

HIGH-FLUX GAS VENTING IN THE EAST SEA, KOREA, FROM ANALYSIS OF 2D SEISMIC REFLECTION DATA

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ABSTRACT

Seismic reflection data from a multi-channel streamer deployed offshore Korea reveal evidence of hydrate-forming gases being vented into the ocean. Numerous, localised vent structures are apparent from reduced seismic reflection amplitude, high seismic velocities, and reflector pull-up. These structures penetrate upward from the base of the gas hydrate stability zone (GHSZ) and are typically several hundred metres wide, and only a few hundred metres high. Underlying zones of reduced reflection amplitude and low velocities indicate the presence of gas many kilometers below the seabed, which migrates upward through near-vertical conduits to feed the vent structures. Where the local geology and underlying plumbing indicates a high flux of gases migrating through the system, the associated vent structures show the greatest change of reflector pull-up (the greatest concentration of hydrate) to be near the seabed; where the local geology and underlying plumbing indicates a moderate flux of gases, the greatest change of reflector pull-up (the greatest concentration of hydrate) is near the base of the GHSZ. The distribution of gas hydrate in the high-flux gas vent is consistent with the recent salinity-driven model developed for a rapid and continuous flow of migrating gas, while the hydrate distribution in the lower-flux vent is consistent with a

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liquid-dominated system. The high-flux vent shows evidence of recent activity at the seabed, and it is likely that a substantial amount of gas is passing, or has passed, through this vent structure directly into the overlying ocean.

Keywords: gas hydrates, seismic, vent, cold seep, Korea, chimney, pockmark

INTRODUCTION

Natural gas hydrate seems to occur in two end-member forms: 1) widespread low-to-moderate concentrations that occur above a regional bottom-simulating reflector; 2) local moderate-to-high concentrations that occur in what look like vent structures. The first form is well modelled by the migration of gas-rich liquids [1], while the second is associated with rapid migration of free gas [2,3].

Here we show examples of the second form of natural gas hydrate from 2D seismic reflection data acquired offshore Korea. The data are of exceptionally high quality, and indicate the presence of gas many kilometers beneath the seabed that feeds into the vent structures. The distribution of gas hydrate in the structures is determined from an analysis of seismic velocities. We find that the hydrate accumulates in greatest concentrations near the seabed in what looks like a high-flux vent, while it accumulates in greatest concentrations near the base of the regional hydrate stability zone in what looks like a low-flux vent. These observations echo those made of analogous structures elsewhere (e.g. offshore Vancouver Island [2]), but are unusually clear in this Korean example. The high- and low-flux systems are adjacent to each other (within 10 km) and are particularly useful type cases of hydrate-choked vent structures in the deep sea.

Details of the methods and analyses we have applied, and are applying, to these data are described in detail by Stoian et al. [4]: in this paper we do not discuss the methods, but focus on the presentation of some preliminary results.

OBSERVATIONS FROM SEISMIC DATA

The seismic data are presented in Fig. 1 after processing with band-pass filtering (40-400 Hz), normal and dip moveout corrections, stacking, spherical-divergence correction, and finite-difference time migration. The migration was conducted with a 2D velocity function obtained from stacking-velocity analysis of the data (which included dip-moveout corrections). Although the stacking-velocity function is relatively smooth and continuous (Fig. 2a), the stacking velocities

contain enough noise (the standard deviation in stacking velocities is about 1 m/s in the gas hydrate stability zone, increasing to about 40 m/s at 2 s two-way time after the seabed reflection) to confound the reliable conversion of these stacking velocities to interval velocities using a standard Dix approach [5]. The migration was thus conducted with a 2D interval-velocity function that was produced by applying Dix's equation to the stacking velocities then heavily smoothing the result. The smoothing was so severe that the migration-velocity function is well represented by the 1D function (illustrated in Fig. 3) obtained from fitting a smooth function to the full suite of stacking-velocity measurements and using Dix's approach [5] to convert that to interval velocities (note: the 2D migration-velocity function did retain some limited structure not represented by the 1D function). Dix's conversion works very well for smooth functions, but not for noisy ones. This problem of converting noisy stacking velocities to interval velocities is well known [6,7], and is being specifically addressed with these data by Stoian et al. [4], who use a constrained inversion of the 2D stacking-velocity function to find the interval velocities (using methods akin to [8], but constrained with either model flatness [9], or model smoothness [10]).

