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Supplementary Material for:

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Distribution of Methane Plumes on Cascadia Margin and Implications for the Landward Limit of Methane Hydrate Stability

Description of Supplementary Materials

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I: Metadata – Multibeam Water Column Data Expeditions, Data Availability, Data Analysis, Credits

Data about the eight multibeam datasets that comprise the U.S. Cascadia margin multibeam (USCMMB) database (Figure S1). Metadata include cruise ID, vessel, chief scientist and expedition leader when available, data download links, data processing and analysis individuals, and funding information.

U.S. Cascadia Margin Multibeam (USCMMB) Seafloor and Water Column Data

Acronyms:

Earth Ocean Interactions (EOI)

Joint Institute for the Study of the Atmosphere and Ocean (JISAO)

National Centers for Environmental Information (NCEI)

National Geophysical Data Center (NGDC)

National Science Foundation (NSF)

National Oceanographic and Atmospheric Administration (NOAA)

Ocean Exploration Trust (OET)

Office of Exploration and Research (OER)

Olympic Coast National Marine Sanctuary (OCNMS)

Oregon State University (OSU)

Rolling Deck to Repository (R2R)

University of Washington (UW)

TN265 (2011)
EM302 30 kHz data collected by R/V *Thompson*. Chief scientist Chris Romsos (OSU). The project was part of the RAPID Multibeam Mapping at NSF Cascadia Initiative.
Raw data download at NCEI/NGDC:
https://www.ngdc.noaa.gov/ships/thomas_g_thompson/TN265_mb.html
Raw data also available at R2R: https://www.rvdata.us/search/cruise/TN265
Raw seafloor and water column data processed and analyzed by Susan Merle (OSU / NOAA EOI).

1605RA (2016) Hydrographic survey number W00311
EM710 70 kHz data collected by the NOAA ship *Rainer*. Party Chief Edward J. Van Den Ameele, CAPT/NOAA. Chief scientist Nancy Wright from the NOAA OCNMS, who provided the ship time. Seafloor data processed by mapping personnel on the *Rainier* and Bran Black (OSU). Water column data analyzed by Erica Sampaga (UW). Postcruise water column data analysis funded by NSF and JISAO. Data download at NCEI/NGDC:
https://www.ngdc.noaa.gov/nos/W00001-W02000/W00311.html

NA070 (2016)
EM302 30 kHz data collected by E/V *Nautilus*, owned and operated by OET. Data requests must go through OET: https://www.oceanexplorationtrust.org/data-request This was a shake-down cruise.

Seafloor data processed by OET personnel during the expedition. Water column data analyzed by Susan Merle (OSU / NOAA EOI).

NA072 (2016)
EM302 30 kHz data collected by E/V *Nautilus*, owned and operated by OET. Chief scientist Robert Embley (OSU/NOAA EOI). Expedition leader Nicole Raineault (OET). Data requests must go through OET: https://www.oceanexplorationtrust.org/data-request Seafloor data processed by OET personnel during the expedition. Water column data analyzed by Susan Merle (OSU/NOAA EOI) during and post expedition. Cruise report available on the NOAA EOI program website: https://www.pmel.noaa.gov/eoi/pdfs/2016-PacificCoast-NA072-CruiseReport-lores.pdf Additional funding provided by NOAA OER.

NA078 (2016)
EM302 30 kHz data collected by E/V *Nautilus*, owned and operated by OET. Expedition leader Nicole Raineault (OET). Data requests must go through OET. https://www.oceanexplorationtrust.org/data-request Seafloor and water column data processed by OET personnel during the expedition, led by Lindsay Gee (OET). Additional funding from NOAA OER.

NA080 leg 2 (2017)
EM302 30 kHz data collected by E/V *Nautilus*, owned and operated by OET. Expedition leader Lindsay Gee (OET). Data requests must go through OET. https://www.oceanexplorationtrust.org/data-request Seafloor and water column data processed by OET personnel during the expedition. Additional funding from NOAA OER.

