Distribution and height of methane bubble plumes on the Cascadia Margin characterized by acoustic imaging

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Received 23 January 2003; accepted 26 March 2003; published 26 June 2003.

[1] Submersible investigations of the Cascadia accretionary complex have identified localized venting of methane gas bubbles in association with gas hydrate occurrence. Acoustic profiles of these bubble plumes in the water column in the vicinity of Hydrate Ridge offshore Oregon provide new constraints on the spatial distribution of these gas vents and the fate of the gas in the water column. The gas vent sites remained active over the span of two years, but varied dramatically on time scales of a few hours. All plumes emanated from local topographic highs near the summit of ridge structures. The acoustic images of the bubble plumes in the water column disappear at water depths between 500 to 460 m, independent of the seafloor depth. This coincides with the predicted depth of the gas hydrate stability boundary of 510 to 490 m, suggesting that the presence of a hydrate skin on the bubble surface prevents them from rapid dissolution. The upper limit of the acoustic bubble plumes at 460 m suggests that dissolution of the residual bubbles is relatively rapid above the hydrate stability zone. *INDEX TERMS:* 4820 Oceanography: Biological and Chemical: Gases; 4259 Oceanography: General: Ocean acoustics; 4806 Oceanography: Biological and Chemical: Carbon cycling. **Citation:** Heeschen, K. U., A. M. Tréhu, R. W. Collier, E. Suess, and G. Rehder, Distribution and height of methane bubble plumes on the Cascadia Margin characterized by acoustic imaging, *Geophys. Res. Lett.*, *30*(12), 1643, doi:10.1029/2003GL016974, 2003.

1. Introduction

[2] Recently a number of gas bubble plumes, containing mostly methane (CH_4) gas, have been discovered by acoustic methods to rise over the slopes of continental margins, apparently in association with the formation of gas hydrates; e.g., in the Guayamas Basin [*Merewether et al.*, 1985], in the Gulf of Mexico [*MacDonald et al.*, 2002], at Blake Ridge [*Paull et al.*, 1995], on the Sakhalin slope in the Sea of Okhotsk [*Salyuk et al.*, 2002] and along the Cascadia accretionary complex [*Suess et al.*, 2001]. These gas bubble plumes originate at sites as deep as 2500 m and have been observed to rise as much as 900 m in the water column [*Merewether et al.*, 1985]. Often, however, the minimum depth in the water column at which the gas bubbles disappear is poorly resolved and in some cases the plumes extend to the sea surface. Furthermore, the persistence of these CH_4 gas bubble plumes in the ocean is remarkable because the ocean is undersaturated in methane, and the bubbles should quickly dissolve. Based on an observed correlation between bubble size and rise rate, *Merewether et al.* [1985] inferred that the CH_4 bubbles were protected by a coating of oil or gas hydrate. The latter was suggested to cause the reduced shrinking rate of methane gas bubbles, which was observed in a CH_4 gas release experiment carried out in the gas hydrate stability zone (GHSZ) in the ocean [*Rehder et al.*, 2002]. The gas hydrate coating should dissociate when the bubbles exit the GHSZ. A coating of oil, on the other hand, should sufficiently protect the bubbles from dissolution until they reach the sea surface, as indicated in the Gulf of Mexico [*MacDonald et al.*, 2002].

[3] In this paper, we use the acoustic backscatter from bubbles in the water column to determine the spatial distribution of bubble plumes and develop a hypothesis about their relation to the water depth along the mid-slope of the central Oregon continental margin.

2. Geologic Setting

[4] At the Cascadia subduction zone, the Juan de Fuca Plate is subducting obliquely beneath the continental North American Plate, where a large accretionary wedge has developed [*MacKay et al.*, 1992] (Figure 1). A strong bottom-simulating reflection (BSR) is widespread at water depths between approximately 600 and 1500 m [*Tréhu et al.*, 1999], indicating the presence of free gas underlying a region in which gas hydrate is stable. The BSR is particularly strong beneath topographic highs such as North Hydrate Ridge (NHR), South Hydrate Ridge (SHR), Southeast Knoll (SEK) and Northwest Knoll (NWK). Free gas, containing 99% CH_4 [*Torres et al.*, 2002], and methane-rich fluids are channeled upwards through faults to feed vents at the seafloor [e.g., *Suess et al.*, 2001; *Torres et al.*, 2002].

