Three-dimensional structure of fluid conduits sustaining an active deep marine cold seep

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[1] Cold seeps in deep marine settings emit fluids to the overlying ocean and are often associated with such seafloor flux indicators as chemosynthetic biota, pockmarks, and authigenic carbonate rocks. Despite evidence for spatiotemporal variability in the rate, locus, and composition of cold seep fluid emissions, the shallow subseafloor plumbing systems have never been clearly imaged in three dimensions. Using a novel, high-resolution approach, we produce the first three-dimensional image of possible fluid conduits beneath a cold seep at a study site within the Blake Ridge gas hydrate province. Complex, dendritic features diverge upward toward the seafloor from feeder conduits at depth and could potentially draw flow laterally by up to 10^3 m from the known seafloor seep, a pattern similar to that suggested for some hydrothermal vents. The biodiversity, community structure, and succession dynamics of chemosynthetic communities at cold seeps may largely reflect these complexities of subseafloor fluid flow. **Citation:** Hornbach, M. J., C. Ruppel, and C. L. Van Dover (2007), Three-dimensional structure of fluid conduits sustaining an active deep marine cold seep, *Geophys. Res. Lett.*, *34*, L05601, doi:10.1029/2006GL028859.

1. Introduction

[2] More than 20 years after their discovery, the complex plumbing systems that feed deepwater cold seeps remain poorly constrained [*Hovland and Judd*, 1988; *King and MacLean*, 1970; *Levin*, 2005; *Paull et al.*, 1984; *Van Dover et al.*, 2003]. Methane seeps liberate carbon from methane hydrate reservoirs and often sustain exotic seafloor communities. The seeps are also important natural laboratories for multidisciplinary studies of physical, chemical, and biological processes in the deep ocean [*Henriet et al.*, 1998; *Levin et al.*, 2003; *Levin*, 2005; *Tryon and Brown*, 2001] and have potential significance as agents of global climate change [*Dickens*, 2003; *Hovland et al.*, 1993; *Milkov*, 2000; *Svensen et al.*, 2004]. Although seafloor manifestations of seeps above diapiric features have been extensively described, characterizing seep plumbing remains a challenge because flow can be highly transient, varying both in time and space along complex and changing conduits systems [*Roberts and Carney*, 1997].

[3] Measurements of seafloor fluid flux and the analysis of the distribution of chemosynthetic organisms at deep marine seeps imply spatial and temporal variability consistent with complex geologic and hydrologic controls on fluid flow [*Levin et al.*, 2003; *Obzhirov et al.*, 2004; *Tryon and Brown*, 2001; *Tryon et al.*, 2002]. Nonetheless, analyses of fluid flux proxies (e.g., pore water geochemistry data, heat flow data, fluxmeter data collected at discrete locations) offer only limited insight into subsurface hydrology due to a lack of spatial and temporal resolution. As a result, studies often attribute seep flux to either isolated near-vertical fluid conduits directly beneath seafloor flux indicators [*Hornbach et al.*, 2005; *Hovland and Judd*, 1988; *Loncke and Mascle*, 2004; *Sager et al.*, 2003] or an inferred network of dendritic, subsurface faults that are generally too small to detect seismically [*Torres et al.*, 2004; *Tryon et al.*, 2002; *Weinberger and Brown*, 2006].

[4] A potentially valuable method for linking heterogeneous seafloor flux indicators to complex subseafloor structure is ultra-high-resolution three-dimensional (3D) imaging. To date, most seismic surveys of seeps have relied on two-dimensional methods. Even when high-quality, multichannel, 3D seismic surveys are obtained, the vertical resolution typically exceeds 5–10 m, meaning that fine-scale structures that channel subsurface fluid flow are not resolvable.

[5] Here we apply an experimental, quasi-3D technique to image fine details of the fluid conduits beneath an active methane seep. The method yields submeter vertical resolution to depths as great as 40 m below seafloor (mbsf) (Figure 1). The resulting images reveal with unprecedented detail the complex, highly three-dimensional faults and suspected flow pathways below a cold seep.