Observations from seismic attributes

The migrated seismic image shows the existence of several features that appear to be vent structures. These are marked by: 1) vertical areas of reduced amplitude in the gas hydrate stability zone; 2) reflector pull-up within the amplitude-blanked areas. These features often (but not always) have brightened seabed reflection amplitudes immediately above them. In this paper, we focus on two such structures. For the reasons described in the following, we interpret the leftmost structure (Fig. 1) as a low-flux feature, and the rightmost structure (Fig. 1) as a high-flux feature. These two features are shown in more detail in Fig. 4, where extracts from the seismic reflection section are shown with corresponding complex-trace attributes. In this figure, the approx-

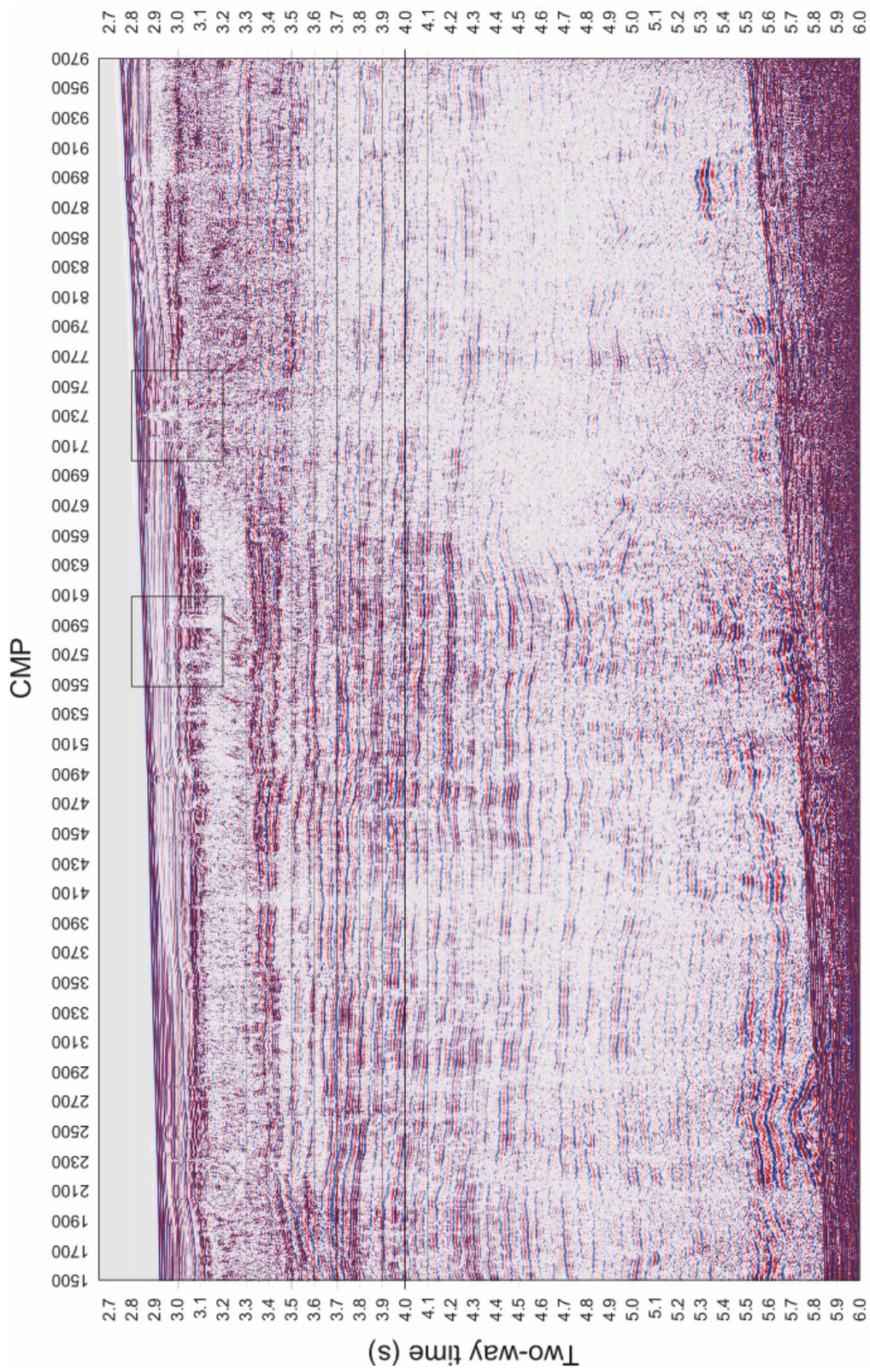


Figure 1: Migrated seismic image of 2D multi-channel streamer data from offshore Korea. The two vents that form the focus of this paper are indicated by the boxes near the seabed at CMPs 5900 and 7300. Processing includes: band-pass filtering (40-400 Hz), normal and dip-moveout corrections, spherical-divergence correction, finite-difference time migration. Lateral variability in amplitudes has been preserved.

