Geophysical Research Letters

RESEARCH LETTER

10.1029/2020GL089906

Key Points:

- Very high resolution (<1 m) deep-towed seismic imaging of the bottom-simulating reflector allows characterizing gas hydrates dynamics
- Irregular bottom-simulating reflector is an indicator of the transient state of a gas hydrate system in the Black Sea
- Pore overpressure and hydrate recrystallization explain the long process of the readjustment of the base of the gas hydrate stability zone

Supporting Information:

- Supporting Information S1

Correspondence to:

F. Colin,
florent.colin@ifremer.fr

Citation:

Colin, F., Ker, S., Riboulot, V., & Sultan, N. (2020). Irregular BSR: Evidence of an ongoing reequilibrium of a gas hydrate system. *Geophysical Research Letters*, 47, e2020GL089906. <https://doi.org/10.1029/2020GL089906>

Received 16 JUL 2020

Accepted 27 SEP 2020

Accepted article online 30 SEP 2020

Irregular BSR: Evidence of an Ongoing Reequilibrium of a Gas Hydrate System

F. Colin¹ , S. Ker¹ , V. Riboulot¹ , and N. Sultan¹

¹Ifremer, REM-GM, Centre de Brest, Plouzané, France

Abstract Gas hydrate (GH) systems constitute methane sinks sensitive to environmental changes such as pressure, temperature, and salinity. It remains a matter of debate as to whether the large GH system of the Black Sea has reached a steady state since the last glacial maximum (LGM). We report on an irregular free gas distribution in specific sediment layers marking an irregular bottom-simulating reflector (BSR). This anomalous free gas distribution revealed by very high resolution seismic images, acquired by a deep-towed multichannel seismic system, might be evidence of an ongoing migration of the base of the GH stability zone (GHSZ). We show that the reequilibrium is not occurring homogeneously as overpressure from hydrate dissociation slows their decomposition in specific sedimentary layers. The Black Sea example highlights that dissociation and the associated methane release in the water column or even in the atmosphere could be largely delayed by overpressure accumulation.

Plain Language Summary Methane hydrate is an ice-like compound composed of a cage of water molecules enclosing a methane molecule. Hydrates can form where water and methane are present under high pressure and low temperatures, for example, in deep-sea sediments. As a result of climate change (e.g., seawater temperature increase), hydrates can melt and release free gas and water. Yet we observe that hydrates are present where they should have melted according to modeling. We explain this irregular melting by differing properties of the host sediments and different quantities of hydrate in the sediments. Methane in the Earth's atmosphere is a strong greenhouse gas. The release of methane from hydrate melting has been proposed as a runaway process where the methane released increases global warming, which further increases hydrate melting and methane release, repeating the cycle. Our results show that the destabilization of a hydrate system is actually a slow process, spanning several millennia. As such, a catastrophic destabilization of a gas hydrate system is unlikely.

1. Introduction

Gas hydrates (GHs) are ice-like solids composed of water cages that trap a host molecule, most commonly methane. Specific conditions are needed for GHs to become stable: low temperature and high pressure (Sloan & Koh, 2008), but salinity has also been demonstrated to be a factor (Dickens & Quinby-Hunt, 1994). GHs constitute an important methane sink (Ruppel & Kessler, 2017) prone to destabilization when environmental conditions are modified, for example, hydrostatic pressure variations caused by sea level change (Maslin et al., 2004), temperature increase by ocean warming (Crémière et al., 2016; Phrampus & Hornbach, 2012) or salinity variations (Riboulot et al., 2018). The free gas released in the sediment may reach the water column, contributing to ocean acidification (Valentine et al., 2001) and possibly, although still subject of debate (McGinnis et al., 2006; Ruppel & Kessler, 2017), also the atmosphere, where it would contribute to global warming.

Improving our understanding of the GH system response to environmental change is therefore essential to enhance our capacity to quantify the free gas released from hydrate destabilization. Geochemical methods (isotope analysis) can be used to assess past destabilizations such as in the Krishna-Godavari Basin consecutive to a sea level drop (Joshi et al., 2014). Other examples of ongoing GH destabilization include Lake Baikal (De Batist et al., 2002) and the U.S. Beaufort margin (Hornbach et al., 2020).

The bottom-simulating reflector (BSR) detected in seismic reflection data is indirect evidence of the presence of GHs in marine sediments. It represents the base of the GH occurrence zone (GHOZ) but can be inconsistent with the predicted one. Many processes can explain the disparity between model and observation, such

as localized heat flow anomalies (De Batist et al., 2002; Suess et al., 1999) or bottom water temperature variations (Phrampus et al., 2014).

The GH system located in the Romanian sector of the Black Sea was recently shown to be in disequilibrium (transient regime) in response to a rise in water level (Constantinescu et al., 2015; Lericolais et al., 2009) and increase in water temperature (Poort et al., 2005) and salinity (Soulet et al., 2010, 2011) since the last glacial maximum (LGM). Hillman et al. (2018) show that in some areas with topographic relief the apparent disequilibrium of this GH system could be generated by a disruption of the geothermal gradient related to a combination of variable thermal properties of the marine sediments and topographic focusing of a submarine canyon. Through a study in a larger area including regions without distinct topographic relief, Ker et al. (2019) systematically estimated a shallower steady-state lower limit of the GHSZ compared with the observed BSR, thus exposing a system in a transient state. In this same area (Figure 1), our interpretation of a new geophysical data set enables us to greatly improve our understanding of this GH system. This paper is based on our observation of the shape of the BSR on very high resolution (VHR) seismic images (vertical resolution <1 m), compared to the predicted depth of the base of the GHSZ (BGHSZ). In addition, our discussion details the impact of our findings on the assessment of GH dynamics.