2. Setting and Methods

[6] The study site is a methane seep located ~300 km east of Charleston, South Carolina on the Blake Ridge Diapir (BRD), the southernmost of ~25 salt diapirs trending northeast-southwest and located landward of the Carolina Trough [*Dillon et al.*, 1982] (Figure 1a). The BRD hosts one of the best studied cold seeps in the North Atlantic [*Hornbach et al.*, 2005; *Paull et al.*, 1996; *Taylor et al.*, 2000; *Van Dover et al.*, 2003]. Analyses of carbonates recovered from boreholes indicate long-lived (at least 10^6 years), if intermittent, methane emission at the seep (Site 996 of the Ocean Drilling Program), and sedimentation rates for the silty clays recovered at depths up to 60 mbsf are 48 m My^{-1} [*Paull et al.*, 1996]. Emplacement of salt at depth has deformed overlying sediments [*Dillon et al.*,

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1982], which have also experienced pervasive, fine-scale normal faulting. Seafloor morphology is also affected by active erosion of the BRD's eastern flank, where dipping strata are truncated at the seafloor.

[7] To image the BRD seep at high resolution and in 3D, we used the *R/V Atlantis*'s Knudsen digital echosounder, which emits a sweeping chirp from 1.5 to 11.5 kHz and yields vertical resolution of ~0.25 m at the BRD. The ship steamed at 6 knots for ~12 h in July 2003, completing a ~6 km^2 3D survey. Data were recorded digitally at ~10 m intervals along 24, 6-km-long survey lines spaced 40 m apart (Figure 1b). The *Atlantis* was equipped with GPS navigation accurate to ~3 m, and ship position was recorded for each chirp. Producing interpretable images (Figure 1c) from the single channel data requires only minimal processing (e.g., bandpass filtering and static shifts for tide-induced sea level variation). Chirp and navigation data were stored in digital SEGY format and rendered in Paradigm Focus3D imaging software.

3. Results

[8] Before creating the 3D image, we first interpreted 2D chirp profiles collected at the site. These data (Figure 2) reveal multiple faults but cannot constrain potential hydraulic connectivity between the faults imaged on individual, parallel survey lines. The 2D chirp data match earlier seismic results, which also imaged isolated, acoustically-transparent chimneys beneath the BRD seep (Figure 1d) [*Hornbach et al.*, 2005; *Paull et al.*, 1996; *Taylor et al.*, 2000]. High permeability faults probably act as primary conduits for methane-laden fluids, and the acoustically-transparent zones likely represent lower permeability sediments located adjacent to the faults and either charged with gassy fluids or affected by cementation and diagenetic processes. Similar acoustically-transparent features are frequently observed in seismic data collected in hydrate provinces and are interpreted to result from (1) attenuation of acoustic signals by gas bubbles, (2) seismic "blanking" caused by grain cementation via gas hydrate formation, (3) loss of sediment grain-to-grain contact created by high pore-pressure, or (4) authigenic carbonate formation [*Dillon et al.*, 1993; *Hovland and Judd*, 1988; *Hovland and Curzi*, 1989; *Lee and Dillon*, 2001; *Sager et al.*, 1999]. Regardless of the mechanism, acoustically-transparent sediments below seeps are typically taken as evidence for past or ongoing fluid migration [*Dillon et al.*, 1993; *Hovland and Judd*, 1988; *Sager et al.*, 2003].

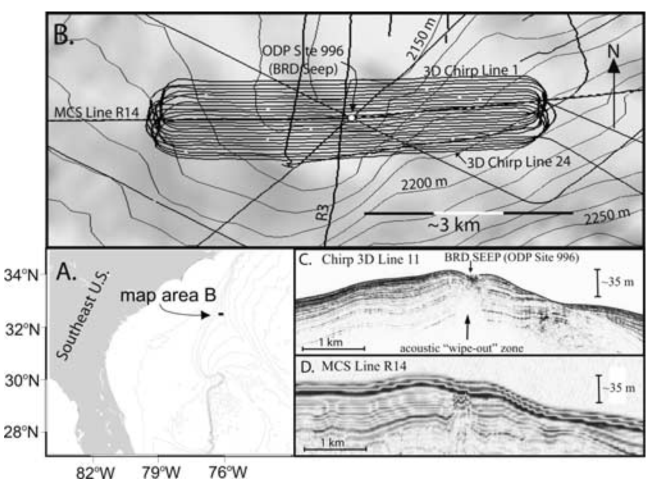

Figure 1. (a) Map view of the 3D survey showing the location of the survey relative to the U.S. East Coast (500 m contour interval). (b) A more detailed map of the 3D chirp survey and the location of high-resolution multichannel seismic (MCS) line R14 (dashed line) acquired over the same area in 2000 [*Hornbach et al.*, 2005]. 3D chirp line numbers increase from line 1 (north) to line 24 (south). Regional chirp line R3 (shown in Figure 2b) runs north-south through the 3D survey. (c) 3D Chirp Line 11 passes directly over the known BRD seep location and images an acoustically transparent zone below the seep at a seafloor pockmark. (d) MCS Line R14, nearly coincident with 3D Chirp Line 11, also images the seep, but at lower resolution than the chirp data in Figure 1c.

