Geophysical constraints on the surface distribution of authigenic carbonates across the Hydrate Ridge region, Cascadia margin

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Abstract

On active tectonic margins methane-rich pore fluids are expelled during the sediment compaction and dewatering that accompany accretionary wedge development. Once these fluids reach the shallow subsurface they become oxidized and precipitate cold seep authigenic carbonates. Faults or high-porosity stratigraphic horizons can serve as conduits for fluid flow, which can be derived from deep within the wedge and/or, if at seafloor depths greater than ~300 m, from the shallow source of methane and water contained in subsurface and surface gas hydrates. The distribution of fluid expulsion sites can be mapped regionally using sidescan sonar systems, which record the locations of surface and slightly buried authigenic carbonates due to their impedance contrast with the surrounding hemipelagic sediment. Hydrate Ridge lies within the gas hydrate stability field offshore central Oregon and during the last 15 years several studies have documented gas hydrate and cold seep carbonate occurrence in the region. In 1999, we collected deep-towed SeaMARC 30 sidescan sonar imagery across the Hydrate Ridge region to determine the spatial distribution of cold seep carbonates and their relationship to subsurface structure and the underlying gas hydrate system. High backscatter on the imagery is divided into three categories, (I) circular to blotchy with apparent surface roughness, (II) circular to blotchy with no apparent surface roughness, and (III) streaky to continuous with variable surface roughness. We interpret the distribution of high backscatter, as well as the locations of mud volcanoes and pockmarks, to indicate variations in the intensity and activity of fluid flow across the survey area and aid in this interpretation. Subsurface structural mapping and swath bathymetry suggest the fluid venting is focused at the crests of anticlinal structures like Hydrate Ridge and the uplifts along the Daisy Bank fault zone. Geochemical parameters link authigenic carbonates on Hydrate Ridge to the underlying gas hydrate system and suggest that some of the carbonates have formed in equilibrium with fluids derived directly from the destabilization of gas hydrate. This suggests carbonates are formed not only from the methane in ascending fluids from depth, but also from the shallow source of methane released during the dissociation of gas hydrate. The decreased occurrence of high-backscatter patches and the dramatic reduction in pockmark fields, imaged on the eastern part of the survey, suggest gas hydrate near its upper stability limit may be easily destabilized and thus, responsible for these seafloor features. High backscatter along the left-lateral Daisy Bank fault suggests a long history of deep-seated fluid venting, probably unrelated to destabilized gas hydrate in the subsurface.

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1. Introduction

Pore fluid expulsion is a common process in accretionary wedges on active continental margins and is coincident with the dehydration and compaction of the sediment column during accretionary wedge development. Fluid expulsion can (1) be episodic along high-porosity stratigraphic horizons and/or faults exposed at the seafloor (e.g. Kulm et al., 1986; Lewis and Cochrane, 1990; Moore and Vrolijk, 1992; Sample, 1996; Sample and Reid, 1998), (2) occur during mud volcanism (e.g. Brown, 1990; Kopf, 2002), and/or (3) occur during diffuse, intergranular fluid flow (e.g. Moore and Vrolijk, 1992 and references therein).

An abundant component in the fluids escaping from organic-rich accretionary wedges is dissolved thermogenic and biogenic methane. When subjected to the lower temperature, lower pressure, and oxidizing bacteria-rich environment near the seafloor surface, these methane-rich fluids can precipitate cold seep carbonates of aragonite, calcite, and/or dolomite compositions (Ritger et al., 1987; Greinert et al., 2001). In addition, some of this methane is temporarily incorporated as free gas into the gas hydrate fabric near the seafloor prior to expulsion (Suess et al., 2001), if at high enough gas concentrations and appropriate pressure (water depths at least 300 m) and temperature (bottom water temperatures approaching 0°C) conditions (Kvenvolden, 1993).

Both surface and deep-towed sidescan sonar surveys offer a unique method for regional mapping of seafloor fluid venting sites because the acoustic impedance contrast (density×sound velocity) between the authigenic carbonates precipitated at these sites and the surrounding hemipelagic sediments is detectable. Sidescan sonar surveys are valuable because they provide a regional-scale survey of seafloor fluid venting occurrences and distributions, and they also help guide later seafloor observation and sampling efforts conducted with manned submersibles, ROVs, tv-camera tows, and coring and dredging devices.

The first documentation of authigenic carbonates and chemosynthetic biological communities associated with pore fluid expulsion on an active continental margin occurred at the first accretionary ridge west of Hydrate Ridge, offshore central Oregon (Fig. 1), in the mid-1980s (Suess et al., 1985; Kulm et al., 1986; Ritger et al., 1987). Since then, other sites along the Pacific rim have also been discovered (e.g. Henry et al., 1989; Le Pichon et al., 1992; Ohta and Laubier, 1987). The occurrence of authigenic carbonates on Hydrate Ridge was documented during ODP (Ocean Drilling Program) Leg 146 drilling in 1992 (see Westbrook et al., 1993), inferred from reprocessed GLORIA sidescan sonar imagery by Carson et al. (1994), and further constrained by submersible observations and seafloor sampling (e.g. Torres et al., 1999; Bohrmann et al., 2000; Greinert et al., 2001). Gas hydrates are also well developed at Hydrate Ridge and were first inferred on seismic reflection profiles collected as the site survey for ODP sites 891 and 892 (MacKay et al., 1992). The widespread distribution of the BSR (bottom simulating reflector), marking the base of gas hydrate stability (Hyndman and Spence, 1992), or the top of a free gas zone trapped beneath the hydrate (MacKay et al., 1994), suggests the ridge is capped by gas hydrate (Tréhù et al., 1999). The first recovery of gas hydrate on Hydrate Ridge occurred during ODP Leg 146 at site 892 (Howland et al., 1995) when the crest of the northern summit was drilled through a hydrologically active fault (Fig. 1). Since then, several researchers have returned to collect samples of the gas hydrate and authigenic carbonates and to conduct other geophysical surveys to characterize the behavior of the hydrate system in this active tectonic setting (e.g. Torres et al., 1999; Bohrmann et al., 2000; Suess et al., 1999, 2001; Tréhù et al., 2002; this study).

