Temporal and spatial evolution of a gas hydrate–bearing accretionary ridge on the Oregon continental margin

Anne M. Tréhu*
Marta E. Torres
College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331-5503, USA
Gregory F. Moore School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, Hawaii 96822, USA
Erwin Suess
Gerhard Bohrmann
GEOMAR, Research Center for Marine Geosciences, Kiel, Germany

ABSTRACT

A seismic-reflection survey on the Oregon continental margin conducted in 1989 indicates the widespread presence of gas hydrate beneath the middle and lower slope of this accretionary margin. The seismic signature of gas hydrate, a bottom simulating reflector (BSR) with negative polarity that locally cuts across stratigraphic horizons, is especially well developed beneath Hydrate Ridge. This anomalously shallow accretionary ridge was drilled during Ocean Drilling Program Leg 146 to study fluid venting. In this paper we focus on the seismic data from the southern part of Hydrate Ridge, where little evidence of active venting has previously been reported but where the seismic data indicate a complicated subsurface plumbing system. Apparent disruptions of the BSR beneath the western ridge flank suggest dissociation of gas hydrate in response to slumping. A double BSR beneath the southern crest suggests hydrate destabilization in response to tectonic uplift and folding. On the basis of these and other observations, we propose a qualitative model for the evolution of a hydrate-bearing ridge in an active accretionary complex in which gas hydrate initially stabilizes the sea floor, permitting construction of large ridges that are then eaten away by slumps along their margins. The north-to-south variation in sea-floor venting and subsurface seismic structure along Hydrate Ridge may reflect different stages in the temporal evolution of one of these ridges.

INTRODUCTION

Gas hydrate is an icelike substance that contains methane or other low-molecular-weight gases in a lattice of water molecules. Methane hydrates are stable under the temperature and pressure conditions generally found in permafrost regions and within marine sediments at water depths greater than 500 m, and are common beneath the continental slope of both active and passive continental margins. They have recently become a major focus of international research because they represent a valuable global reservoir of hydrocarbons (Kvenvolden, 1988a), a potential source of an important greenhouse gas (e.g., Kvenvolden, 1988b; Paull et al., 1991; Dickens et al., 1997), and a possible cause of massive slope destabilization (Henriet and Mienert, 1998).

For the past 25 yr, the main approach used to evaluate the presence of gas hydrate in sea-floor sediments has been through a geophysical proxy known as the bottom-simulating reflection (BSR). The BSR is a seismic reflection that approximately mimics the sea floor, cuts across reflections of stratigraphic origin, and has a negative polarity, indicating that it results from a decrease in acoustic impedance (e.g., Shipley et al., 1979; Hyndman and Spence, 1992). Several studies (e.g., Hyndman et al., 1992; Tréhu et al., 1995; Brown et al., 1996) have confirmed that this reflection occurs approximately where one would predict the base of the gas hydrate stability zone (GHSZ), within the uncertainties arising from our current estimates of gas and pore-water composition, although it may be systematically offset in sediments in which capillary forces inhibit gas hydrate formation (Ruppel, 1997).

In this paper we report on seismic indicators of gas hydrate presence beneath Hydrate Ridge, a bathymetric feature found ~10 km east of the deformation front in the accretionary complex of the Cascadia subduction zone offshore Oregon (Fig. 1)[1]. The northern crest of this ridge was the site of Ocean Drilling Program (ODP) drilling (Leg 146) in 1992. Massive gas hydrate was recovered from the southern crest in 1996 using a large video-guided grab sampler (Bohrmann et al., 1998; Suess et al., 1999). We first summarize sea-floor observations indicative of fluid venting, and then discuss the subsurface seismic structure and correlate it with sea-floor morphology. These observations lead us to suggest a qualitative model for the temporal evolution of such ridges in which there is a dynamic feedback between gas hydrate formation and slope stability.