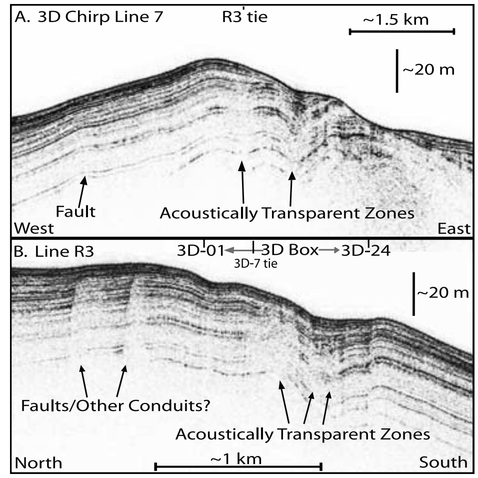

Figure 2. (a) 3D chirp line 7 showing the location of two acoustically-transparent zones and suggesting more than one fluid conduit beneath the seep. (b) Regional chirp line R3, shot north-south through the volume, reveals multiple acoustically-transparent zones both inside and outside the 3D survey. Faults are readily identified, and acoustic wipeout zones typically occur along or near fault planes.

[9] Integrating the closely spaced chirp lines into a 3D volume, we create the first detailed 3D image of faults and acoustically-transparent zones below a methane seep. From this image, the 3D pattern of faults and suspected fluid conduits emerges, revealing the complexity of the subseafloor plumbing system. No large parabolic reflection cones are observed in 2D seismic images at wipe-out zones, and reflections remain significantly lower in amplitude below the acoustically-transparent regions. Thus, the acoustically-transparent zones signify high attenuation and not out-of-plane reflections (e.g., Figures 1c and 2). Cutting through these acoustically-transparent zones is a series of high-angle (~60° dip) normal faults that form part of the pervasive NW-SE trending system of such faults in the region (Figures 2 and 3). Many of these faults are expressed as seafloor surface escarpments and extend beyond the penetration depth of the chirp signal.

