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# Escape of methane gas from the seabed along the West Spitsbergen continental margin

Graham K. Westbrook,[1] Kate E. Thatcher,[1] Eelco J. Rohling,[2] Alexander M. Piotrowski,[3]
Heiko Pälike,[2] Anne H. Osborne,[4] Euan G. Nisbet,[5] Tim A. Minshull,[2]
Mathias Lanoisellé,[5] Rachael H. James,[2] Veit Hühnerbach,[2] Darryl Green,[2]
Rebecca E. Fisher,[5] Anya J. Crocker,[2] Anne Chabert,[2] Clara Bolton,[2]
Agnieszka Beszczynska-Möller,[6] Christian Berndt,[2,7] and Alfred Aquilina[8]

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[1] More than 250 plumes of gas bubbles have been discovered emanating from the seabed of the West Spitsbergen continental margin, in a depth range of 150–400 m, at and above the present upper limit of the gas hydrate stability zone (GHSZ). Some of the plumes extend upward to within 50 m of the sea surface. The gas is predominantly methane. Warming of the northward-flowing West Spitsbergen current by 1°C over the last thirty years is likely to have increased the release of methane from the seabed by reducing the extent of the GHSZ, causing the liberation of methane from decomposing hydrate. If this process becomes widespread along Arctic continental margins, tens of Teragrams of methane per year could be released into the ocean. **Citation:** Westbrook, G. K., et al. (2009), Escape of methane gas from the seabed along the West Spitsbergen continental margin, *Geophys. Res. Lett.*, *36*, L15608, doi:10.1029/2009GL039191.

## 1. Introduction

[2] Methane released from gas hydrate in submarine sediments has been invoked as an agent of past climate change [*Nisbet*, 1990, 2002; *Thomas et al.*, 2002; *Dickens*, 2003; *Kennett et al.*, 2003]. Beneath the seabed, the gas hydrate stability zone (GHSZ) for a specific gas or gases and salinity of water [e.g., *Sloan and Koh*, 2007] is defined by temperature (dependent on water temperature and geothermal gradient) and pressure (dependent on water depth plus depth beneath seabed). Dissociation of hydrate in response to increased temperature or reduced pressure has the potential to produce a rapid release of methane that has accumulated as hydrate over a long time from weak or moderate migration of methane as free gas or in solution. Comparatively little, however, is known about methane fluxes from dissociating hydrate in the present-day marine environment.

[3] In the Arctic, the GHSZ is especially sensitive to climate change, because the degree of temperature change is greater than at lower latitudes. A multidisciplinary marine geological, geophysical, and geochemical expedition was undertaken with the RRS James Clark Ross between 23 August and 24 September 2008 to investigate the role of the GHSZ in the release and retention of methane from geological sources along the West Spitsbergen continental margin, between 78° and 80°N. Here the depth and temperature of the water have varied greatly over the past 15 kyr [*Forman et al.*, 2004; *Hald et al.*, 2004], and, at present, the GHSZ (for pure methane and water with 3.5 wt % NaCl) is expected to taper out at its landward limit at a depth of about 400 m, where water temperature is 3°C (Figure 1).

## 2. Observations

[4] More than 250 active plumes of bubbles emanating from the seabed were discovered in water depths shallower than 400 m (Figure 1). Some of the plumes extended upward to within 50 m of the sea surface. The plumes were detected initially with a Simrad EK60 ‘fishfinder’ sonar, providing the 3D locations of the bubbles. Rates of upward movement of the bubbles were estimated to be 0.08–0.25 m/s, from the tilt of the plumes induced by a 0.5–1.0 knot current (0.25–0.5 m/s) and from the rates of ascent of pulses of bubbles observed when the ship was stationary above plumes. Several of the most closely studied plumes exhibited a pulsating behaviour, with periods of several minutes, and repeated visits to some plumes showed that they vary in strength over periods of a few days.

[5] Fissures and holes in the seabed, which are shown by high-resolution multibeam bathymetry and side-scan sonar images, locally control the positions of some plumes. Beneath the area of the plumes, seismic reflection sections show acoustic scattering that is typical of rising trains of gas bubbles, and down slope, beneath the GHSZ, the presence of free gas is indicated by negative polarity reflections, bright spots, attenuation of the high frequency content of the signal and velocity pull-down.