GAS HYDRATES ON THE OREGON CONTINENTAL MARGIN

The Juan de Fuca plate is subducted obliquely beneath North America at a rate of about 4.5 cm/yr offshore of the northwestern United States

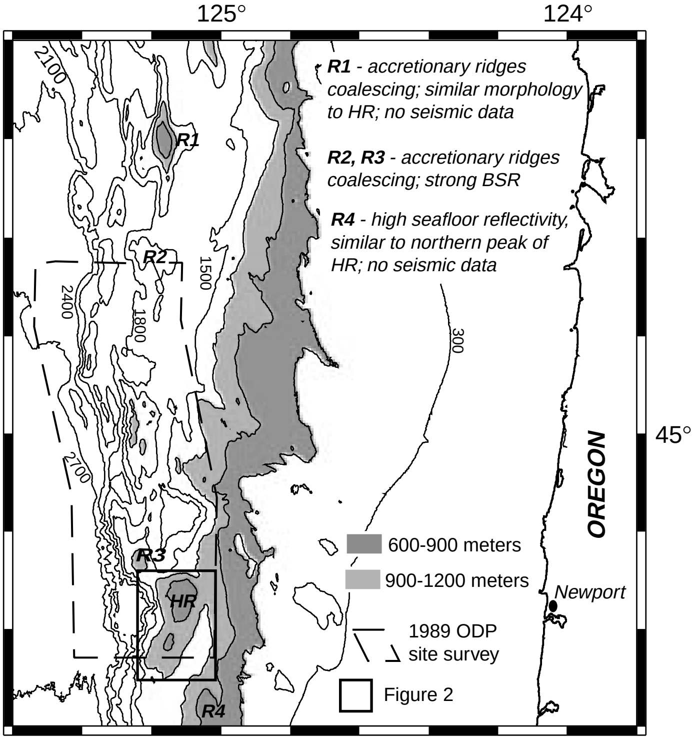

Figure 1. Topography of central Oregon continental margin. Depths of 1200–600 m, depth range of Hydrate Ridge (HR), are shaded. R1–R4—other accretionary ridges that, for reasons listed in figure, may be similar to HR. BSR—bottom simulating reflector; ODP—Ocean Drilling Program.

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*E-mail: trehu@oce.orst.edu.

[1] GSA Data Repository item 9977, Shaded relief maps of the continental slope in the region covered by Figure 1, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, editing@geosociety.org, or at www.geosociety.org/pubs/drpint.htm..

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and southwestern Canada. At present, most of the sediment on the subducting plate, which contains large volumes of sandy and silty turbidites, appears to be accreted to the continental margin (MacKay, 1995). Upward advection of fluids that originate in underthrust sediments is probably responsible for the presence of gas hydrate here and in many other active accretionary complexes.

Gas hydrate and its geophysical proxies appear to be particularly well developed beneath Hydrate Ridge, a 25-km-long and 15-km-wide ridge in the young accretionary complex with a northern peak at a depth of ~600 m and a southern peak at a depth of ~800 m (Fig. 2A). Hydrate Ridge appears to be capped by gas hydrate, as indicated by a nearly ubiquitous and strong BSR (Fig. 3). Sea-floor camera tows and diving with both manned and remotely operated submersibles first revealed massive carbonates and communities of vent-dependent organisms on the northern peak several years ago (Linke et al., 1994). The observation of an upward deflection of the BSR where it is cut by a fault was used to site drilling (ODP Leg 146 Scientific Party, 1993). Vigorous streams of methane bubbles (Fig. 2A) have been observed emanating from vents on the sea floor on the northern peak of Hydrate Ridge (Suess et al., 1999), indicating rapid transport of methane-rich fluids through the gas hydrate stability zone. Formation of gas hydrate during sampling of the bubbles was observed with a remotely operated vehicle during August 1998 (Torres et al., 1998), suggesting that gas hydrates are probably also forming on the sea floor.

In contrast, the southern part of Hydrate Ridge shows less evidence for focused fluid flow on the sea floor. Regionally, there are no significant departures from the predicted BSR depth in existing seismic data (Zwart et al., 1996). Locally, a 700-m-long sea-floor video-camera tow across the southern peak of Hydrate Ridge shows a smooth sea floor characterized by soft sediment and occasional white patches of massive gas hydrate, chemosynthetic clams, and bacterial mats (Bohrmann et al., 1998). Three small, bubbling vents are observed in the video; however, these vents must be very young because they are not associated with the carbonate structures and vent communities typical of vents on the northern part of the ridge.