On Hydrate Ridge and in other accretionary
ridges within the hydrate stability zone, a close association between gas hydrates and carbonates may exist because fluids dewatered from the prism not only supply methane to the gas hydrate stability zone, but also transfer heat to shallower depths, which can induce the destabilization of the gas hydrate (Suess et al., 2001). On both the northern and southern summits of Hydrate Ridge, the authigenic carbonate and pore water carbon and oxygen isotopes support this association by suggesting the carbonates are precipitated in part from methane derived from destabilized gas hydrate (Bohrmann et al., 1998; Greinert et al., 2001). This observation suggests destabilized gas hydrate can contribute to the total accumulation of authigenic carbonate precipitated during accretionary wedge dewatering and compaction. With this in mind, an understanding of the regional distribution of subsurface structures (faults and folds) and the extent of the gas hydrate stability zone is necessary to make interpretations about the possible origins of fluid venting patterns interpreted on sidescan sonar records and observed on the seafloor.

Our recent research efforts have been focused on identifying the structural controls on the distribution of authigenic carbonates in the Hydrate Ridge region and their relationship to the underlying gas hydrate system. In this paper, we present the results of our 1999 SeaMARC 30 (SM30) deep-towed sidescan sonar survey coupled with seafloor observations and samples and subsurface geologic mapping, based on seismic reflection data, to determine the distribution of authigenic carbonates and their relationship to large-scale subsurface structures and the underlying gas hydrate system across the Hydrate Ridge region.

2. Tectonic setting

2.1. Cascadia accretionary prism

The Juan de Fuca Plate is currently being sub-
ducted obliquely beneath the North American Plate along the Washington, Oregon, and Northern California continental margins (Fig. 1). The Cascadia accretionary prism evolved in response to this oblique subduction and is composed of folded and faulted abyssal plain turbidites and hemipelagic sediments (Kulm and Fowler, 1974). This oblique convergence also creates a right-lateral shear couple within the upper to lower continental slope and off the Washington and Oregon margins nine WNW-trending left-lateral strike-slip faults, antithetic to the shear couple, have been identified on the continental slope and abyssal plain (Goldfinger et al., 1992, 1997). The accretionary wedge widens from 60 km off southern Oregon to 150 km off the northern Olympic Peninsula of Washington, where the thick Pleistocene Astoria and Nitinat fans are presently being accreted to the margin. The active accretionary thrust faults of the lower slope are characterized by mostly landward-vergent thrusts on the Washington and northern Oregon margins and seaward-vergent thrusts on the central and southern Oregon margin (Goldfinger et al., 1992; MacKay et al., 1992; MacKay, 1995). The landward-vergent province may be related to the subduction of...
rapidly deposited and overpressured sediment from the Astoria and Nitinat submarine fans (Seely, 1977; MacKay, 1995). Off Washington and northern Oregon the broad accretionary prism is characterized by low wedge taper and widely spaced accretionary thrusts and folds, which offscrape virtually all of the incoming sedimentary section. Sparse age data suggest the prism is Quaternary in age and is building westward at a rate close to the orthogonal component of plate convergence (Goldfinger et al., 1996). This young accretionary wedge abuts a steep slope break that separates it from the oceanic and volcano-clastic Siletz terrane that underlies the continental shelf (Snavely, 1987). Above this basement is a modestly deformed Eocene through Holocene forearc basin sequence (Snavely, 1987; McNeill et al., 2000). Hydrate Ridge lies within the northern end of the seaward-vergent province, offshore central Oregon, and is the second seaward-vergent accretionary thrust ridge from the deformation front (Fig. 1). It is bordered on east and west by slope basins, Hydrate Ridge Basin-East (HRB-E) and Hydrate Ridge Basin-West (HRB-W).

2.2. Structure of the Hydrate Ridge region

The Hydrate Ridge region is a highly deformed portion of the accretionary wedge that results from oblique subduction-driven compression. The faults and folds in the region were initially mapped by Goldfinger et al. (1992, 1997) and MacKay et al. (1992) and MacKay (1995) and document the landward to seaward structural vergence change across the region as well as the presence of two deep-seated left-lateral strike-slip faults (the Daisy Bank and Alvin Canyon faults of Goldfinger et al., 1997). Using the same multichannel seismic data set presented in these papers and in Tréhu et al. (1999) across Hydrate Ridge, we have created a regional structure map that includes the previously mapped structures and the smaller-scale folds and faults previously identified, but not correlated across the region (Figs. 2 and 3). Based on the mapped structures, Hydrate Ridge

