# Migration and venting of deep gases into the ocean through hydrate-choked chimneys offshore Korea

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## ABSTRACT

**It has recently been recognized that, in addition to low concentrations of widespread natural gas hydrate associated with bottom-simulating seismic reflectors, highly concentrated hydrate can occur in local seafloor fluid venting structures. Such structures extend upward into the regional gas hydrate stability field and sometimes allow gases to escape into the overlying ocean. These hydrate-choked chimneys are especially prospective as an energy resource because they contain high hydrate concentrations. Furthermore, they may be one of the most important conduits into the ocean-atmosphere system for deep methane. We present an analysis of two-dimensional seismic reflection data from offshore Korea that give a complete picture of gas migrating from a deep source zone to feed hydrate-choked vent structures at the seafloor. The gases migrate upward through networks of fractures imaged as steep amplitude striations in both diffuse and concentrated distributions. We present an example of a high-flux gas vent fed through fracture swarms emanating from a 10–15-km-wide catchment zone of source gases residing 3–4 km below the seabed. The geological context and the inferred distribution of hydrate within this feature are consistent with recent models in which seabed gas venting is a consequence of elevated pore fluid salinities that are produced by a high flux of gases migrating independently of the pore water. In contrast, a nearby vent that is not plumbed into the same high-flux system appears to be dominated more by gas-rich liquids. We present these two vent structures as type cases for high- and low-flux fluid escape systems in the seabed. Furthermore, we suggest that since the amount of gas trapped as hydrate within the vents is small compared with the amount in the underlying reservoir, the greatest risk for increased methane input to the atmosphere associated with climate-driven oceanic warming is not the melting of hydrate, but an increase in the number of deep reservoirs able to vent gases through the seabed that occurs as the regional gas hydrate stability zone thins.**

## INTRODUCTION

Most early studies of marine gas hydrate focused on the widespread regional form that mainly resides near the base of the hydrate stability zone several hundreds of meters below the seafloor. Although the total amount of this type of hydrate may be large, the estimated concentrations are usually low (at most a few tens of percent of pore volume), such that this type is not an attractive target for energy recovery. Furthermore, this type of hydrate usually occurs well below the seafloor, so it is not affected by ocean warming for many thousands of years thereafter. The influence of this type of hydrate on the global carbon cycle is thus likely to be small over the short term. However, it has recently been recognized that natural gas hydrate also occurs in local vent structures (hundreds to thousands of meters in diameter), where focusing of rising gas-rich fluids produces high concentrations of hydrate (typically several tens of percent of pore volume). These structures sometimes extend to the seafloor and are often associated with gas plumes in the overlying ocean (e.g., Paull et al., 1995; Suess et al., 1999; Sassen et al., 2001; Heeschen et al., 2003; Charlou et al., 2004). The hydrate in these vent structures is attractive for natural gas recovery due to its high concentration; it may also be important to the short-term global carbon cycle since close proximity to the seabed means it responds quickly to ocean warming.

The two types discussed above provide end-member forms for the occurrence of natural gas hydrate. The layer of low concentrations that is widely distributed near the base of the regional gas hydrate stability zone (GHSZ) is associated with a characteristic bottom-simulating seismic reflector (BSR) under special conditions of low upward fluid flow and moderate to high pressure and geothermal gradients (e.g., Haacke et al., 2007, 2008, and references therein). Formation of this widespread hydrate layer inhibits the regional diffuse upwelling of natural gas and gas-rich liquids, and prevents the transfer of these gases through the seabed and into the overlying ocean. Much of the upwelling gas is channeled into local vent structures, however, and subsequently passes through the GHSZ and into the ocean without being trapped by the formation of hydrate (see Judd and Hovland, 2007).

There has been considerable debate as to how gas or gas-rich fluid is able to reach the seafloor without combining with pore fluid to form hydrate when it first enters the regional GHSZ (i.e., near BSR depth). The possibilities include: (1) rapid upward movement of gas, such that reaction kinetics or water availability limits the rate of hydrate formation (e.g., Zuhlsdorff and Speiss, 2004); (2) upward bending of the stability field due to rising warm fluids (e.g., Wood et al., 2002); and (3) locally increased pore fluid salinity that enables hydrate to coexist with gas and water. This three-phase zone can occur by salt exclusion during rapid hydrate formation (e.g., Zatsepina and Buffett, 1998; Liu and Flemings, 2007). The mechanism by which gas is able to pass through the regional GHSZ is important, since seafloor venting may represent a significant source of methane in the oceans and atmosphere and may make an increasingly large contribution to the Earth's atmospheric greenhouse as the oceans warm and sea levels rise.

