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[EA]Gas Hydrate Reservoirs of the Southern Hikurangi Subduction Margin: Insights From Geophysics And Numerical Modelling*

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Abstract

This presentation summarizes key research results over the last five years related to gas hydrate formation styles on the southern Hikurangi margin. We describe a range of processes, including:

- Gas migration into the GHSZ. Dipping layers of alternating lithologies (e.g. sands and shales) are known to play an important role in fluid migration and gas hydrate formation. The Hikurangi margin has many examples that highlight this process. Additionally, there are locations where vertical gas migration through "chimneys" leads to the formation of concentrated hydrates on the chimney margins.
- Gas hydrate formation in response to canyon incision. By cutting down into the substrate, canyons lead to a pronounced downward shift of the base of the GHSZ. This downward shift can capture free gas beneath the hydrate system and convert it into gas hydrates. With time, this process can lead to concentrated gas hydrates beneath incising canyons.
- Folding and asymmetric sedimentation. Recent research has shown that concentrated gas hydrate formation tends to favor landward-dipping strata over seaward-dipping strata. This is probably due to relationships between asymmetric sedimentation in accretionary wedges and pronounced gas hydrate recycling on the landward sides of thrust ridges.

These processes have resulted in a broad array of gas hydrate accumulations on the margin. Although the deposits have not been drilled, their expressions in seismic data are like concentrated deposits elsewhere around the world, for example in the Nankai Trough and the Gulf of Mexico. Ongoing work is focusing on understanding the importance of fault zone permeability structure and reservoir lithology for the formation of concentrated hydrate deposits.

Introduction and Methods

New Zealand's southern Hikurangi margin (Figure 1) is characterized by highly oblique convergence and subduction of the Pacific Plate beneath the Australian Plate (Wallace et al., 2012). Compression leads to widespread folding, faulting, and dewatering processes that play key roles in fluid migration into the gas hydrate stability zone (GHSZ). Large submarine canyons and smaller gullies dramatically change the seafloor topography, influencing gas hydrate stability in the underlying sediments. Canyons also deposit coarse-grained sediments down their axes and onto slope basins, probably providing good quality reservoir rocks for gas hydrate formation.

Our methods for understanding gas hydrate systems are primarily underpinned by controlled-source seismic reflection data, acquired both for oil and gas exploration and for academic studies into gas hydrates. By focusing on higher resolution re-processing of industry seismic datasets, we improve the imaging of the gas hydrate system and model seismic velocities. A combination of amplitude analysis and seismic velocities helps us to identify regions where gas hydrates occur in relatively high concentrations. We supplement our seismic methods with gas hydrate formation modelling using the Petromod™ software. Petromod™ is routinely used in oil and gas research to investigate the formation of hydrocarbons and model their migration and accumulation through geological time in realistic models (both 2D and 3D) of the sub-surface. The software has also been modified to include the formation of gas hydrates (Kroeger et al., 2015). As such, it is ideal for quantitative testing of conceptual models that we have developed from seismic observations.

Results and Discussion

Layer-Parallel Versus Sub-Vertical Gas Migration into the GHSZ

Focused gas migration into the gas hydrate stability zone from below is a key process for the formation of concentrated hydrate deposits (Boswell et al., 2012). Upward gas migration often exploits strong permeability anisotropy resulting from inter-bedded shale and sand deposits. In these settings, permeability is much higher along layers than across layers (Frederick and Buffett, 2011). We see many manifestations of this on the southern Hikurangi margin (e.g. Crutchley et al., 2015; Fraser et al., 2016), where concentrated gas hydrate deposits are constrained to particular layers in the sub-surface (Figure 2A). Less common, but also widely observed beneath anticlinal ridges, are gas hydrate accumulations that have formed from sub-vertical gas migration into the GHSZ (e.g. Fraser et al., 2016). One of the most striking examples of this phenomenon was presented by Fraser et al. (2016), where a gas chimney within the GHSZ has developed above a thick underlying free gas zone (Figure 2B). The gas chimney is surrounded by anomalously high-velocity sediments that indicate concentrated gas hydrate accumulations have formed on the margin of the gas injection feature.

