communities are robust indicators of fluid emis-
sion from the seafloor. The bivalves (clams, mussels) present at BRD and CFD require sulfide and/or methane (mussels only) to survive. Discrete, non-overlapping distributions of bivalve species at the BRD seep have previously been interpreted as indicating differences in underlying chemical flux, or possibly competition for sulfide (Van Dover et al., 2003). We find the same non-overlapping bivalve distribution within the larger BRD, while the CFD lacks mussels. The absence of mussels at CFD may reflect differences in larval transport patterns, habitat suitability related to substrate, or hydrological systems and methane availability, or some combination of variables. Regardless, the occurrence of clams and bivalve mats at CFD verifies the presence of significant sulfide in the sediments, a product of the anaerobic oxidation of methane.

All seven WCAs identified in this study extend at least 1 km above the seafloor and originate within 20 m of benthic chemosynthetic communities, suggesting that the WCAs are sourced in seeps emitting methane and sulfide. In the water column, gas bubbles, whether coated with gas hydrate or not, are strong acoustical targets, and plumes extending hundreds of meters above the seafloor have previously been detected in the Gulf of Mexico and on the Spitsbergen margin, Norway (Weber et al., 2012; Westbrook et al., 2009). With the data analyzed here, we cannot discern if the WCAs are made up of bubbles or hydrate shells around bubbles. Van Dover et al. (2003) previously observed hydrate-coated gas bubbles just above the seafloor at the BRD seep. The resolved BRD and CFD WCAs disappear ~250 m below the top of the water-column hydrate stability zone (Table 1; Fig. 2), which should occur at ~800 m water depth based on the CTD constraints. Gas hydrate probably plays a role in bubble ascen-
sion through the water column at these sites, but measurements of bubble size, rise rate, and gas content would be required to assess the relative importance of gas bubbles and hydrate-encrusted bubbles in forming the detected plumes.

Although never the subject of a sustained monitoring program, active methane flux has been consistently observed at the BRD seep over the past 17 yr (Hornbach et al., 2005; Paull et al., 1995, 1996; Van Dover et al., 2003). Using methane flux constraints from a deep-sea seep with a similar ebullition character (20.7 mol/d at in situ pressure; McGinnis et al., 2006), we estimate that the single known BRD seep site may have released 1.54 tons of carbon into the water column within this 17 yr period (see the flux calculation in the GSA Data Repository1).

Seep Frequency, Elusiveness, and Diapirism
The relationships between the underlying diapir structure and shallow-sedimentary pathways that govern seabed fluid flux are relatively well constrained at the BRD (Hornbach et al., 2007b; Paul et al., 1996; Taylor et al., 2000). This study proves that fluid conduits extend north of the diapir as mapped by Taylor et al. (2000), but the true areal extent of the BRD has probably not yet been fully determined (see Fig. DR1 in the Data Repository). In contrast, the areal extent of the CFD is well constrained, but sub-seafloor migration pathways have still not been identified in low- or high-frequency seismic data (Dillon et al., 1982; Paull et al., 1996). Based on downward extrapolation of heat-flow data (Ruppel et al., 1995), the GHZS could thin by more than 200 m over the CFD. However, neither drilling at nearby ODP sites, nor HOV Alvin dives 3911, 3913, and 3914, found evi-
dence for modern methane flux at the CFD. Our discovery of a previously unknown seep within 700 m of ODP Sites 991 and 992 suggests highly localized, and possibly temporally variable, subsurface fluid conduits.

The discovery of venting at the CFD is provocative. The interplay among the Cape Fear slide complex, underlying methane hydrates/free gas, and salt tectonics remains uncertain (Carpenter, 1981). ODP Sites 991, 992, and 993 were drilled to test the hypothesis that decomposition of gas hydrate at the base of the GHZS might have fluidized sediment and induced the slope failure that led to the Cape Fear slide, the largest (~25,000 km²) slide on the Atlantic seaboard of the United States. The ODP sites revealed evidence of mass movements, but minimal indications of fluid flow (Paull et al., 1996). More recently, Hornbach et al. (2007a) confirmed that, for all but the shallowest slide event, sliding occurred well above the GHZS, implying that rapid hydrate dissociation and associ-
ated free gas escape did not trigger and probably did not exacerbate the slide. Our new observations indicate that this area also experiences ongo-
ing fluid migration, an additional factor to be considered when assessing modern seafloor stability at the site.

In addition to the Blake Ridge and Cape Fear diapirs, we collected shipboard data over two other known diapirs (Dillon et al., 1982) and a hypothesized fault associated with a southwest-northeast–trending escarpment (Hornbach et al., 2007a) (Fig. 1). We found neither WCAs nor clear indications of subsurface zones of low reflectivity associated with these features. These sites may not be loci for seabed fluid flux; alternatively, as with the CFD, more-detailed investigations may be required to resolve fluid flux activity.

1GSA Data Repository item 2013222, flux calculation and Blake Ridge dia-
pir map, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
Biogeographical Implications

Characterizing the affinities and the evolutionary relationships among different chemosynthetic populations is a major focus in deep-sea research (German et al., 2011). On the North American Atlantic margin, deep-water (>1000 m water depth) chemosynthetic communities have previously only been identified at the BRD seep site and the Laurentian Fan (Mayer et al., 1988). Documentation of chemosynthetic communities in this work and recent investigations at Baltimore Canyon (offshore Maryland) (Brooke and Ross, 2012) aid in connecting these sparse, yet potentially related, communities. Further, the coincidence of these communities with diapirs suggests that the suite of diapirs along the Carolina Trough (Dillon et al., 1982) could act as habitat “stepping stones” for biological transport and chemosynthetic community connectivity along the North American Atlantic margin. The history of exploration at the Blake Ridge and Cape Fear diapirs indicates that successive multiscale geophysical and biogeochemical research efforts may be required to resolve more cold seeps along the Atlantic margin.

CONCLUSION

New high-resolution surveys using state-of-the-art sensors reveal evidence for discrete, active methane venting from the Blake Ridge gas hydrate province. The plumes originate at seafloor locations characterized by irregular bathymetry and chemosynthetic communities that rely on hydrogen sulfide and/or methane to sustain metabolic processes. These results significantly expand the known areal coverage of cold seep chemosynthetic communities on the Atlantic margin of the United States, thus providing hints about biogeographic connectivity. That the Blake Ridge gas hydrate province, the archetypal low-saturation gas hydrate province, regularly releases methane streams to the overlying ocean at widely distributed cold seep sites suggests that microbial hydrate systems perturbed by features like diapirs may play an important role in transporting methane to the ocean-atmosphere system. In addition, these results underscore the value of repeated interdisciplinary investigations at nested spatial scales and resolution to constrain the frequency, distribution, and flux rates of active seep sites.

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