Geology

Probable patterns of gas flow and hydrate accretion at the base of the hydrate stability zone

--Manuscript Draft--

Manuscript Number:	G36047
Full Title:	Probable patterns of gas flow and hydrate accretion at the base of the hydrate stability zone
Short Title:	Seismic Imaging of Hydrate Accretion
Article Type:	Article
Keywords:	hydrate; flow; bottom simulating reflection; gas
Corresponding Author:	Richard Davies Durham University Durham, Co Durham UNITED KINGDOM
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Durham University
Corresponding Author's Secondary Institution:	
First Author:	Richard Davies
First Author Secondary Information:	
Order of Authors:	Richard Davies
	Jinxiu Yang
	Richard Hobbs
	Ang Li
Order of Authors Secondary Information:	
Manuscript Region of Origin:	MAURITANIA
Abstract:	Marine gas hydrate is the largest carbon reservoir in the global organic carbon cycle but there is limited knowledge of how hydrate is accreted in space and time. Three-dimensional (3-D) seismic imaging of the dipping base of the deep water marine gas hydrate from offshore Mauritania reveals extraordinary patterns of vertical chimneys and connected teardrop-shaped trails of both high and low seismic reflection amplitudes. The high amplitude trails are interpreted as being caused by the downward transition from hydrate to free gas bearing sediments. Their teardrop form shows that gas emanating from the chimneys flowed up dip. The geometrically similar, lower amplitude trails are potentially earlier flows that may have already converted to hydrate. For this area we propose a model of intermittent flow of gas to the base of the hydrate. Active flows were blocked up dip by earlier, probably hydrate-clogged chimneys and may have been laterally confined by flows that had already converted to hydrate that lay in their path. The process of hydrate formation reduces sediment permeability and may suppress subsequent gas flows, resulting in the emergence of patterns of gas flow and hydrate accretion. Based on this interpretation, hydrate accretion could be a self-organising phenomenon.
Suggested Reviewers:	Joe Cartwright He reviewed the original submission
	Mads Huuse He reviewed the original submission
	Carolyn Ruppel

	Her work is relevant to this paper

Probable patterns of gas flow and hydrate accretion at the base of the hydrate stability zone

Richard J. Davies[1], Jinxiu Yang[2,3], Richard Hobbs[2] and Ang Li[2]

[1]School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, Tyne and Wear, NE1 7RU, UK
[2]Centre for Research into Earth Energy Systems (CeREES), Department of Earth Sciences, Durham University, Science Labs, Durham DH1 3LE, UK
[3]Research Institute of Unconventional Oil & Gas and New Energy, China University of Petroleum (Huadong), No.66 Changjiang West Road, Huangdao District, Qingdao, Shandong, 266555, China

E-mail: richard.davies@ncl.ac.uk

ABSTRACT

Marine gas hydrate is the largest carbon reservoir in the global organic carbon cycle but there is limited knowledge of how hydrate is accreted in space and time. Three-dimensional (3-D) seismic imaging of the dipping base of the deep water marine gas hydrate from offshore Mauritania reveals extraordinary patterns of vertical chimneys and connected teardrop-shaped trails of both high and low seismic reflection amplitudes. The high amplitude trails are interpreted as being caused by the downward transition from hydrate to free gas bearing sediments. Their teardrop form shows that gas emanating from the chimneys flowed up dip. The geometrically similar, lower amplitude trails are potentially earlier flows that may have already converted to hydrate. For this area we propose a model of intermittent flow of gas to the base of the hydrate. Active flows were blocked up dip by earlier, probably hydrate-clogged chimneys and may have been laterally confined by flows that had already converted to hydrate that lay in their path. The process of hydrate formation reduces sediment

permeability and may suppress subsequent gas flows, resulting in the emergence of patterns of gas flow and hydrate accretion. Based on this interpretation, hydrate accretion could be a self-organising phenomenon.

INTRODUCTION

Marine gas hydrate is a frozen compound of water and gas that can occur around the deep water margins of continents. Its dissociation has been linked to past climate change (Dickens, 2001). Hydrate formation is controlled by pressure, temperature and the concentration of dissolved gas, which needs to be higher than its solubility in pore water (Xu and Ruppel, 1999). The base of the hydrate stability zone (BHSZ) can be anything from a few meters to hundreds of meters below the seabed. It can coincide with the base of the hydrate, although this is not necessarily the case (Xu and Ruppel, 1999) and may be marked by a bottom simulating reflection (BSR) (e.g. Dillon, et al., 1980).

The process by which gas converts to hydrate and recycles between the two phases is well understood on the basis of experiment and theory (e.g. Maini and Bishnoi, 1981; Xu and Ruppel, 1999; Buffett and Zatsepina, 2000). Seismic reflection data provide remote sensing of some of the processes (e.g. Tréhu et al., 2004; Hornbach et al., 2008; Bangs et al., 2011; Hornbach et al., 2012). But we still know relatively little about how gas migrating to the hydrate stability zone (HSZ) accretes as hydrate in deep water sedimentary successions in space and time. We focus on 3-D seismic imaging of the offshore Mauritania BSR (Fig. 1) and describe intricate patterns of seismic reflection amplitude at the BSR that provide new insights into the processes.