NA088 (2017)
EM302 30 kHz data collected by E/V *Nautilus*, owned and operated by OET. Expedition leader Lindsay Gee (OET). Data requests must go through OET. https://www.oceanexplorationtrust.org/data-request Seafloor and water column data processed by OET personnel during the expedition. Additional funding from NOAA OER.

RR1712 (2017)
EM122 12 kHz data collected by the R/V *Revelle*. Chief scientist Bill Chadwick (OSU/NOAA EOI). Only two transit lines on Cascadia margin used in this compilation. Raw data download at NCEI/NGDC: https://www.ngdc.noaa.gov/ships/roger_revelle/RR1712_mb.html Raw data also available at R2R: https://www.rvdata.us/search/cruise/RR1712 Seafloor and water column data processed and analyzed by Susan Merle (OSU/NOAA EOI). Funding provided by NSF.

All multibeam surveys: The positions of individual bubble streams and clustered emission sites for all the water column data will also be available for download on the NOAA EOI website at the time of publication. https://www.pmel.noaa.gov/eoi/Cascadia-margin.html

II: Bubble Emission Site Normalization Methods

Because all the water column data in the USCMMB study have correlated multibeam seafloor data, the sites could be normalized based on the percentage of the US margin mapped (Figure 7c, Table

S1). The percentage of emission sites per 100 m depth interval were divided by the percentage of the margin mapped within that depth interval.

The emission sites were also normalized based on the percentage of the total area of the US margin per 100 m depth interval. The percentage of sites per 100 m interval were divided by the percentage of the margin that 100 m depth interval represents (Figures 7d, 7e, Table S1).

III: Information Regarding Table 1*: Emission-Site-Statistics – U.S. margin-only.docx*

Bubble emission site statistical information, on the USCM. These statistics were used to create the histograms on Figure 7.

- Column A: [depth range (m)] 100 m depth intervals.
- Column B: [area of margin (km^2)] The area of the margin within that 100 m depth range interval.
- Column C: [% of margin] The percentage of the total margin that 100 m depth range interval represents.
- Column D: [area mapped - USCMMB (km^2)] The area mapped (USCMMB multibeam data only) within that 100 m depth range interval.
- Column E: [% of margin mapped – USCMMB data only] The percentage of the margin mapped within that 100 m depth interval.
- Column F: [# of USCMMB sites] The number of USCMMB clustered emission sites within that 100 m depth interval, 849 total sites.
- Column G: [% of total USCMMB sites (849)] The percentage of the total USCMMB sites on the margin within that 100 m depth interval.
- Column H: [normalized USCMMB: % of sites / % mapped] Normalized emission sites, based on the percentage of sites within a 100 m interval divided by the percentage of the margin mapped with co-registered seafloor and water column data (USCMMB multibeam).
- Column I: [normalized USCMMB: % of sites / % of margin] Normalized USCMMB emission sites, based on the % of total sites within a 100 m interval divided by the % of the margin that depth interval represents.
- Column J: [# of ALL sites: USCMMB and *Riedel et al.*, (2018)] The number of emission sites within each 100 m depth interval. All sites on the U.S. margin which combines USCMMB and *Riedel et al.,* (2018), 1300 total sites. *Riedel et al.,* (2018) includes *Johnson et al.,* (2015) compilation.
- Column K: [% of ALL sites: USCMMB and *Riedel et al.*, (2018)] The percentage of emission sites within each 100 m depth interval. All sites on the U.S. margin which combines USCMMB and *Riedel et al.,* (2018). *Riedel et al.,* 2018 includes *Johnson et al.,* (2015) compilation.
- Column L: [normalized ALL sites: USCMMB and *Riedel et al.* (2018)]: % of sites / % of margin] Normalized emission sites, based on the % of total sites within a 100 m interval divided by the % of the margin that depth interval represents. All sites on the U.S. margin which combines USCMMB and *Riedel et al.*, (2018). *Riedel et al.,* 2018 includes *Johnson et al.,* (2015) compilation.

