

Oil & Natural Gas Technology

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Quarterly Research Performance Progress Report (Period ending 03/31/2017)

Characterizing the Response of the Cascadia Margin Gas Hydrate Reservoir to Bottom Water Warming Along the Upper Continental Slope Project Period: October 1, 2013 – March 31, 2017

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EXECUTIVE SUMMARY

In October 2013, the University of Washington initiated a study funded through DOE-NETL entitled: Characterizing the response of the Cascadia margin gas hydrate reservoir to bottom water warming along the upper continental slope. The objective of this project is to understand the response of the WA margin gas hydrate system to contemporary warming of bottom water along the upper continental slope. Through pre-cruise analysis and modeling of archive and recent geophysical and oceanographic data, we (1) inventoried bottom simulating reflectors along the WA margin and defined the upper limit of gas hydrate stability, (2) refined margin-wide estimates of heat flow and geothermal gradients, (3) characterized decadal scale temporal variations of bottom water temperatures at the upper continental slope, and (4) used numerical simulations to provide quantitative estimates of how the shallow boundary of gas hydrate stability responds to modern environmental change. The results of the pre-expedition analysis of historic bottom water temperatures and the simulations of the response of the upper limit of gas hydrate stability to intermediate water warming on the Washington margin have been published (Hautala et al., 2014). The work on characterizing regional heat flow was presented at the AGU Fall Meeting (Salmi et al., 2015) and a paper summarizing the results is in press (Salmi et al., *in press*). A synthesis of seep distribution along the Washington margin was published in *Geochem. Geophys. Geosyst.* (Johnson et al., 2015). These pre-cruise results provided the context for a systematic geophysical and geochemical survey of methane seepage along the upper continental slope from 48° to 46°N during a 10-day field program on the *R/V Thompson* from October 10-19, 2014. This systematic inventory of methane emissions along this climate-sensitive margin corridor and comprehensive sediment and water column sampling program provided data and samples for Phase 3 of this project that focused on determining fluid and methane sources (microbial, thermogenic, gas hydrate dissociation), sinks, and fluxes within the sediment and water column, and how they relate to contemporary intermediate water warming.

During the 2014 research expedition, we discovered 9 active seep sites between ~470 and 520 m water depth and imaged 22 bubble plumes with heights commonly rising to ~300 m below sea level with some reaching to near the sea surface. Some of the seep sites are controlled by local margin structure, mainly extensional faults and ridges. We collected 22 gravity cores and 20 CTD/hydrocasts from the 9 seeps. The sediment cores were sub-sampled at high-resolution for pore water geochemical analyses. In addition, we collected ~400 water samples to characterize the hydrocarbon concentrations and distribution within the water column at the 9 active seep sites surveyed at the upper limit of methane hydrate stability. We analyzed for pore water salinity, pH, and alkalinity shipboard, as well as bottom water C₁-C₄ concentrations. The shore-based geochemical program is complete. We completed the shore-based pore water Cl, Br, NH₄, SO₄, Na, K, Ca, Mg, Li, B, Sr, Ba, and Si concentration analyses, the $\delta^{18}\text{O}$, δD , and $\delta^{13}\text{C}$ -DIC analyses, as well as the sediment porosity analyses. In addition, we analyzed bottom water samples both at seep sites and at background locations for noble gas ratios. During this reporting period we finished the pore water hydrocarbon concentration analyses and the water column hydrocarbon analyses at the three high-flux sites.

