RESEARCH PERFORMANCE PROGRESS REPORT

Hydrate Evolution in Response to Ongoing Environmental Shifts

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1. ACCOMPLISHMENTS

Major project goals:

The project shall investigate the influence of sediment properties on the development and dissociation of hydrate anomalies. This shall include the development of quantitative, predictive models for the growth and dissociation of hydrate anomalies in response to variations in environmental forcing and gas supply. In working toward this end, major project goals include:

i. the analysis of solubility changes with pore geometry and hydrate saturation in realistic, three-dimensional porous media using Monte Carlo integration techniques;
ii. the development of numerical models for hydrate anomaly growth and decay that use the solubility predictions as input and enable comparison against available field observations; and
iii. the formulation of a model to treat segregated hydrate growth using an extension to the formalism developed to describe frost heave.

The project shall examine how environmental change can cause the evolution of slope-strength heterogeneities, such as those associated with the presence of hydrate anomalies. The central hypothesis is that the stability of hydrate-bearing slopes will be affected when they experience pore-pressure changes and consolidation triggered by environmental change. In pursuing this line of research, major project goals include:

i. developing a numerical treatment of pore pressure evolution in response to hydrate dissociation and consolidation that can a) incorporate the solubility formulation discussed above, and b) use the Mohr-Coulomb failure criterion in an infinite-slope stability model to approximate the potential for failure; and
ii. using a rate-and-state friction formulation to examine slope stability in response to movement on finite slip-patches that correspond with hydrate anomalies and localized changes in pore pressure and consolidation.

The project shall examine how flow and matrix instabilities can lead to the development of gas-escape features in marine sediments. This modeling task will examine conditions for the persistence and nucleation of solitary gas-escape features, and the spacing of gas-escape features in pockmark fields. The over-riding motivation is the need to quantify the potential for enhanced gas escape as a result of perturbations due to environmental change. In working towards this end, major project goals include:

i. using a commercial finite-element package to examine the persistence of gas transport through steady-state chimneys that penetrate the methane hydrate stability zone, and subsequently extending this treatment to examine potential mechanisms to excite flow and/or matrix instabilities that lead to the development of such features; and
ii. developing semi-analytical models to examine the hypothesis that pockmark fields develop from a convective instability tied to fluid flow beneath the MHSZ.

Milestone Status:

The first milestone was reached as forecast at the end of quarter 2, the second at the end of quarter 3, the third and fourth at the end of quarter 4.

Milestone Status Report

Milestone Title/Description	Planned Completion Date	Actual Completion Date	Verification Method	Comments
Solubility Calculator	30-Jun-14	30-Jun-14	comparison against published data and idealized cases	further verification tests planned; improved during Q3 to better approximate 3D effects
Consolidation Code	30-Sep-14	30-Sep-14	predictions constrained by published empirical tests from Hydrate ridge	1D consolidation model driven by changes in effective stress and fluid density
Walker-Ridge Anomaly Simulator	31-Dec-14	31-Dec-14	comparison against published data	ongoing efforts to incorporate effects of sedimentation and microbial generation
Infinite-Slope Stability Analysis	31-Dec-14	31-Dec-14	comparison against idealized results in published work	soon to be superceded by finite slope analysis with non-local elastic effects

Additional milestones will be added to the milestone status report in future RPPRs as their forecast completion dates are reached.

Accomplishments under these goals:

We have made considerable progress towards meeting several project goals.

Project graduate student, Julia Irizarry, is working with the PI to examine the influence of sediment properties on gas solubility within the hydrate stability zone. Julia has developed a MATLAB code that is capable of generating 3-dimensional random packings of spherical particles with prescribed particle-size distributions. The code can take 2-dimensional slices through such a synthetic porous medium and calculate porosity and specific surface area for comparison against empirical data with the same particle-size distributions. The initial version of the solubility calculator evaluated 3D effects in calculating both the influence of wetting interactions well after hydrate nucleation, and the onset of hydrate nucleation in each pore, but it approximated the 3D curvature of hydrate-liquid interfaces in crevices between particles using only one of the two principal radii of curvature. This method has now been refined to more accurately account for 3D effects by rotating the coordinate frame into the plane defined by the centers of the two nearest particles and each test point prior to determination of the first principal radius of curvature. Following the geometrical arguments of Cahn, Dash and Fu (1992) we expect the second principal radius of curvature to be much larger so that the mean curvature approaches the inverse of the first principal radius of curvature. Hence, the treatment is expected to fully capture 3D effects both at low and at high hydrate saturations, and deviate only slightly at intermediate saturations. Julia has tested the code against the results of simpler 2D formulations, and found good agreement with the results of freezing experiments by Cahn, Dash and Fu (1992), who used mono-dispersed particles. Further efforts to compile data for more rigorous comparisons are ongoing. Julia collaborated with the PI in writing a conference paper describing the initial version of the solubility calculator, which she presented at the ICGH conference in Beijing, and followed this up with an updated presentation at the Fall meeting of the American Geophysical Union.