Gas Hydrate Formation Beneath Submarine Canyons

The rapid erosion into the sub-seafloor caused by submarine canyons can have a pronounced impact on gas hydrate stability (Davies et al., 2012). Hornbach et al. (2003) proposed a mechanism by which submarine canyons, causing a localized downward shift in the base of gas hydrate stability (BGHS), can lead to capturing of free gas into concentrated gas hydrate deposits. Seismic velocities beneath canyons on the southern Hikurangi margin suggest that this same process could be taking place here. Numerical simulations of gas accumulation and gas hydrate formation in a transient model of seafloor erosion (Crutchley et al., 2017) show how this process can take place (Figure 3). An important factor in this modelling was that free gas is effectively trapped beneath low permeability (hydrate-bearing) strata before being incorporated into the hydrate accumulation after the BGHS moves down in response to canyon incision.

The Role of Folding and Asymmetric Sedimentation

The widespread gas hydrate accumulations that can be identified from high reflectivity within the GHSZ on the southern Hikurangi margin lent themselves to a regional study into relationships between anticlinal folding and hydrate formation (Crutchley et al., 2018). Folding in the wedge results in a wide range of angles between dipping strata and the BGHS, alternating between landward-dipping and seaward-dipping (Figure 4). We notice a distinct preference for concentrated gas hydrate accumulations to form in landward-dipping strata, and in layers that cross the BGHS at angles greater than ~5°. We interpret that a key process in this phenomenon of landward-dipping gas hydrate accumulations is the asymmetric nature of sedimentation in a deforming wedge, where uplifted ridges act as barriers to downslope sedimentation. Preferential sedimentation on the landward flanks of ridges leads to pronounced gas hydrate recycling in landward-dipping strata. This can favor the development of thick gas columns beneath the BGHS that drive gas back into the GHSZ to form concentrated deposits.

Outlook

Gas Hydrate Reservoir Sediments

A significant knowledge gap for our understanding of gas hydrate systems on the Hikurangi margin is reservoir composition and quality. Although recent IODP drilling on the northern Hikurangi margin will provide important insight, there are indications that the northern part of the margin is quite different to the southern margin (Pecher et al., 2019). Sediment samples collected during a recent research voyage give perhaps our best insight yet into reservoirs for hydrate formation on the southern margin. Samples of these sediments are currently with GFZ Potsdam for laboratory gas hydrate formation experiments.

Modelling of Fault Zone Permeability and Gas Hydrate Formation

Faulting clearly plays at least an indirect role in the distribution of gas hydrate on the margin. It is known, for example, that concentrated hydrates form around localized extensional and compressional structures (Wang et al., 2017). Recent and on-going research (Hillman et al., 2019) is looking more closely at the potential role of faults as preferred fluid migration pathways, which depends on the architecture of fault zone permeability.

Improvements in Seismic Imaging

By combining high-resolution multi-channel seismic reflection data with conventional industry data-sets, we are working on improving the sub-surface characterization of gas hydrate systems. Different pre-stack seismic inversion methods are also being considered that will help to constrain small scale acoustic variability that provides better insight into gas hydrate distribution and concentration.

References Cited

Boswell, R., T.S. Collett, M. Frye, W. Shedd, D.R. McConnell, and D. Shelander, 2012, Subsurface Gas Hydrates in the Northern Gulf of Mexico: Marine and Petroleum Geology, v. 34/1, p. 4-30. doi.org/10.1016/j.marpetgeo.2011.10.003

Boswell, R., 2009, Is Gas Hydrate Energy Within Reach?: Science, v. 325/5943, p. 957-958. doi:10.1126/science.1175074

Chatterjee, S., G. Bhatnagar, B. Dugan, G.R. Dickens, W.G. Chapman, and G.J. Hirasaki, 2014, The Impact of Lithologic Heterogeneity and Focused Fluid Flow Upon Gas Hydrate Distribution in Marine Sediments: Journal of Geophysical Research: Solid Earth, v. 119, 24 p. doi:10.1002/2014JB011236