2. Methods: HR and VHR Seismic Data

We used legacy high-resolution (HR) seismic data acquired in 1998 during the BLASON cruise (Lericolais, 1998). The HR seismic profile Bla1-7 (Figure 2a) was obtained using a small airgun source (central frequency: 150 Hz) and a short 24-channel streamer with a maximum offset of 335 m (Popescu et al., 2006). The seismic profile was converted from time to depth using a constant velocity (seawater velocity, 1,482 m/s). We also used HR data that were acquired in 2015 during the GHASS cruise (Ker & Riboulot, 2015) using a small airgun source (central frequency: 110 Hz) and a 96-channel streamer with a maximum offset of 650 m (locations in Figure S1 in the supporting information). Profile HR31a (Figure S2) was processed using a prestack depth imaging sequence (Ker et al., 2019). Seismic resolution of profiles Bla1-7 and HR31a is in the order of 3 m vertically and 15 m horizontally.

To investigate the GHSZ in detail, we used VHR deep-towed multichannel seismic data acquired during the GHASS cruise with Ifremer seismic equipment (SYstème SIsmique de Fond, SYSIF). SYSIF is composed of a Janus-Helmholtz acoustic source (220–1050 Hz) and a 52-channel streamer with a maximum offset of 110 m, tailored for working under high-hydrostatic pressure environments (Ker et al., 2010; Marsset et al., 2014). Recent developments based on wave-equation datuming allowed for fine-scale velocity analysis on SYSIF seismic data sets down to 50–100 m below seafloor (mbsf) (Colin et al., 2020). Because of the limited length of the streamer, velocity analysis cannot be accomplished any deeper and the velocity field at depth is defined with neighboring HR data analysis. Seismic resolution of the SYSIF profile PL01PR12 presented in Figure 3a (and Figures S3–S5) is less than 1 m vertically and 3 m horizontally.

3. Results

The study area is situated at 700 to 1,000 m water depth between Canyon 1 and Canyon 2 (Riboulot et al., 2017, Figure 1a) and far from any large topographic effects. However, the seafloor is riddled with dozens of mounds, visible on the bathymetric and seismic data (Figure 1b). The mounds, up to 30 m high, are inherited morphologies from the compressional bulges of a regional mass transport deposit (MTD) located around 50 mbsf (Riboulot et al., 2017).

3.1. Stratigraphy

The sedimentary column is dominated by three vertically stacked seismic facies (Figures 2 and 3). The HR seismic profile Bla1-7 provides a representative overview of the stratigraphy (Figure 2).

1. In the first 50 to 75 mbsf, a thick sedimentary layer is characterized by a stack of two seismic facies, one dominated by parallel seismic reflections and the second by chaotic reflections (shallow hatched green patch in Figure 2b).
2. Under the draping, an acoustically transparent seismic facies shows the presence of a 50 m thick MTD. Under the small mounds, the MTD is thicker and consists of a chaotic seismic facies with remnant

Figure 1. Map of the study area. (a) Location of the study area on the continental slope of the Black Sea. The blue shaded area marks where the BSR is present, blue line: outcrop of the BSR, red line: upper limit of the predicted BGHSZ, blue-green dots: acoustic gas flares identified during the GHASS cruise (Riboulot et al., 2017). (b) Bathymetric map of the area with the location of the seismic profiles, blue-green dots: acoustic gas flares. (c) Interpolated depth map of the BSR under the seafloor, the blue lines represent observations of the BSR on seismic profiles. The purple crosses show the presence of free gas above the regional trend of the BSR, and the red dashed polygon delimits the inferred location of a more concentrated hydrate thick bed.

stratigraphy, consistent with compressional bulges (Frey-Martinez et al., 2006) (deeper hatched green patch in Figures 2b and 3b).

3. The regional MTD rests on well-stratified sediments. The seismic facies is composed of subparallel and subhorizontal reflectors. The alternating low- and high-amplitude reflections may reflect a difference in porosity or permeability. The observed normal faults cross through the regional BSR without offsetting it (Figures 2 and 3).

3.2. BSR and Gas-Charged Layers

On profile Bla1-7 (Figure 2), the BSR is observed either as a continuous reflector crossing the stratigraphy or the alignment of strong amplitude terminations of reflectors. This “discontinuous” BSR (Shedd et al., 2012; Vanneste et al., 2001) is the most common type in the area. The BSR deepens seaward from 200 to 330 mbsf as water depth increases from 750 to 1,000 m. Below the BSR typical gas-charged layers are identified through reflections characterized by high amplitude and negative polarity relative to seafloor reflections (Figures 2c and 2d). Seismic attenuation associated with the presence of free gas does not allow identifying the base of the sediment layers below the regional MTD nor the base of the free gas zone.