DATA AND GEOLOGIC SETTING

The seismic data (Fig. 1) are minimum phase and a positive acoustic impedance is recorded as a red-black reflection (trough-peak). The dominant frequency is ~50 Hz and we assume a velocity of ~1700 m/s therefore the tuning thickness ($\lambda/4$) is ~8.5 m. The bin spacing is 25 × 25 m. The BSR is a black-red reflection which can be both discordant and concordant with stratal reflections within the study area. Where it is discordant it is marked by aligned terminations of high amplitude, black-red reflections. The root mean square of reflection amplitude was used in amplitude maps of the BSR as it produced the clearest map patterns.

The margin (Fig. 1A) is characterised by debris flows, turbidity currents and hemi-pelagic settling (Henrich et al., 2010). Two hydrocarbon exploration wells (Fig. 1A) show the succession is Recent to Pliocene in age (Vear, 2005). The BSR dips at ~2.3° towards the West and shallows from ~200 m below the seafloor to intersect the seabed at the 636 m isobath (Figs. 1AB). Below the BSR are vertical seismic chimneys (see Davies and Clarke, 2010) interpreted to be clusters of hydraulic fractures that allow for fluid migration to the HSZ (e.g. Moss and Cartwright, 2010).

OBSERVATIONS

The patterns occur on a single black-red reflection where the BSR is concordant with stratal reflections (Fig. 2A and 2B). This reflection marks the change from high and low amplitude reflections below, to consistently low and moderate amplitude, continuous reflections above (Fig. 2D). The area is surrounded by discordance between the BSR and stratal reflections which allows the reflection to be accurately located. For these reasons we are confident that the reflection mapped is the BSR.

The intersections of the chimneys with the BSR are circular to ovoid and of high or low amplitude (blue and purple colors respectively – Figs. 2AB and 3A). Some chimney intersections overprint others (e.g. chimney 2 overprints chimney 1 - Fig. 2B). High amplitude, dip-parallel trails emanate from the high amplitude intersections and low amplitude trails emanate from low amplitude intersections. They extend up dip for up to 6 km (Fig. 2A). Generally, high amplitude trails are deflected around low amplitude trails and the low amplitude chimney intersections (e.g. marked X on Fig. 2A and 2D). The converse does not occur. Cross-cutting relationships are not common, the only example (marked 3 in Fig. 2B) shows a high amplitude trail cross-cutting a low amplitude one. On seismic sections, trails are black-red reflections and a contiguous part of the BSR (e.g. marked Y and Z on Fig. 2C).

In a second example (Figs. 3A-D), two normal faults occur above a salt diapir and below the BSR (Figs. 3B and 3C). Above them are a number of black-red reflections (marked Z on Figs. 3B and 3D). The uppermost occurs at the level of the BSR. They are trails of low and high reflection amplitudes (marked F1-F4 on Fig. 3A). Again high amplitude trails deflect around low amplitude chimney intersections. Where a chimney penetrates the BSR rather than terminating at it, a trail of low reflection amplitude is again located up dip of it (Figs. 4A and 4B).

To test whether these patterns are not unique to the BSR and occur at other levels, deeper reflections well below the BSR were mapped (DR1). DR1 shows that moderate amplitude trails also emanate from chimneys at deeper levels, but in contrast they have narrow, straight geometries. There is velocity pull-up beneath and differential compaction folding above.

INTERPRETATION

All the trails, at the BSR or deeper levels (DR1), emanate from chimneys and are strata- and dip-parallel. They are likely to be flows of gas and pore fluid emanating from the chimneys and flowing up dip below lower permeability beds in the succession (e.g. Moss and Cartwright, 2010). Those deeper than the BSR with associated velocity pull-ups, are interpreted to be high velocity features. They are most likely gas flows that have undergone subsequent diagenetic cementation (e.g. Housen and Musgrave, 1996).

Regarding the patterns at the BSR, their amplitude depends on the impedance of the hydrate and sub-hydrate sediment. In the absence of other lithological effects, a strong negative polarity reflection (black-red) should be indicative of a hydrate layer over sediment containing > 4% saturation of free gas because this is sufficient to cause a drop in impedance (Carcione and Tinivella, 2000).

In contrast for hydrate concentrations of up to 40-50%, impedance does not change significantly (Carcione and Tinivella, 2000; Zhang et al., 2012). Hydrate saturations in fine-grained sediment are unlikely to exceed this (Chabert et al., 2011). Also we rarely see evidence for high amplitude reflections above the BSR that could be the result of high hydrate saturations (*cf*. Hornbach et al., 2008). For these reasons hydrate-saturated sediment over water-saturated sediment or the boundary between two layers of hydrate-saturated sediment with different concentrations should both result in a low, rather than high amplitude reflection. Consequently on the basis of seismic amplitude alone, the low amplitude trails could correspond to either water-bearing or hydrate-bearing sediment whereas high amplitude trails correspond to free gas bearing sediments, resulting in the observed BSR.