Crutchley, G.J., K.F. Kroeger, I.A. Pecher, J.J. Mountjoy, and A.R. Gorman, 2017, Gas Hydrate Formation Amid Submarine Canyon Incision: Investigations from New Zealand's Hikurangi Subduction Margin: Geochemistry, Geophysics, Geosystems, v. 18/12, p. 4299-4316. doi.org/10.1002/2017GC007021

Crutchley, G.J., D.R.A. Fraser, I.A. Pecher, A.R. Gorman, G. Maslen, and S.A. Henrys, 2015, Gas Migration into gas Hydrate-Bearing Sediments on the Southern Hikurangi Margin of New Zealand: Journal of Geophysical Research, v. 120/2, p. 725-743. doi.org/10.1002/2014JB011503

Crutchley, G.J., K.F. Kroeger, I.A. Pecher, and A.R. Gorman, 2018, How Tectonic Folding Influences Gas Hydrate Formation: New Zealand’s Hikurangi Subduction Margin: Geology, v. 47/1, p. 39-42. doi.org/10.1130/G45151.1

Davies, R.J., K.E. Thatcher, S.A. Mathias, and J. Yang, 2012, Deepwater Canyons: An Escape Route for Methane Sealed by Methane Hydrate: Earth and Planetary Science Letters, v. 323-324, p. 72-78.

Fraser, D.R., A.R. Gorman, I.A. Pecher, G.J. Crutchley, and S.A. Henrys, 2016, Gas Hydrate Accumulations Related to Focused Fluid Flow in the Pegasus Basin, Southern Hikurangi Margin, New Zealand: Marine and Petroleum Geology, v. 77, p. 399-408. doi.org/10.1016/j.marpetgeo.2016.06.025

Frederick, J.M., and B.A. Buffett, 2011, Topography-and Fracture-Driven Fluid Focusing in Layered Ocean Sediments: Geophysical Research Letters, v. 38/8. doi.org/10.1029/2010GL046027

Hillman, J.I.T., G.K. Crutchley, and K.F. Kroeger, 2019, Distribution of Faulting and Gas Hydrates in the Southern Hikurangi Margin: 2019 AAPG Asia Pacific Region Geosciences Technology Workshop, Gas Hydrates – From Potential Geohazard to Carbon-Efficient Fuel?, Auckland, New Zealand, April 15-17, 2019, Proceedings.

Hornbach, M.J., W.S. Holbrook, A.R. Gorman, K.L. Hackwith, D. Lizarralde, and I.A. Pecher, 2003, Direct Seismic Detection of Methane Hydrate on the Blake Ridge: Geophysics, v. 68/1, p. 92-100.

Kroeger, K.F., A. Plaza-Faverola, P.M. Barnes, and I.A. Pecher, 2015, Thermal Evolution of the New Zealand Hikurangi Subduction Margin: Impact on Natural Gas Generation and Methane Hydrate Formation - A Model Study: Marine and Petroleum Geology, v. 63, p. 97-114.

Liu, X., and P.B. Flemings, 2007, Dynamic Multiphase Flow Model of Hydrate Formation in Marine Sediments: Journal of Geophysical Research: Solid Earth, v. 112/B3. doi.org/10.1029/2005JB004227

Matsumoto, R., M. Hiromatsu, M. Sato, and YK10-08 Shipboard Scientists, 2011, Fluid Flow and Evolution of Gas Hydrate Mounds of Joetsu Basin, Eastern Margin of Japan Sea: Constraints from High-Resolution Geophysical Survey by Auv: Proceedings of the 7th International Conference on Gas Hydrates (ICGH 2011), Edinburgh, Scotland, United Kingdom, July 17-21, 2011, p. 459-468. https://www.pet.hw.ac.uk/icgh7/papers/icgh2011Final00468.pdf. Website accessed August 2019.