SEA-FLOOR MORPHOLOGY AND SUBSURFACE STRUCTURE

To look for clues about the possible relationships among topography, tectonics, fluid flow, and gas hydrate occurrence on Hydrate Ridge, we reexamined the seismic-reflection data collected as a site survey for ODP Leg 146 in the region of Hydrate Ridge. This survey comprises a series of lines 1–5 km apart that image a structurally diverse part of the Oregon accretionary complex (Fig. 1; MacKay, 1995). Six of the profiles crossing Hydrate Ridge are displayed here (Fig. 3). (Page-size monochrome versions of these seismic sections and examples of individual seismograms are available: see footnote 1.) We discuss the observations along an approximately west to east traverse.

The steep western boundary of Hydrate Ridge is riddled with canyons and has probably also been eaten away by slumping. Just east of this boundary, in the central part of the ridge, we observe a series of morphological benches (B1 and B2 in Figs. 2A and 3). Beneath these benches, the BSR is either highly disrupted or not detectable, as can best be seen on MCS 4, where B1 corresponds to a very bright and rough horizon between CMP (common midpoint) 1500 and CMP 1720 (see CMP 1600–1850 on MCS 3). The correlation among the benches, disrupted BSRs, and high-amplitude but chaotic reflectivity within the gas hydrate stability zone suggests that the benches reflect slump deposits and that slumping has resulted in dissociation of gas hydrate and/or release of free gas from beneath the gas hydrate stability zone.

To the north and east of B1, the BSR is present but discontinuous (CMP 1240–1450 on MCS 4; 1200–1450 on MCS 5). On MCS 4, the disruption ends abruptly at an ~30 m offset in the sea floor. Figure 2B shows a bathymetric detail of this feature. We interpret this to represent the incipient headwall of the next generation of slumping. The BSR is similarly offset, suggesting that this incipient slump is rooted well beneath the BSR, probably at the base of the free gas zone. Vertical seismic profiles conducted as part of ODP Leg 146 suggest that this zone extends for at least 50 m beneath the BSR (MacKay et al., 1994).

Beneath the southern crest of Hydrate Ridge, the seismic profiles reveal a complicated pattern of coherent reflections that we interpret as evidence for subsurface plumbing related to the presence of gas hydrate and free gas. This is in marked contrast to the northern crest, where few coherent sub-BSR reflections are observed, probably because most of the seismic energy is scattered by the hard, rough sea floor. Two different types of reflections appear to cut across the BSR beneath the ridge crest on lines 1–5. The first consists of reflections from sedimentary strata that abruptly decrease in amplitude as they cut across the BSR (e.g., MCS 2—CMP 2500–2600; MCS 3—CMP 2000–2100). Results from ODP Leg 164 on the Blake Ridge suggest that this amplitude pattern probably results from enhancement of sub-BSR reflectivity by gas concentrated along stratigraphic boundaries rather than from suppression of reflectivity by the presence of disseminated gas hydrate (Holbrook et al., 1996). The second cuts across stratigraphic reflections and the BSR on line 2 between CMP 2120 and CMP 2340 and is characterized by a strong negative polarity. This double BSR appears beneath a slight anticline and adjacent syncline (A1 in Fig. 2, A and C), and we tentatively attribute it to gas hydrate dissociation related to growth of this anticline. Because it is a local feature, we rule out regional uplift, sea-level change, or change in bottom-water temperature, which have been suggested as causes of double BSRs observed elsewhere.

At greater depth beneath the axis of the ridge, we observe a front of discontinuous bright reflections. We speculate that this may represent the base of the region of free gas. Large-aperture seismic data along a profile crossing the northern crest of Hydrate Ridge suggest that very low seismic velocities (<1.9 km/s) extend for ~500 m beneath the BSR before increasing rapidly, suggestive of a thick free gas layer. However, no velocity data are available from the southern part of Hydrate Ridge, where the reflectivity front is strongest. Confirmation of a gassy layer hundreds of meters thick would have important implications for estimates of total methane content and slope stability.