Project graduate student, Alexander Handwerger, is working with the PI to examine how slope stability within the hydrate stability zone can be affected by environmental change. Alex has developed a preliminary model that determines the time over which a given magnitude of consolidation must occur to cause a slope to become unstable. In late March, Alexander presented this work in a poster at the Gordon Research Conference on Natural Gas Hydrates in Galveston, Texas. He has since collaborated with the PI in writing a conference paper describing his work, which he presented at the ICGH conference in Beijing. Alexander has also developed a model for the influence of rate-and-state dependent friction and elastic stress-transmission on slope stability. This goes beyond the capabilities of conventional slope-stability formulations, which typically appeal to factor of safety arguments for infinite slope analyses. Instead, by performing an elastic analysis, Alexander is examining how stress is transmitted by the accumulation of strain between regions that undergo different amounts of slip. When the size of the slipping patch is small, stress transmission to nearby stable regions prevents catastrophic failure even after the local factor of safety is reduced below unity. When the patch exceeds a critical nucleation size, however, a landslide is expected to result. Alexander presented these results at the fall meeting of the American Geophysical Union and has since begun preparing his results for publication. As part of his efforts, Alexander has also completed an analysis of the infinite-slope stability problem for comparison, and verified that his results are consistent with published analyses.

Project graduate student, Brandon Vanderbeek, is working with the PI to examine the conditions under which gas escape features can penetrate through the methane hydrate stability zone and exit at the seafloor. Brandon has made excellent progress in using the conservation laws to derive governing equations that describe water, methane, salt, and heat flow. He developed a working two-phase model for the coupled evolution of dissolved gas, heat, salt, and hydrate in submarine sediments in response to a specified advective supply through the lower boundary. He has since extended this model to include a dynamic three-phase stability boundary and treat the evolution of free gas concentration below. Efforts to make this three-phase zone grow towards the seafloor in a physically realistic fashion have met with modest success. An initially promising mechanism invokes the effects of solubility variations associated with grain size changes along dipping layers that are known to produce hydrate anomalies that can lead to the formation of salinity anomalies. However, we have found that, on their own, such salinity anomalies are unlikely to be sufficiently pronounced to enable the three-phase zones to propagate significant distances. Brandon has shown that their effects can be magnified in combination with the influence of focused advection of heat from below, but we have set this line of research aside for the time being so that Brandon can focus more of his attention on further modifying the hydrate anomaly generator to account for the influence of sedimentation and microbial production.

In pursuit of the project goals, the PI has made contact with several groups of hydrate researchers who may be able to provide empirical data to test some of our model formulations. We anticipate that this will lead to one or more fruitful collaborations during the proposal period.

Opportunities for training and professional development provided by the project:

This quarter, the project involved research activities by three graduate students under the mentorship of the PI.

Dissemination of results to communities of interest:

Project results were communicated in two poster presentations at the Gordon Research Conference on Natural Gas Hydrates in Galveston, Texas. In addition, the PI acted as a discussion leader at that conference. In Galveston, the PI and project graduate students, Alexander Handwerger and Brandon Vanderbeek, communicated with other conference attendees and had many informal scientific discussions on matters related to the project goals.

Project graduate students Julia Irizarry and Alexander Handwerger each took the lead in writing conference papers for the International Conference on Gas Hydrates in China, and gave poster presentations summarizing their results.

Project graduate students Julia Irizarry, Alexander Handwerger, and Brandon Vanderbeek each participated in the Fall meeting of the American Geophysical Union in December 2014. Presentations by Julia and Alexander summarized some of their efforts towards meeting the project goals.

Plans during the next reporting period to accomplish project goals:

The project team shall continue to make progress toward the project goals during the coming quarter in several different ways.

Project graduate student, Julia Irizarry, has begun to write about her results related to the solubility perturbations produced by pore-scale effects. This effort will form the bulk of Julia's MSc. thesis and a related publication that may or may not include some aspects of the anomaly simulations for Walker Ridge.

Project graduate student, Alexander Handwerger, has begun to write a paper that describes his model treatment of the influence of rate-and-state dependent friction and non-local stress-transmission on slope stability. The model is ideal for describing the perturbations to slope stability produced by the dissociation of hydrate anomalies. Because of the generality of the treatment, we have decided to focus our first publication on the modeling strategy and it's capabilities - leaving the more specific example of hydrate dissociation to a second publication that will be prepared later in the calendar year

Project graduate student, Brandon Vanderbeek, is extending his modeling treatment to incorporate the effects of sedimentation and microbial production. We have not yet decided whether these efforts will be used to improve upon the Walker-Ridge simulations for Julia's paper or whether they will instead be saved for a later publication. We anticipate making this decision sometime during the next reporting period.