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[1] School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, UK.

[2] National Oceanography Centre Southampton, University of Southampton, Southampton, UK.

[3] Godwin Laboratory for Palaeoclimate Research, Department of Earth Sciences, Cambridge University, Cambridge, UK.

[4] Bristol Isotope Group, Department of Earth Sciences, University of Bristol, Bristol, UK.

[5] Department of Earth Sciences, Royal Holloway University of London, Egham, UK.

[6] Climate Sciences, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany.

[7] Leibniz Institute of Marine Sciences at University of Kiel (IFM-GEOMAR), Kiel, Germany.

[8] Organic Geochemistry Unit, Bristol Biogeochemistry Research Centre, School of Chemistry, University of Bristol, Bristol, UK.

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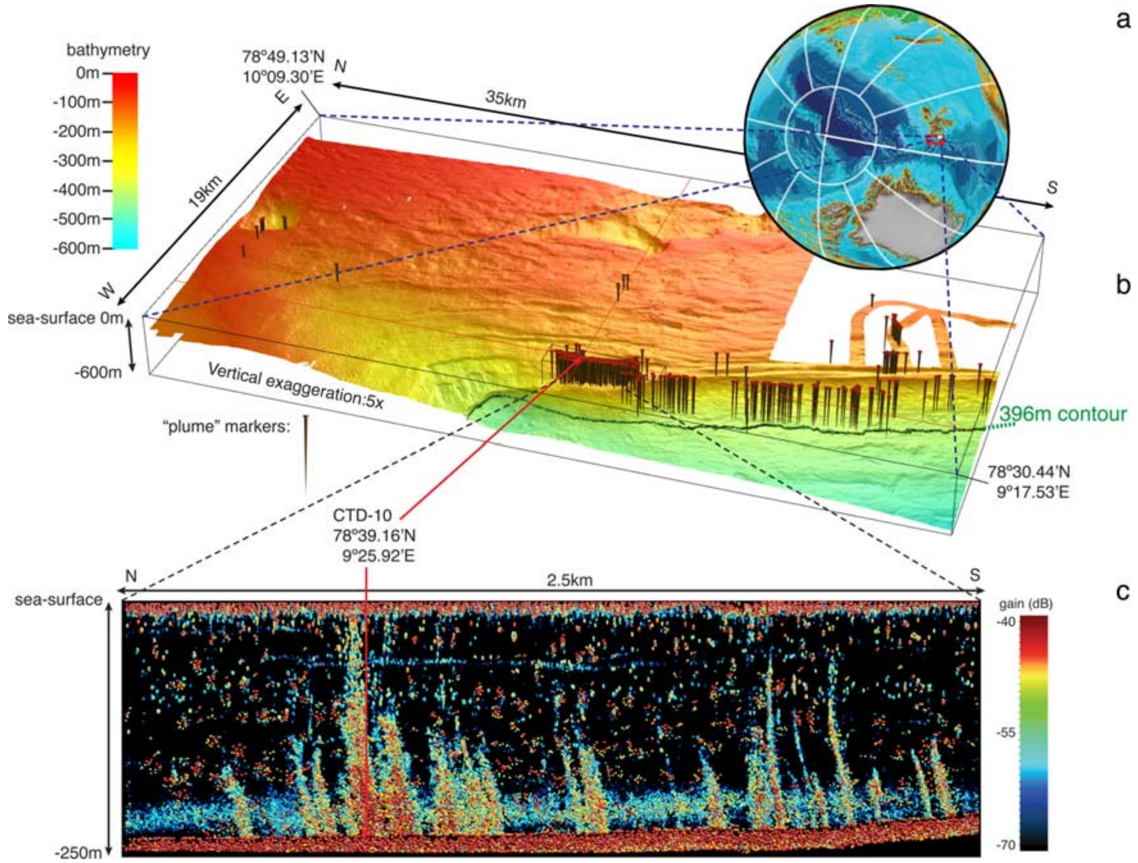