The eastern boundary of Hydrate Ridge is marked by a northeast-trending alignment of anticlines and circular mounds. We speculate that these features have developed along a shear zone that is antithetic to well-documented northwest-trending strike-slip faults (Goldfinger et al., 1997) and may accommodate some of the oblique component of subduction. To the north, the BSR is uplifted and weak beneath the mounds, suggestive of fluid venting (V2 and V3 in Figs. 2A and 3). To the south, these features are underlain by high reflectivity at and beneath the BSR, suggesting gas accumulation (A2 and A3 in Figs. 2 and 3).

The seismic data indicate that the BSR occurs within younger sediments of a slope basin east of Hydrate Ridge on lines 1–3. Within this basin, the BSR is relatively weak. The accretionary complex beneath and to the east of this basin shows very strong, discontinuous reflectivity. A similar pattern of chaotic, strong reflectivity beneath the middle slope has been associated with anomalously low seismic velocity along a profile located ~10 km north of line 9 (Tréhu et al., 1995) and may be attributed to the presence of dispersed free gas resulting from gas hydrate dissociation in response to burial beneath slope sediments. This hypothesis predicts low mechanical strength in this region, possibly increasing the likelihood of massive landslides.

DISCUSSION

Temporal Evolution of Venting on Hydrate Ridge

We interpret the contrast in sea-floor character and subsurface structure between the northern and southern parts of Hydrate Ridge to indicate temporal evolution of a system in which venting and gas hydrate formation and dissociation are closely coupled. In this qualitative model, the northern part of the ridge represents a later stage in the evolution of the system. Venting of methane bubbles at the sea floor here indicates rapid passage through the gas hydrate stability zone of methane-rich fluids that originate beneath the zone. These fluids probably move through conduits that are isolated from water because of deposition of gas hydrate or authigenic carbonate

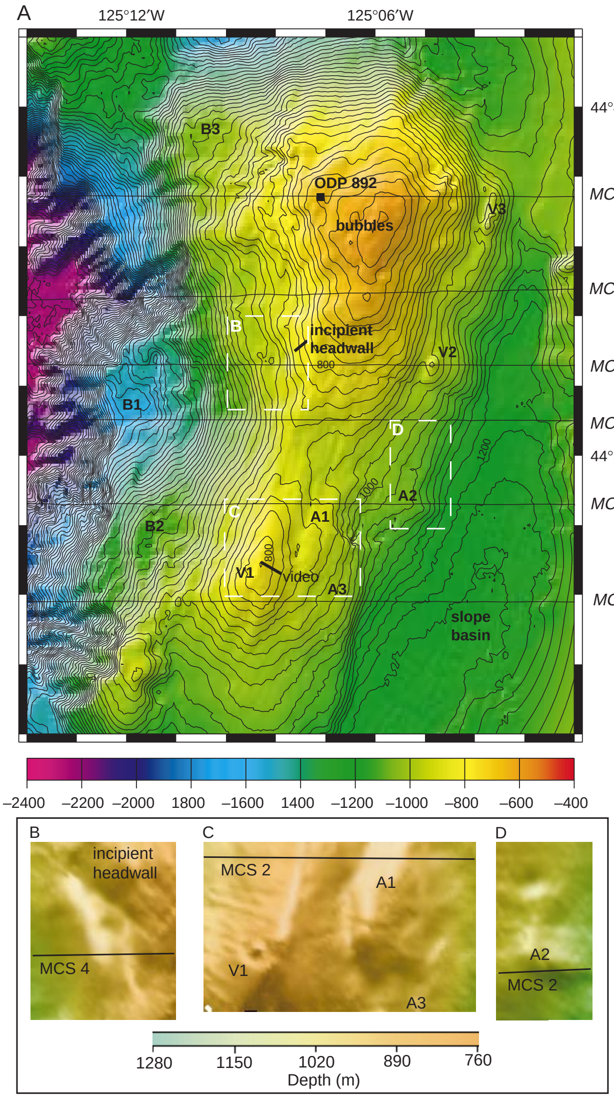

Figure 2. A: Hydrosweep bathymetry of Hydrate Ridge. Illumination is from the northwest. Contour interval is 25 m. Locations of seismic lines in Figure 3 are also shown. A1–A3 are anticlinal structures underlain by anomalies in BSR and sub-BSR (bottom simulating reflector) reflectivity; V1–V3 are interpreted to be mud volcanoes or vents; B1–B3 are morphologic benches interpreted to indicate slumping. B, C, D: Detailed bathymetry of features discussed in text. SeaBeam data are from Torres et al. (1998).