In this article we present evidence from seismic images of vent structures and their underlying source zones offshore Korea that supports aspects of the Liu and Flemings (2007) model for locally high pore fluid salinities when the vent is part of a high-flux system. Our data also suggest that hydrate-choked vents are able to form as part of lower-flux systems in which gases move through the upper part of the GHSZ and the seabed as a dissolved phase in upwelling pore water. We compare two adjacent vents thought to represent high- and low-flux systems and show how these different styles of venting are expressed in seismic reflection data. Most important, our data show a complete picture of both the hydrate-choked vents and the underlying source zone of deep gases. The deep gases migrate upward through discrete zones of steep hydrofractures, become locally focused through the shallow sediments, and eventually escape through the seabed. We suggest that the amount of gas migrating from the deep source zone is far larger than the amount of gas trapped as hydrate within the vents. Although the concentrations of hydrate in such structures can be high, the amount of gas that would be released into the ocean by

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melting of the hydrate is likely small compared with the amount of gas venting from the source zone directly into the ocean. Consequently, it is the quantity of gas in the deep source zones and the efficiency with which these zones are able to vent that is most important in terms of the global carbon cycle. The key change in venting that would occur in response to climate-driven oceanic warming may not be an effect on the hydrate itself, but rather a decrease in the gas flux required to penetrate the GHSZ and the seabed in the style of the high-flux vent presented in this paper. The absolute flux required to achieve this style of venting would decrease if bottom-water warming significantly thins the regional gas hydrate stability zone.

## SEISMIC INDICATIONS OF GAS HYDRATE AND UNDERLYING GAS

Multichannel seismic reflection data were acquired by the Korea Institute of Geoscience and Mineral Resources (KIGAM) using a single, 240 channel, 3500-m-offset streamer towed with an airgun array that provided strong amplitudes up to 350 Hz (Park, 2008). The example seismic line we discuss (Fig. 1) runs approximately north-south near the center of the Ulleung Basin in the southern part of the East Sea (Sea of Japan), between South Korea and Japan. The seismic data show numerous localized zones of amplitude blanking and reflector pull-up (in time sections) in sediments within the GHSZ (Lee et al., 2005). Two such features, shown in Figures 1 and 2, labeled A and B, are the focus of this paper. Seismically similar features have been investigated from a variety of geographic areas, including the Niger Delta (Hovland et al., 1997), Norwegian margin (Hovland and Svensen, 2006), Blake Ridge (Paull et al., 1995), and the Cascadia margin (Suess et al., 1999; Riedel et al., 2006). Where suitable physical and chemical measurements have been made, features such as those in Figure 1 have been shown to contain significant quantities of gas hydrate. This interpretation is applicable to our examples from the Ulleung Basin, where stacking-velocity analysis shows that the amplitude-blanked zones correspond to positive velocity anomalies likely due to high-velocity gas hydrate (Fig. 3). Recent drilling has provided further evidence of substantial amounts of gas hydrate in this area, including high concentrations retrieved from the two features specifically addressed in this paper (Chun et al., 2008; Park, 2008). These data are not publicly available, however, and are not discussed further in this paper.

Seismic velocities were determined from a stacking analysis with three rounds of dip-moveout correction. The error of measurement for stacking velocities in the GHSZ is ~5 m/s, increasing to ~10 m/s at 1 s subseabed, and to 40 m/s at 2 s subseabed. The stacking-velocity highs corresponding to features A and B exceed the errors of measurement in the GHSZ. The difference between the stacking velocities and their regional median also shows a broad (10–15 km wide) low-velocity zone deep beneath vent feature B that is not present beneath vent feature A (Fig. 3). This deep low-velocity zone corresponds with a broad area of