**Figure 1.** (a) Location of survey area west of Svalbard; IBCAO bathymetry [*Jakobsson et al.*, 2008]. ((b) Positions of plumes acoustically imaged with the EK60 sonar, depicted by "pins", superimposed on perspective view of the bathymetry of part of the area of plume occurrence. Bathymetry is from EM120 multibeam survey of cruise JR211 gridded at 20-m resolution, combined with high-resolution survey data from the Norwegian Hydrographic Service for the shallower-than-200-m part of the map. The 396-m isobath is the expected landward limit of the GHSZ. (c) Part of record from an EK60 acoustic survey from JR211, showing examples of observed plumes. Amplitude of acoustic response is given by the colour of the "bubbles". All plumes show a deflection towards the north caused by the West Svalbard Current. The seabed, at around 240-m depth, is shown by the strong (red) response. The position of CTD cast 10 is indicated by vertical red arrow.

[6] Sampling of the plumes was undertaken using dynamic positioning of the vessel in conjunction with real-time USBL acoustic location of the rosette sampler on CTD casts. Analyses of the water samples, using the standard static headspace - gas chromatography technique [*Kolb and Ettre*, 1997], revealed that methane concentrations within the plumes were elevated to up to 20 times background values (Figure 2). Salinity and temperature were nearly constant and light transmission was reduced in the main part of the sampled plumes. In some localities, we found enhanced methane concentrations in the water column, even though distinct plumes of bubbles were absent. This could be indicative of very recent plume activity or of diffuse escape of gas in solution from the seabed. The time-variant behaviour of some seeps, and the apparent presence of diffuse seepage, complicate volumetric estimates of the rates of gas escape from the sea floor.

## 3. Origin of Bubble Plumes

[7] The greatest concentration of plumes lies just landward of the edge of the GHSZ. Plumes also occur on the shelf as far as 15 km from the GHSZ, some of them in water shallower than 200 m. Even with a seabed temperature of 0°C, the hydrate stability zone does not exist in water depths shallower than 300 m. So it is probable that many of the plumes are directly fed by the primary geological methane source in this area and that gas seeps have existed since the margin was flooded as glacial ice retreated about 13 ka [*Landvik et al.*, 2005] and sub-glacial permafrost melted. It appears that the GHSZ restricts methane outflow from the seabed by converting methane to hydrate and possibly, in combination with the seaward dip of the strata, by diverting up slope the flow of methane that has not entered the GHSZ, because of the reduction in permeability caused by the presence of hydrate (Figure 3a). A similar situation occurs in the Black Sea, west of Crimea [*Naudts et al.*, 2006]. Methane, however, can also be released from dissociating hydrate during periods when warming causes the GHSZ to contract (Figure 3b).

[8] Progressive warming of the northward-flowing West Spitsbergen current (WSC) of about 1°C over the last 30 years in the area in which the plumes occur is shown by CTD casts made over the period 1975 to 2008 (Figure 4). This is consistent with other observations of warming of the WSC [*Schauer et al.*, 2004, 2008; *Walczowski and*

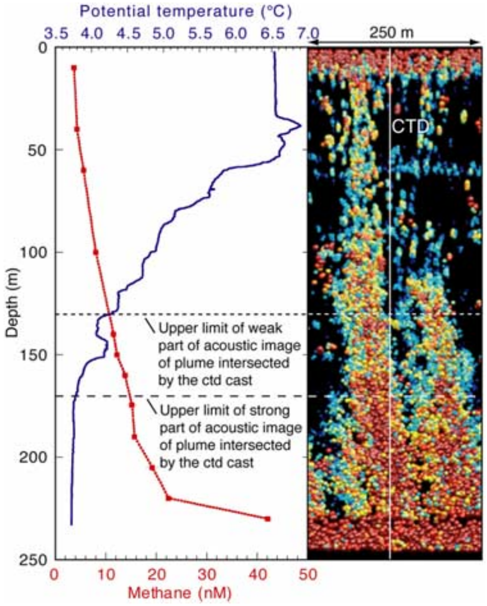

**Figure 2.** Results from CTD cast 10, which intersects a bubble plume. See Figure 1 for location. Methane concentration increases consistently downwards and shows a strong increase in the lowermost 40 m of the cast to a value of 42 nM.