Fig. 3. (A) Example section of a seismic reflection profile (line 9) from the ODP Leg 146 site survey (location shown in Fig. 2, inset). The data are time-migrated and depict relative true amplitudes. The amplitude scale grades from white to black. (B) Notice the small-scale folds (a = anticline; s = syncline) and strike-slip faults (sense of slip not detectable). A small thrust fault is also present. Variations in the degree of deformation across the Hydrate Ridge region can be seen by mapping these small-scale features along with the previously mapped larger structures (Goldfinger et al., 1992, 1997; MacKay et al. (1992); MacKay (1995). This line in particular shows the concentration of deformation near the northwestern corner of Hydrate Ridge.
Ridge appears to be bounded at its north and south end by the left-lateral strike-slip Daisy Bank and Alvin Canyon faults. The geometry and slip direction of these faults implies clockwise rotation of the block contained between them within an overall right-lateral shear couple (Goldfinger et al., 1997). Oblique subduction-driven right-lateral shear of the Hydrate Ridge block could be responsible for the apparent clockwise rotation of Hydrate Ridge (Johnson et al., 2000; Johnson et al., in preparation). The eastern edge of the block occurs at the contact with the Siletz terrane, which forms a strong backstop for the accretionary prism (Fleming and Tréhu, 1999) and is likely the eastern edge of the right-lateral shear couple responsible for the strike-slip faults. The concentration of tightly spaced structures at the north end of HRB-E, the apparent bulge in the abyssal plain protothrusts southwest of Hydrate Ridge, the wider spacing of structures at the south end of HRB-E, and the decrease in abyssal plain protothrusts to the northwest may serve as evidence for clockwise block rotation, however, in this paper we focus on the distribution of structures rather than their origins. Although the main fault or faults responsible for the formation of Hydrate Ridge are not imaged on the existing seismic reflection profiles, the asymmetric morphology of the ridge, with its more steeply dipping and eroded western flank, suggests it is cored by one or more seaward-vergent thrust faults, similar to the thrust anticlines seen throughout the wedge and commonly observed in fold-thrust belts (Suppe, 1983). The greater relief of the northern summit of the ridge, compared to the southern summit, also suggests net slip along the underlying structures may be greater toward the north.

3. Methods

3.1. Imaging the carbonates

The observed authigenic carbonates present in the Hydrate Ridge region are exposed at the seafloor or slightly buried by a few centimeters of hemipelagic mud (Bohrmann et al., 1998; Kulm and Suess, 1990; Suess et al., 2001). Because of the acoustic impedance (density × sound velocity) contrast between the carbonates and the surrounding sediments, sidescan sonar can be used to image the distribution of authigenic carbonates across the region at the surface and in the shallow subsurface (Johnson and Helferty, 1990). In regions bearing seafloor gas hydrate, like Hydrate Ridge, there is also an acoustic impedance contrast between the gas hydrate and the surrounding hemipelagic sediments. Although smaller than that due to carbonate, the impedance contrast between gas hydrate at the seafloor and hemipelagic sediments may be sufficient to produce an intermediate backscatter signal. Because of the limited bandwidth of current analog sonars and variations in the towfish depth during the survey, however, the sonar gain must be adjusted frequently, which makes post-cruise quantitative analysis of variations in backscatter strength problematic. Because of this, we do not attempt to differentiate between authigenic carbonates and seafloor gas hydrate of intermediate backscatter strength across the survey, except where confirmed by seafloor observations.

3.2. SeaMARC 30 survey

To maximize our seafloor resolution and in order to image carbonates buried by a thin veneer
of hemipelagic mud we chose the low-frequency (30 kHz), deep-towed, SM30 sidescan sonar system, operated by Williamson and Associates in Seattle, WA, USA. The sonar was towed at a depth of ~200 m above the seafloor and collected data in ~3.0-km swaths across the entire region and ~1.5-km swaths across the crest of Hydrate Ridge. The frequency on the port side is 27 kHz and on the starboard side 30 kHz. The gain of the sonar was adjusted manually in 10, 3-dB steps to gain approximately equal record intensity across the survey. Navigation was by Sonardyne USBL (Ultra-Short BaseLine acoustic positioning). The R/V New Horizon was used to tow the SM30 at 2–3 knots. The sidescan images were acquired and processed using Triton Elics International Isis sonar processing software, and ultimately georeferenced and gridded at 1-m pixel resolution for the entire survey using Erdas Imagine software. The survey was designed to image the surface and shallow subsurface authigenic carbonate and gas hydrate in the Hydrate Ridge region, spanning a corridor from the deformation front on the west to beyond the predicted upper hydrate stability limit (450–500 m; Tréhu et al., 2002) on the east. Included on the eastern edge of the survey was the southeast extent of the Daisy Bank fault zone, a deep-seated left-lateral strike-slip fault, and likely fluid flow conduit, spanning here, just above the upper depth limit of hydrate stability (Goldfinger et al., 1996). Carson et al. (1994) attempted to remove the bathymetric signal from shallow-towed GLORIA regional sidescan data in an effort to constrain the extent of authigenic carbonate on Hydrate Ridge. These low-frequency (6.5 kHz) GLORIA data can record deeply buried features, however, making superficial interpretations problematic. Nevertheless, our deep-towed SM30 data support the general interpretations of Carson et al. (1994), but at much higher resolution and across not only Hydrate Ridge, but the slope and shelf to the east.

Fig. 5. Slope map of the Hydrate Ridge region created from swath bathymetric data gridded at 50 m (see Section 4.2 for data sources). Slope variations were calculated from the 50-m grid using Erdas Imagine software. Slopes are shaded in 5° increments. Category I and II backscatter patches are outlined in black. Notice the coincidence of the backscatter with the regions of lowest slope. Category III backscatter occurs in the low-slope regions only on the tops of uplifts associated with the Daisy Bank fault zone. The coincidence of high backscatter with low slope suggests the backscatter signal is most likely due to changes in surface roughness and sediment composition rather than bathymetry.
3.3. High backscatter and carbonates

The intensity of backscatter on sidescan sonar records is a function of (1) the angle of incidence of each beam (the bathymetric variations on the seafloor—the slope), (2) the physical characteristics of the surface (microscale roughness), (3) the intrinsic nature of the surface (composition—density) and (4) the frequency and pulse characteristics of the sonar (Blondel and Murton, 1997). One of the important effects on the backscatter signal received by the sidescan sonar is the effect due to bathymetric slope (1, above). Steep seafloor bathymetry sloping toward the passing sonar has enhanced backscatter strength compared to those slopes dipping away from the sonar. Because of this signal enhancement, differentiation between sediment types based on backscatter strength is best determined in regions of low slope. On Hydrate Ridge submersible dives, tv-camera tows, and seafloor samples (see Section 4.3) have documented that authigenic carbonates are present where bathymetric variation is minimal and high backscatter is dominant on the imagery. Similarly, across much of the survey, the seafloor slopes are less then 5° (see Section 4.2), suggesting high backscatter in these regions is more likely related to changes in rock and sediment composition on the seafloor rather than a bathymetric effect.