IV: Information Regarding Supplemental Table S1: *Bubble-Streams-USCMMB.xlsx*
(spreadsheet in Supplementary-Tables-S1-S4.xlsx)

2510 individual bubble stream seafloor locations, geo-picked with FMMidwater© software, from the 8 multibeam datasets (USCMMB) on the U.S. Cascadia margin that are the focus of this study. Information provided in the spreadsheet includes the following:

- Column A: [Cruise ID] Multibeam expedition identification.
- Column B: [Vessel] Vessels include: NOAA ship *Rainier*, E/V (exploration vessel) *Nautilus*, R/V (research vessel) *Thompson*, and R/V *Revelle*.
- Column C: [MB System] Multibeam echosounder sonar system, all of which collected co-registered seafloor and water column data.
- Column D: [Freq kHz] Frequency of the multibeam system.
- Column E: [Longitude] Geo-picked longitude of the bubble stream at the seafloor.
- Column F: [Latitude] Geo-picked latitude of the bubble stream at the seafloor.
- Column G: [MB line] Multibeam line number.
- Column H: [Reviewed] Individual and/or institution accountable for the geo-picked bubble stream locations. Reviewers include: SM (Susan Merle, OSU/NOAA EOI); ES (Erica Sampaga, UW); OET (Members of the E/V *Nautilus* mapping team led by Nicole Rainault and Lindsay Gee).
- Column I: [Zgrid] The multibeam seafloor grid value at the geo-picked bubble stream seafloor location. The processed multibeam data have sound velocity profiles applied which make the grid depth (Zgrid) more accurate than the Zgeopick value.
- Column J: [Zgeopick] QPS FMMidwater© beamfan depth value at the geo-picked bubble stream seafloor location. No ray tracing is applied to the beamfan ping.
- Column K: [Rise] Rise height of the bubble stream in the water column when available. Not all reviewers picked the rise height. Due to the geometry of the beamfan, unless the bubble stream is located at nadir the rise height may be truncated (clipped). The rise height can also be obstructed by noisy surface ocean conditions and biota in the water column.
- Column L: [Description] When available.

V: Information Regarding Supplemental Table S2: *All-Streams-USCMMB-Riedel2018.xlsx*
(spreadsheet in Supplementary-Tables-S1-S4.xlsx)

3481 individual bubble stream seafloor locations on the U.S. Cascadia margin (Fig. 7a). The USCMMB individual bubble stream data combined with *Riedel et al.,* (2018), which includes *Johnson et al.,* (2015). The bubble streams from the datasets are compared in figure 7a. The information provided in the spreadsheet includes the following:

- Column A: [Cruise / Data source] Expedition identification. USCMMB and *Riedel et al.*, (2018) bubble stream data combined,which includes *Johnson et al.*, (2015) bubble streams, many of which are fisherman's flares with no fishing vessel identified.
- Column B: [System] Sonar system used to collect the bubble stream data.
- Column C: [Data set] Includes USCMMB, *Riedel et al.,* (2018), *Johnson et al.,* (2015).
- Column D: [Longitude] Longitude of the bubble stream at the seafloor.
- Column E: [Latitude] Latitude of the bubble stream at the seafloor.
- Column F: [Zgrid] The multibeam seafloor grid value at the geo-picked bubble stream seafloor location, only for USCMMB data
- Column G: [Zgeopick] Geo-picked seafloor depth values, most of which were derived from QPS FMMidwater© software. Available for all data sets.

VI: Information Regarding Supplemental Table S3: *Emission-Sites-USCMMB.xlsx*
(spreadsheet in Supplementary-Tables-S1-S4.xlsx)

849 clustered emission sites (Fig. S2). Information regarding the 300 m-radius clustered seep emission sites, calculated from the file bubble-streams-USCMMB.xls. The clustering of the individual bubble streams is based on *Johnson et al.*, (2015). The emission site locations north of Astoria canyon to the Strait of Juan de Fuca are published in *Johnson et al.* (2019).