2. PRODUCTS

Journal Publications: Nothing yet to report.
Books or other non-periodical, one time publications: Nothing yet to report.

Other publications, conference papers and presentations:

4 Conference presentations without papers.
At the Gordon Research Conference on Natural Gas Hydrates in Galveston, Texas from March 23-28, 2014, two project-related posters were presented. The PI was the sole presenter of "*Hydrate anomalies in heterogeneous sediments*". Project graduate student, Alexander Handwerger was the lead presenter, with the PI as co-presenter of a poster on "*Submarine landslides induced by environmental changes and hydrate dissociation along the continental shelf*". In addition, the PI acted as an invited discussion leader for a conference session on "*Gas Hydrate, Ice Cores and Climate*".

At the Fall Meeting of the American Geophysical Union, one project-related poster and one project-related talk were presented. Project graduate student, Alexander Handwerger was the speaker, with the PI and colleagues, Josh Roering, George Hilley and Rob Skarbek as co-authors on "*A rate- and state-dependent friction model to describe the seasonal motion of slow-moving earthflows and quantify their potential for catastrophic failure*". Project graduate student, Julia Irizarry, was the lead presenter, with the PI as co-presenter of a poster on "*Growth and decay of hydrate anomalies in marine sediments*".

2 Conference presentations with papers.
For the 8th International Conference on Gas Hydrates (ICGH8-2014) in Beijing, China, 28 July – 1 August, 2014, our group contributed two papers to the conference proceedings volume. The first is entitled "*How methane solubility changes with hydrate saturation, pore size and salt content in polydispersed media*", by Julia T. Irizarry and Alan W. Rempel. The second is entitled "*Environmental change, hydrate dissociation, and submarine slope failure along continental margins: The role of saturation anomalies in landslide triggering*", by Alexander L. Handwerger and Alan W. Rempel.

Websites or other internet sites: Nothing yet to report.
Technologies or techniques: Nothing yet to report.
Inventions, patent applications, and/or licenses: Nothing yet to report.
Other products: Nothing yet to report.

3. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

Individuals who have worked on the project:

Name:	Alan Rempel
Project Role:	PI
Nearest person month worked:	0 academic month (rounded from 0.25)

Contribution to Project:	Supervised project graduate students. Coauthored conference papers for the Fall AGU meeting.
Collaborated with individual in foreign country:	No
Travelled to foreign country:	No

Name:	Julia Irizarry
Project Role:	Graduate Student
Nearest person month worked:	3 academic months
Contribution to Project:	Model development for 3D solubility affects and anomaly generation.
Collaborated with individual in foreign country:	No
Travelled to foreign country:	No

Name:	Alexander Handwerger
Project Role:	Graduate Student
Nearest person month worked:	3 academic months
Contribution to Project:	Model development for stress transmission and rate-and-state effects.
Collaborated with individual in foreign country:	No
Travelled to foreign country:	No

Name:	Brandon Vanderbeek
Project Role:	Graduate Student
Nearest person month worked:	1.5 academic months
Contribution to Project:	Model development for hydrate accumulation.
Collaborated with individual in foreign country:	No
Travelled to foreign country:	No

Organizations involved as partners: None.

Other significant collaborators or contacts involved: Nothing yet to report.

4. IMPACT

Impact on the development of the principle discipline(s) of the project:

No peer-reviewed publications have yet been produced, though writing has begun on two project-related papers.

Project posters were presented at the 2014 Gordon Research Conference on Natural Gas Hydrates. These posters both garnered significant interest and discussion. In addition, the

PI acted as a discussion leader for one of the conference sessions. The PI and both project graduate students who were in attendance had several informal discussions about the project goals and preliminary results with other hydrate researchers.

Two conference papers were published in the *Proceedings of the 8th International Conference on Gas Hydrates (ICGH8-2014), Beijing, China, 28 July – 1 August, 2014*, and related poster presentations were made in Beijing. These efforts will be expanded upon in future peer-reviewed publications.

One poster presentation and one oral presentation were given at the 2014 Fall Meeting of the American Geophysical Union in San Francisco, CA.

Impact on other disciplines: Nothing yet to report.

Impact on the development of human resources:

The project is an integral part of the training for three graduate students, who will include portions of the project research in their theses.

Impact on physical, institutional, and information resources: Nothing yet to report.

Impact on technology transfer: Nothing to report.

Impact on society beyond science and technology: Nothing yet to report.

Dollar amount of the award's budget spent in foreign country(ies): $2,747.