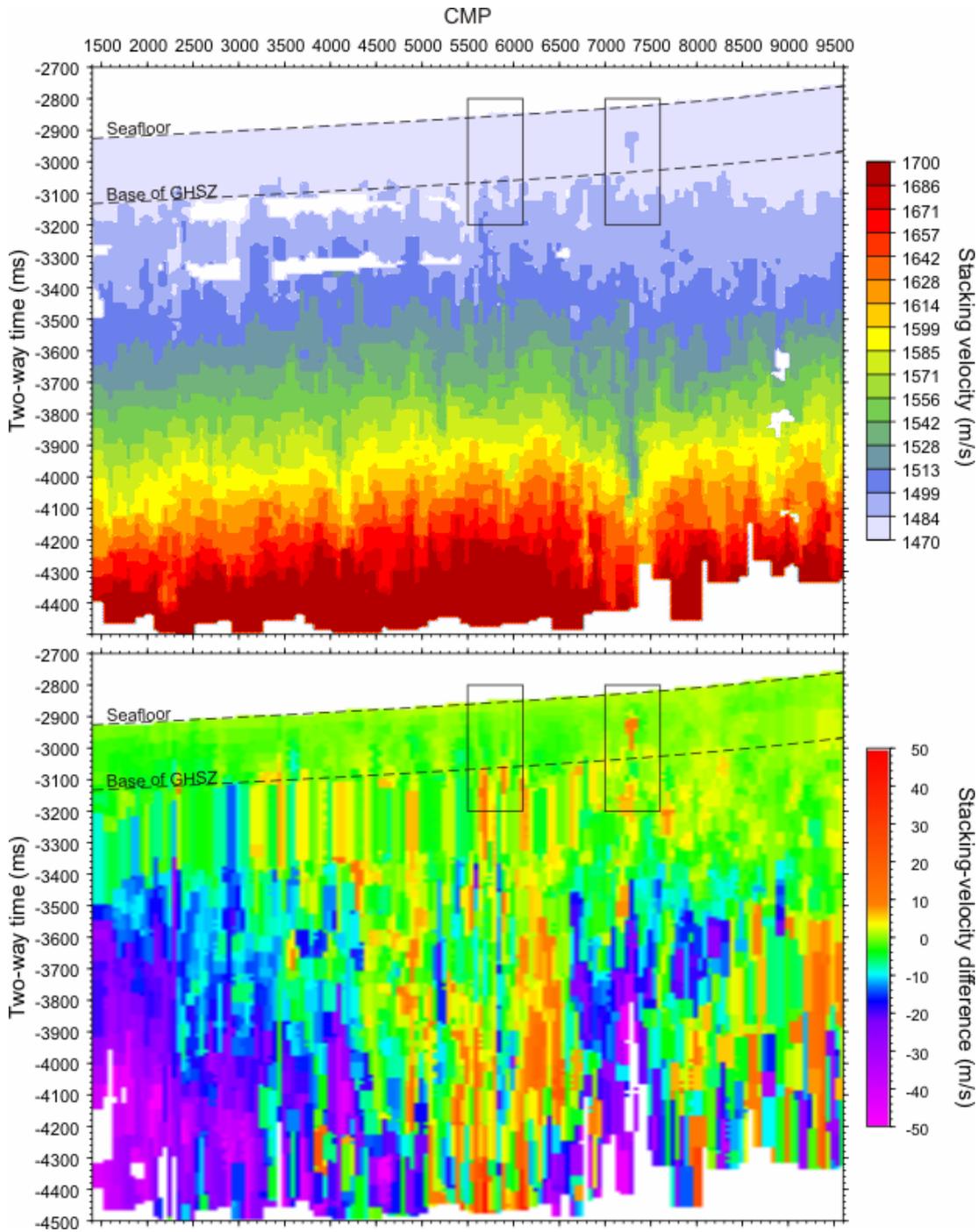


Figure 2: Seismic stacking velocity (a) and stacking-velocity anomaly (b) from the dip-moveout-corrected data. The locations of the two vent structures are indicated by the boxes. The velocity anomaly plot was produced by subtracting the median-average velocity curve of Fig. 3 from the velocities in panel (a) of this figure. The magnitude of the velocity anomalies should be compared with the errors of measurement discussed in the text. Generally, the orange and red is significant within the gas hydrate stability zone but not beneath. In deeper parts of the section, blue and indigo are just above the magnitude of significance.

imate base of the gas hydrate stability zone is indicated with the green dashed line at about 3.1 s two-way time. The depth to this boundary was predicted from the regional heat flow (see the discussion in Stoian et al., [4]) and is coincident with a simultaneous decrease in instantaneous frequency and increase in instantaneous amplitude (Fig. 4). One observation of particular importance is the presence of a very bright diffraction in the pre-stack data that occurs at the seabed above the rightmost vent feature. This indicates the presence of an angular chunk of hard material at or near the seabed that is likely an outcrop of carbonate or gas hydrate. Both of these materials form in response to the expulsion of natural gases.

Observations from seismic velocities

Although the heavily-smoothed interval velocities were good enough for migration purposes, they are not well enough determined to be useful for interpreting the data. The stacking velocities themselves have some utility, however, as illustrated by Fig. 2. The 2D stacking-velocity function shows the presence of a significant high-velocity anomaly corresponding to the rightmost vent feature of Fig. 1. Furthermore the stacking velocities indicate a broad region of low-velocity sediments lying beneath the rightmost vent feature.