- Column A: [Latitude] Latitude of the emission site, central value.
- Column B: [Longitude] Longitude of the emission site, central value.
- Column C: [# of bubble streams] The number of bubble streams clustered into the emission site.
- Column D: [Standard deviation] Standard deviation of the individual bubble streams clustered into the seep site. The more widely spaced the bubble streams, the higher the standard deviation value. The standard deviation is 0 if there is only 1 bubble stream within the emission site.
- Column E: [Zgrid (m)] The gridded depth value at the center of the emission site. The source of the grid values are USCMMB data at 25 m resolution

VII: Information Regarding Supplemental table S4: *All-Emission-Sites-USCMMB-Riedel2018.xlsx*
(spreadsheet in Supplementary-Tables-S1-S4.xlsx)

1300 emission sites derived from 3481 individual bubble streams on the US Cascadia margin, (Fig. 7b). The USCMMB individual bubble stream data are combined with *Riedel et al.,* (2018), which includes *Johnson et al.,* (2015). Much of the bubble stream data *in Riedel et al.,* (2018) was acquired by single beam sonar, EK60 in particular, with no corresponding seafloor data. Nevertheless *Riedel et al.,* (2019) does provide a large database in shallow water, which is sparse in the USCMMB data. The bubble streams were clustered into 300 m-radius seep emission sites based on *Johnson et al,.* (2015).

- Column A: [Latitude] Latitude of the emission site, central value.
- Column B: [Longitude] Longitude of the emission site, central value.
- Column C: [# of bubble streams] The number of bubble streams clustered into the emission site.
- Column D: [Standard deviation] Standard deviation of the individual bubble streams clustered into the seep site. The more widely spaced, the higher the standard deviation. The standard deviation is 0 if there is only 1 bubble stream included in the site.
- Column G: [Zgrid (m)] The gridded depth value at the center of the emission site. Depth values derived from the *Goldfinger et al.,* (2017) compilation grid at 100 m resolution. These depth values are less accurate than the ones derived from the USCMMB gridded multibeam data.