[5] During the TECFLUX (TECtonically-induced material FLUXes) program, a wide variety of mostly video-guided tools were used to investigate venting processes at the Oregon continental margin [*Suess et al.*, 2001; *Torres et*

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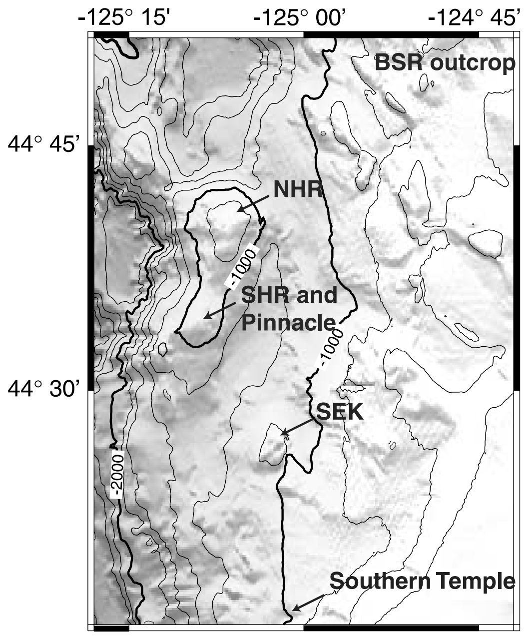

Figure 1. Bathymetry of the study area and sites of acoustic surveys. NHR = Northern Hydrate Ridge, SEK = Southeast Knoll, SHR = Southern Hydrate Ridge.

al., 2002]. Active methane gas ebullition was observed at NHR, SHR, and SEK. Echosounding systems using 12.5 and 18 kHz proved to be of great use for imaging these bubble plumes in the water column, and aided in locating and sampling of vent sites.

3. Methods

[6] Acoustic detection is a particularly suitable tool for finding and characterizing gas bubbles in the ocean. It is based on the strong absorption and scattering effect gas bubbles have on sound, which are further enhanced by a factor of $10^3 – 10^4$ at the particular resonant frequency of the bubble. According to *Clay and Medwin* [1977], the bubble resonant frequency is inversely proportional to the bubble radius. The bubble resonant radii increase with water depth.

[7] Backscattered sound was used to detect gas bubbles in the water column during five cruises in 1999 and 2000 with RV Atlantis (AT 3-35B), RV Sonne (SO143 and SO148), RV Thompson (TN112), and RV Wecoma (W1099a) including detailed surveys at NHR, SHR, and SEK. On all acoustic surveys carried out for mapping of bubble plumes we used a source with a frequency of 12.5 kHz and a beam width of 15°, resulting in a swath width of roughly 160 m at 600 m water depth and 210 m at 800 m depth. The swath width of the acoustic beam on a moving ship leads to a distortion of the actual width of the bubble plumes. The widths of the acoustic signals therefore overestimate the width of the bubble plumes in the water column by about as much as the swath width. The 18 kHz acoustic system of SONNE with a beam width of 20° was only used to guide water column sampling, and the results are not integrated into the acoustic surveys. However, the upper limits of the acoustic plumes equal those of the 12.5 kHz signals within the given resolution. The bubble resonant radii at the given source frequencies and water depths were 2.3 mm (700 m) and 2.0 mm (500 m) for the 12.5 kHz source and 1.6 mm (700 m) and 1.3 mm (500 m) for 18 kHz, respectively ($Ka \gg 1$ [*Clay and Medwin*, 1977, equation 6.3.10]). While acoustic plumes were detected with the 12.5 and 18 kHz sources and showed equivalent distributions, a 3.5 kHz source simultaneously used with a few 12.5 kHz observations did not detect acoustic plumes. It can be assumed that bubbles with the corresponding resonant radii of 6.6 to 7.8 mm were absent. These observations are in agreement with video analyses from *Rehder et al.* [2002], who observed average bubble radii of 2.5 to 4 mm at the gas vents of SHR. At NHR bubble radii were estimated to be 2 to 5.5 mm based on the size of conduit openings [*Torres et al.*, 2002]. It is likely that the acoustic systems available were not able to detect few single bubbles with radii different from the resonant radius.