5. CHANGES/PROBLEMS

Changes in approach and reasons for change: Nothing to report.
Actual or anticipated problems or delays and actions or plans to resolve them: Nothing to report.

Changes that have a significant impact on expenditures:

Each project component is proceding within the forecast expenditures. However, we have been fortunate to recruit graduate student, Brandon Vanderbeek, to work on gas escape features during year 1 of the project, whereas we had originally planned to delay recruiting a graduate student for this purpose until year 2. The primary impact on expenditures thus far is that the cost-share expenditures for student support from external sources has been increased. In addition, the travel expenses planned for the Gordon Research Conference were reduced because the PIs registration fees were waived as part of an invitation to lead a discussion. Following fruitful discussions at that Conference, and anticipating the potential for increased student costs with the early recruitment of the third project graduate student, the PI decided against attending the ICGH meeting in Beijing in July. Further cost savings came as a result of the Geology department awarding a "summer sweetener" to project graduate student Julia Irizarry for one month

of summer pay. The University of Oregon also paid for one of the graduate students' airline tickets to the ICGH in China. Most importantly for the grant expenditures, the University of Oregon changed their policy on PhD student tuition effective fall 2014 so that most of these costs are now covered by the College of Arts and Sciences (this affects the tuition support for project graduate students Alexander Handwerger and Brandon Vanderbeek, but not for Julia Irizarry).

Significant changes in use or care of human subjects, vertebrate animals and/or biohazards: Nothing to report.

Change of primary performance site location from that originally proposed: Nothing to report.

6. SPECIAL REPORTING REQUIREMENTS

The PI participated in a Project Kick Off Meeting on November 15, 2013 by web-ex with the DOE Project officer and several additional DOE staff.

The PI was in regular contact by phone and email with program manager, Sandra McSurdy. Sandra McSurdy has been replaced as project program manager by Joe Renk.

The PI gave a continuation presentation that was organized by project program manager, Joe Renk, on December 11, 2014.

7. BUDGETARY INFORMATION

See the attached chart showing the Baseline Report. Form SP-424A broke the project budget for each one year budget period into four equal quarterly divisions that did not account for the detailed planned federal spending estimates provided in the PMP (Table 3) or the planned distribution of time commitment by the project graduate students and the PI, or the timing of conference travel. The variance in spending that is noted in the attached Baseline Report is partly attributed to the coarse nature of the spending forecast in SP-424A, and is expected to average out over the remainder of the current budget period. Other factors are discussed in section 5 on Changes above.

Note that, as in the second quarterly report (RPPR 2, dated July 31,2014) the non-federal share of expenses reported for Q1 has been revised and corrected from that reported in the first quarterly report (RPPR 1, dated April 30, 2014). The PI made an error in calculating the non-federal cost share that should be attributed to graduate student support. Sponsored project services personnel at the University of Oregon have corrected this mistake and have agreed to track and supply the PI with all budgetary information that will be provided in this and future reports.

Baseline Report	Budget Period 1								Budget Period 2							
	Q1		Q2		Q3		Q4		Q1		Q2		Q3		Q4	
	01/01/14-03/31/14		04/01/14-06/30/14		07/01/14-09/30/14		10/01/14-12/31/14		01/01/15-03/31/15		04/01/15-06/30/15		07/01/15-09/30/15		10/01/15-12/31/15	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Baseline Cost Plan																
Federal Share	$32,517	$32,517	$32,518	$65,035	$32,518	$97,553	$32,517	$130,070	$36,683		$36,684		$36,684		$36,683	$276,804
Non-Federal Share	$12,486	$12,486	$12,486	$24,972	$12,486	$37,458	$12,486	$49,944	$5,449		$5,449		$5,449		$5,449	$71,740
Total Planned	$45,003	$45,003	$45,004	$90,007	$45,004	$135,011	$45,003	$180,014	$42,132		$42,133		$42,133		$42,132	$348,544
Actual Incurred Cost																
Federal Share	$47,118	$47,118	$18,078	$65,196	$42,080	$107,276	$18,933	$126,209								
Non-Federal Share	$9,958	$9,958	$13,352	$23,310	$8,582	$31,892	$19,329	$51,221								
Total Incurred Costs	$57,076	$57,076	$31,430	$88,506	$50,662	$139,168	$38,262	$177,430								
Variance																
Federal Share	$14,601	$14,601	-$14,440	$161	$9,562	$9,723	-$13,584	-$3,861								
Non-Federal Share	-$2,528	-$2,528	$866	-$1,662	-$3,904	-$5,566	$6,843	$1,277								
Total Variance	$12,073	$12,073	-$13,574	-$1,501	$5,658	$4,157	-$6,741	-$2,584								