If, at first glance, the BSR appears to dip smoothly on profile Bla1-7, some segments seem irregular (Figure 2b). The submetric resolution VHR image enables to identify a complex geometry of the BSR (Figures 3 and S3–S5). In some locations, gas-charged layers marked by isolated enhanced reflections (ERs) with greater amplitudes seem to be present above the regional trend of the BSR (purple reflectors in Figure 3b). Some of these gas-charged reflectors have a dashed appearance with diffraction hyperbolae (Figures 3b, 3e, and 3f).

Figure 2. Typical sedimentary architecture of the study area. (a) HR seismic reflection profile Bla1-7 (location in Figure 1b) showing the location of the closeup views c, d, e, and f. (b) The interpreted profile shows the sedimentary column marked by the presence of a “discontinuous” BSR delimiting the free gas occurrence zone and the GH. c, d, and e: Closeup views showing the signature of the seafloor, the BSR, and the high-amplitude reflector inside the GHZO. f: Closeup view matching the VHR profile presented in Figure 3.

These diffractions highlight the presence of heterogeneities smaller than the lateral resolution of the VHR seismic data (<3 m). These heterogeneities are likely free gas patches as indicated by the phase reversal (Figure 3d). This complex free gas distribution makes the precise identification of the BSR location difficult. Figure 1c shows the distribution of the BSR depth in this area and highlights the locations of anomalous gas-charged reflectors present above the regional trend of the BSR (purple crosses). The penetration of high-frequency acoustic signals (220–1050 Hz, Colin et al., 2020; Ker et al., 2014) is sensitive to the presence of free gas, specifically where the bubble diameter is larger than 20 mm (Tóth et al., 2015). Therefore, seismic wave penetration of more than 100 m under the gas front may indicate a low free gas content (Figure 3a). The paleo-BSR observed at around 340 mbsf (Figure 2b) is not ubiquitous in the area and expresses a past boundary between GH and free gas (Zander et al., 2017).

3.3. Gas Hydrate-Bearing Layer

The extent of the GHZO (orange zone in Figure 2b) is assumed from positive P -wave velocity anomalies identified on the neighboring profile HR31a (Ker et al., 2019). Velocity analysis could not be performed on profile Bla1-7 because of the limited offset of the streamer. The GHZO on profile HR31a is situated between the MTD and the BSR (Ker et al., 2019). However, for profile Bla1-7 the upper limit cannot be precisely defined (Figure 2). We identify an isolated high-amplitude reflection within the assumed GHZO on Figures 2b and 3b (orange reflector). The polarity of the reflection (Figure 2d) is identical to that of the seafloor reflection (Figure 2b). The VHR signature of the recorded wavelet (Figure 3c) corresponds to the

Figure 3. The irregular BSR. (a) VHR seismic reflection profile PL01PR12 (location in Figures 1 and 2). (b) The interpreted profile shows the free gas-GH boundary. Several free gas-related ERs are present above the regional trend of the BSR (numbered 1 to 6). (c) High-amplitude isolated reflector within the assumed GHZO. (d) Acoustic signature of a gas charged layer. (e, f) Closeup views showing the free gas-related ERs composed of many diffractions (e) and presenting a patchy aspect (f).

convolution of the source wavelet with a Heaviside function, indicating a step-like discontinuity in the acoustic impedance. Accordingly, we interpret this reflector as the top of a thick bed with higher impedance. Because this reflector is in the same stratigraphic layer as where free gas can be identified (Figure 3d) and within the presumed GHZO, we interpret this reflector as the top of a more concentrated hydrate deposit.

4. Discussion

4.1. Implications of the Irregular BSR

The complex gas front observed on the VHR seismic data indicates the presence of free gas further up the stratigraphy in specific layers. When addressing the mechanism responsible for the irregular shape of the BSR, we consider two possible states of the western Black Sea GH system: a steady state or a transient state.

4.1.1. In a Steady-State System

The coexistence of free gas and GHs in the GHSZ has been reported in several steady-state GH systems around the world (Crutchley et al., 2015; Gorman et al., 2002; Gullapalli et al., 2019; Haacke et al., 2009; Netzeband et al., 2005; Riedel et al., 2006; Sultan et al., 2011, 2014; Tréhu et al., 2004; Vanneste

et al., 2001). Two groups of mechanisms have been proposed to explain the coexistence of GHs and free gas within the GHSZ: free gas transport (Meyer et al., 2020; Riedel et al., 2006; Sultan et al., 2014) or hydrate formation limitation (Haeckel et al., 2004; J. Liu et al., 2019; X. Liu & Flemings, 2007; You & Flemings, 2018).

With respect to the first group of mechanisms, free gas invasion into the GHSZ can be observed in the presence of vertical/subvertical features such as chimneys, along faults, under high or low flux of free gas (Crutchley et al., 2014; Gorman et al., 2002; Gullapalli et al., 2019; Haacke et al., 2009; Ker et al., 2019). In the present case, we observe on the VHR seismic images free gas along subhorizontal strata but not along vertical discontinuities. These free gas accumulations could result from percolation through permeable sedimentary layers. However, this requires high differential pressure (Meyer et al., 2018), yet the low seismic attenuation indicates minimal amounts of free gas accumulation. Consequently, free gas transport seems an unlikely mechanism explaining the observed complex free gas distribution.