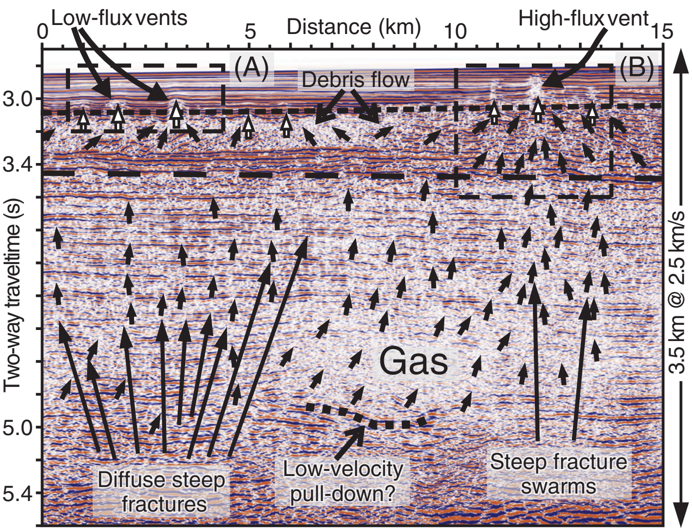


**Figure 1. Time-migrated section from line KIGAM UBGH-043. Two vent structures discussed in text and shown in Figure 2 are marked here by dashed boxes. Processing flow includes normal moveout (NMO) corrections and stacking, frequency filtering between 20 and 250 Hz, finite-difference time migration, and time-dependent (laterally invariant) exponential gain. Uninterpreted seismic reflection image used to produce this figure is available in the GSA Data Repository.[1]**

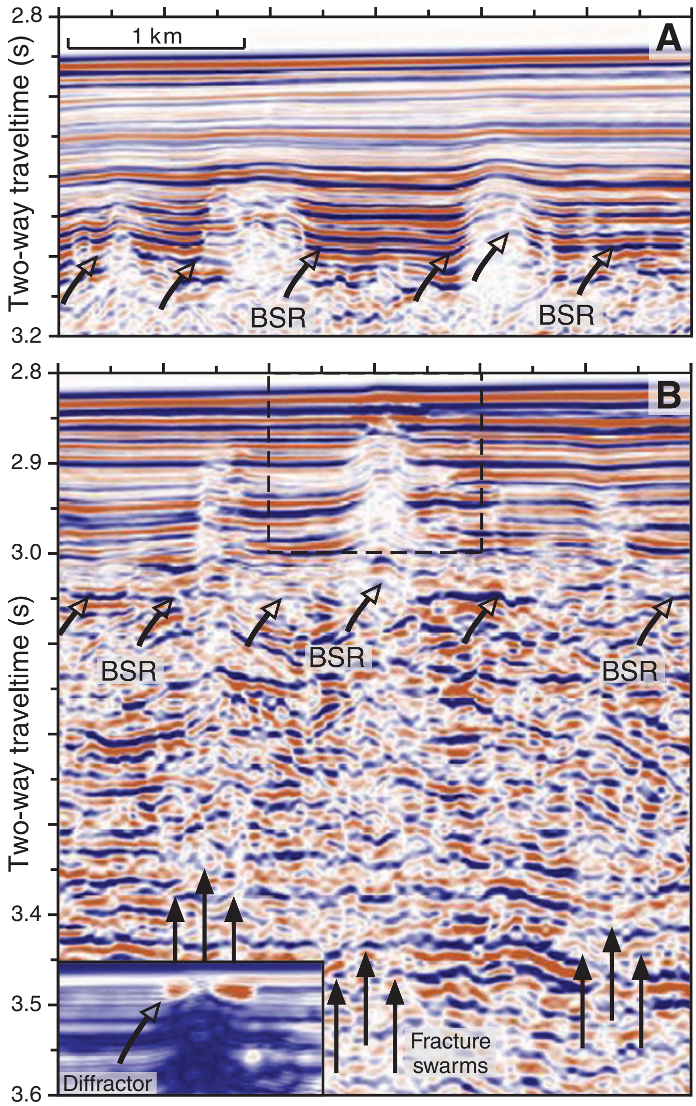


**Figure 2. Detailed seismic reflection sections from two boxed areas of Figure 1. Inset (B) is envelope amplitude of dashed area. Steep amplitude striations in and beneath vent feature B are fractures referred to in text. BSR—bottom-simulating reflector.**

[1]GSA Data Repository item 2009124, uninterpreted seismic reflection image used to produce Figure 1, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