The gas flows that are below the BSR (DR1), that have probably undergone subsequent diagenetic cementation, show little evidence for lateral deflections. This contrasts with the gas flows at the BSR, which loop around and envelop the low amplitude chimneys (Figs. 2 and 3). This is irrespective of whether the chimneys terminate at the BSR (Fig. 2) or penetrate it (Fig. 4). Since the BSR can be low or high amplitude where chimney intersections occur, it is unlikely low amplitude intersections are simply due to complex fracturing and therefore poor reflectivity. Poor reflectivity would also not explain the deflections of the gas trails around low amplitude chimney intersections. Instead the deflections are consistent with the chimneys being lower permeability features, perhaps because fractures are clogged with hydrate (Holland et al., 2008; Haacke et al., 2009; Bangs et al., 2011). It cannot be ruled out that hydrate in fractures could also produce some scattering of seismic energy and be a contributory factor for the low seismic amplitude response (Westbrook et al., 2008).

The low amplitude trails have a similar geometry to the free gas flows, except the free gas flows are diverted around them but the converse does not occur (Fig. 2B). Because of the similarity between the high and low amplitude trails and because low amplitude trails are enveloped and rarely cross-cut by the gas flows, we interpret the low amplitude trails to be earlier gas and water flows that have subsequently converted to hydrate, clogging pore spaces. This forced subsequent gas flows to be diverted. The alternative, which cannot be ruled out is that they are water-bearing strata immediately below the hydrate which formed as shadow zones, up dip of the chimneys (e.g. marked ‘wakes’ in Figs. 4A and 5A).

Since the top and base of the gas flows are unresolved, the amplitude of the reflection is moderated by the thickness of the gas layer, which is probably hosted in heterogeneous, interbeds of sand, silt and clay grade material (Henrich et al., 2010). Potentially, the highest amplitudes (yellow and red colors in Figs. 2AB and 3A) occur where there is a tuned response between the top and base of the gas ($\lambda/4$ - ~8.5 m) and the lower amplitudes (cyan colors) in the distal parts of the flows are where the thickness of the gas is ~ $\lambda/8$ (~ 4.25 m) (Widness, 1973). Interpretation of amplitudes below this level (blue colors – in Figs. 2AB and 3A) are ambiguous as they could be a) thin layers with >4% saturation of free gas; b) thin layers with <4% gas saturation c) fully water saturated strata or even (d) thin hydrate saturated layers.

IMPLICATIONS AND CONCLUSIONS

As flows generally do not cross cut each other this is probably not a reactive-transport process caused by warmer fluids or localised elevations in the salinity of the pore fluid (Torres et al., 2004; Liu and Flemings, 2006) which could lead to positive feedback and self-organisational patterns. Conceptually many different 3-D patterns could develop (Fig. 5AB) or none at all, depending on factors such as whether positive or negative feedback dominates. Inherited characteristics could also be an important determinant, for example whether the BHSZ is horizontal or dipping and the angularity of the intersection of the BSR with stratal reflections. The interrelationships support negative feedback where hydrate conversion suppressed subsequent gas flows by reducing sediment permeability. Continued mapping the bases of other hydrates with 3-D seismic data may establish (a) whether this is a rare or common phenomenon (b) what patterns can form and (c) a better understanding of the complexities of how gas enters this carbon reservoir.

ACKNOWLEDGMENTS

We are grateful to the Landmark University Grant Program for providing seismic interpretation software. Joe Cartwright, Mads Huuse, Andy Aplin, Simon Mathias and Christian Berndt and two anonymous reviewers are thanked for their reviews and informal comments. Dave Stevenson and Gary Wilkinson are acknowledged for managing the seismic interpretation facility and Petronas and Tullow Oil for permission to use the seismic reflection data.

FIGURE CAPTIONS

Figure 1 A: Map of the seabed. Inset – the location of Mauritania and the dataset. B: Amplitude map of the BSR. Black arrow in this and subsequent figures points directly up dip. Dashed white lines – lines of intersection (LoIs, see Davies et al., 2012). The 636 m isobath is where the BSR intersects the seabed. White boxes mark location of maps used in subsequent figures.

Figure 2 A: Amplitude map showing trails of high and low reflection amplitude. Black circles on this and subsequent figures – intersections of chimneys with the BSR. Dashed black lines – boundaries between high and low seismic amplitudes interpreted to be boundaries to gas flows. Red arrows in this and subsequent figures – interpreted directions of gas flow. B: A portion of the amplitude map in A. C and D: Representative zig-zag seismic lines through vertical chimneys and regions of high and low reflection amplitudes. Dotted yellow lines in this and subsequent figures – location of the BSR.

Figure 3 A: Amplitude map of the BSR. B: Representative seismic line across the high amplitude regions of the amplitude map. C: Dip magnitude map of the green horizon marked in part B showing two northeast-southwest striking normal faults. Dark gray and black colors – faults. D: A portion of the representative seismic line showing the flows F1 - F4 that are also marked on A.

Figure 4 A: Amplitude map of the BSR. White arrows – interpreted directions of gas flow. B: Example of a vertical seismic chimney that penetrates the BSR. LA – low amplitude up dip of the chimney, HA – high amplitude down dip of the chimney.