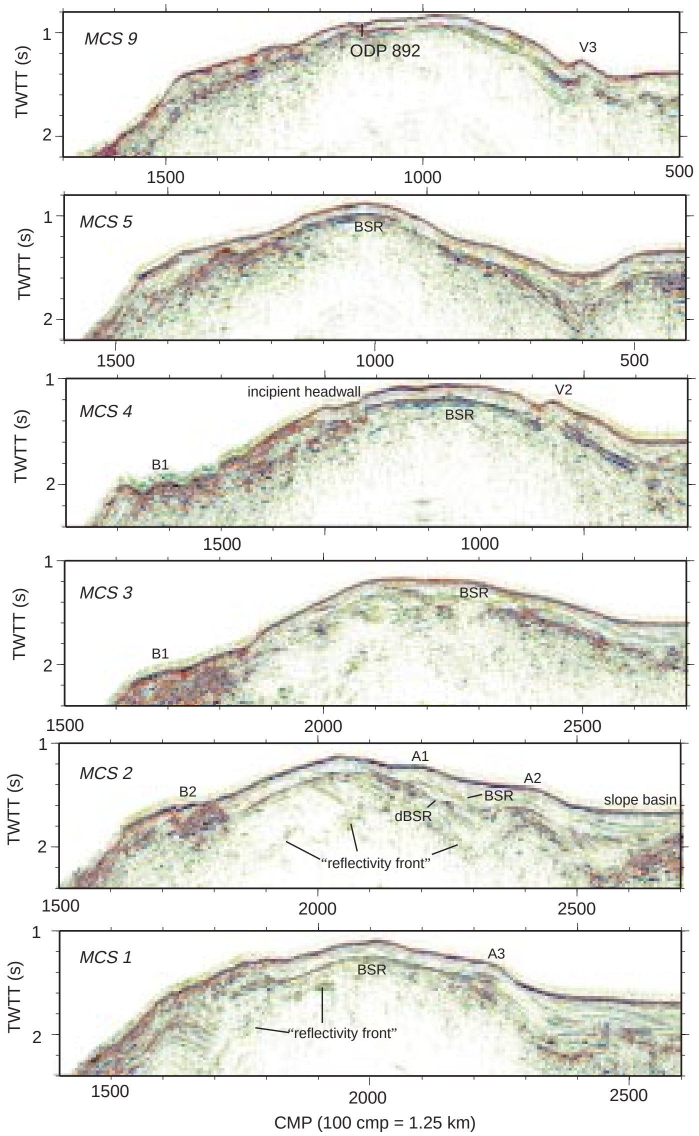

Figure 3. Selected seismic profiles across Hydrate Ridge. Line locations are shown in Figure 2. Data were acquired with tuned 4560 in^3 air-gun array fired at 25 m intervals and 144 channel stream with group spacing of 25 m, yielding 72-fold data. Data processing included t^2 gain, spiking deconvolution, bandpass filtering (8–65 Hz), normal moveout correction, stacking, and finite-difference migration (MacKay, 1995). Data are plotted at same scale with relative amplitude differences preserved. Red indicates large positive amplitudes and blue indicates large negative amplitudes; gray and green are smaller positive and negative amplitudes. dBSR (bottom simulating reflector) indicates apparent double BSR beneath A1. Morphological features are labeled as in Figure 2. TWTT—two-way traveltime; CMP—common midpoint.

along their walls (Suess et al., 1999). Although individual conduits are probably transitory, the blocky carbonate (and hydrate?) crust covering the sea floor indicates that venting has been active for some time.