The distribution of seismic velocity anomalies is better determined by subtracting a reference velocity curve from the 2D stacking-velocity function and plotting the difference (Fig. 2b). The reference curve was obtained by compiling the full suite of stacking-velocity measurements made on the line in question to a single dataset, then calculating a running-median down the dataset (Fig. 3). The median is a good representation of the 'normal' velocity curve if the number of picks from areas with unusually high or low velocities (i.e. from the vent features) is small compared with the total number of picks. The plot of velocity difference shows high-velocity anomalies in the gas hydrate stability zone that correspond well with the vent structures imaged in Fig. 1. The velocity difference also indicates two regions of anomalously low-velocity, one of which is the broad low-velocity region, discussed above, that was evident in Fig. 2a.

The magnitude of the velocity anomalies in Fig. 2b should be considered in light of the errors in the stacking-velocity measurement, which are best represented by twice the standard deviation shown in Fig. 3 plus the systematic error produced

by the use of a hyperbolic moveout (about 3 m/s). The total error for stacking-velocity measurements in the gas hydrate stability zone is about 5 m/s, increasing to about 12 m/s at a two-way time of 4 s and to about 40 m/s at a two-way time of 5 s. As depth increases, the systematic component of error reduces, since the hyperbolic moveout approximation improves, but the random component of error (represented by the standard deviation) increases. The low-velocity anomalies at about 4 s two-way time in Fig. 2b are thus in excess of the measurement errors and are significant, as are the high-velocity anomalies in the gas hydrate stability zone.