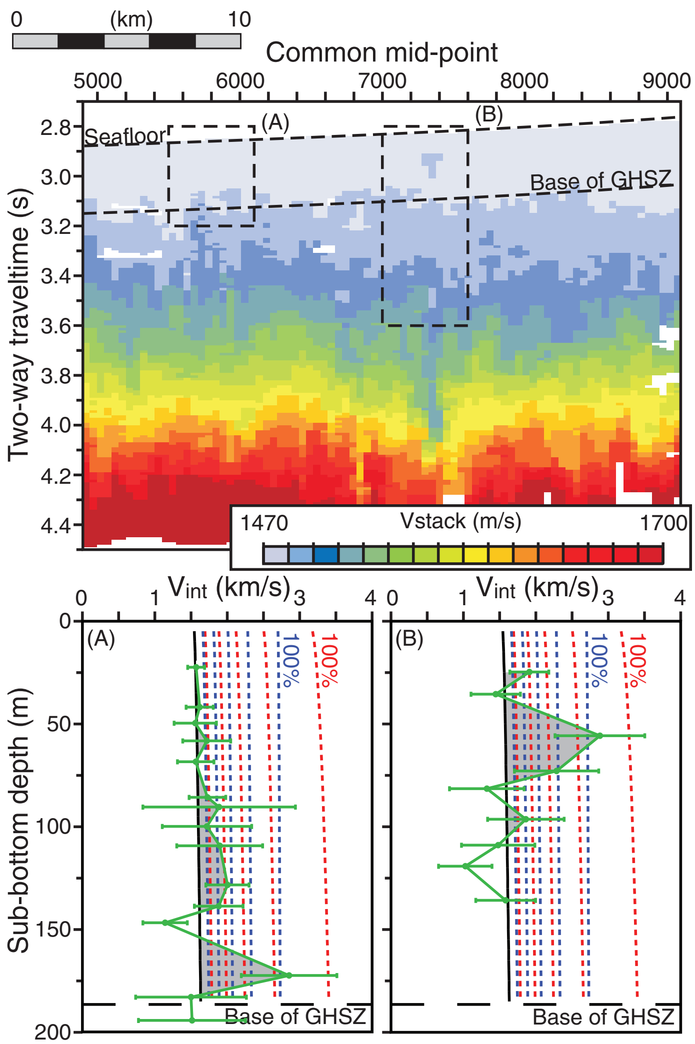


**Figure 3. Stacking velocities (top) and interval velocities inside vent structures from traveltime pull-up (bottom). Solid black line is hydrate-free reference curve; high velocities ($V_{int}$, shaded gray) indicate presence of gas hydrate. Vertical dashed lines in lower panels are interval velocities with hydrate in pore space (blue) and as part of the frame (red) for concentrations between 20% and 100% in 20% increments (modeled with method of Helgerud et al., 1999). GHSZ—gas hydrate stability zone.**

reduced reflection amplitude in the seismic image (Fig. 1) and is capped by a bright horizon at ~3.5 s two-way traveltime (twtt); the frequency content of reflections decreases markedly across this horizon.

Errors in the stacking velocities and their traveltimes prevent accurate conversion to interval velocity. However, an independent estimate can be obtained from the reflection pull-up in the blank zones (Fig. 3) if it is assumed that the pull-up originates from physically flat reflectors (although this assumption may lead to overestimated interval velocities). Interval velocities for the equivalent hydrate-free and gas-free sediments are derived by Dix's (1955) approach applied to a smooth trendline passing through the full suite of stacking-velocity data.

## DISCUSSION AND INTERPRETATION

The deeper part of the seismic image beneath vent feature B (Fig. 1) shows a correlation between widespread amplitude blanking, reduced frequency content, and the broad zone of low seismic velocity. These observations indicate a deep source zone of gas feeding the overlying hydrate-choked conduit. The pattern of reflectivity indicates gas accumulating in two areas, around 4.6 s twtt, that extend upward in near-vertical fingers to the cap horizon at 3.5 s twtt (Fig. 1). Close inspection of the migrated section (Fig. 2) shows that the vertical fingers are composed of steep amplitude striations that are probably swarms of cracks and fractures with the character of hydrofractures as described by Zuhlsdorff and Speiss (2004). Above the cap horizon, incoherent reflections from the chaotic debris flow are brightened, indicating the focusing of lower concentrations of gas toward the base of vent feature B (which carries the gas through the seafloor and into the overlying ocean).

The apparent gas migration pathways and funneling of deep gases into the base of vent feature B from a catchment area 10–15 km wide suggest a high gas flux into this vent. A high upward flux of gas would also account for the large velocity anomaly (due to hydrate) in the vent that is approximately three times greater than that in nearby vent features. Finally, the pre-stack data showed an unusually bright diffraction at the seabed immediately above vent feature B that corresponds to the bright seabed reflection in the migrated image (see Fig. 2B inset). This diffraction suggests a sustained period of recent gas expulsion with enough flux to have either physically perturbed the seabed or produced a large amount of seafloor hydrate or carbonate.

The seismic interval velocities (Fig. 3) infer a hydrate concentration within vent feature B that is greatest near the seabed (80% ± 30% of pore space), with normal velocities beneath indicating a very low concentration of hydrate in liquid, or a mixture of hydrate and gas. This distribution is consistent with predictions from the Liu and Flemings (2007) model, in which rapid formation of hydrate from migrating gas decoupled from upwelling liquid consumes water while excluding salts, thus changing the local stability conditions until hydrate coexists with liquid and gas (Zatsepina and Buffett, 1998) and gases can pass through the GHSZ to the ocean. Near the seabed, where the salinity gradient is large, the local salinity anomaly is reduced by upward diffusion, enabling further formation of hydrate near the seafloor.