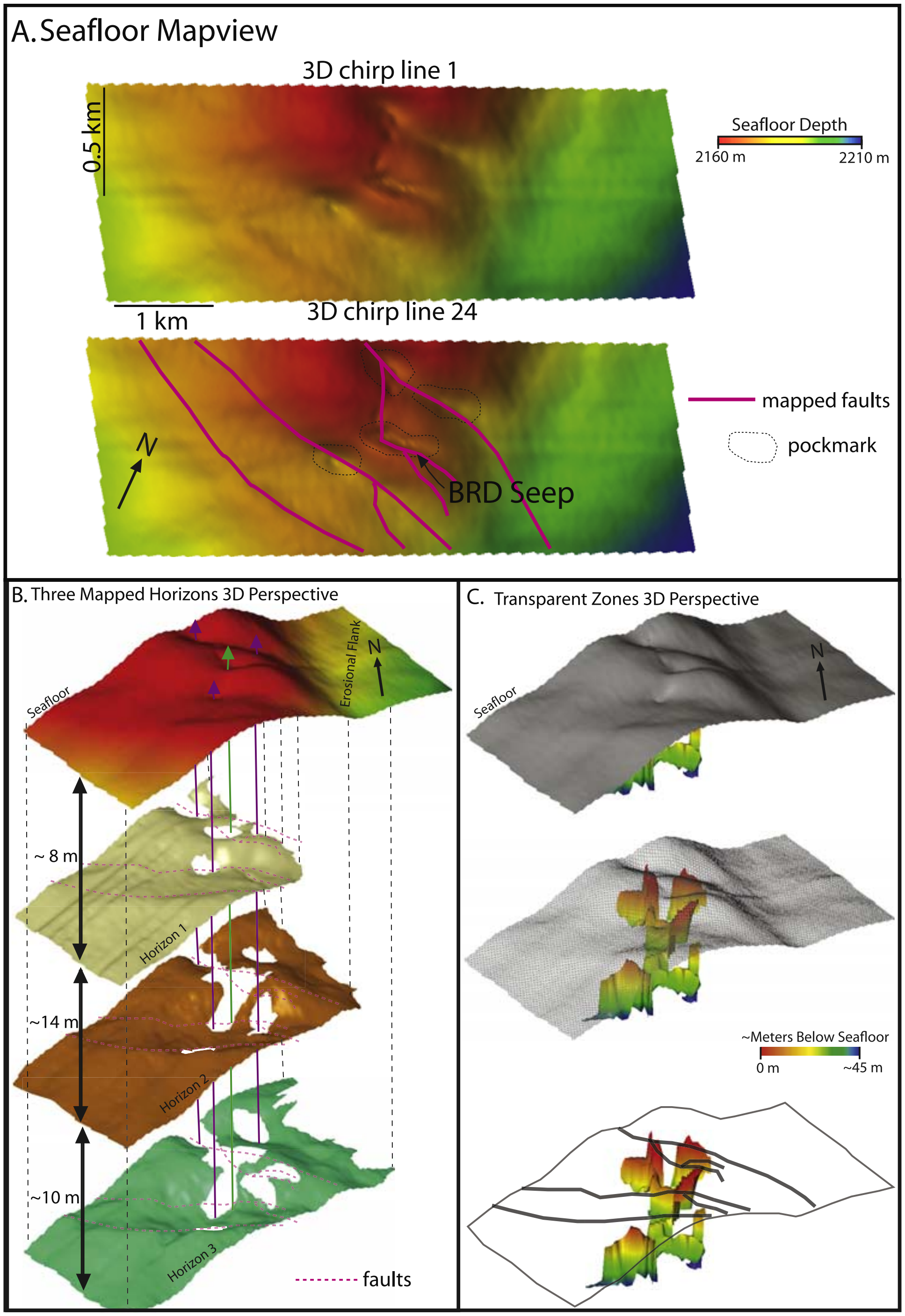

Figure 3. (a) Seafloor surface map created from the 3D chirp data shows the location of pockmarks and fault traces. *DSV Alvin* has explored only one pockmark, known as the BRD seep. (b) 3D view of the BRD seafloor and three discrete, subseafloor sedimentary layers. The subhorizontal sedimentary layers are shown vertically separated to highlight the anomalous "holes" (areas of low seismic reflectivity) that we interpret as indicating fossil or active fluid migration. At greater depths (Layers 2 and 3), the distinct holes in Layer 1 converge, consistent with merging of the finer-scale, near-seafloor, branching conduits into a single, major conduit. The green arrow denotes the possible flow path for methane emitted at the seafloor at the BRD seep, and purple arrows indicate other possible fluid pathways. Note that all of these possible flow paths pass through low seismic reflectivity "holes" at depth and through pockmarks at the seafloor. (c) 3D image of the seafloor with respect to underlying fluid conduits. Here, only the acoustically-transparent zones are shown. The top image overlays the seafloor on the conduit system; the middle image renders the seafloor semitransparent and reveals possible subseafloor flow pathways; the bottom removes the seafloor, showing the conduits color-coded by their depth beneath the seafloor. Conduit dimensions are difficult to determine accurately, but an area of sediment more than 300 m across appears to be affected by fluid flow in the vicinity of the high permeability conduits (faults). At ~10 mbsf, the acoustically-transparent sediments form branches that have average diameters of up to 120 m.

[10] A surprising finding is that chirp lines acquired up to a kilometer away from the known seafloor seep reveal other interconnected, acoustically-transparent areas, implying previously unrecognized flow paths and perhaps other seafloor-breaching conduits (Figures 2 and 3). Whether these newly discovered flow paths are active or relict fluid conduits remains unclear. Each of the near-seafloor transparent zones is associated with a seafloor pockmark or depression of up to 5 m relief (Figure 3a). Such pockmarks have sometimes been interpreted as indicators of active or fossil fluid flux [*Hovland and Judd*, 1988; *Hovland et al.*, 2005; *Paull and Ussler*, 2005; *Svensen et al.*, 2004]. The seafloor chemosynthetic community that has been extensively investigated by *DSV Alvin* [*Van Dover et al.*, 2003] lies directly above the central, acoustically-transparent feature in our image, but no such seafloor exploration for flux indicators (e.g., biota, authigenic carbonates) has yet been carried out at the pockmarks located above the newly identified transparent zones.