VIII: Supplementary Figures

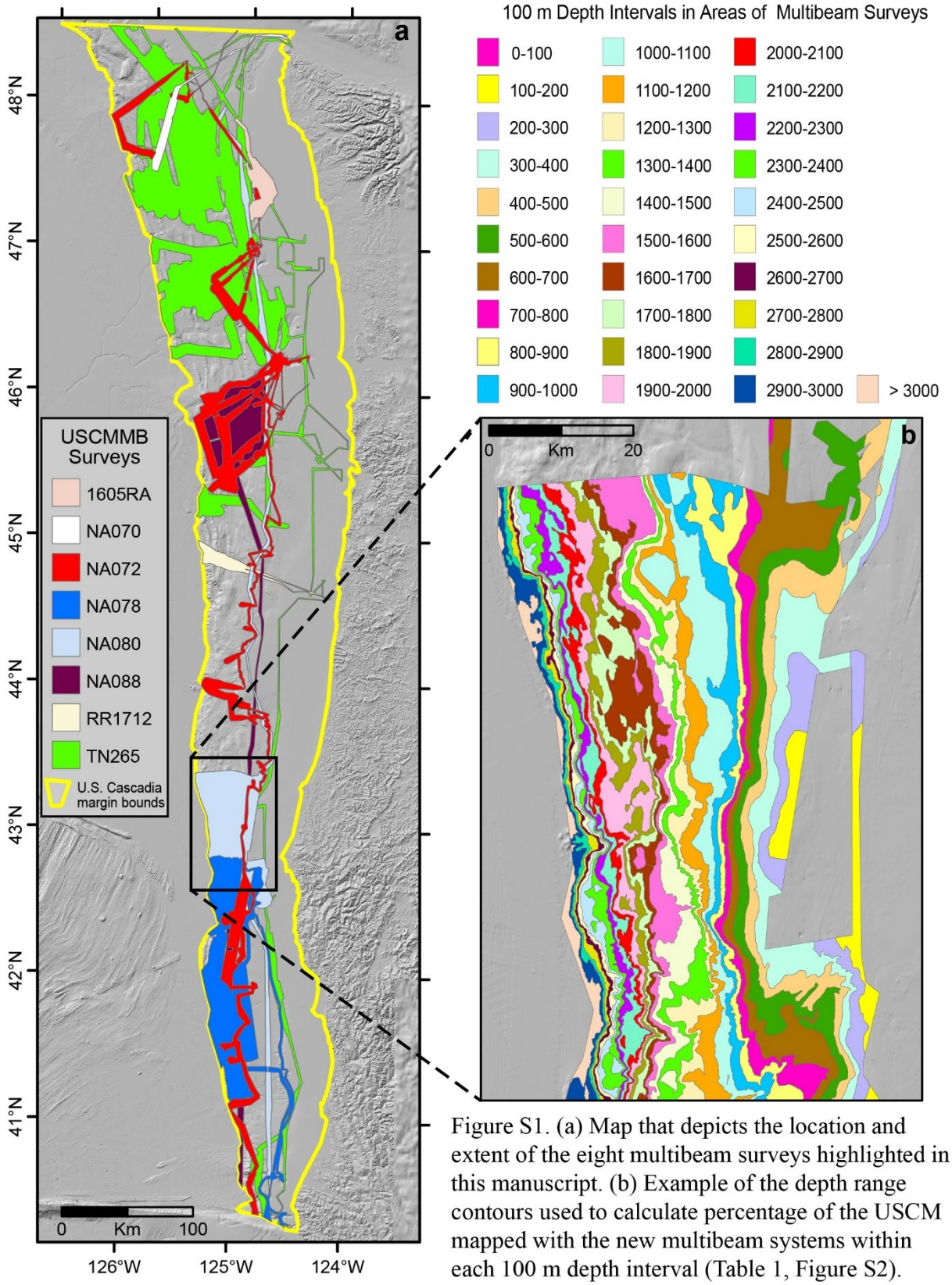

Figure S1. (a) Map that depicts the location and extent of the eight multibeam surveys highlighted in this manuscript. (b) Example of the depth range contours used to calculate percentage of the USCM mapped with the new multibeam systems within each 100 m depth interval (Table 1, Figure S2).