4. Observations and Discussion

[8] Strong acoustic signatures indicative of bubble plumes in the ocean were observed near the summits of NHR, SEK and SHR (Figure 2a–2c). They were found in surveys conducted 1 to 2 years apart, suggesting that they are robust features. In contrast, no acoustic plumes were found at other potential sites, such as: 'Southern Temple', an unusual topographic feature that resembles a mud

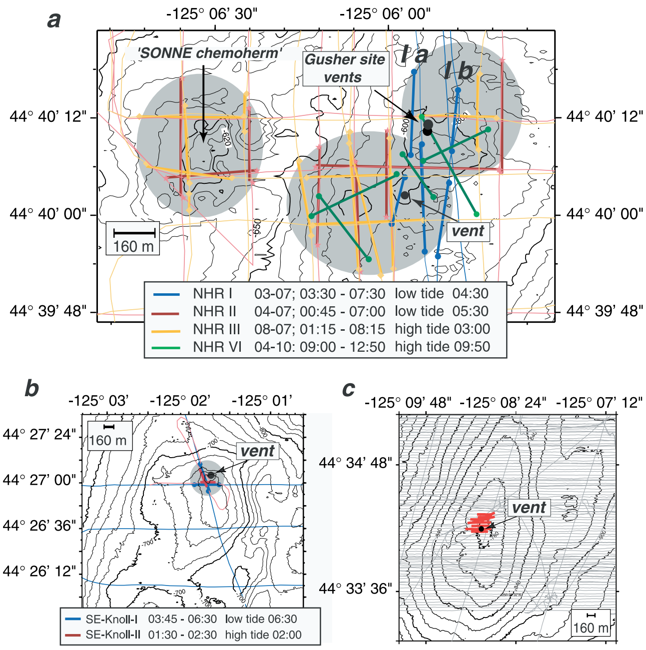

Figure 2. Detailed acoustic surveys completed at NHR, SEK, SHR; (a) Four repeated surveys (thin lines) at NHR show three distinct locations with acoustic signals (gray shaded circles). The thick colored lines represent the location of the acoustic signals during the various surveys. I a and I b mark the survey lines shown in Figure 3. (b) At SEK two surveys were completed which found one acoustic signal. (c) One acoustic signal was found at SHR. The thin gray lines represent the ship track. The black dots indicate the locations at which gas vents were seen with submersibles and ROPOS [*Torres et al.*, 1999; *Linke et al.*, 2001; *Tryon et al*, 2002].

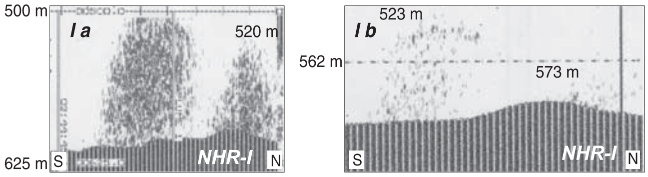

Figure 3. Examples of the variable strength and width of acoustic plumes at NHR from crossings I a and I b (see Figure 2). The depths indicated above the acoustic signals mark the upper limits of the detected backscatter. The x-axis is not in scale.

volcano; the 'BSR-Outcrop', a site where a strong BSR intersects the seafloor [*Tréhu et al.*, 1995]; the 'Pinnacle chemoherm', a 30 m high carbonate pinnacle 250 m southwest of the summit of SHR (see Figure 1).

[9] The acoustic plumes at NHR and SEK overlie local topographic highs which correspond to regions of very high seafloor reflectivity in side scan sonar observations [*Clague et al.*, 2001]. Seafloor video indicates that these include 'chemoherms', massive structures formed from authigenic carbonates [e.g., *Torres et al.*, 1999; *Tréhu et al.*, 1999]. The acoustic plume at SHR is also found at a topographic high, but here the seafloor reflectivity is intermediate in strength, corresponding to a region where massive hydrate is abundant in the shallow subsurface [*Suess et al.*, 2001].