The interpretation of the velocity anomalies in Fig. 2b (which is based on experience and results from a wide variety of geophysical applications, including results from drilling and seismic experiments applied to similar vents offshore Vancouver Island [11]) is relatively simple: high velocities correspond to gas hydrate; low velocities correspond to gas.

The vent features are further investigated by determining the distribution of gas hydrate within them from the position and magnitude of the high-velocity anomalies. This can not yet be done by converting the stacking velocities to interval velocities for the reasons discussed above, but an estimate can be made by using the reflection pull-up (relative to surrounding sediments) in conjunction with the reference-velocity curve in Fig. 3. The paraphase (Fig. 4) is useful for tracking reflections through the body of the vent features, and is used to quantify the degree of reflector pull-up in the high-velocity vent structures. The pull-up measurements give the interval velocities shown in Fig. 5.

The rightmost vent feature (the high-flux vent) shows the greatest velocities near the seabed (the vertical dashed line in Fig. 5 indicates the reference velocity of Fig. 3), while the leftmost feature (the low-flux vent) shows the greatest velocities are near the base of the hydrate stability zone. The rightmost vent feature (the high-flux vent) has normal velocities between the high-velocity anomaly and the base of the regional gas hydrate stability zone.

INTERPRETATION OF SEISMIC DATA

The zone of low seismic velocity in deep sediments beneath the rightmost vent feature corresponds with a broad area of reduced seismic reflection amplitude. We suggest that the reduced