Figure 5 Planform and conceptual cross-sectional patterns at a BSR that is concordant with stratal reflections. A: Schematic planform patterns of younger and older chimneys, gas flows, flows that have converted to hydrate and wakes (up dip of hydrate-clogged chimneys). Black arrows – progressive hydration of gas flow. B: Schematic cross-section across flows including conceptual stacking patterns of flows that have converted to hydrate.

DR1 A: Seismic line across two high amplitude trails from beneath the BSR. Yellow dashed line – BSR. White circles – intersection of chimneys with the reflection. B: Amplitude map of black dashed horizon in A, located below the BSR, showing moderate amplitude trails emanating from chimney tops.

REFERENCES CITED

Bangs, N.L.B., Hornbach, M.J., Berndt, C., 2011, The mechanics of intermittent methane venting at South Hydrate Ridge inferred from 4D seismic surveying: Earth and Planetary Science Letters, v. 340, p. 105-112.

Buffett, B.A., Zatsepina, O.Y., 2000, Formation of gas hydrate from dissolved gas in natural porous media: Marine Geology, v. 164, p. 69-77.

Carcione, J.M., Tinivella, U., 2000, Bottom-simulating reflectors: Seismic velocities and AVO effects, Geophysics, v.65, p. 54-67.

Chabert, A., Minshull,T. A., Westbrook, G. K., Berndt,C., Thatcher, K. E., Sarkar, S., 2011, Characterization of a stratigraphically constrained gas hydrate system along the western continental margin of Svalbard from ocean bottom seismometer data. Journal of Geophysical Research, v. 116, B12102.

Davies, R.J., Clarke, A.L., 2010, Methane recycling between hydrate and critically pressured stratigraphic traps, offshore Mauritania: Geology, v. 38, p. 963-966.

Davies, R.J., Thatcher, K.E., Armstrong, H., Yang, J., Hunter, S., 2012, Tracking the relict bases of marine methane hydrates using their intersections with stratigraphic reflections: Geology, v. 40, p. 1011-1014.

Dickens, G.R., 2001, The potential volume of oceanic methane hydrates with variable external conditions: Organic Geochemistry, v. 32, p. 1179-1193.

Dillon, W.P.J., Grow, J.A., Paull, C.K., 1980, Unconventional gas hydrate seals may trap gas off southeast U.S: Oil & Gas Journal, v. 78, p.124–130.

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, v. 37, p. 531-534.

Henrich, R., Cherubini Y., Meggers H., 2010, Climate and sea level induced turbidite activity in a canyon system offshore the hyperarid Western Sahara (Mauritania): The Timiris Canyon: Marine Geology, v. 275, p. 178-198.

Holland, M., Schultheiss, P., Roberts, J., Druce, M., 2008, Observed Gas Hydrate Morphologies in Marine Sediments, in Proceedings of the 6th International Conference on Gas Hydrates (ICGH '08), Vancouver, Canada.

Hornbach, M. J., Saffer, D.M., Holbrook, W. S.,Van Avendonk, H. J. A., Gorman, A.R., 2008, Three-dimensional seismic imaging of the Blake Ridge methane hydrate province: Evidence for large, concentrated zones of gas hydrate and morphologically driven advection, Journal of Geophysical Research, v. 113, B07101.

Hornbach, M. J., Bangs, N. L., Berndt, C., 2012, Detecting hydrate and fluid flow from bottom simulating reflector depth anomalies, Geology, v. 40, p. 227-230.

Housen, B.A., Musgrave, R.J., 1996, Rockmagnetic signature of gas hydrates in accretionary prism sediments: Earth and Planetary Science Letters, v. 139, p. 509-519.

Liu, X., Flemings, P.B., 2006, Passing gas through the hydrate stability zone at southern Hydrate Ridge, offshore Oregon: Earth and Planetary Science Letters, v. 241, p. 211-226.

Maini, B.B., Bishnoi, P.R., 1981, Experimental investigation of hydrate formation behaviour of a natural gas bubble in a simulated deep sea environment: Chemical Engineering Science, v. 36, p. 183-189.

Moss, J. L., Cartwright, J. 2010, 3D seismic expression of km-scale fluid escape chimneys from offshore Namibia, Basin Research, v. 22, p. 481–501.

Torres, M.E., Wallmann, K., Tréhu, A.M., Bohrmann, G., Borowski, W.S., Tomaru, H., 2004, Gas hydrate growth, methane transport, and chloride enrichment at the southern summit of Hydrate Ridge, Cascadia margin off Oregon, Earth and Planetary Science Letters, v. 226, p. 225–241.

Tréhu, A.M., Flemings, P. B., Bangs, N. L., Chevallier, J., Gràcia, E., Johnson, J. E., Liu, C. –S., Liu, X., Riedel, M., Torres, M.E., 2004, Feeding methane vents and gas hydrate deposits at south Hydrate Ridge, Geophysical Research Letters, v. 31, L23310.