Pull-up of a faint BSR around and beneath vent feature B indicates some degree of upward bending of the GHSZ due to warm upwelling fluids (after Wood et al., 2002). This phase-boundary roughness is not large, however, and does not explain the very shallow concentrated gas hydrate in this vent. The last model for gas expulsion through hydrate-choked conduits that we consider, that of reaction kinetics or water shortage, seems unlikely to play a significant role in this system, given that: (1) there is already a high concentration of hydrate in the vent on which to nucleate further growth of this phase; and (2) although water may be limited in very narrow hydrate-filled channels, some of the vent structures are >1 km wide and water is generally in abundance in these near-surface porous marine sediments.

We suggest that vent feature B is a type-case example of a high-flux, hydrate-choked vent that allows deeply sourced gases to pass through the regional GHSZ and exit through the seabed. We prefer the salinity effect as the dominant mechanism allowing gases to pass through the regional GHSZ, although the upwelling of warm fluids must play a role. Conversely, vent feature A appears not to be plumbed-in to the same system, and sediments beneath show a more diffuse distribution of hydrofractures (the steep amplitude striations in the migrated image), suggesting a lower upward flux of gases. The hydrate in this feature is most concentrated near the base of the regional GHSZ (Fig. 3), where the blank zone is located (Fig. 2), and decreases gradually toward the seabed. This hydrate distribution implies a lower upward methane flux that has produced a three-phase zone that only partly penetrates the GHSZ (see the numerical simulations reported by Liu and Flemings, 2007). Above the three-phase zone, we suggest that hydrate has formed from upward movement of gases dissolved in liquids (e.g., the model of Hyndman and Davis, 1992) to produce a distribution with approximately exponential form after the shape of the hydrate-water solubility curve in that part of the seabed (Zatsepina and Buffett, 1998).

Our data show seabed gas venting in two different styles (either decoupled from, or dissolved in, the pore water) that depend on the flux of source gas (respectively high flux and low flux), which in turn depends on the plumbing feeding gases from underlying reservoirs (see Judd and Hovland, 2007). If the oceans were to warm in response to climate forcing, the regional GHSZ would thin, consequently lowering the flux of migrating gases required to cause venting in the style of our example high-flux vent. Thus, although oceanic warming would not change the reservoir properties of the underlying source zones, the efficiency with which smaller reservoirs and conduits are able to directly vent gases into the ocean would increase. The amount of gas trapped as hydrate within the vents is considerably smaller than the amount of gas in the underlying reservoirs; consequently, the amount of gas released by melting hydrate within the vents is likely to be much smaller than the additional gas released by the increased ability of underlying reservoir systems to vent through the seafloor.

## CONCLUSIONS

Our analysis of seismic reflection data from the Ulleung Basin indicates that blank zones (up to 1 km wide) above the GHSZ contain high velocities produced by concentrated gas hydrate. One example structure has high-velocity hydrate in 80% ± 30% of pore space just beneath the seabed and appears to vent gases directly into the ocean. It has the characteristics expected of a feature fed by a high flux of upwelling gases, and is connected to a deep source zone (10–15 km diameter) of concentrated gases through discrete networks of steep cracks and fractures. A second, nearby, structure does not reach the seafloor and has high-velocity hydrate (also in 80% ± 30% of pore space) only just above the base of the GHSZ. The seismic image indicates that this structure is the result of a low flux of gas input from a diffuse region of underlying fractures. In both cases, deep gases migrate from many kilometers beneath the seabed to feed the hydrate-choked vents, the difference in flux being attributed to the concentration of the source zone. We prefer the salinity feedback effect driven by migrating gases as the dominant mechanism allowing gas to pass through the GHSZ in the high-flux vent. In the low-flux vent we suggest that gases pass through the upper part of the GHSZ and the seabed as a dissolved phase only. Our data thus show two different styles of gas venting from adjacent, local systems 10 km apart that appear to be type-case examples for vents fed by high and low fluxes of gas.

If ocean warming were to significantly thin the regional gas hydrate stability zone, we expect some lower flux venting systems to adopt the behavior of the higher flux systems with a three-phase zone that reaches the seabed. This would increase the efficiency with which smaller gas conduits are able to vent at the seabed and allow gases to directly enter the ocean. The amount of gas venting through the seabed would thus increase. This is not due to a change in the hydrate itself, but rather a decrease in the flux of migrating gas that is required to penetrate the GHSZ and reach the seabed.

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