Pecher, I.A., G.J. Crutchley, P. Oluwunmi, R. Coffin, K. Heeschen, A. Cook, P. Barnes, L. LeVay, and Expedition 372 and 375 Scientists, 2019, The Gas Hydrate Petroleum System of the Northern Hikurangi Margin, New Zealand: AAPG Asia Pacific Region Geosciences Technology Workshop, Gas Hydrates – From Potential Geohazard to Carbon-Efficient Fuel?, Auckland, New Zealand, April 15-17, 2019, Proceedings.

Singhroha, S., S. Bünz, A. Plaza-Faverola, and S. Chand, 2016, Gas Hydrate and Free Gas Detection Using Seismic Quality Factor Estimates From High-Resolution P-Cable 3D Seismic Data: Interpretation, v. 4/1, p. SA39-SA54. doi.org/10.1190/INT-2015-0023.1

Wallace, L., P. Barnes, J. Beavan, R. Van Dissen, N. Litchfield, J. Mountjoy, R. Langridge, G. Lamarche, and N. Pondard, 2012, The Kinematics of a Transition from Subduction to Strike-Slip: An Example From The Central New Zealand Plate Boundary: Journal of Geophysical Research: Solid Earth, v. 117, no. B02405, 24 p. doi:10.1029/2011JB008640

Wang, H., G.J. Crutchley, and T. Stern, 2017, Gas Hydrate Formation in Compressional, Extensional and Un-Faulted Structural Settings – Examples from New Zealand's Hikurangi Margin: Marine and Petroleum Geology, v. 88, p. 69-80. doi.org/10.1016/j.marpetgeo.2017.08.001

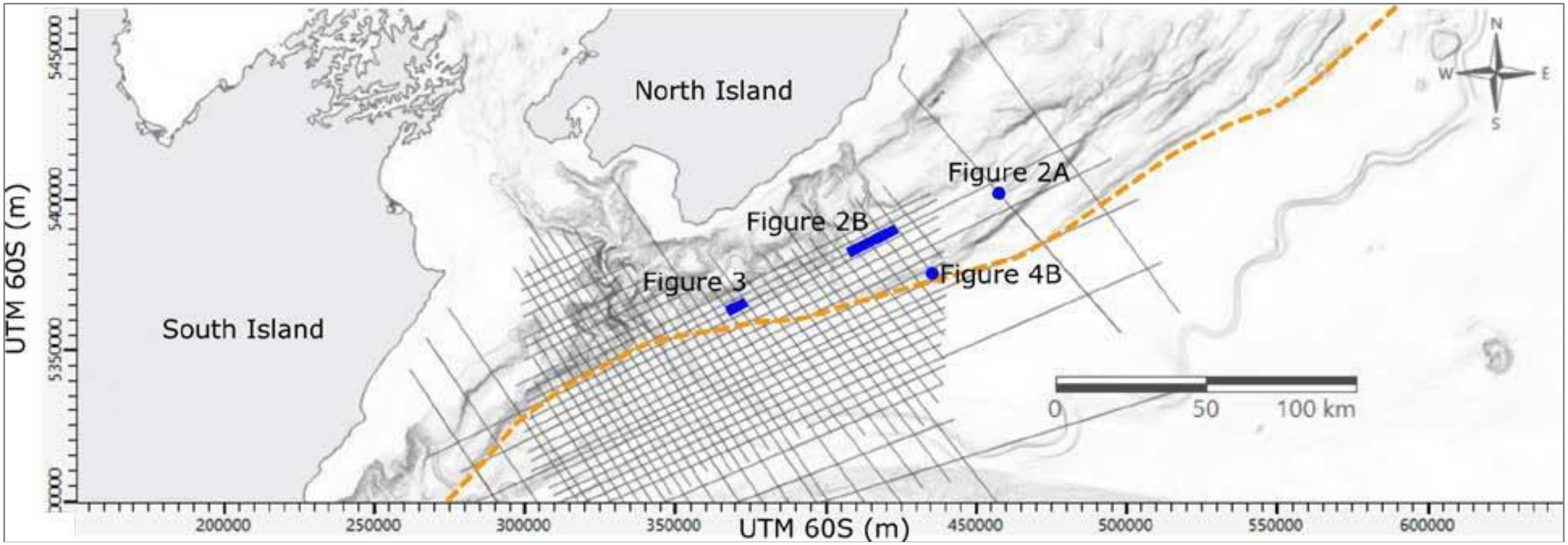

Figure 1. Map of the southern end of the Hikurangi subduction margin. Broken orange line = approximate location of deformation front. Blue lines are locations of subsequent figures.