Hydrocarbons heavier than CH₄ were not detected in either pore water or bottom water samples, suggesting any gas hydrate present is Structure I. Pore water data show decreasing chloride concentrations downcore at several sites with measured values as low as 170 mM (30% of

seawater value), and the sulfate-methane transition zone occurs between 50-80 cm below the sea floor. Pore water solute, noble gas, and isotope ratios suggest that pore water freshening is not the result of methane hydrate dissociation and pore water freshening from at least three sites is due to clay dehydration at depths where temperatures exceed 60°C. Analysis of a suite of chemical geothermometers brackets the temperature of the fluid source between 100-250 °C, warmer fluid source temperatures than typically sampled at continental margin seep sites, but not surprising considering the young age of the subducting lithosphere at the Cascadia subduction zone. Based on the geochemical dataset, active gas hydrate formation is occurring at the site that is about 10 m deeper than the calculated upper limit of methane hydrate stability. Only a few of the sites have pore water profiles in steady state, suggesting a dynamic biogeochemical system at the upper continental slope along the entire WA margin.

The preliminary geochemistry and modeling results were presented at the fall American Geophysical Union meeting in San Francisco (Whorley et al., 2015), and were presented at the Gordon Research Conference on Natural Gas Hydrate Systems in Galveston, TX (Whorley et al., 2016). A synthesis of the pore water geochemistry results is provided in a paper in the proceedings of the 9th International Conference on Gas Hydrates (Whorley et al., 2017), an extended abstract summarizing seep dynamics at Hydrate Ridge was also accepted for this conference (Solomon et al., 2017), and a manuscript synthesizing the results of this research program is in preparation for *Earth and Planetary Science Letters* (Whorley et al., *in prep.*). Multibeam bathymetry and acoustic backscatter intensity data from the 2014 cruise and an *R/V Atlantis* expedition at the southern Washington margin in 2013 was coupled with *in-situ* video observations, multi-channel seismic profiles, and other calibration data to assess the distribution of seafloor and shallow subsurface authigenic carbonate over the Cascadia margin. A paper detailing the results of this analysis was submitted during this reporting period to *Journal of Geophysical Research* (Miller and Johnson, *submitted*). In addition, a paper describing earthquake-triggered sediment gravity flows along the Cascadia margin was submitted to *Journal of Geophysical Research* and is in press (Johnson et al., *in press*). E. Solomon gave the final presentation for this award to DOE on March 30, 2017, and the final report will be submitted in June 2017.

The results of our 2014 research expedition prompted and guided a hydroacoustic survey and several *ROV Hercules* dives at the Astoria Canyon seep sites during Ocean Exploration Trust *E/V Nautilus* Expedition 072 entitled “Seeps and Ecosystems of the Cascadia Margin”. The data collected during *E/V Nautilus* Expedition 072 are open-access, and will complement and expand upon our data collected at this seep site in 2014. During the expedition, they identified over 400 new seep sites between 125 and 1624 meters water depth along the Washington and Oregon margins. The results of the *E/V Nautilus* expedition were presented at the AGU fall meeting (Embley et al., 2016). Furthermore, the results of the pore water geochemical program guided a proposal submitted to the Deep Carbon Observatory during this reporting period aimed at characterizing the microbial community at the seep site hosting fluid flow sourced at temperatures >150 °C; Graw and Colwell (OSU), Solomon and Whorley (UW).

PROGRESS, RESULTS, AND DISCUSSION

Task 1.0 Project management and planning

Completed in previous reporting period - The project management plan was finalized and submitted on October 17, 2013.

Task 2.0 Compile relevant archive data

Completed in previous reporting period – We have compiled the relevant MCS profiles and swath bathymetry on the WA margin. All available high-resolution CTD, glider and ARGO float temperature profiles, extending to depths below 200 m, were extracted and compiled from the World Ocean Database 2013 (National Oceanographic Data Center) for the region 124.5°W to 127.5°W and 46.5°N to 48.5°N off the Washington margin. We have also compiled all of the acoustic backscatter data from archive and recent (EM122 and EM302 data) *R/V Langseth*, *R/V Thompson*, and *R/V Atlantis* expeditions at the Washington margin.