[10] Whereas SHR and SEK each had one distinct plume, three separate bubble plumes were observed simultaneously in the water column above NHR (Figure 2). At SEK and SHR, the vent sites found with submersibles coincide with the acoustic signals in the water column, while at NHR, submersible observations are only available for two of the three acoustic plumes (Figure 2). The discovery of acoustic signals from three gas vent areas at NHR implies that the methane gas flux of 6.10^4 mol day^{-1} for NHR calculated from submersible observations of the Gusher site [*Torres et al.*, 2002] is probably underestimated. Long-term acoustic observations with calibrated, digital instruments are needed to obtain a precise estimate of the gas fluxes.

[11] Despite the limitation of our acoustic observations, the data provide insights into temporal variability and persistence of the plumes over the two years of investiga-

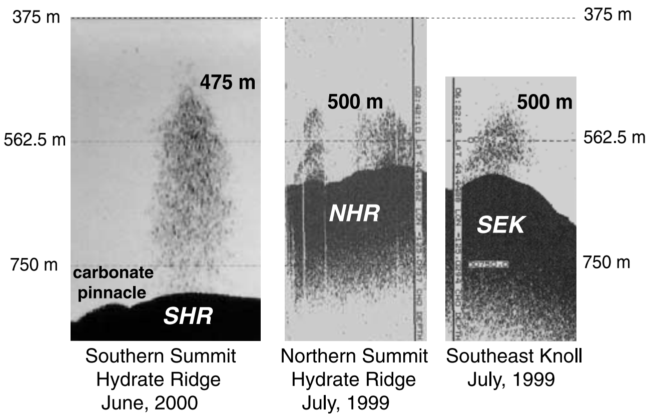

Figure 4. Similar height of the acoustic signals from the vent sites at SHR, NHR and SEK. The depth above the acoustic signals marks their upper limit.

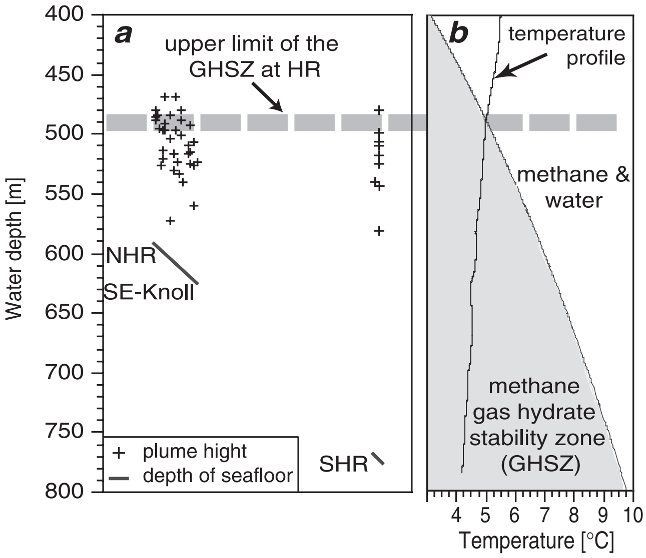

Figure 5. Relationship between the height of the acoustic backscatter images from 12 and 18.5 kHz sources and the upper limit of the gas hydrate stability zone. (a) shows the heights of the acoustic signals at NHR, SEK and SHR (crosses) and the corresponding sea floor depth (bar). In (b) the upper limit of the gas hydrate stability field (gray) at HR is derived from an equation of *Dickens and Quinby-Hunt* [1994] for pure methane gas using the temperature profiles taken at SHR during the cruise AT3-35b [*Torres et al.*, 1999].

tions. Whereas the plume positions were rather stable and the plumes remained active over the time-scale of the investigation, the strength and width of the acoustic signals were highly variable over a time-scale of a few hours. This is demonstrated in Figures 2 and 3. The width of the acoustic plumes varied between 100 and 600 m. Taking into account the swath width of the acoustic beam, this corresponds to variations between thin bubble streams and bubble plumes of several 100 m in diameter. In addition, the plumes even vanished on a few occasions. For example, on SO148 an acoustic plume that had been observed consistently for 1.5 hours at SHR disappeared completely within a few minutes. This phenomenon was also observed by video at the gas vents [*Torres et al.*, 2002].