*Piechura*, 2007]. The temperature data were taken from the World Ocean Database [*Boyer et al.*, 2006], Hydrobase2 (http://www.whoi.edu/science/PO/hydrobase) and cruises of the Alfred Wegener Institute [*Schauer et al.*, 2008]. To reduce seasonal bias, only data from May to October were used. A bivariate regression of the average temperature of the bottom 10 m of each of the CTDs in the depth range 200–700 m against depth and date indicates that the average rate of warming has been about 0.03°C $yr^{-1}$. This general trend is also shown by averaging temperatures for each CTD in the depth ranges 300–350, 350–400 and 400–450 m, which span the expected depth of the top of the GHSZ (Figure 4c).

[9] A 1°C rise in temperature will have caused the limit of the GHSZ to retreat a horizontal distance of about 950 m down the continental slope of 2° from a depth of 360 m to 396 m, releasing methane from hydrate (see auxiliary material).[1] Farther down the continental slope, hydrate occupies (on average) about 9% of pore space of half the hydrate stability zone [*Westbrook et al.*, 2008]. If a similar proportion of hydrate (assuming 50% porosity) occupied the GHSZ retreat zone, the average annual loss of methane to the water would be about 900 kg per metre length of margin, and hence, the 30-km-long plume-area would lose about 0.027 Tg $yr^{-1}$ from dissociating hydrate, in addition to methane from primary sources.

## 4. Possible Implications for the Arctic Methane Budget

[10] Widespread seeps of methane from the seabed around Spitsbergen [*Knies et al.*, 2004], elevated concentrations of methane in the bottom water of the shelf and uppermost continental slope of SW Spitsbergen [*Damm et al.*, 2005] and the occurrence of a plume east of Bear Island [*Lammers et al.*, 1995] indicate seepage of methane into the ocean over a large area. If the hydrate-to-methane budget of the plume area can be extended to the 22,300 $km^2$ of seabed in the depth range of 360–400 m along the northern, western and southern margins of the Svalbard archipelago as far as an eastern limit at 40.4°E [*Jakobsson et al.*, 2008], the potential methane release by hydrate dissociation may be about 20 Tg $yr^{-1}$. Hydrate dissociation is potentially significant for a large proportion of the Arctic continental slope, because the WSC feeds into the Arctic Ocean. Increased warming by Atlantic water has been observed in the Nansen basin [*Quadfasel et al.*, 1991] and propagating along the Siberian continental margin [*Polyakov et al.*, 2007]. Increasing temperature will cause the reduction of the GHSZ and possibly release many tens of Teragrams of methane per year, depending on how much hydrate is present.

[11] The release of tens of Teragrams of methane per year would be a notable fraction of the annual global atmospheric methane flux of 500–600 Tg $yr^{-1}$ [*Houweling et al.*, 2006] and comparable with the 20–40 Tg $yr^{-1}$ estimated for methane flux from all geological sources on land [*Etiope et al.*, 2009], but it is unlikely that more than a very small fraction of the methane in the observed plumes reaches the atmosphere directly. The acoustic images of the bubble plumes show very few that reach the sea surface, and even for these it is probable that nitrogen and other gases would have largely replaced methane in the bubbles during their ascent [cf. *McGinnis et al.*, 2006]. Some methane, however, will transfer to the atmosphere by equilibration. Methane concentration measured in surface seawater, 3.7 ± 0.2 nM, in the area in which plumes were observed was higher than the concentration of 3.0 nM calculated (using the equation of *Wiesenburg and Guinasso* [1979]) for seawater in equilibrium with ambient air at 1840 ppb, the methane mixing ratio in contemporaneous air measurements made on the cruise. Also, given the generally episodic nature of gas venting from the seabed, one cannot exclude the possibility of, as yet unobserved, periods of more vigorous activity, in which methane may be expelled to the atmosphere. Lastly, it should not be overlooked that the addition of methane to the ocean is itself important, because oxidation of methane in the water column increases ocean acidity and lowers levels of dissolved oxygen, with consequent implications for marine biodiversity [*Valentine et al.*, 2001; *Riebesell*, 2008].