4. Results

4.1. Sidescan sonar survey

The complete mosaiced survey gridded at 1-m pixel resolution for both the ~3-km and ~1.5-km swaths is presented in Fig. 4. The E–W tracklines were collected in order from south (track 1) to north (track 11), beginning at the southeastern corner of the survey. All odd numbered tracklines were collected towing the sonar from east to west and even numbered tracks from west to east. Thus, at the overlap between tracklines the same geologic feature is imaged twice, but with insonification from opposing directions. At the overlap, the more detailed swath is generally shown. The 1.5-km swaths over the crest of Hydrate Ridge were towed NE–SW along the axis of the ridge. Dark gray to black lines along the centers of each trackline are the nadirs (no data recovery beneath the towfish). White thin continuous lines across the slope basin east of Hydrate Ridge are surface returns recorded by the sonar. Continuous high backscatter along the nadirs on E–W lines 6–8 is an artifact of the sonar.

4.2. Backscatter patterns and bathymetric slope

Examination of the survey mosaic reveals the high-backscatter patterns (light tones) generally can be divided into three categories: (I) circular to blotchy with apparent surface roughness, (II) circular to blotchy with no apparent surface roughness, and (III) streaky to continuous with variable surface roughness (Fig. 4). Category I high backscatter is concentrated mainly on the northern summit and northeastern end of Hydrate Ridge and to a lesser extent on the southern summit of Hydrate Ridge. Category II high backscatter is concentrated on the eastern edge of HRB-E, and eastward up to the 700-m bathymetric contour. It also extends spatially from north to south across the entire survey in this region. Category III high backscatter is present on the western edge of the survey in regions of steep bathym-

Fig. 6. (A) SM30 coverage and ground truth across Hydrate Ridge. TVG (tv-grab) and OFOS (tv-camera tow) tracks from Sonne Leg 143 are shown. Mud volcanoes MV1, MV2, and MV3 are shown (see Section 4.4) as well as the Southern Hydrate Ridge (SHR) pinnacle (note the acoustic shadow on the imagery). The intermediate backscatter on SHR represents seafloor gas hydrate as observed in Alvin dives (Torres et al., 1999). (B) OFOS track 216 across NHR (from Bohrmann et al., 2000). The diagram was constructed from deep-towed video observations of the seafloor. Note the coincidence of the chemoherm carbonates and carbonate crusts with the regions of highest backscatter along the track. (C) A bottom type map constructed from Alvin observation on NHR (from Torres et al., 1999). Again note the coincidence of high backscatter on the survey and the carbonates observed on the seafloor. (D) Alvin photograph of the carbonate on the SHR pinnacle (photo courtesy of Marta Torres, Oregon State University). Notice the large fracture in the middle of the image.
Fig. 7. (A) SM30 coverage at the western edge of HRB-E. Notice the circular category II high-backscatter patches. Tv-camera tow tracks and the gravity and multicorer sites described in the text are shown. (B) Methane distribution in surface sediment multicorer samples taken at some of the backscatter patches shown in A. Samples taken at a bright-backscatter patch (SO148/75-1B-MUC) yielded high methane, at a dark-backscatter patch (SO143/31-1A-MUC) lower methane, and at a low-backscatter reference site, at the center of HRB-E (SO143/63-1A-MUC), an even lower methane concentration. (C) Methane distribution in two surface sediment gravity core samples (locations shown in A). High methane was found in both gravity core samples, one taken from a dark-backscatter patch (SO143/32-2-SL) and a second from a bright-backscatter patch (SO143/35-1-SL). Gravity core (SO148-76-SL) taken at a very bright-backscatter patch recovered carbonates and gas hydrates. Tv-camera tow track SO148/9 also documented authigenic carbonate at the surface (on the same backscatter patch sampled by gravity core SO148/76-SL). The remaining tv-camera tows documented only sediments and bacterial mats at the surface, suggesting that some of the high-backscatter patches may be caused by authigenic carbonates and/or gas hydrates slightly buried by hemipelagic sediment.
etry associated with the large submarine canyon and steep slopes on the western flank of Hydrate Ridge, and in the southeastern corner of the survey, associated with subtle breaks in slope. Category III high backscatter is also present along the Daisy Bank fault zone to the northeast.

To determine the effect of slope on the backscatter intensity, a slope map was created from 50-m gridded bathymetry, which is the highest-resolution grid available across the entire survey area (Fig. 5). Newly acquired high-resolution EM300 data across Hydrate Ridge and HRB-E (from Clague et al., 2001), EM120 data across HRB-W, and EM300 from HRB-E to Daisy Bank (collected by the authors in 2002) are the three primary data sets used in this bathymetric grid. Additional bathymetric data sets (EM300 and EM120 swaths from Jack Barth at Oregon State University and lower-resolution data sets, NOAA EEZ SeaBeam 16 and National Ocean Service hydrographic soundings) were used to fill in gaps in coverage. The inclusion of lower-resolution data in the grid limits the resolution to 50 m, however, yields coverage coincident with the SM30 survey. Examination of bathymetric slope reveals much of the high backscatter (category I and II) on Hydrate Ridge, HRB-E, and the seafloor west of Daisy Bank occurs in regions with the lowest slope, $<10^\circ$, mostly $<5^\circ$. The high backscatter observed in regions with the highest slope, on the western edge of the survey where slopes exceed $15^\circ$ surrounding HRB-W and along some of the Daisy Bank fault uplifts, is likely
enhanced by the steep bathymetry. The only major exception to this is observed on some of the low-slope, high-to-moderate backscatter seen on the flat-topped ridges of the Daisy Bank fault zone (Figs. 4 and 5; see Section 4.3). With the slope effect to the backscatter intensity minimized in regions of low slope, the backscatter can be interpreted to result from contrasts in surface roughness and/or harder or denser sediment composition across the survey.
4.3. Groundtruthing the sonar