Task 3.0 Estimate sediment porosity and in situ thermal conductivities

Completed in a previous reporting period – We converted existing archive MCS data to Vp-vs-depth profiles and then used these data to estimate sediment porosities. From the estimated sediment porosities, we calculated thermal conductivities along the WA continental slope. We have completed a compilation of sediment core archives from legacy coring programs on WA margin for sediment lithology in order to provide guidance regarding the distribution and partitioning of the sediments into turbidites and pelagic sediments within a specific geographic area. These data are necessary to convert seismic velocities and structural components into a plausible model of thermal conductivity.

Task 4.0 Constrain hydrate distribution and geothermal gradients

Completed in a previous reporting period – We have evaluated Bottom Simulating Reflectors (BSRs) from the COAST MCS cruise to establish the distribution of gas hydrates and geothermal gradients along the WA margin in combination with heat flow measured during our recent WA margin heat and fluid flow survey (Johnson et al., 2013; Johnson et al., 2014). This work has been completed for the region surveyed during the COAST MCS expedition in 2012, which overlaps with our proposed track-line for our research expedition in October 2014. We evaluated BSRs from other legacy datasets along the WA margin, including both commercial (Western Geophysical) and USGS MCS expeditions in the area.

Task 5.0 Analyze recent temperature data and long-term bottom water record

Completed in a previous reporting period – As stated in the Executive Summary, after filtering, there are 2122 high-quality, open-ocean temperature profiles that were linearly interpolated to 10 m depth intervals ranging from 50 to 1000 m. Averaged over the entire region, the temperature at the upper limit of gas hydrate stability shows persistent warming over the last 40 years. The time series also clearly shows the influence of the Pacific Decadal Oscillation (PDO) at the upper limit of gas hydrate stability. Taking into account other independent variables such as latitude, water depth, and the monthly Pacific Decadal Oscillation (PDO) index, our calculations studying sensitivity to methodological choices yield a constant and significant warming trend off the WA margin from 1960 to present.

Task 6.0 Non-steady state thermal simulations and impact of bottom water warming on the upper limit of the gas hydrate stability field

Completed in a previous reporting period – In collaboration with Robert Harris at Oregon State University we used a 2-D finite-element conductive heat flow model to simulate the change in temperature distribution in the shallow sediments at the upper limit of gas hydrate stability resulting from the warming intermediate-depth water temperatures. The upper boundary of the thermal model is based on the historic temperature records on the WA margin, and the bottom boundary condition is set by the heat flow estimated from regional BSR data, historic heat flow surveys, and borehole data. In situ thermal conductivity is estimated from MCS data using vertical seismic velocity profiles to estimate porosity, then porosity is converted to thermal conductivity (Task 3.0). Thermal diffusivities were also measured during a recent GeoPRISMS expedition off the coast of WA by Johnson and Solomon (Johnson et al., 2013, EOS: Homola et al., *Elementa*, 2015). The base of the gas hydrate stability zone is calculated integrating the Pitzer equations in Tishchenko et al. (2005). The model is stepped through time over the 45-year historic record of bottom water temperatures for the WA margin. Results show that the upslope limit of the gas hydrate stability zone on the WA margin is sensitive to the contemporary warming of intermediate waters and retreats downslope over the 40-year period along all three profiles simulated along the margin. This modeling effort guided the field program in Phase II of the research project. The results of the characterization of the long-term bottom warming trend and these model simulations are described in Hautala et al. (2014).

Task 7.0 Planning and Preparations for Research Expedition

Completed in a previous reporting period – During this reporting period, the PIs met weekly to discuss our sampling strategy, work flow, and cruise track. We completed planning and preparations for the October 2014 research expedition at the beginning of the quarter. The expedition occurred from 10-19 October 2014, and we successfully achieved the objectives of the cruise plan and were able to sample many more sites than originally planned.