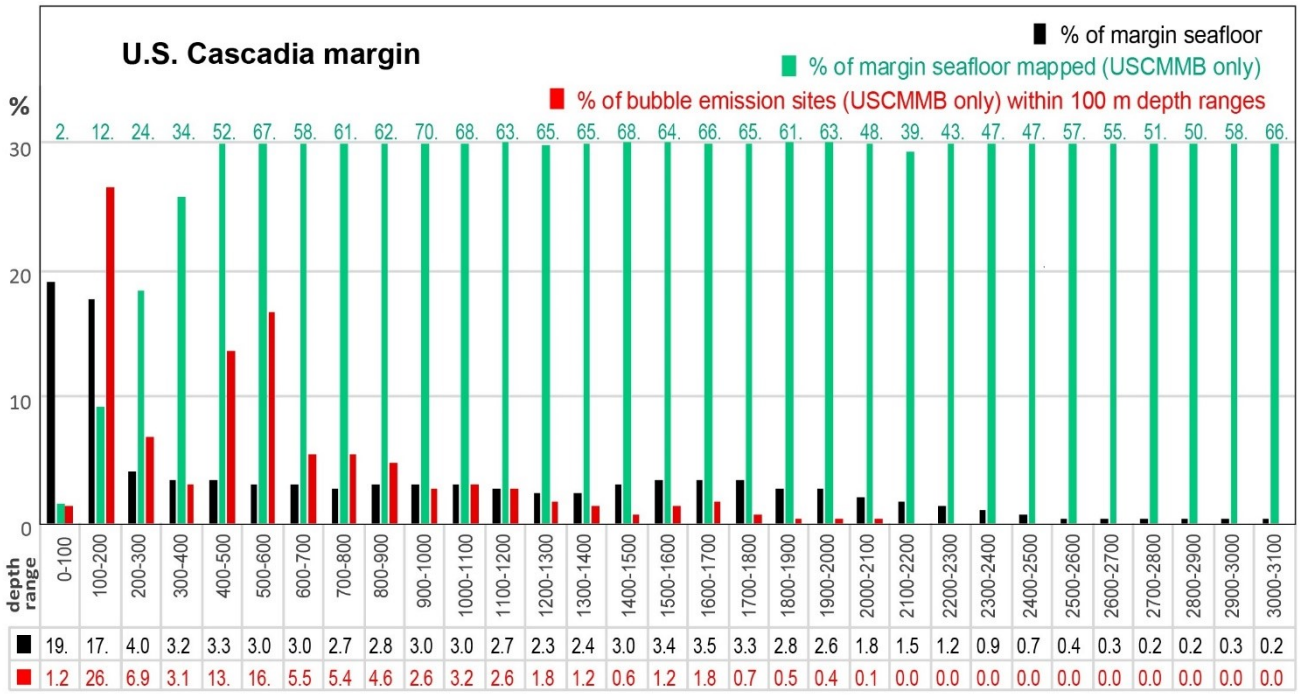

Figure S2. Histogram that illustrates the USCM 100 m depth intervals related to the percentage of the margin that depth range represents, how much of it has been mapped with co-registered seafloor and water column data from this study (USCMMB), and the percentage of bubble emission sites within those 100 m depth ranges.

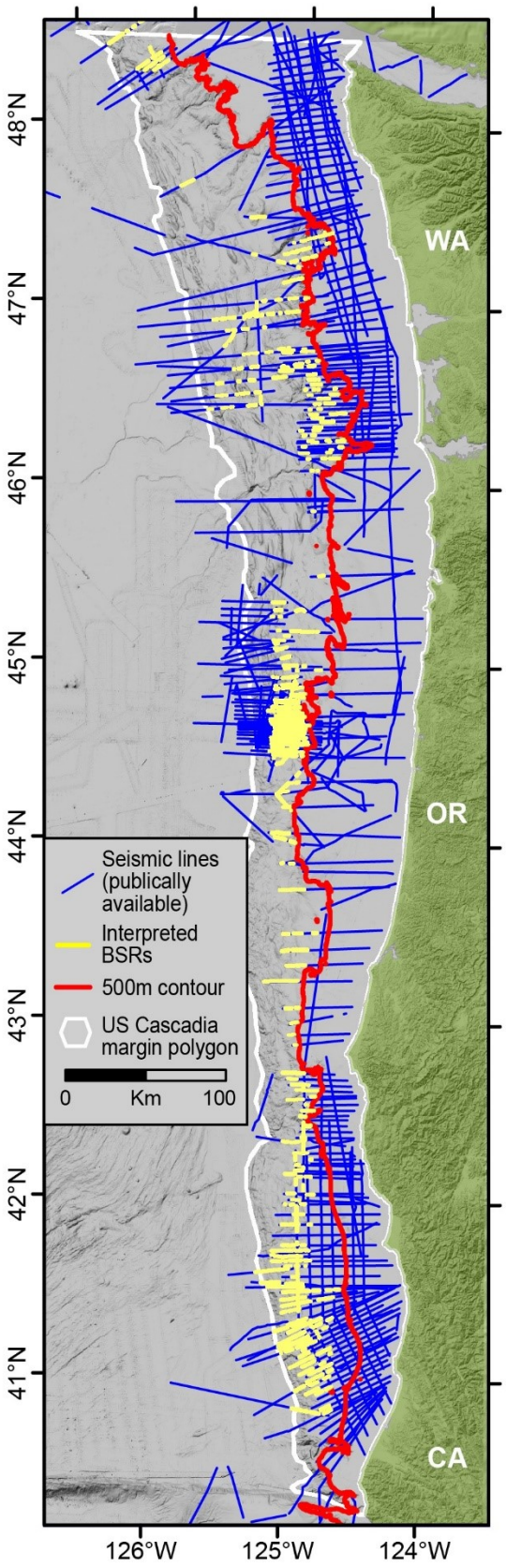

Figure S3. Revised from Phrampus et al., (2017) figure 1. Blue lines are seismic lines used to determine the presence of BSRs (yellow lines). Red line is the 500 m contour. Seismic surveys include: "L-4–77-NC, L-5–77-WO, L-5-81-NC, L-11-80-WO, W-6-75-NC, W-8-75-NP, W-9-78-NC, W-18-75-NP, W-29-80-WO, and W-39-85-WO from the USGS; EW0208 from UTIG; GT8909 and MGL1212 from LDEO; report 97-009 from IRIS; and surveys VI-85 and VI-89 from the Canadian Repository."