## 5. Conclusions

[12] New observations of a large number of gas plumes on the W Spitsbergen margin significantly extend the observational context of important gas seeps in the Arctic region. Their occurrence and activity appear to be controlled by the GHSZ, which is sensitive to changes in water temperature. The occurrence of plumes in the zone from which the GHSZ has retreated over the last 30 years implies that at least part of the methane feeding the plumes comes from dissociating hydrate. This has wide significance for methane release from Arctic continental margins, if

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GL039191.

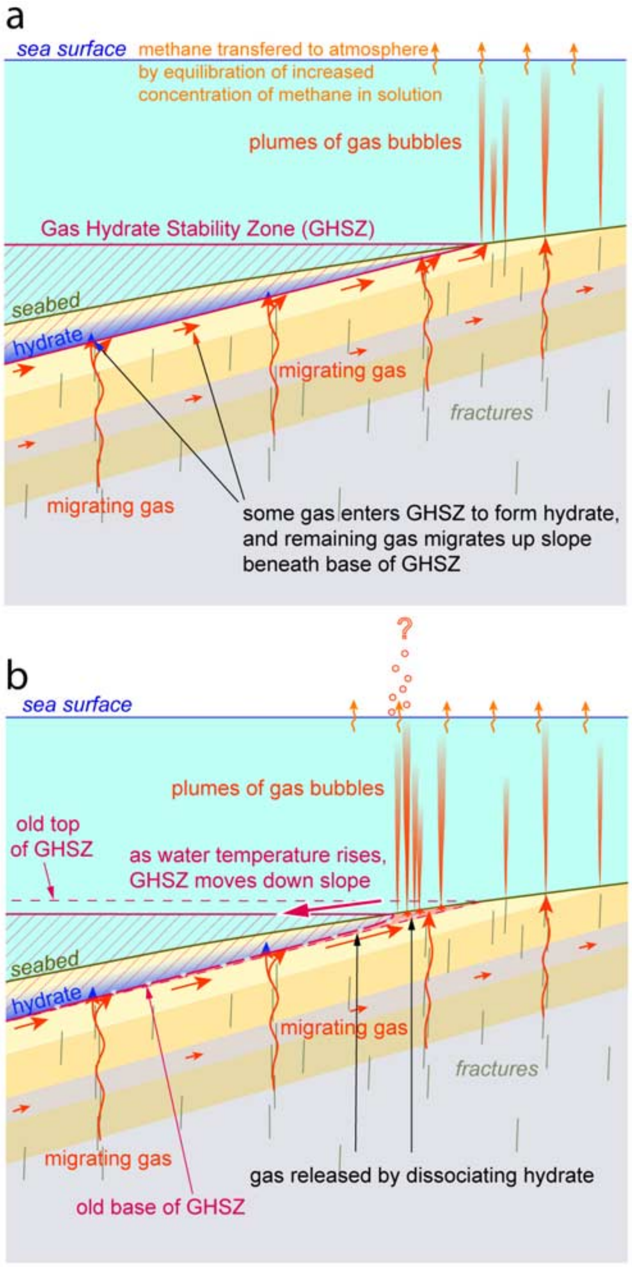

**Figure 3.** (a) Migrating methane gas is restricted from reaching the seabed in the GHSZ by its conversion to hydrate and by the overall reduction in permeability caused by the growth of hydrate at the base of the GHSZ, which may divert a proportion of the gas to flow up slope. Methane gas escaping from the seabed beyond the GHSZ rises as bubbles through the seawater. Most of the methane appears to dissolve in the water. Some dissolved methane will enter the atmosphere by equilibration. (b) An increase in the temperature of the seawater causes the GHSZ to contract down slope, dissociating hydrate to methane and water. The time-dependence of this process is illustrated in the auxiliary material. Where the GHSZ is removed entirely, all the released gas is free to move to the seabed, guided by local variation in lithology and structure. Where a thinner GHSZ remains, gas from the dissociated hydrate at its base can migrate into the GHSZ to form hydrate again and may also migrate up slope.