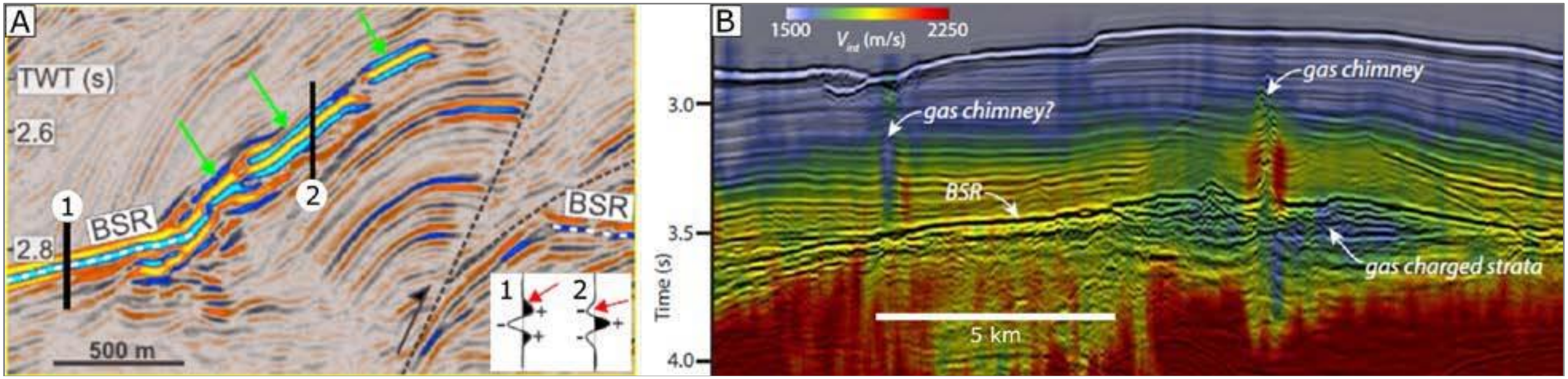

Figure 2. A) Example of layer-constrained hydrate formation manifested as a highly reflective segment extending upward toward the seafloor from the BSR (after Crutchley et al., 2015). B) Hydrate formation on the margins of a vertical gas injection feature (after Fraser et al., 2016).