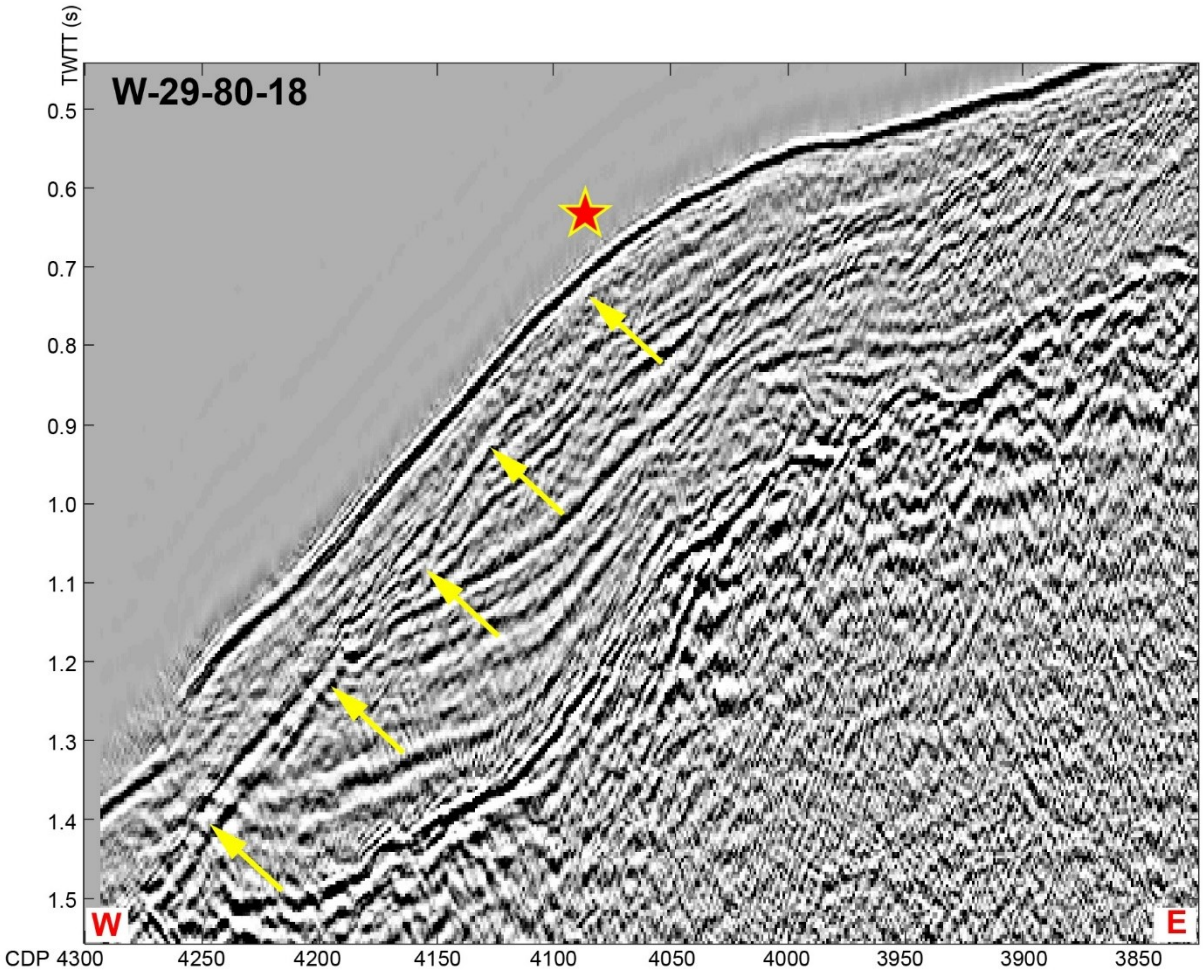

Figure S4. The Red star is a methane plume at 461 m depth, shallower than the 496 m hydrate stability depth. The yellow arrows point to the BSR, which rises to the FEMHS at the seafloor. From Torres et al., (2009).