[12] These variations may reasonably be explained by temporal changes in the gas venting, which was observed to weaken or even vanish at high tide in video observations at NHR [*Torres et al.*, 2002]. However, the acoustic detection frequently showed strong plumes during high tide at NHR and SHR. This indicates that multiple mechanisms modulate gas release, as suggested by *Tryon et al.* [2002] and *Heeschen and Collier* [2002].

[13] On all surveys, the tops of the acoustic plumes were observed at heights of 540–470 m below the sea surface at all gas vent sites, even though the seafloor depth ranged from 590 m at NHR to 780 m at SHR (Figure 4). Strong signals from the center of the well-mapped plumes generally rose to a depth of 480 ± 20 m. Weaker signals extended between 540 to 500 m below the sea surface, which might in part be due to the sideswipes of the gas plumes. These acoustic observations are supported by submersible moni-

toring of the rising gas bubbles conducted within the plumes at NHR. In the field of view of the submersible a clear decrease in the number and size of bubbles was observed at about 450 m depth [*Linke et al.*, 2001; *Suess et al.*, 2001].

[14] Usually the dissolution rate of rising gas bubbles is controlled by the partial pressure difference between the gas bubble and its environment, the solubility, the bubble size, the rise velocity, and adsorbed surfactants [e.g., *Clift et al.*, 1978]. It is unlikely that these parameters are different at NHR and SHR and thus could explain why the bubble plumes last about three times longer at SHR. Instead, we propose that formation of a methane hydrate skin around the bubbles as they enter the water column explains their modified behavior throughout the GHSZ, which includes decreased shrinking rates, a concept also applied by others [*Merewether et al.*, 1985 and literature therein; *Rehder et al.*, 2002].

[15] The consistency of the acoustic plume height at ~480 m below the sea surface also supports the idea of gas hydrate amouring of the rising bubbles, since this water depth is very close to the upper limit of the GHSZ. Above Hydrate Ridge, this limit should be at about 505 to 485 m (Figure 5). Therefore the rapid disappearance of the acoustic signals can be interpreted to be the result of dissolution of the gas hydrate skin and subsequent enhanced shrinking of the residual gas bubbles soon after they rise above the stability zone. It can be argued that due to the low sensitivity of the acoustic system the depth of complete dissolution can not be resolved. However, the results of the acoustic data are supported by the depth distribution of the stable carbon isotopic ratio of methane, $\partial^{13}C\text{-}CH_4$ in the water column above the vent sites at Hydrate Ridge [*Heeschen and Collier*, 2002]. Whereas the influence of the isotopically light vent methane with $\partial^{13}C\text{-}CH_4$ of -60 ± 6‰ PDB could be seen within the GHSZ, in general this isotopic signature quickly shifted towards −30‰ PDB at water depths shallower than 480 m. This heavier methane likely originates from sources on the upper continental slope and appears to dominate over any methane that might penetrate from below.

5. Conclusions

[16] This study, which analyzed sites of naturally sourced methane plumes that emerge into the ocean within the hydrate stability zone, provides strong supporting evidence for the importance of the "hydrate skin" mechanism for influencing the transport of methane through the water column. It also provides evidence for the stability of these plumes over time scales of years and underlines the importance of calibrated, long-term acoustic observatories for evaluating methane flux from bubbling methane vents on the seafloor.

[17] **Acknowledgments.** We greatly appreciate the support at sea by the masters and crews of R/V Atlantis, R/V Sonne, R/V Thompson and R/V Wecoma. We also thank Marta Torres and Magnus Eek for their indispensable help at sea. Financial support for this work was granted by the National Science Foundation (OCE-9731157; OCE-9811-471, OCE-9731-23, and OCE-9906990) and the German Federal Ministry of Education and Research (Fkz 03G0143A and 03GO148A).

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