4.3.1. Category I backscatter – Hydrate Ridge

Samples from the seafloor and deep-towed video camera data (Bohrmann et al., 1998; Greinert et al., 2001; Suess et al., 2001) as well as Alvin observations (Torres et al., 1999) on both the northern and southern summits of Hydrate Ridge have confirmed the presence of extensive authigenic carbonates and gas hydrates. During R/V Sonne Legs 143-1, 2, and 3, deep-towed tv-cameras, termed OFOS (Ocean Floor Observation System) and TVGs (tv-guided grab samplers) were deployed across the Hydrate Ridge region.
A graphic log representing the video observations along OFOS track 216 is shown in Fig. 6B. We observe a close correlation between high backscatter on the sidescan sonar and the slabs, cobbles, and boulders of authigenic carbonates observed in the OFOS videos along all three tracks, 216, 213 and 223 (Fig. 6A). OFOS track 223 documents carbonate only near the crest of Hydrate Ridge, where the backscatter is of intermediate intensity but the pattern resembles a pavement of carbonate that extends well into the saddle between the south and north summits (Fig. 6A). In all of the TVG samples shown (Fig. 6A), authigenic carbonates were also recovered from the seafloor, again coincident with locations of high backscatter.

Observations made during five *Alvin* dives on the northern summit of Hydrate Ridge resulted in a map of the bottom types, characterizing the seafloor as consisting of massive carbonates, mostly carbonates, mixed sediments and carbonates, sediments, or clams and/or microbial mats (Torres et al., 1999; Fig. 6C). On the southern summit of Hydrate Ridge, six *Alvin* dives resulted in the discovery of a very large carbonate chemosynthetic pinnacle, which stands nearly 50 m above the seafloor (Torres et al., 1999). The dive sites were concentrated at the largest high-backscatter patch on the southern summit of Hydrate Ridge. In the middle of this patch, the acoustic shadow cast by the large pinnacle carbonate can be seen (Figs. 4 and 6A,D). Investigation by *Alvin* of the intermediate-intensity backscatter present northeast of the pinnacle resulted in the identification of gas hydrate at the seafloor, which was previously sampled with a large TVG (Suess et al., 1999). This suggests the sidescan sonar may have imaged seafloor gas hydrate here and recorded it with intermediate backscatter intensity (Fig. 6A), alternatively, the intermediate backscatter could be caused by buried authigenic carbonate not recovered by the TVG. During the same *Alvin* dives, the small high-backscatter circle northeast of the pinnacle was also investigated, however no carbonate or gas hydrate was observed at the seafloor surface (Torres et al., 1999). We suggest sediments cover the authigenic carbonate or hydrate likely responsible for this acoustic signal, as the SM30 has previously imaged objects of high-impedence contrast buried by several meters of soft sediment (M. Williamson, personal communication, 1999).

4.3.2. **Category II backscatter – Eastern Slope Basin**

Tv-camera tows conducted in 1999 across some of the high-reflectivity category II backscatter patches indicated only sediments and bacterial mats at the surface, suggesting carbonates and/or hydrates if present here are buried beneath a thin veneer of sediment (Fig. 7A). A tv-camera tow conducted during the R/V *Sonne* (SO148) cruise in 2000, however (Linke and Suess, 2001), documented bacterial mats, clam fields, and some authigenic carbonates present at the seafloor in this same region (Fig. 7A). In addition to the tv-camera tows, three category II circular backscatter patches were cored (by gravity or multicorer) during R/V *Sonne* cruises SO143 and SO148 (Fig. 7A). All of the cored sites showed unusually high methane contents in the sediment compared to a reference site (SO143-63-1A-MUC) in the center of the basin (Fig. 7A-C). There appears to be a qualitative relationship between the brightness of the circular patches in the sidescan sonar image and the methane distribution with depth in cores. The highest methane content was recorded at the bright patch at site SO143/35-1-SL with almost 1000 nmol/g within the first 100 cmbsf, whereas the reference site in the center of HRB-E barely exceeds 1 nmol/g (Fig. 7B). At the dark patch (sites SO143/32-2-SL and SO143/31-1A-MUC) the methane content gradually increased towards 10 nmol/g in the shallow part, but exceeded 200 nmol/g at > 500 cmbsf (Fig. 7B and C). The brightest patch (site SO148/75-1B-MUC) showed by far the highest near-surface methane concentration (~8 nmol/g at 10 cmbsf) and at greater depth, reached by gravity coring (SO148/76-SL), contained disseminated gas hydrates and authigenic carbonates. Although limited sampling and seafloor observations have occurred across the entire category II backscatter region (Fig. 4), the similar shape and backscatter intensity of the circular patches suggests they may represent authigenic
carbonate, as they appear to have the same backscatter strength as the known carbonates on the crest of Hydrate Ridge. The lack of visible surface roughness and blurry nature of the circular patches, however, may indicate many of them are buried by a thin drape of hemipelagic sediment. The close association of the authigenic carbonates and gas hydrates recovered in gravity core SO148-76-SL also suggests gas hydrates may be present at many of the category II circular patches.

4.3.3. Category III backscatter – Daisy Bank

Category III high-backscatter sites are coincident with regions of high slope (Figs. 4 and 5), however, a major exception to this occurs on the flat-topped ridges associated with the Daisy Bank fault zone (Fig. 4). Seafloor observations by the Delta submersible document abundant carbonate chimneys, doughnuts, and slabs, within 100–150 m of the fault traces and tabular carbonate blocks up to 6 m in length on the top of Daisy Bank (Goldfinger et al., 1996). Recent examination of the 1992 Delta submersible dive videos with the new SM30 sidescan data indicates the extensive high-to-moderate backscatter with apparent surface roughness observed on the top of Daisy Bank is due to cobbles, blocks, and slabs of well-lithified sediments and carbonates (Fig. 8). Although the uplifts associated with the Daisy Bank fault northwest of Daisy Bank have higher backscatter than the top of Daisy Bank, the slope effect due to their steep-sided, linear nature likely enhances some of their backscatter signal, even though lithologically they may be similar to Daisy Bank.