Task 8.0 Research Expedition

Completed in a previous reporting period – We surveyed the upper continental slope of the WA margin from the Strait of Juan de Fuca to the Columbia River. During the expedition, we sampled nine independent seep sites at the upper limit of gas hydrate stability, deployed 39 gravity cores and two piston cores, deployed 20 CTD casts for full water column sampling, and sub-sampled >300 sediment whole-rounds for pore water geochemical analyses. We conducted ‘localized’ EM 302 surveys over each seep site to better refine targets for detailed coring and water column sampling. The survey at each site included EM302 and 3.5 kHz cross-track surveys, ADCP surveys to determine ‘down-current’ direction of emissions, CTD and Niskin bottle casts, and a suite of gravity cores for pore fluid chemistry. The cores were immediately sub-sampled shipboard in a cold room for both geochemistry and microbiology, and hydrocarbon samples collected along the core length will be analyzed via headspace methods on shore. Pore fluids were extracted in Ti squeezers under a hydraulic press and with Rhizon samplers. Salinity, alkalinity, and pH were immediately analyzed shipboard, and the remaining pore fluid samples were preserved for shore-based hydrocarbon, major and minor element, and stable isotope ratio analyses. Approximately 23 Niskin water samples were collected from each of the 20 during CTD/hydrocasts targeting the seep sites. Water samples were preserved for shore-based geochemical analyses.

Task 9.0 Processing of Geophysical Data

Completed this reporting period – We processed the remaining ship-board geophysical data during this reporting period. Though we processed the multi-beam bathymetry and mid-water column data in real-time shipboard using Fledermaus and the FM-Midwater tool, additional post-expedition processing was completed during a previous reporting period, and the new results were presented at the Gordon Research Conference on Natural Gas Hydrate Systems in Galveston, TX (Whorley et al., 2016) and will be presented at the 9th International Conference on Gas Hydrates (Whorley et al., 2017). In addition, an analysis of the acoustic backscatter data collected during the 2014 research expedition and another expedition at the Washington margin on the *R/V Atlantis* in 2013 was used to assess the distribution of seep-related authigenic carbonate deposits and their relationship to margin structure. A manuscript detailing the results of this analysis was submitted to *Journal of Geophysical Research* during this reporting period (Miller and Johnson, submitted). Analysis of the heat flow data collected during the 2014 *R/V Thompson* was also completed during this reporting period.

Tasks 10.0-12.0 Shore-based Geochemical Analyses and Modeling

Completed this reporting period, additional modeling continuing post-award – Pore water and water column sub-samples were preserved for each type of analysis and are stored under the appropriate conditions at UW. The Cl, SO₄, Br, NH₄, Na, K, Ca, Mg, Li, B, Sr, Ba, Si, porosity, $\delta^{18}\text{O}$, δD , $\delta^{13}\text{C-DIC}$, and noble gas analyses are complete. The pore water and water column C₁-C₄ hydrocarbon analyses were completed this reporting period. The pore water minor element analyses were completed during the previous reporting period. Preliminary modeling of the solute profiles for water and methane fluxes was conducted this reporting period and additional fine-tuning will continue post-award. A synthesis of the geochemical program was prepared as a paper for the proceedings of the 9th International Conference on Gas Hydrates (Whorley et al., 2017) and a comprehensive manuscript describing the results of the geochemistry program is in preparation for submission to *Earth and Planetary Science Letters*.

CONCLUSIONS

The first six tasks comprise Phase 1 of the research project aimed at providing the context for a systematic geophysical and geochemical survey of methane seepage along the upper continental slope of the WA margin. These six tasks have been completed. We completed the preparations for the research expedition (Task 7), and successfully conducted the field program from 10-19 October 2014 completing Phase II of this project. We completed Phase III/Budget Period 2 this reporting period, which focused on post-expedition analyses, interpretation, publication, and reporting. One paper and one extended abstract were accepted to the 9th International Conference on Gas Hydrates (Solomon et al., 2017; Whorley et al., 2017). A comprehensive manuscript detailing the results of the geochemistry program is in preparation, a manuscript detailing the results of acoustic backscatter analysis to assess the distribution of seafloor authigenic carbonate deposits along the Washington margin has been submitted (Miller and Johnson, *submitted*), a paper describing earthquake-triggered sediment gravity flows along the Cascadia margin was submitted and is in press (Johnson et al., *in press*), and Solomon gave the final presentation of this project to DOE on March 30, 2017. The final report for this project will be submitted in June 2017.