Vear, A., 2005, Deep-water plays of the Mauritanian continental margin. In Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum

Geology Conference (Eds Doré A.G. and Vining B. A.) (The Geological Society London), p. 1217-1232.

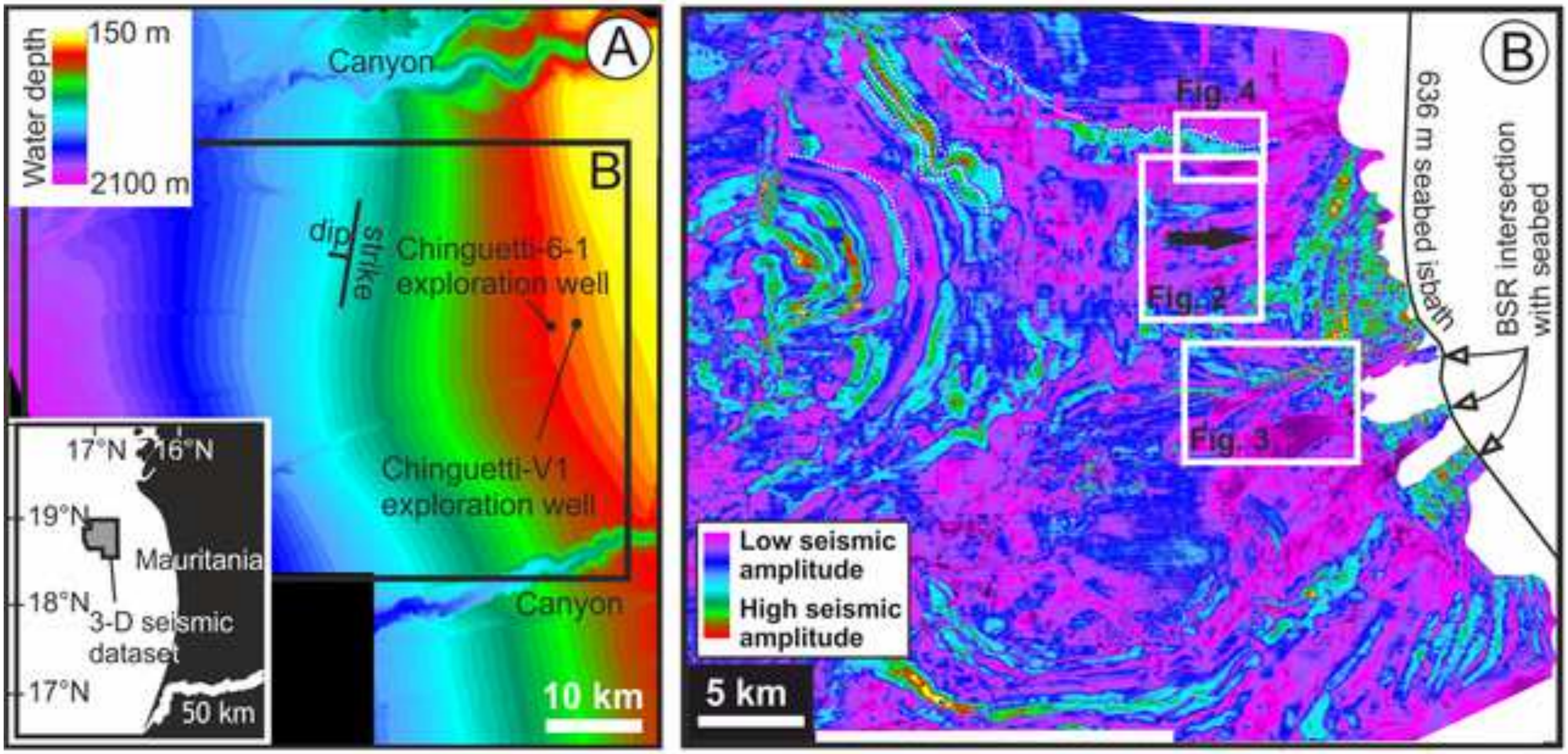
Westbrook, G., Exley R., Minshull, T., Nouzé, H., Gailler, A., Jose T., Ker S., Plaza, A., 2008, High-resolution 3D seismic investigations of hydrate-bearing fluid escape chimneys in the Nyegga region of the Vøring Plateau, Norway. Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008), Vancouver, British Columbia, CANADA.

Widness, M., 1973, How thin is a thin bed? Geophysics, v. 38, p. 1176-1180.

Xu, W., Ruppel, C., 1999, Predicting the occurrence, distribution, and evolution of methane gas hydrate in porous marine sediments, Journal of Geophysical Research: Solid Earth v. 104, p. 2156-2202.

Zhang, Z., McConnell, D. R., Han D., 2012, Rock physics-based seismic trace analysis of unconsolidated sediments containing gas hydrate and free gas in Green Canyon 955, Northern Gulf of Mexico, Marine and Petroleum Geology, v. 34, p. 119-133.