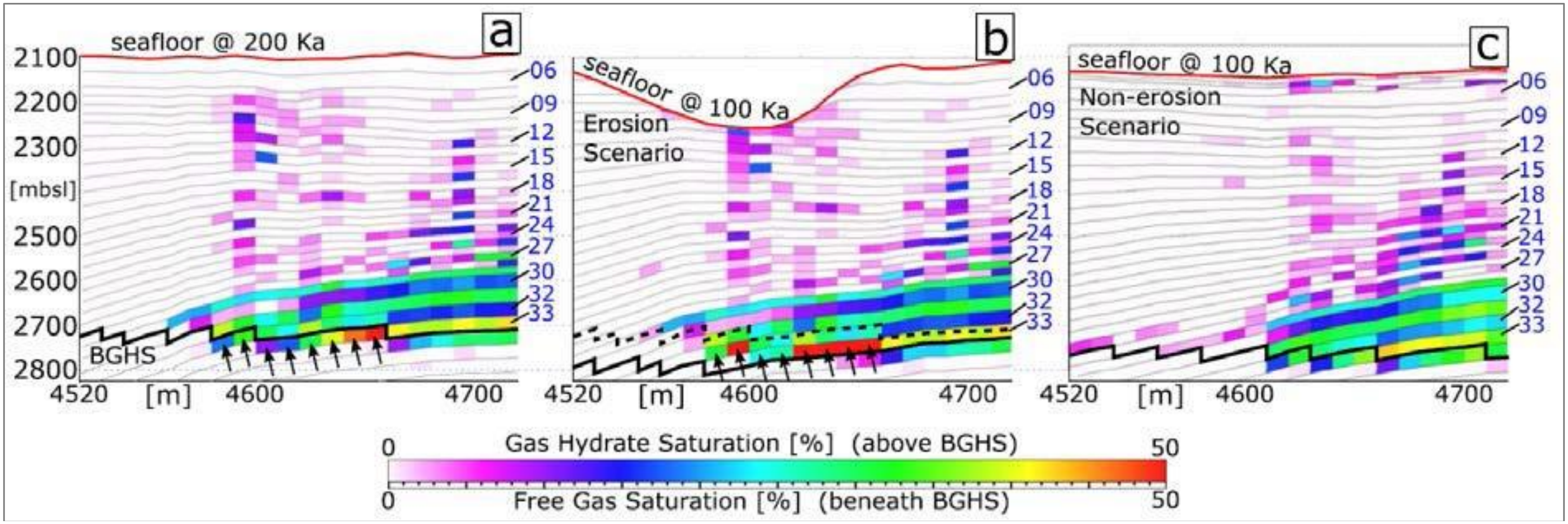

Figure 3. Petromod gas hydrate formation modelling results at a submarine canyon (after Crutchley et al., 2017). Red line is the seafloor, heavy black line is the BGHS. a) Prior to canyon incision, hydrate forms in dipping strata. Free gas accumulates beneath the concentrated hydrates, beneath the BGHS. b) With seafloor incision, the BGHS moves downward and captures the free gas from (a) and converts it into hydrate. c) The case at the same time step as (b), but without canyon erosion, for reference.

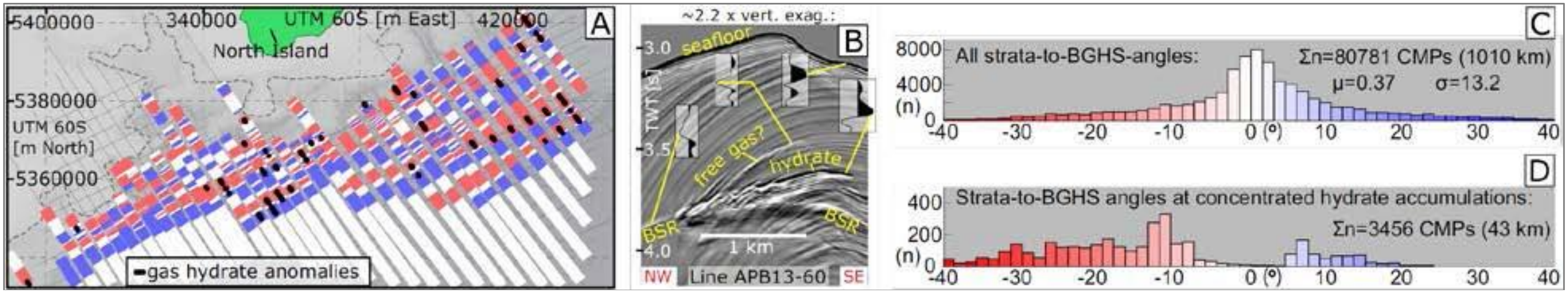

Figure 4. After Crutchley et al. (2018). A) Map of concentrated gas hydrate accumulations (black dots) plotted on top of strata dip direction at the BGHS (red=landward dipping; blue=seaward dipping; white=sub-parallel to BGHS). B) An example of a concentrated hydrate accumulation in seismic data. C) Histogram of strata-to-BGHS angles in the mapped area (A). Note: negative angles are landward-dipping, positive are seaward-dipping. D) Histogram of strata-to-BGHS angles that are coincident with concentrated hydrates, showing the strong preference for landward-dipping strata.