Regarding the second kind of mechanism, sediment layers with variable thermal diffusivities would lead to a nonlinear geothermal gradient, which could bring the sediment layers alternatively in and out of the GHSZ. We observe six BSR irregularities within a 140 m depth interval (Figure 3a). Therefore, such a mechanism would require sediments with heterogeneous thermal diffusivity so that the sediment's temperature profile crosses the GH stability law six times in 140 m. Such thermal diffusivity profile is highly unlikely. Free gas composition is also excluded as a driving factor as the gas is composed of more than 99.6% biogenic methane in the area (Riboulot et al., 2018). Therefore, it is difficult to hold hydrate formation limitation responsible for the irregular BSR in this steady-state system.

4.1.2. In a Transient State System

A GH system could be in transient state because of salinity anomalies in the sediment that have yet to equilibrate (Riboulot et al., 2018). A local change in pore water salinity modifies the stability conditions and prevents GH formation in high-salinity layers (Figure S6). The six BSR irregularities we observe (Figure 3a) require sharp positive salinity anomalies. The prerequisite of such variability is a rapid alternation between marine and lacustrine sequences. Such a rapid alternation has never been documented and has not been reported from borehole data (Calvert & Batchelor, 1978; Riedel et al., 2020). In addition, the sharp boundaries required seem unrealistic, as salt diffusion would have occurred since sedimentation, even in the least permeable layers.

In a transient state, a heterogeneous GH dissociation is a possible mechanism explaining the irregular BSR. This heterogeneity could result from (i) different sediment permeability, (ii) variable GH concentrations, or (iii) a combination of both.

In the first case of different sediment permeability, the dissipation of the excess pore pressure generated by GH dissociation is facilitated in layers with higher permeability. However, in lower sediment permeability, the generated overpressure accumulates and delays further dissociation by recrystallizing part of the GHs (Sultan, 2007). As a result, the BGHSZ moves more slowly in sediments with lower permeability. In three MeBo drilling sites, Riedel et al. (2020) describe “sand layers several millimeters in thickness” as “typical” in the deeper units, between 45 and 140 mbsf. The analysis of long-piston cores also shows the presence of sandy layers of thickness increasing with depth (Martinez-Lamas et al., 2020). These observations indicate the presence of higher permeability layers within the overall fine grained sediments of the area.

In the second case of sedimentary layers with higher GH concentration, the dissociation produces more free gas and higher pore overpressure. In these layers, the overpressure can delay hydrate dissociation. However, in sedimentary layers with lower GH concentration the generated pore overpressure is lower and does not slow GH dissociation as much. Therefore, the BSR will shoal faster than in layers with higher GH concentration.

4.2. Most Likely Mechanism Explaining the Irregular BSR

Our observations of an irregular BSR support the hypothesis that the upward migration of the base of the GHZO (BGHOZ) is a long-lasting process and that the western Black Sea GH system is still in a transient state (Poort et al., 2005). In a neighboring area, Zander et al. (2017) suggest that the Danube area is still adapting to increased water temperature and is not thermally stable. West of Canyon 1, the geothermal gradient was measured at 24.5°K/km by Riboulot et al. (2018). Ker et al. (2019) showed that the predicted BGHSZ computed with a gradient of 24.5°K/km is not in agreement with the observed BSR depth in the

Different permeabilities of the sedimentary layers

Figure 4. Conceptual model of the evolution of the GHZO in response to environmental changes explaining the processes at the origin of the “irregular BSR”. Each case is composed of three phases (a, b, and c) detailed in the discussion.

study area. We confirm this result for profile Bla1-7 as modeling of the steady-state BGHSZ (Sultan et al., 2010) shows that the observed BSR is currently shallower than the LGM modeling yet deeper than the present-day modeling (Figure S7). The intermediate depth of the BSR supports the hypothesis of a transient state of the hydrate system.

In the following paragraphs, we propose two simplified kinematic models representing the upward migration of the BGHOZ caused by environmental changes (Figure 4). The models represent two end-members explaining the heterogeneous GH dissociation: a case in which only permeability comes into play (Model 1) and a case in which only the GH concentration varies (Model 2). Both models are illustrated with reference to the same three stages spanning several millennia and backed by modeling and VHR seismic interpretations. For both models, at the first stage (Figures 4a1 and 4a2) the GH system is at equilibrium under LGM pressure/temperature/salinity (PTS) conditions. The BGHSZ1 matches with the BSR and delimits free gas accumulation underneath the GHZO.

For the second stage of Model 1 (Figure 4b1), the PTS conditions are still adjusting since the LGM, and we observe a shallower BGHSZ2. Below the BGHSZ2, GHs start dissociating and generate overpressure in the sedimentary layers. At the last stage (Figure 4c1), the PTS conditions have stabilized and the BGHSZ3 corresponds to the steady-state BGHSZ. In lower permeability layers, the excess pore pressure accumulates and prevents further GH dissociation thus delaying the migration of the BGHOZ. However, the higher permeability of particular layers prevents the buildup of excess pore pressure. This process is effective regardless of the hydrate concentration in the layer as the excess pressure can be evacuated on the free gas occurrence side. Therefore, GH destabilization occurs more rapidly in higher permeability layers and free gas is present at shallower depths. The free gas occurrence zone moves upward but much slower in low-permeability layers.

For the second stage of Model 2 (Figure 4b2), the PTS conditions are also adjusting. Between BGHSZ1 and BGHSZ2, GHs start dissociating and release free gas. In layers containing more GHs, additional excess pressure is generated and overpressure accumulates. However, in layers containing less GHs, the excess pressure generated is lower. At the third stage (Figure 4c2), GH dissociation is slowed down in relation to accumulated overpressure. Therefore, the shoaling of the BSR is delayed by significant overpressure in layers with higher GH concentration. Whereas in layers with smaller amounts of GHs, the generated overpressure does not impede dissociation as much and the BSR migrates quicker.