Figure
Click here to download high resolution image



Figure

Click here to download high resolution image

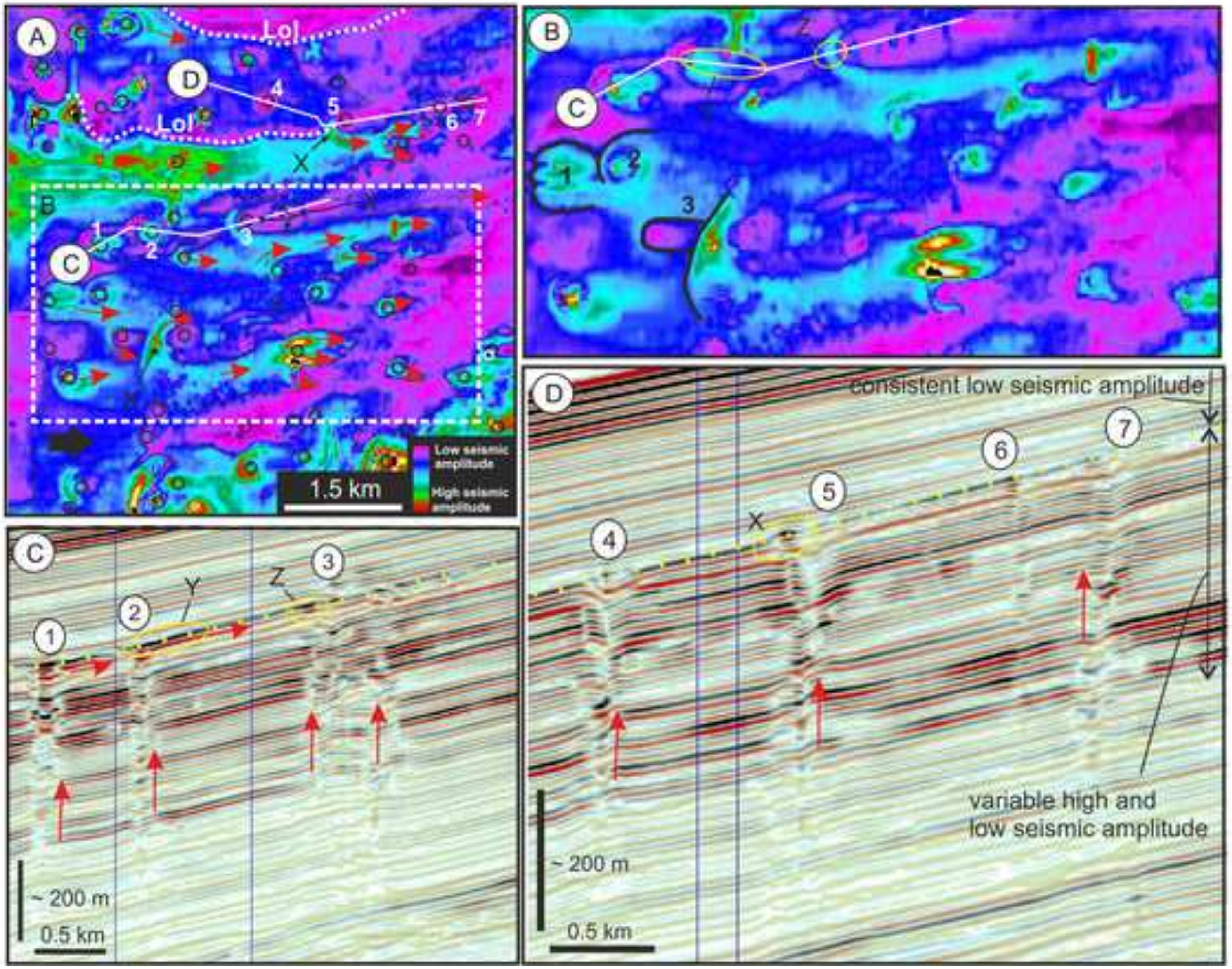


Figure