[11] By following subhorizontal strata through the 3D volume, we map the acoustically-transparent zones as distinct "holes" in otherwise continuous stratal surfaces (Figure 3b). The analysis reveals at least four apparently interconnected transparent zones that appear to converge at depth (see auxiliary material[1]). All of these transparent zones intersect faults (Figure 3). If, indeed, the transparent zones represent past or current fluid conduits, then analysis of the 3D seismic images suggests multiple conduits, not merely a single vertical chimney, likely serve as the primary fluid flow pathways in the shallow subsurface beneath the seep.

4. Discussion and Conclusions

[12] The 3D chirp image reveals complex subseafloor fluid flow characterized by an intricate, interconnected system of faults and acoustically-transparent zones (Figure 3b). Although the relative flux along these structures remains unclear, we suggest that these seismic features indicate a dendritic flow network sustaining the BRD cold seep, similar to the networks inferred to exist at other seafloor hydrothermal sites [*Levin et al.*, 2003; *Torres et al.*, 2002; *Tryon et al.*, 2002]. Such conduit systems may dominate mass transport in a variety of permeable hydrogeologic environments on land and in the oceans [e.g., *Gorelick et al.*, 2005], but this is the first time a dendritic system at a deep marine cold seep has been imaged in detail. The branching nature of the BRD flow system implies that lateral fluid flow through divergent, high permeability conduits embedded within low permeability muds may be a critical process at cold seeps [*Sibuet et al.*, 1988]. Even with significant (~20:1) vertical exaggeration in the 3D image, lateral shifts in the fluid conduits are evident (Figure 3c). The spatial separation of the conduits suggests that fluids may travel up to a kilometer away from the central conduit.

[13] The dendritic nature of the flow system implies both horizontal and vertical components to fluid flow and likely contributes to disparities of up to several orders of magnitude for BRD seep fluid flux estimated using various approaches [*Egeberg*, 2000; *Hornbach et al.*, 2005]. Flux estimates based on the analysis of the pore water geochemistry in recovered sediment cores [*Egeberg*, 2000] inherently assume one-dimensional flow due to their dependence on borehole data. Estimates of fluid flux that rely on characteristics of 2D seismic images combined with heat flow data [*Hornbach et al.*, 2005] capture more of the gross 2D structure, but ignore details about lateral flow pathways that are not seismically-resolvable. The complexity of the potential fluid conduits as revealed by the 3D image and the relatively large estimated diameter (>100 m) of the areas affected by fluid flow near each resolvable conduit branch (Figure 3c) make it likely that any 1D flow model and indeed many 1D direct (e.g., fluxmeter) or proxy (borehole-based) measurements of near-seafloor flow at discrete locations are spatially aliased and may yield inaccurate integrated flux estimates at seeps.

[14] The complex and perhaps ephemeral dendritic fluid conduits that we identify at the BRD seep likely influence the diversity, distribution, and longevity of chemosynthetic biota. Unlike hydrothermal-vent systems that can be ephemeral on time scales of days to decades [*Van Dover*, 2000], many seeps are thought to supply a relatively steady source of chemicals that maintain chemosynthetic biota [*Bergquist et al.*, 2003]. The putative spatiotemporal stability of seep ecosystems like the BRD has been postulated to account for higher biological diversity of seep faunas compared to those of vents [*Sibuet and Olu*, 1998; *Turnipseed et al.*, 2003]; however, the dendritic plumbing system we have imaged likely leads to more spatially heterogeneous and more transient flow than is commonly ascribed to the BRD seep. This finding is also in agreement with the concept of self-sealing seeps and faults, where mineral and bacterial precipitation processes, as well as hydrate formation, may continually change subseafloor fluid flow patterns [*Hovland*, 2002; *Nimblett and Ruppel*, 2003]. While seep processes in the area of the BRD may be long-lived (>10^6 years), biological populations may experience more ephemeral conditions, perhaps similar in spatial and temporal scale to those that have been documented by seafloor fluxmeter measurements at active margin methane vents [*Tryon and Brown*, 2001].

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