In both cases, in layers of higher permeability or lower GH concentration, it is likely that the free gas release is not homogeneous and occurs within patches. Variations in permeability and GH concentrations describe the nonuniform seaward migration of the BGHOZ.

4.3. Significance of our Findings

The scenario presented could explain the irregular geometry of the BSR and would confirm a transient state of the GH system in the western Black Sea. Consequently, the depth of a BSR cannot be used to determine accurately the geothermal gradient or heat flux when the GH system is not in a steady state.

The BGHSZ is often considered as a weak zone in terms of pore pressure and slope stability. The coexistence between pore overpressure and recrystallization of hydrates prevents the formation in high excess pore pressure at the BGHSZ. The maximum excess pore pressure generated by GH dissociation is limited by the GH stability law and in our case is not sufficient to achieve hydrofracturing (Figure S8).

The possibility of a runaway dissociation of GH leading to rapid global warming events, known as the “clathrate gun hypothesis”, has been debated for some time (Hill et al., 2006; Kennett et al., 2000). The long transient state of the western Black Sea for 9 Kyr and the delaying process we present confirm the low likelihood of a catastrophic destabilization of a GH system.

5. Conclusion

We report on the abnormal migration of the BGHOZ through the observation of an irregular BSR. The irregular BSR reflects a transient state of the hydrate system in the Romanian sector of the Black Sea. The detection of the irregular morphology of the BSR was made possible through seismic data acquired by SYSIF, a unique VHR multichannel deep-towed seismic acquisition system. The irregular BSR is proposed to be the consequence of two complementary processes occurring as the BGHSZ moves upward with time: an increased excess pore pressure generated by higher concentrations of GHs in certain strata and an overpressure accumulation in lower permeability sediments. The combination of the two processes accumulates high pore pressure, which causes recrystallization of GHs, thus delaying the BGHSZ migration. The heterogeneous sediment properties and hydrate concentrations explain the disparity between the observed BSR and the current steady-state modeling of the BGHSZ. These processes delay the dissociation of GHs and make a runaway dissociation of a GH system an unlikely hypothesis. The key point of our findings is that the simple observation of an irregular morphology of a BSR is sufficient to reveal the transient state of the GH system. The depth of a BSR can therefore not be used to determine accurately the geothermal gradient or heat fluxes when the GH system is not in a steady state.

Data Availability Statement

Data are accessible online (<https://doi.org/10.17882/74866>).

Acknowledgments

The support by officers and crew during the BLASON and GHASS cruises on board R/V Le Suroît and Pourquoi pas? is appreciated as is the dedication of the Genavir and Ifremer technical staff. We thank Bruno Marsset for his considerable work on deep-towed seismic. We thank Alison Chalm and Shane Murphy for the revision of the English language. We thank Marc De Batist and Joe Cartwright for their comments that helped us to improve this paper.

References

- Calvert, S. E., & Batchelor, C. H. (1978). Major and minor element geochemistry of sediments from hole 379a, leg 42b, deep sea drilling project. *Initial Reports of the Deep Sea Drilling Project*, 42 Pt. 2, 527–541. <https://doi.org/10.2973/dsdp.proc.42-2.1978>
- Colin, F., Ker, S., & Marsset, B. (2020). Fine-scale velocity distribution revealed by datuming of VHR deep-towed seismic data: Example of a shallow gas system from the western Black Sea. *Geophysics*, 1–50. <https://doi.org/10.1190/geo2019-0686.1>
- Constantinescu, A. M., Toucanne, S., Dennielou, B., Jorry, S. J., Mulder, T., & Lericolais, G. (2015). Evolution of the Danube deep-sea fan since the last glacial maximum: New insights into Black Sea water-level fluctuations. *Marine Geology*, 367, 50–68. <https://doi.org/10.1016/j.margeo.2015.05.007>
- Crémière, A., Lepland, A., Chand, S., Sahy, D., Condon, D. J., Noble, S. R., et al. (2016). Timescales of methane seepage on the Norwegian margin following collapse of the Scandinavian ice sheet. *Nature Communications*, 7(1), 1–10. <https://doi.org/10.1038/ncomms11509>
- Crutchley, G. J., Fraser, D. R. A., Pecher, I. A., Gorman, A. R., Maslen, G., & Henrys, S. A. (2015). Gas migration into gas hydrate-bearing sediments on the southern Hikurangi margin of New Zealand. *Journal of Geophysical Research: Solid Earth*, 120, 725–743. <https://doi.org/10.1002/2014JB011503>
- Crutchley, G. J., Klaeschen, D., Planert, L., Bialas, J., Berndt, C., Papenberg, C., et al. (2014). The impact of fluid advection on gas hydrate stability: Investigations at sites of methane seepage offshore Costa Rica. *Earth and Planetary Science Letters*, 401, 95–109. <https://doi.org/10.1016/j.epsl.2014.05.045>
- De Batist, M., Klerkx, J., Van Rensbergen, P., Vanneste, M., Poort, J., Golmshtok, A. Y., et al. (2002). Active hydrate destabilization in Lake Baikal, Siberia? *Terra Nova*, 14(6), 436–442. <https://doi.org/10.1046/j.1365-3121.2002.00449.x>
- Dickens, G. R., & Quinby-Hunt, M. S. (1994). Methane hydrate stability in seawater. *Geophysical Research Letters*, 21(19), 2115–2118. <https://doi.org/10.1029/94GL01858>