4.4. Other fluid venting manifestations

Also present on the crest of Hydrate Ridge and along its northeastern flank are three mud volcanoes, MV1, MV2, and MV3 (Fig. 9). The circular craters at the centers of mud volcanoes MV1 and MV3 are clearly visible on the sidescan imagery, however, MV2 is less obvious because of the high backscatter caused by the surrounding carbonates, but a circular crater associated with this high backscatter is visible on high-resolution bathymetry (Clague et al., 2001). Mud volcanoes are one of several types of surface expressions of mud intrusions, which occur as overpressured, multiphased pore fluids (methane and water) and sediments are expelled at the seafloor surface (Brown, 1990). The two mud volcanoes present near the crest of Hydrate Ridge (MV1 and MV2) are coincident with the abundant carbonate chemohemers documented on the northern summit of the ridge, while the mud volcano on the eastern flank of the ridge (MV3) has breached the crest of a smaller secondary anticline (Fig. 9). The two northern mud volcanoes (MV2 and MV3) show high backscatter on the sidescan over their eruption and consequently oxidized to precipitate carbonate (Fig. 9). The more southerly mud volcano imaged with more subdued backscatter is coincident with the general decrease in backscatter toward the saddle region of Hydrate Ridge.

Active fluid venting in the form of hydrate-coated bubbles has also been observed on both the northern and southern summits of Hydrate Ridge during Alvin dives (Torres et al., 1999) and tv-camera tows (Suess et al., 1999) and acoustically imaged in 12- and 18-kHz subbottom profiles (Torres et al., 1999; Bohrmann et al., 2000; Henechsen et al., 2003). Methane has also been measured in high-concentration plumes in the water column above Hydrate Ridge (Suess et al., 2001). Additional evidence for fluid or gas escape, imaged on the SM30 survey, is present in the central to eastern region of the survey as a band of pockmark fields (Fig. 10). The pockmark fields are limited on their eastern side by the ~550-m contour and on the western end by the ~1050-m contour. Some of the pockmarks are coincident with the locations of category II high backscatter and others appear to be isolated in lower-backscatter sediments.

5. Discussion

5.1. Backscatter distribution

Confirmation of the backscatter patterns on
Hydrate Ridge by abundant seafloor observations makes them the most well-constrained features in the survey. In addition, the highest level of detail can be seen by looking at the 1.5-km swaths, which only cover the top of Hydrate Ridge (Fig. 4). Examination of this imagery in particular reveals the variations in backscatter strength and seafloor features from the northern to the southern summit of the ridge. The northern summit is characterized by extensive authigenic carbonate chemohermis and gas hydrates of high to intermediate backscatter intensity and the surface of the ridge appears to break apart toward the saddle region, between the two summits, coincident with a dramatic decrease in large carbonate chemohermis. The carbonates appear to become reestablished, to a much lesser degree, toward the southern summit and result in the large pinnacle structure (Fig. 4).

Category I and II high-backscatter patterns are both blotchy to circular and only differ in their apparent surface roughness. They are both also only present in the regions of the survey where gas hydrate is either inferred by the presence of the BSR (Tréhu et al., 1999; Tréhu and Flueh, 2001) or confirmed by recovered samples (Hovland et al., 1995; Suess et al., 2001). On Hydrate Ridge the apparent surface roughness of the category I high backscatter has been groundtruthed by Alvin, deep-towed video observations, and seafloor samples and is likely due to the fresh exposure of the authigenic carbonates and gas hydrates on the seafloor. In contrast to the erosional environment of Hydrate Ridge, the eastern slope basin and region to the east likely have a higher sedimentation rate, which may tend to bury authigenic carbonates and hydrates precipitated near the seafloor surface. This could explain the smooth texture and the variable backscatter intensity of the category II high-backscatter sites in these regions. Seafloor observations and core also suggest at least some of the category II high-backscatter sites contain authigenic carbonate and gas hydrate buried by hemipelagic sediments. The similar nature of the category II backscatter patches across the survey suggests they may all have this same composition, however, with only a few of the category II backscatter sites investigated at the seafloor, further groundtruthing in the central and eastern part of the survey is needed to truly verify their compositions.

5.2. Relationship to geologic structures

5.2.1. Hydrate Ridge region

The pattern of extensive authigenic carbonates, the presence of three mud volcanoes, and observed seafloor gas discharge suggest fluid venting is highly concentrated on northern Hydrate Ridge. Structurally, the northern summit is shallower, at a depth of ~ 600 m, than the southern summit, at ~ 800 m. This difference in bathymetry suggests the ridge is effectively plunging to the southwest creating a structural trap at the northern summit for any fluids and gases to migrate toward and accumulate. A large accumulation of free gas is inferred beneath the northern summit of Hydrate Ridge based on seismic velocity and attenuation (Tréhu and Flueh, 2001) and it is this pool of gas, which likely supplies the gas hydrate–authigenic carbonate system in the near-surface sediments. The extensive occurrence of authigenic carbonates on the northern summit suggests it has recorded either a longer history or a higher rate of methane expulsion than that recorded by the southern summit. U/Th ages from northern summit authigenic carbonates may indicate a long history of methane expulsion is more likely, as samples of the carbonate carapace there yield ages between 68,700 and 71,700 years, while samples from the southern summit pinnacle range in age from 7300 to 11,400 years (Teichert et al., 2003). The conduits for methane expulsion at the northern end of the ridge could be faults and fractures, similar to those imaged on the 1.5-km swath sidescan data in the saddle between the northern and southern summits of Hydrate Ridge (Fig. 9). Perhaps, some of these conduits are bending-moment normal faults created during flexure at the crest of Hydrate Ridge. Bedding-parallel faults created during flexural slip folding, out of sequence thrust faults, or high-porosity stratigraphic horizons could also serve as conduits. Unfortunately, details of the shallow subsurface structure at the crest of Hydrate Ridge cannot be resolved on
the existing seismic reflection data, so the true nature of the conduits can only be speculated at this time. The important observation, however, is that the carbonates appear to be well developed at the northern summit of Hydrate Ridge, where concentrated structural deformation is likely. The first accretionary anticline just west of Hydrate Ridge shows abundant evidence for fluid expulsion at its crest (Kulm and Suess, 1990) and the location of the mud volcano (MV3) on the eastern flank of the northern summit of Hydrate Ridge also coincides with the crest of a smaller anticline (Fig. 9). These associations suggest anticlinal folding may help to focus fluids until faults or fractures, potentially caused by the folding, or exposed high-porosity stratigraphic horizons create the conduits needed for subsequent fluid expulsion. Future correlation of the