Click here to download high resolution image

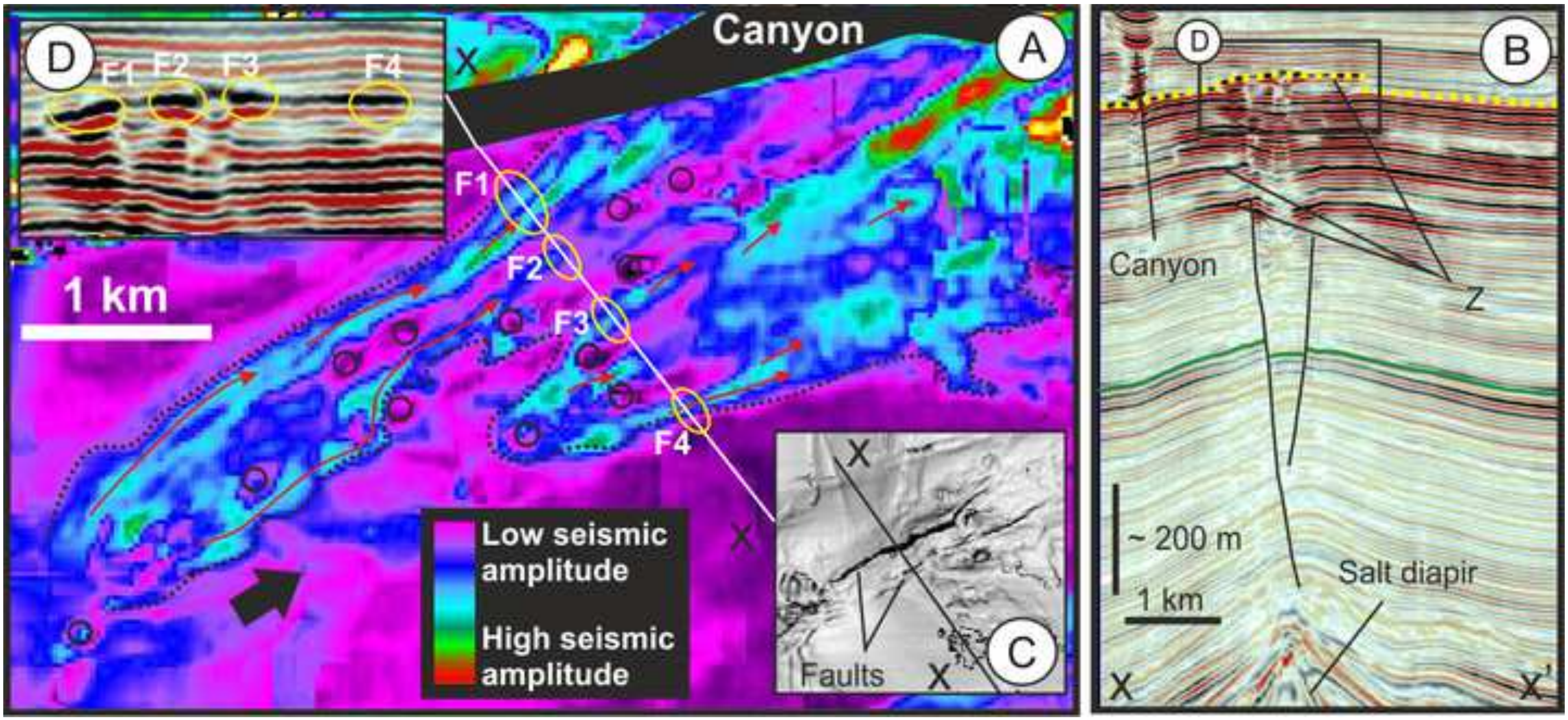


Figure
Click here to download high resolution image

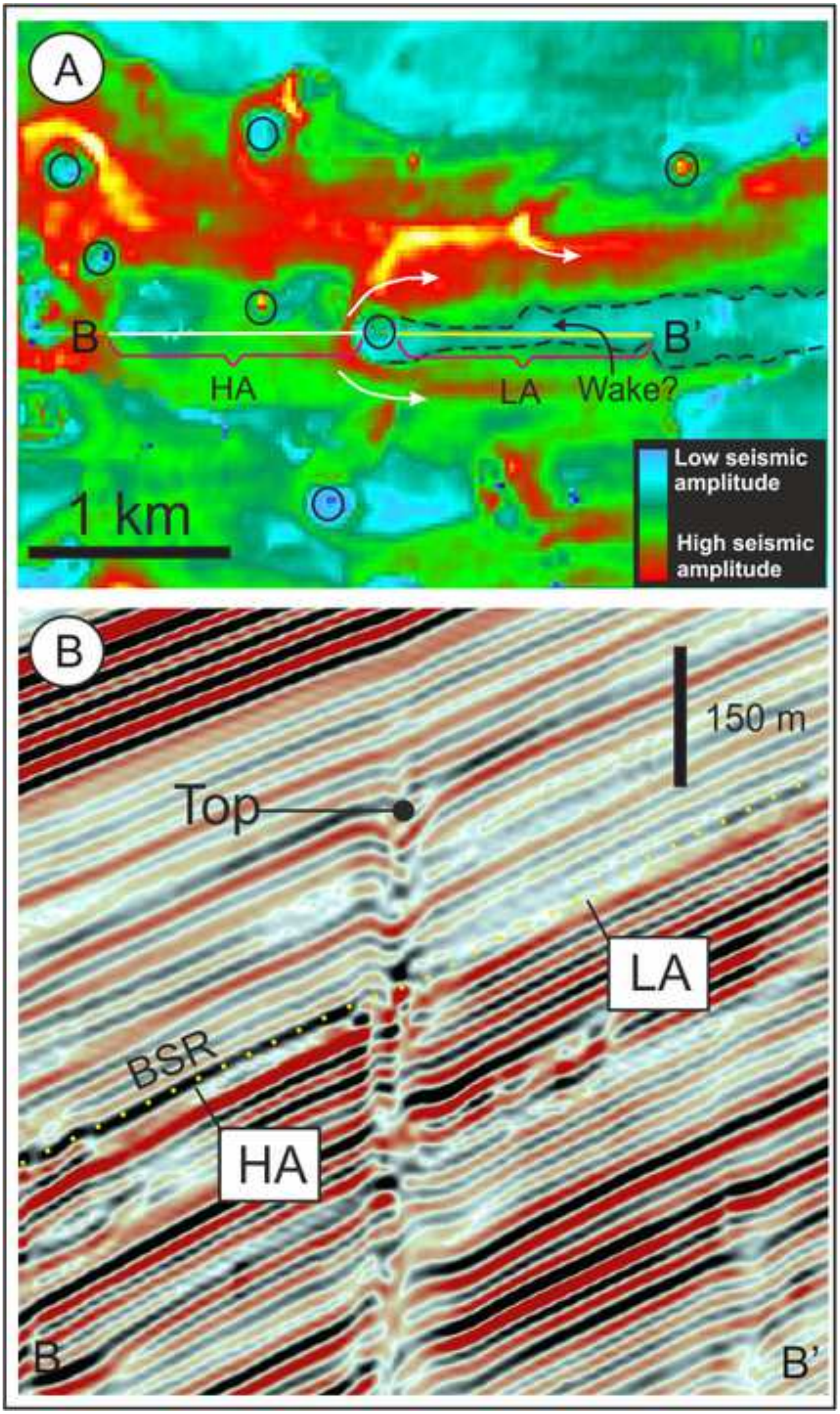