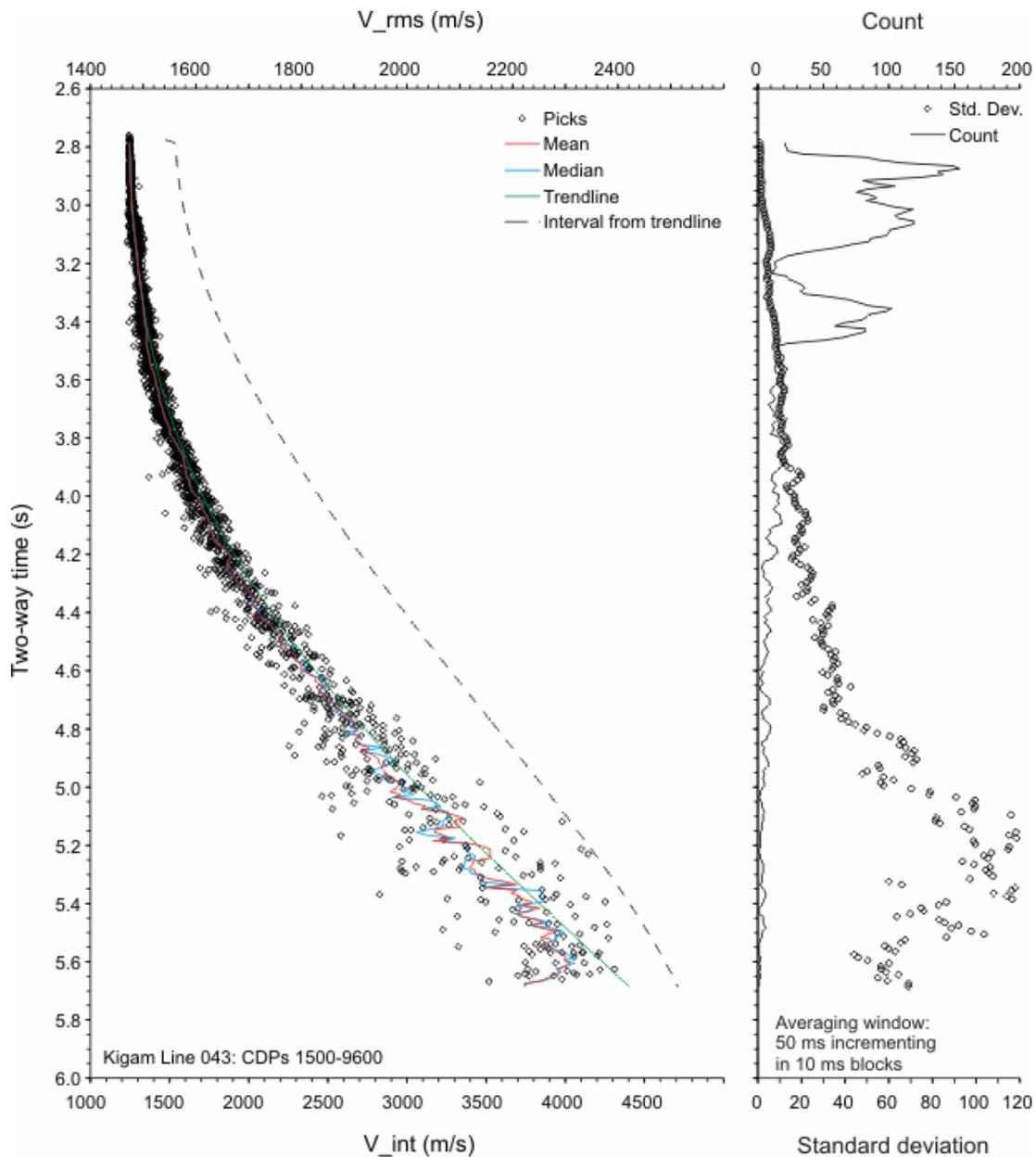


Figure 3: Compendium of stacking-velocity measurements from Fig. 2a plotted as a 1D function. The datapoints were used to calculate a running mean (red), a running median (blue), and a best-fit polynomial trendline (green). The trendline (which is smooth and continuous) was used to calculate an interval-velocity function from Dix's equation [5] (dashed line). The statistics of the averages are shown to the right, where the number of samples in the running 50 ms time window and the standard deviation from the mean value in the 50 ms time window are plotted against time at the centre of the window. The running averages were calculated by incrementing the 50 ms time window in 10 ms blocks.