MILESTONE STATUS

Milestone #1 – Determination of the gas hydrate distribution and geothermal gradients along the WA continental slope based on COAST MCS data

Completed June 2014, however additional work continues on legacy datasets north of the COAST survey area.

Milestone #2 – Finalize planning for cruise tracks/stations, identification of shipboard scientific party, and preparations for on-board data/sample acquisition and processing.

Completed September 2014.

Milestone #3 – 2014 field program on the R/V Thompson

Completed October 2014.

Milestone #4 – The first series of reports and publications reporting the results of the research program

Completed, September 2015, additional abstracts and journal articles have been submitted/published since the completion of this milestone.

Milestone #5 – Complete the geophysical and geochemical analytical programs

Completed, March 2017, additional papers and journal articles have been submitted/published

Milestone #6 – Project completion

Completed, March 2017, DOE final presentation, submission of last quarterly report, DOE final report will be submitted in June 2017

COST STATUS

During the fourteenth quarter, a total of \$25,183 was spent to support the post-expedition analytical program and project reporting (the cost breakdown by month is below).

January 2017 = \$15,635

February 2017 = \$4,774

March 2017 = \$4,774

PROBLEMS OR DELAYS

None.

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Whorley, T.L. *, Solomon, E.A., Torres, M.E., Johnson, H.P., Berg, R.D. *, Philip, B.T. **, 2015. Evaluating active methane hydrate dissociation along the Washington margin in response to bottom water warming, AGU Fall Meeting, San Francisco, CA, Abstract OS23B-2015.

Whorley, T.L. *, Solomon, E.A., Torres, M.E., Johnson, H.P., Berg, R.D. *, Philip, B.T. **, 2016. Evaluating water and methane sources at the upslope limit of methane hydrate stability along the Washington margin, Gordon Conference on Natural Gas Hydrate Systems, 29 Feb – 3 March, 2016, Galveston, TX.

Philip, B.T. **, Denny, A.R. *, Solomon, E.A., Kelley, D.S., 2016. Time-series measurements of bubble plume variability and water column methane distributions above Southern Hydrate Ridge, Oregon, *Geochem. Geophys. Geosyst.*, 17, 1182-1196.

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PRODUCTS

Whorley, T.L. *, Solomon, E.A., Philip, B.T. *, Torres, M.E., Johnson, H.P., 2017. Investigating the response of methane hydrates to modern bottom water warming along the upper continental slope of the Cascadia margin, paper, 9th International Conference on Gas Hydrates, Denver, CO, USA, 15 pages.

Solomon, E.A., Kowalski, L. **, Whorley, T.L. *, 2017. Chronic downward flow of seawater in bacterial mats at Hydrate Ridge – mechanisms and biogeochemical significance, Extended Abstract, 9th International Conference on Gas Hydrates, Denver, CO, USA.

Miller, U.K. **, Johnson, H.P., *submitted*. Distribution and evolution of authigenic carbonate on a segment of the Cascadia margin, *Journal of Geophysical Research*.

Johnson, H.P., Gomberg, J.S., Hautala, S.L., Salmi, M.S., *in press*. Sediment gravity flows triggered by remotely-generated earthquake waves, *Journal of Geophysical Research*.

Salmi *, M.S., Johnson, H.P., Harris, R.N., *in press*. Thermal environment of the southern Washington region of the Cascadia Subduction Zone, *Journal of Geophysical Research*.

Final DOE presentation, March 30, 2017

Completion of this quarterly report

* denotes graduate student

** denotes undergraduate student