- Frey-Martinez, J., Cartwright, J., & James, D. (2006). Frontally confined versus frontally emergent submarine landslides: A 3D seismic characterisation. *Marine and Petroleum Geology*, 23(5), 585–604. <https://doi.org/10.1016/j.marpetgeo.2006.04.002>
- Gorman, A. R., Holbrook, W. S., Hornbach, M. J., Hackwith, K. L., Lizarralde, D., & Pecher, I. (2002). Migration of methane gas through the hydrate stability zone in a low-flux hydrate province. *Geological Society of America*, 30(4), 327–330. [https://doi.org/10.1130/0091-7613\(2002\)030<0327:MOMGTT>2.0.CO;2](https://doi.org/10.1130/0091-7613(2002)030<0327:MOMGTT>2.0.CO;2)
- Gullapalli, S., Dewangan, P., Kumar, A., Dakara, G., & Mishra, C. K. (2019). Seismic evidence of free gas migration through the gas hydrate stability zone (GHSZ) and active methane seep in Krishna-Godavari offshore basin. *Marine and Petroleum Geology*, 110, 695–705. <https://doi.org/10.1016/j.marpetgeo.2019.07.052>
- Haacke, R. R., Hyndman, R. D., Park, K.-P., Yoo, D.-G., Stoian, I., & Schmidt, U. (2009). Migration and venting of deep gases into the ocean through hydrate-choked chimneys offshore Korea. *Geology*, 37(6), 531–534. <https://doi.org/10.1130/G25681A.1>
- Haeckel, M., Suess, E., Wallmann, K., & Rickert, D. (2004). Rising methane gas bubbles form massive hydrate layers at the seafloor. *Geochimica et Cosmochimica Acta*, 68(21), 4335–4345. <https://doi.org/10.1016/j.gca.2004.01.018>
- Hill, T. M., Kennett, J. P., Valentine, D. L., Yang, Z., Reddy, C. M., Nelson, R. K., et al. (2006). Climatically driven emissions of hydrocarbons from marine sediments during deglaciation. *Proceedings of the National Academy of Sciences*, 103(37), 13,570–13,574. <https://doi.org/10.1073/pnas.0601304103>
- Hillman, J. I. T., Burwicz, E., Zander, T., Bialas, J., Klaucke, I., Feldman, H., et al. (2018). Investigating a gas hydrate system in apparent disequilibrium in the Danube fan, Black Sea. *Earth and Planetary Science Letters*, 502, 1–11. <https://doi.org/10.1016/j.epsl.2018.08.051>
- Hornbach, M. J., Harris, R. N., & Phrampus, B. J. (2020). Heat flow on the U.S. Beaufort margin, Arctic Ocean: Implications for ocean warming, methane hydrate stability, and regional tectonics. *Geochemistry, Geophysics, Geosystems*, 21, e2020GC008933. <https://doi.org/10.1029/2020GC008933>
- Joshi, R. K., Mazumdar, A., Peketi, A., Ramamurty, P. B., Naik, B. G., Kocherla, M., et al. (2014). Gas hydrate destabilization and methane release events in the Krishna–Godavari Basin, Bay of Bengal. *Marine and Petroleum Geology*, 58, 476–489. <https://doi.org/10.1016/j.marpetgeo.2014.08.013>
- Kennett, J. P., Cannariato, K. G., Hendy, I. L., & Behl, R. J. (2000). Carbon isotopic evidence for methane hydrate instability during quaternary interstadials. *Science*, 288(5463), 128–133. <https://doi.org/10.1126/science.288.5463.128>
- Ker, S., Le Godinec, Y., Marsset, B., Westbrook, G. K., Gibert, D., & Minshull, T. A. (2014). Fine-scale gas distribution in marine sediments assessed from deep-towed seismic data. *Geophysical Journal International*, 196(3), 1466–1470. <https://doi.org/10.1093/gji/ggt497>
- Ker, S., Marsset, B., Garziglia, S., Le Godinec, Y., Gibert, D., Voisset, M., & Adamy, J. (2010). High-resolution seismic imaging in deep sea from a joint deep-towed/OBH reflection experiment: Application to a mass transport complex offshore Nigeria. *Geophysical Journal International*, 182(3), 1524–1542. <https://doi.org/10.1111/j.1365-246X.2010.04700.x>
- Ker, S., & Riboulot, V. (2015). GHASS cruise, R/V Pourquoi Pas, <https://doi.org/10.17600/15000500>
- Ker, S., Yannick, T., Sultan, N., Bernard, C., Scalabrin, C., Ion, G., & Marsset, B. (2019). Anomalous deep BSR related to a transient state of the gas hydrate system in the western Black Sea. *Geochemistry, Geophysics, Geosystems*, 20, 442–459. <https://doi.org/10.1029/2018GC007861>