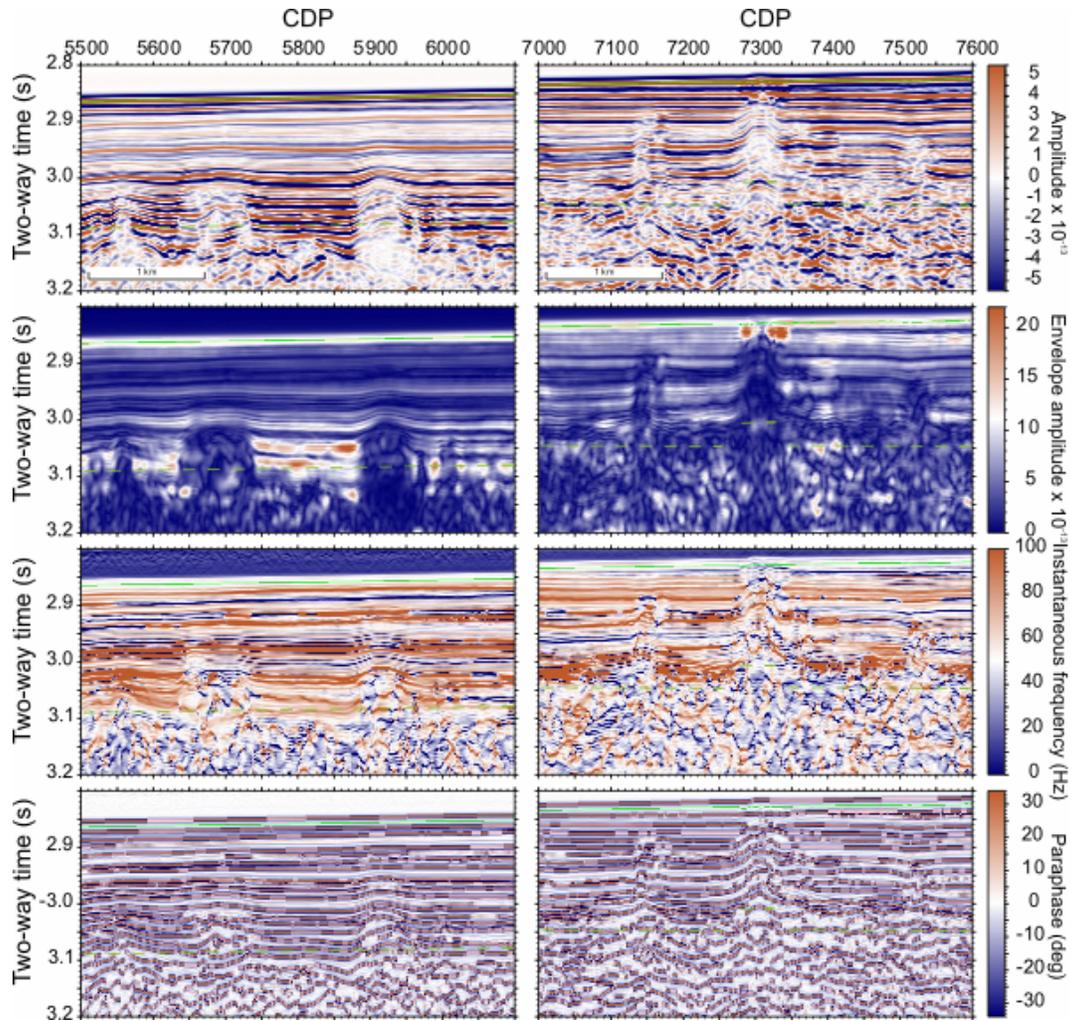


Figure 4: Close-up images of the two vent structures imaged in the migrated seismic section (top), with complex trace attributes (envelope amplitude, instantaneous frequency, and paraphase [instantaneous phase with long-period trend removed]) plotted beneath. The solid green line is the seabed, while the dashed green line is the approximate base of the hydrate stability zone. The area covered by these plots is the area of the boxes in Fig. 1.

amplitudes below about 3.5 s two-way time (which, incidentally, appears to be a low-permeability horizon that traps underlying gases to some degree) are indicative of gas in the sediments, and this gas is responsible for reducing the seismic velocity. This interpretation is important, since we can then use the reduced reflection amplitude as a proxy for the presence of gas in order to determine the distribution of that gas. The pattern of reduced reflection amplitude indicates near-vertical zones of gas that lead up from two source areas at around 4.6 s two-way time to the bright horizon at 3.5 s. The near-vertical zones are not truly vertical, they wander

laterally by a small amount, which indicates that they are not amplitude shadows cast by the overlying vent structures that they feed. The character of the reflection section changes above the bright horizon at 3.5 s two-way time. The upward-migrating gases brighten reflectors above this horizon, rather than dim the reflectors, and the bright reflections seem to funnel toward the rightmost vent feature. The change from dimming to brightening is expected for gases that are in higher concentrations in deeper sediments (the dimmed zone) than in shallow sediments (the brightened zone). We also see a reduction in frequency content for arrivals later than 3.5 s two-