Fig. 11. Schematic diagrams depicting the environments likely responsible for each of the backscatter categories. Suggested pathways responsible for the delivery of fluids to the shallow subsurface and gas hydrate stability zone (BSR labeled) are shown in the lower block diagram. Fluids migrate and accumulate at structural highs like Hydrate Ridge and the first accretionary ridge (FAR) and to a lesser extent on the eastern slope east of HRB-E. The structural highs are local sites of tension and it is likely faults and fractures permeate their crests. Category I backscatter occurs in this environment and, in the presence of abundant gas hydrate, fluid flow responsible for the carbonate precipitation at the surface is characterized as structurally influenced and gas hydrate related. Category II backscatter occurs on the eastern slope, east of HRB-E. It is characterized by variable intensity and a patchy distribution of backscatter patterns, suggestive of sporadic seafloor venting. It also lies in a region of the wedge that is mildly deformed, thus structural control on fluid expulsion sites is unlikely. Fluid flow responsible for this backscatter is likely diffuse and related to disruptions in the underlying gas hydrate. Category III backscatter across the Daisy Bank fault zone suggests long-term deep-seated fluid flow. Its location above the hydrate stability zone and the linear backscatter patterns suggest this region is dominated by structurally controlled non-gas hydrate related fluid flow.
high-backscatter sites on Hydrate Ridge with higher-resolution seismic reflection data, however, will ultimately yield better insight into these processes.

5.2.2. Daisy Bank fault zone

Most of the category III high-backscatter sites are coincident with high slope, however a major exception to this occurs on the flat-topped ridges associated with the Daisy Bank fault zone (Fig. 4). High backscatter along the fault scarp and uplifts along the fault zone suggest either authigenic carbonate presence or an older more lithified and uplifted section of the stratigraphy capable of high backscatter, or a combination of the two. Seafloor observations in the Delta submersible document abundant carbonate chimneys, doughnuts, and slabs, within 100–150 m of the fault traces and tabular carbonate blocks up to 6 m in length on the top of Daisy Bank (Goldfinger et al., 1996). Authigenic carbonates have also been observed at the Wecoma left-lateral strike-slip fault to the north and isotopic measurements on them suggest the fluid source is deep within the sedimentary section (Sample et al., 1993). The high backscatter at Daisy Bank is shallower (200 m) than the predicted hydrate stability zone (~450–500 m; Tréhu et al., 2002), and like the Wecoma fault, it likely taps a deeper methane source to precipitate the carbonates present near the seafloor surface. A long-term history of structurally controlled deep fluid venting along the Daisy Bank fault is also suspected due to the pervasive high backscatter present along its length. Such a large active fault conduit is likely to deliver a significant volume of fluid to the seafloor surface, perhaps accommodating much of the regional dewatering of the accretionary wedge. These focused fluids, once expelled, result in the significant carbonate precipitation observed on the seafloor and inferred by the high backscatter along the fault zone.

5.2.3. HRB-E and eastern slope

Highly focused fluid flow is evident on Hydrate Ridge and along the Daisy Bank fault, however, in the region between these structures the backscatter pattern is much more diffuse (Fig. 4). Category II high backscatter, circular to blotchy with no apparent surface roughness, dominates the region along the eastern edge of HRB-E and eastward toward the Daisy Bank fault zone. The association between the pattern of fluid venting and bathymetry suggests some of the high-backscatter patches may be coincident with abrupt changes in slope, perhaps caused by small-amplitude folds in the subsurface (similar to those shown in Fig. 3). Much of the category II backscatter, however, appears as small, scattered patches in areas of low slope across the region, suggestive of low-volume diffuse fluid venting. The coincidence of the category II backscatter with the hydrate stability zone may indicate fluid venting is associated with shallow disruptions in the underlying gas hydrate system. The lack of significant surface roughness on the category II high backscatter, however, and subtle variations in backscatter strength suggest these features may be buried by variable amounts of hemipelagic sediment. This may indicate that either (1) fluid venting is currently not active at some of the sites across the region (where the backscatter is circular but of intermediate reflectivity), (2) fluid venting and carbonate precipitation are continuous, but occur at a slower rate than hemipelagic sedimentation, or (3) there is an episodic nature to the fluid venting, permitting active fluid escape at some sites (e.g. the highest-backscatter sites) while abandoning others (e.g. intermediate-backscatter patches, possibly covered by hemipelagic sediment since their last activity). We suggest the apparent variability in fluid venting and authigenic carbonate precipitation across this region could be attributed to disruptions in the subsurface gas hydrate system. In this region, perhaps larger faults at depth are responsible for the delivery of pore fluids to the gas hydrate stability zone within the upper seafloor sediments. Once there, the fluids only escape by (1) direct fault conduits to the seafloor, which seem unlikely here since there are few linear manifestations of fluid venting, (2) rapid fluid expulsion, resulting in pockmarks on the seafloor, or (3) diffuse fluid flow, through high-porosity conduits or microfractures. We suggest the latter two processes occur across this region, as circular high-backscatter patches can be seen associated
with pockmarks (Fig. 10) and high-porosity conduits are likely in a wedge characterized by turbidite sedimentation (Kulm and Fowler, 1974).