- Lericolais, G. (1998). BLASON cruise, R/V Le Suroit. <https://doi.org/10.17600/98020030>
- Lericolais, G., Bulois, C., Gillet, H., & Guichard, F. (2009). High frequency sea level fluctuations recorded in the Black Sea since the LGM. *Global and Planetary Change*, 66(1–2), 65–75. <https://doi.org/10.1016/j.gloplacha.2008.03.010>
- Liu, J., Haeckel, M., Rutqvist, J., Wang, S., & Yan, W. (2019). The mechanism of methane gas migration through the gas hydrate stability zone: Insights from numerical simulations. *Journal of Geophysical Research: Solid Earth*, 124, 4399–4427. <https://doi.org/10.1029/2019JB017417>
- Liu, X., & Flemings, P. B. (2007). Dynamic multiphase flow model of hydrate formation in marine sediments. *Journal of Geophysical Research*, 112, B03101. <https://doi.org/10.1029/2005JB004227>
- Marsset, B., Menut, E., Ker, S., Thomas, Y., Regnault, J.-P., Leon, P., et al. (2014). Deep-towed high-resolution multichannel seismic imaging. *Deep Sea Research, Part I*, 93, 83–90. <https://doi.org/10.1016/j.dsr.2014.07.013>
- Martinez-Lamas, R., Toucanne, S., Debret, M., Riboulot, V., Deloffre, J., Boissier, A., et al. (2020). Linking Danube river activity to Alpine ice-sheet fluctuations during the last glacial (ca. 33–17 ka BP): Insights into the continental signature of Heinrich Stadials. *Quaternary Science Reviews*, 229, 106136. <https://doi.org/10.1016/j.quascirev.2019.106136>
- Maslin, M., Owen, M., Day, S., & Long, D. (2004). Linking continental-slope failures and climate change: Testing the clathrate gun hypothesis. *Geology*, 32(1), 53–56. <https://doi.org/10.1130/G20114.1>
- McGinnis, D. F., Greinert, J., Artemov, Y., Beaubien, S. E., & Wüest, A. (2006). Fate of rising methane bubbles in stratified waters: How much methane reaches the atmosphere? *Journal of Geophysical Research*, 111, C09007. <https://doi.org/10.1029/2005JC003183>
- Meyer, D. W., Flemings, P. B., & DiCarlo, D. (2018). Effect of gas flow rate on hydrate formation within the hydrate stability zone. *Journal of Geophysical Research: Solid Earth*, 123, 6263–6276. <https://doi.org/10.1029/2018JB015878>
- Meyer, D. W., Flemings, P. B., You, K., & DiCarlo, D. A. (2020). Gas flow by invasion percolation through the hydrate stability zone. *Geophysical Research Letters*, 47, e2019GL084380. <https://doi.org/10.1029/2019GL084380>
- Netzeband, G. L., Hübscher, C. P., Gajewski, D., Grobys, J. W. G., & Bialas, J. (2005). Seismic velocities from the Yaquina forearc basin off Peru: Evidence for free gas within the gas hydrate stability zone. *International Journal of Earth Sciences*, 94(3), 420–432. <https://doi.org/10.1007/s00531-005-0483-2>
- Phrampus, B. J., & Hornbach, M. J. (2012). Recent changes to the Gulf Stream causing widespread gas hydrate destabilization. *Nature*, 490(7421), 527–530. <https://doi.org/10.1038/nature11528>
- Phrampus, B. J., Hornbach, M. J., Ruppel, C. D., & Hart, P. E. (2014). Widespread gas hydrate instability on the upper U.S. Beaufort margin: U.S. Beaufort margin hydrate instability. *Journal of Geophysical Research: Solid Earth*, 119, 8594–8609. <https://doi.org/10.1002/2014JB011290>
- Poort, J., Vassilev, A., & Dimitrov, L. (2005). Did postglacial catastrophic flooding trigger massive changes in the Black Sea gas hydrate reservoir? *Terra Nova*, 17(2), 135–140. <https://doi.org/10.1111/j.1365-3121.2005.00599.x>
- Popescu, I., De Batist, M., Lericolais, G., Nouzé, H., Poort, J., Panin, N., et al. (2006). Multiple bottom-simulating reflections in the Black Sea: Potential proxies of past climate conditions. *Marine Geology*, 227(3–4), 163–176. <https://doi.org/10.1016/j.margeo.2005.12.006>
- Riboulot, V., Cattaneo, A., Scalabrin, C., Gaillot, A., Jouet, G., Ballas, G., et al. (2017). Control of the geomorphology and gas hydrate extent on widespread gas emissions offshore Romania. *Bulletin de La Société Géologique de France*, 188(4), 26. <https://doi.org/10.1051/bsgf/2017182>