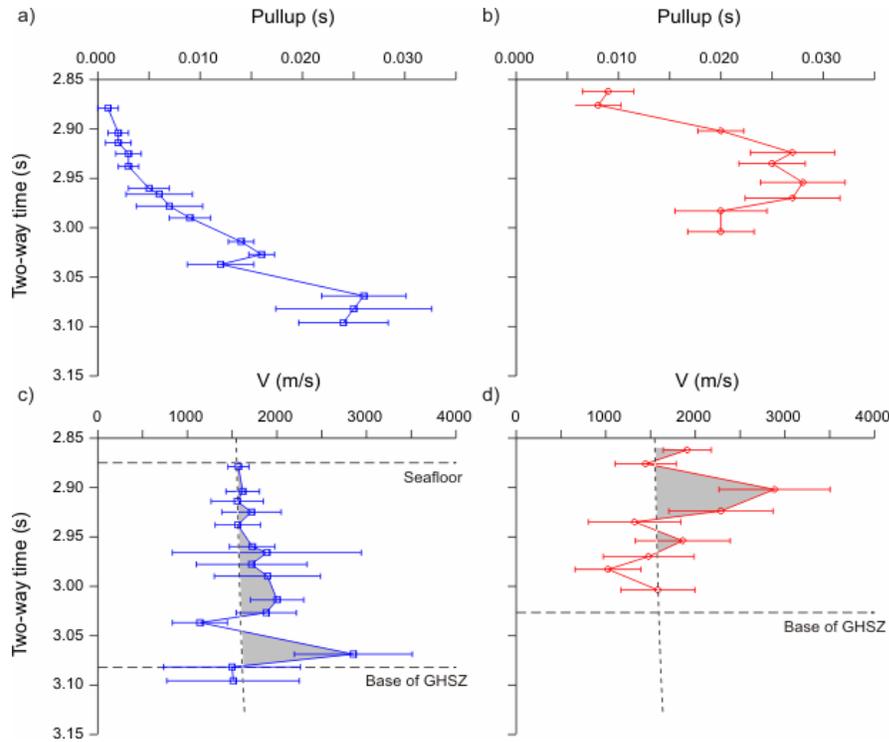


Figure 5: Seismic reflection pull-up (top) and interval velocity (bottom) estimated from the degree of pull-up relative to surrounding sediments. This calculation uses the interval-velocity function derived from the trendline of Fig. 3 to represent the velocity of normal (hydrate-free and gas-free) sediments.

way time, and this is consistent with an increase in gas concentration below this horizon.

The plumbing that feeds the rightmost vent feature with gases is notably absent from sediments beneath the leftmost feature. We suggest that the plumbing discussed above feeds a high flux of gases into the rightmost vent, and that some of these gases may migrate laterally along the chaotic zone between 200 and 400 ms beneath the seabed reflection to feed the leftmost vent. The leftmost vent is thus a lower-flux feature. The difference in gas flux is probably responsible for the difference in the distributions of gas hydrate within the vents (Fig. 5). The hydrate distribution determined for the high-flux vent is consistent with the model of a salinity-driven three-phase zone that develops upward from the base of the regional gas hydrate stability zone and allows gases to pass directly into the ocean [3]. The hydrate distribution determined for the low-flux vent is consistent with a small, proto-three-phase

zone developing near the base of the regional hydrate stability zone, with an overlying distribution that is produced by the migration of gas-rich liquids.

CONCLUSIONS

Seismic reflection data from offshore Korea provide evidence of the migration and venting of deep gases into the ocean. Patterns of seismic velocity anomalies that correlate with patterns in seismic attributes (such as reflection amplitude and instantaneous frequency) indicate the presence of deep gases that are migrating near vertically to feed a high-flux vent. This vent shows a strong seabed diffraction that is indicative of recent

gas expulsion. The vent has a large accumulation of gas hydrate within it that reaches its greatest concentrations near the seabed. Beneath this zone of concentrated gas hydrate and the base of the regional hydrate stability field, sediments in the vent show no velocity anomaly relative to the regional norm. Adjacent to the high-flux vent is a second vent feature that does not have the same underlying plumbing. We suggest this feature is a much lower-flux system, and this explains the different distribution of gas hydrate within it. Seismic velocity anomalies indicate the greatest concentration of gas hydrate in this low-flux vent occurs near the base of the hydrate stability zone, with overlying concentrations decreasing gradually toward the seabed. We suggest that gas hydrate in this vent is formed mainly by a liquid-dominated mechanism, while gas hydrate in the high-flux vent is formed mainly by a flux of free gas.

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