5.3. Landward limit of gas hydrate stability

Pockmarks terminate near the eastern end of the survey area at \( \sim 550 \) m, coincident with the eastern extent of the BSR, as interpreted on the only multichannel seismic reflection profile (line 8) that extends this far east from the ODP Leg 146 site survey (Fig. 10). This suggests the pockmarks may represent the surface manifestation of gas hydrate dissociation near the landward limit of gas hydrate stability in this region. Because pockmarks typically result from rapid fluid or gas escape through a relatively thin sedimentary section (Brown, 1990) the shallow source of methane in gas hydrate near its stability boundary may be a likely source for this fluid expulsion. The \( \sim 550 \)-m contour corresponds with only the easternmost pockmark field on the survey. Most of the pockmark fields appear to terminate at the \( \sim 700 \)-m contour to the west, coincident with the abrupt termination of category II backscatter (Fig. 10). The coincidence of the termination of the BSR on seismic line 8 with the easternmost pockmark field on the survey and the other pockmark fields suggests the hydrate stability limit extends to the \( \sim 550 \)-m depth near seismic line 8, but lies deeper to the west, at 700 m, across the rest of the survey (Fig. 10). We suggest the distribution of pockmarks and category II backscatter patches and their eastern termination serves to delineate the landward limit of gas hydrate stability, and thus fluid venting related to gas hydrate destabilization in this region.

6. Backscatter patterns and fluid flow

Schematic diagrams describing the possible environments responsible for the three categories of backscatter and the potential pathways for the fluids are shown in Fig. 11. Fluid flow, driven by compaction and dewatering of the wedge, in the Hydrate Ridge region supplies fluids to the hydrate stability zone via faults and fractures, dipping stratigraphic horizons, or during diffuse intergranular fluid flow. Authigenic carbonates can precipitate from the methane in these fluids as they interact directly with seawater in the shallow subsurface and/or as methane is released during the destabilization of gas hydrate. The distribution of high backscatter across the Hydrate Ridge region suggests fluids pond in anticlinal structures like Hydrate Ridge and the first accretionary ridge, while migrating away from or completely abandoning more undeformed portions of the wedge (e.g. HRB-E, where there is only one high-backscatter patch, Fig. 4). The crests of anticlinal structures like Hydrate Ridge are under local tension and it is likely that fractures and faults serve as the major vertical fluid flow conduits to the seafloor. However, because Hydrate Ridge lies within the hydrate stability zone and carbonates derived from destabilized gas hydrate have been identified there (Bohrmann et al., 1998; Greinert et al., 2001) it is likely that both structurally influenced fluid migration and the destabilization of gas hydrate contribute to the authigenic carbonates imaged on the sidescan imagery. Therefore we classify the category I backscatter environment as structurally influenced and gas hydrate related (Fig. 11). Category II backscatter occurs in a mildly deformed portion of the wedge within the region of gas hydrate stability. The hydrate system here is likely fed by up-dip fluid flow along porous stratigraphic horizons or deeper faults out of HRB-E (evidenced by the abundant backscatter on the eastern edge of HRB-E and on Hydrate Ridge, both up-dip of HRB-E). In the middle portion of the survey (HRB-E to the Daisy Bank fault) the bathymetric expression of major subsurface structures is minimal, suggesting the subsurface is only mildly deformed (Fig. 1). The high-backscatter patterns in the category II region suggest fluid pathways to the surface are diffuse or fluids advect at slower rates. Variable backscatter intensity, due to buried authigenic carbonates, may also suggest a sporadic history of fluid venting, although high methane content in the near-surface sediments suggests active upward fluid flow. The lack of significant subsurface structure in the category II backscatter region and its location within the hydrate stability zone suggest authigenic carbonate precipitation is most likely re-
lated to the destabilization of gas hydrate in this region. The category II backscatter environment is thus characterized as diffuse and gas hydrate related (Fig. 11). Category III backscatter, not related to major slope changes, occurs along the Daisy Bank fault zone. Here, high backscatter patterns suggest fluid flow has been continuous and likely deep-seated. In addition most of the Daisy Bank fault zone lies above the eastern hydrate stability limit (≈550 m at the shallowest). The environment responsible for the Daisy Bank category III backscatter is thus classified as structure controlled and non-gas hydrate related (Fig. 11).

7. Conclusions

Based on seafloor mapping using high-resolution SM30 sidescan sonar data coupled with seafloor observations, samples, and subsurface geologic mapping the following conclusion can be made: (1) the blotchy to circular category I high backscatter present on Hydrate Ridge is indeed authigenic carbonate, (2) the category II high backscatter present along the eastern side of the survey is likely authigenic carbonate, with some gas hydrate, slightly buried by hemipelagic sediment, (3) both category I and II high-backscatter sites represent carbonates that may have precipitated from destabilized gas hydrate and show an intimately linked gas hydrate carbonate system, however on Hydrate Ridge, direct fluid migration from depth also likely contributes to the carbonate precipitation, (4) breached anticlines not only serve to trap and aid in the migration of fluids and gases through the sediment column, but also serve as escape pathways, providing a local extensional environment at their crests for fluid expulsion, (5) diffuse gas hydrate-related fluid flow is likely responsible for the category II high backscatter on the eastern slope, east of HRB-E, (6) category III backscatter associated with the Daisy Bank fault zone is likely derived from deep-seated fluids that have a long history of escape along the fault and are likely unrelated to the destabilization of gas hydrate, and (7) the abrupt decrease in pockmark fields and category II backscatter patches on the eastern edge of the survey area may serve to delineate the landward limit of gas hydrate stability across this region.

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