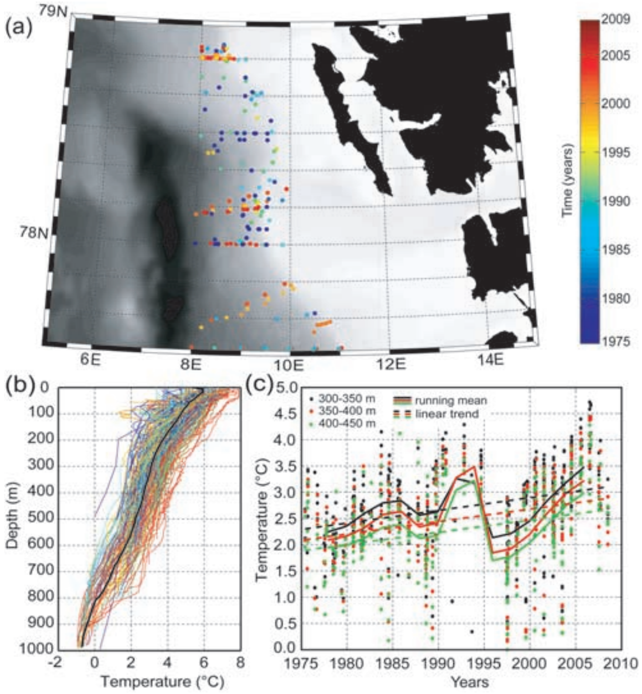

**Figure 4.** (a) Positions of the CTDs west of Spitsbergen from which temperatures were analysed for the period 1975–2008. Colour indicates the year in which each measurement was taken. Water depth ranges from less than 200 m (white) to greater than 3000 m (darkest grey). (b) Temperature versus depth for each CTD, colour coded by year. (c) Average temperature in depth ranges 300–350 (black), 350–400 (red) and 400–450 m (green) for each of the CTD casts for the period 1975–2008. Dashed lines are the best-fit linear regression lines for the averages. Solid lines show 5-year running means of the averages.

increasingly warmer water enters from the Atlantic. Further exploration of hydrate and monitoring of methane release are needed to quantify the likely magnitude of future emissions.

[13] **Acknowledgments.** This work was funded by the Natural Environment Research Council as part of its Arctic Initiative for the International Polar Year 2007–2008. Part of the bathymetric image shown in Figure 1 comes from data provided by the Norwegian Hydrographic Service. The captain and crew of RRS James Clark Ross during Cruise JR211 provided essential support for the acquisition of the data.

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A. Aquilina, Organic Geochemistry Unit, Bristol Biogeochemistry Research Centre, School of Chemistry, University of Bristol, Bristol BS8 1TS, UK.

C. Berndt, Leibniz Institute of Marine Sciences at University of Kiel (IFM-GEOMAR), Wischhofstrasse 1–3, D-24148 Kiel, Germany.

A. Beszczynska-Möller, Climate Sciences, Alfred Wegener Institute for Polar and Marine Research, D-27515 Bremerhaven, Germany.

C. Bolton, A. Chabert, A. J. Crocker, D. Green, V. Hühnerbach, R. H. James, T. A. Minshull, H. Pälike, and E. J. Rohling, National Oceanography Centre Southampton, University of Southampton, European Way, Southampton SO14 3ZH, UK.

R. E. Fisher, M. Lanoisellé, and E. G. Nisbet, Department of Earth Sciences, Royal Holloway University of London, Egham TW20 0EX, UK.

A. H. Osborne, Bristol Isotope Group, Department of Earth Sciences, University of Bristol, Bristol BS8 1RJ, UK.

A. M. Piotrowski, Godwin Laboratory for Palaeoclimate Research, Department of Earth Sciences, Cambridge University, Cambridge CB4 2TY, UK.

K. E. Thatcher and G. K. Westbrook, School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston B15 2TT, UK. (g.k.westbrook@bham.ac.uk)