In the south, morphological evidence for focused sea-floor venting is limited to a single mud volcano–like structure southwest of the southern crest of the ridge (V1 in Fig. 2C). Bacterial mats, clam colonies, and several bubbling gas vents are observed in sea-floor videos, but these vents are not associated with massive authigenic carbonate deposits on the sea floor, suggesting that focused venting has only recently begun here. The seismic data, however, show evidence for a variety of subsurface fluid transport mechanisms. A double BSR east of the southern crest suggests shallowing of the BSR in response to folding. The deeper, relict BSR appears to intersect the contemporary BSR. The large negative amplitude of this event may result from fluids trapped beneath it because of diagenetic reactions related to gas hydrate dissociation that have decreased the permeability across this surface. Stratigraphic reflections with both positive and negative polarity cut across both the relict BSR and the contemporary BSR. In some cases, amplitudes are greater beneath the BSR and may indicate concentrations of free gas between stratigraphic horizons, as has been observed elsewhere. In other cases, stratigraphic reflectivity is enhanced above the BSR, perhaps indicative of concentrations of hydrate along stratigraphically defined fluid pathways. The lack of resolvable depth anomalies in the contemporary BSR suggests that these conduits do not extend to the sea floor.

North-south variation in the subsurface structure of the mounds aligned along the eastern flank of Hydrate Ridge, which suggests active venting in the north and trapping of gas beneath the BSR in the south, is also consistent with this model.

Gas Hydrates and Slope Stability

Numerous qualitative links between gas hydrate dissociation and sea-floor instability have been documented (Henriet and Mienert, 1998). The seismic data from Hydrate Ridge suggest that slumps rooted at the base of gassy sediments underlying the BSR result in pervasive upward flow of warm fluids and destabilization of gas hydrate. A similar correlation between faulted and collapsed depressions on the Blake Ridge and a weak and disrupted BSR was documented by Dillon et al. (1998). The strong reflectivity within the predicted gas hydrate stability zone beneath the inferred slumps may result either from trapped gas or from diagenetic carbonates formed when gas hydrate dissociated and gas was released. Thus, slope instability is an important factor controlling dissociation of gas hydrates in situ.

We speculate that there is a feedback process in which the morphology of the ridge is affected by the presence of gas hydrate. Accretionary ridges, in general, are formed by sediment underthrusting and folding. Pecher et al. (1996) argued that the resulting tectonic uplift is an effective mechanism for concentrating gas hydrate by gradually moving the base of the gas hydrate stability zone upward, resulting in dissociation of gas hydrate followed by upward migration and reprecipitation of the released methane (Brown et al., 1996). We suggest that the flat top of Hydrate Ridge results from initial strengthening of the sediments, permitting the ridge to grow higher and wider than it would have otherwise. Development of fluid overpressures beneath the hydrate cap may eventually undermine the stability of the ridge, causing the edges to collapse. The presence of other anomalously broad, shallow, or reflective ridges that seem to originate as structural ridges (e.g., R1–R4 in Fig. 1) and recent laboratory measurements indicating that the presence of gas hydrate increases sediment strength (Zhang et al., 1999; Winters et al., 1999) provide qualitative support for this model.

SUMMARY

On the basis of sea-floor morphology and subsurface structure, we conclude that the northern part of Hydrate Ridge is more mature than the southern part. Beneath the southern part of the ridge, the complicated pattern of crosscutting stratigraphic and BSR-type reflections suggests subsurface fluid flow that is focused in the vicinity of the BSR and becomes diffuse near the sea floor. This heterogeneous flow pattern may drive the development of subsurface overpressures and the growth of subsurface conduits until they breach the sea floor, as is observed on the northern peak of Hydrate Ridge. That this suggested evolution of the hydrological and diagenetic environment may initially strengthen the sediments, leading to oversteepening of slopes and less frequent but larger slump events, is suggested by the shallow depth, smooth top, and steep sides of Hydrate Ridge. Hydrate Ridge may thus represent a typical, but transient, stage in the life of a hydrate-bearing ridge in an accretionary environment.

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