Figure
Click here to download high resolution image

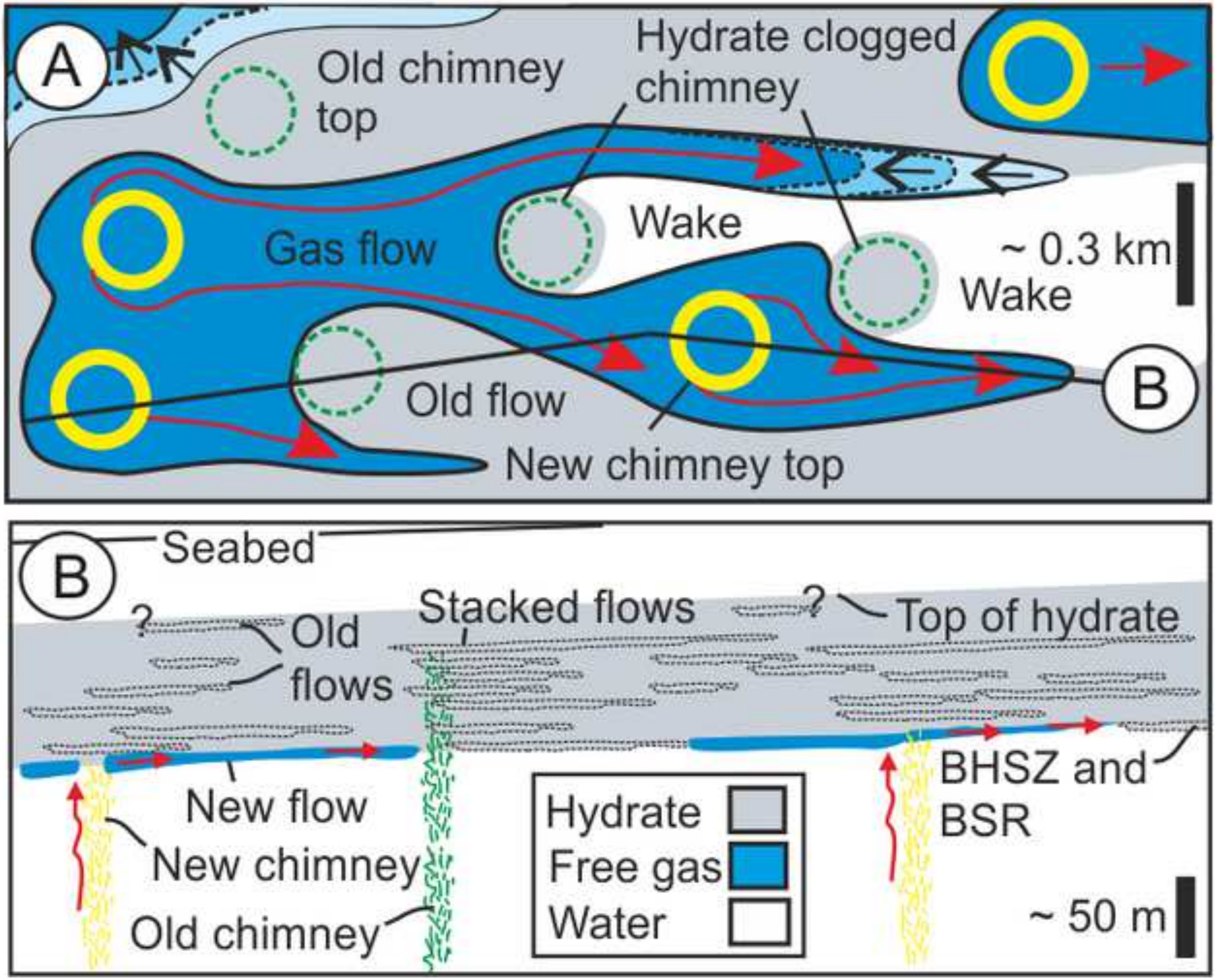


Figure
Click here to download high resolution image