- Riboulot, V., Ker, S., Sultan, N., Thomas, Y., Marsset, B., Scalabrin, C., et al. (2018). Freshwater lake to salt-water sea causing widespread hydrate dissociation in the Black Sea. *Nature Communications*, 9(1), 1–8. <https://doi.org/10.1038/s41467-017-02271-z>
- Riedel, M., Freudenthal, T., Bergenthal, M., Haeckel, M., Wallmann, K., Spangenberg, E., et al. (2020). Physical properties and core-log seismic integration from drilling at the Danube deep-sea fan, Black Sea. *Marine and Petroleum Geology*, 114, 104192. <https://doi.org/10.1016/j.marpetgeo.2019.104192>
- Riedel, M., Novosel, I., Spence, G. D., Hyndman, R. D., Chapman, R. N., Solem, R. C., & Lewis, T. (2006). Geophysical and geochemical signatures associated with gas hydrate-related venting in the northern Cascadia margin. *GSA Bulletin*, 118(1–2), 23–38. <https://doi.org/10.1130/B25720.1>
- Ruppel, C. D., & Kessler, J. D. (2017). The interaction of climate change and methane hydrates. *Reviews of Geophysics*, 55, 126–168. <https://doi.org/10.1002/2016RG000534>
- Shedd, W., Boswell, R., Frye, M., Godfriaux, P., & Kramer, K. (2012). Occurrence and nature of “bottom simulating reflectors” in the northern Gulf of Mexico. *Marine and Petroleum Geology*, 34(1), 31–40. <https://doi.org/10.1016/j.marpetgeo.2011.08.005>
- Sloan, E. D., & Koh, C. A. (2008). *Clathrate hydrates of natural gases*. Baco Raton: CRC Press.
- Soulet, G., Delaygue, G., Vallet-Coulomb, C., Böttcher, M. E., Sonzogni, C., Lericolais, G., & Bard, E. (2010). Glacial hydrologic conditions in the Black Sea reconstructed using geochemical pore water profiles. *Earth and Planetary Science Letters*, 296(1–2), 57–66. <https://doi.org/10.1016/j.epsl.2010.04.045>
- Soulet, G., Ménot, G., Lericolais, G., & Bard, E. (2011). A revised calendar age for the last reconnection of the Black Sea to the global ocean. *Quaternary Science Reviews*, 30(9–10), 1019–1026. <https://doi.org/10.1016/j.quascirev.2011.03.001>
- Suess, E., Torres, M. E., Bohrmann, G., Collier, R. W., Greinert, J., Linke, P., et al. (1999). Gas hydrate destabilization: Enhanced dewatering, benthic material turnover and large methane plumes at the Cascadia convergent margin. *Earth and Planetary Science Letters*, 170(1–2), 1–15. [https://doi.org/10.1016/S0012-821X\(99\)00092-8](https://doi.org/10.1016/S0012-821X(99)00092-8)
- Sultan, N. (2007). Excess pore pressure and slope failures resulting from gas-hydrates dissociation and dissolution. *Offshore Technology Conference*. Offshore Technology Conference, Houston, Texas, U.S.A. <https://doi.org/10.4043/18532-MS>
- Sultan, N., Bohrmann, G., Ruffine, L., Pape, T., Riboulot, V., Colliat, J.-L., et al. (2014). Pockmark formation and evolution in deep water Nigeria: Rapid hydrate growth versus slow hydrate dissolution. *Journal of Geophysical Research: Solid Earth*, 119, 2679–2694. <https://doi.org/10.1002/2013JB010546>
- Sultan, N., Marsset, B., Ker, S., Marsset, T., Voisset, M., Vernant, A. M., et al. (2010). Hydrate dissolution as a potential mechanism for pockmark formation in the Niger delta. *Journal of Geophysical Research*, 115, B08101. <https://doi.org/10.1029/2010JB007453>
- Sultan, N., Riboulot, V., Ker, S., Marsset, B., Géli, L., Tary, J. B., et al. (2011). Dynamics of fault-fluid-hydrate system around a shale-cored anticline in deepwater Nigeria. *Journal of Geophysical Research*, 116, B12110. <https://doi.org/10.1029/2011JB008218>
- Tóth, Z., Spiess, V., & Keil, H. (2015). Frequency dependence in seismoacoustic imaging of shallow free gas due to gas bubble resonance. *Journal of Geophysical Research: Solid Earth*, 120, 8056–8072. <https://doi.org/10.1002/2015JB012523>
- Tréhu, A. M., Flemings, P. B., Bangs, N. L., Chevallier, J., Gràcia, E., Johnson, J. E., et al. (2004). Feeding methane vents and gas hydrate deposits at south hydrate ridge. *Geophysical Research Letters*, 31, L23310. <https://doi.org/10.1029/2004GL021286>
- Valentine, D. L., Blanton, D. C., Reeber, W. S., & Kastner, M. (2001). Water column methane oxidation adjacent to an area of active hydrate dissociation, Eel river basin. *Geochimica et Cosmochimica Acta*, 65(16), 2633–2640. [https://doi.org/10.1016/S0016-7037\(01\)00625-1](https://doi.org/10.1016/S0016-7037(01)00625-1)
- Vanneste, M., De Batist, M., Golmshtok, A., Kremlev, A., & Versteeg, W. (2001). Multi-frequency seismic study of gas hydrate-bearing sediments in Lake Baikal, Siberia. *Marine Geology*, 172(1–2), 1–21. [https://doi.org/10.1016/S0025-3227\(00\)00117-1](https://doi.org/10.1016/S0025-3227(00)00117-1)
- You, K., & Flemings, P. B. (2018). Methane hydrate formation in thick sandstones by free gas flow. *Journal of Geophysical Research: Solid Earth*, 123, 4582–4600. <https://doi.org/10.1029/2018JB015683>
- Zander, T., Haeckel, M., Berndt, C., Chi, W.-C., Klauke, I., Bialas, J., et al. (2017). On the origin of multiple BSRs in the Danube deep-sea fan, Black Sea. *Earth and Planetary Science Letters*, 462, 15–25. <https://doi.org/10.1016/j.epsl.2017.01.006>