Oil & Natural Gas Technology

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Quarterly Progress Report
(Period ending July 31th, 2013)

Gas Hydrate Dynamics on the Alaskan Beaufort Continental Slope: Modeling and Field Characterization
Project Period: October 1, 2012 – September 30, 2015

Submitted by:

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ABSTRACT

The third quarter of research associated with the DE-FE0010180 grant included progress on four separate tasks: (1) completion of BSR stability modeling in the U.S. Beaufort Sea using legacy (1977) DOE seismic data, (2) completion of 2D/3D heat flow code parallelization, (3) completion of a draft for JGR-Solid Earth detailing initial results (4) continuation of research vessel scoping for the up-coming 2014 cruise. We have made significant progress on all tasks. We have now completed a high-resolution steady-state 3D heat flow model for the entire U.S. Beaufort Margin. The results demonstrate that the BSR is anomalously deep along much of the margin edge. In the eastern Beaufort the anomalously deep BSR can be explained partially by recent intermediate ocean water temperature warming. In the western Beaufort, however, ocean temperature changes alone cannot explain the anomalously deep BSR. Our analysis suggests glaciation, isostatic rebound effects, geochemical variations, poor velocity models associated perhaps with permafrost, unanticipated downward fluid advection, significantly higher hydrate concentrations impeding downward heat flow due to endothermic reactions, or anomalously cold surface temperatures in the Canada Beaufort during the LGM play an important role in hydrate instability in this region. Regardless of the cause, the analysis implies hydrate instability across this region is likely irreversible for the short-term (next few 100 years) in the Beaufort. These results have potentially significant implications for slope (in)stability in this region, and are outlined in detail in a draft manuscript. During the past quarter, we also parallelized the 3D diffusive heat flow model. This improvement, which takes advantage of computational GPUs results in a model speed up of ~100x for 3D modeling and ~70x for 2D modeling. This code advancement represent a major time-saving improvement as high resolution (meter-scale) 3D models now take a matter of days instead of months to run. We look forward to implementing this code with recent data collected across the Beaufort during the next two years of this study. Using this improved model and the results from it in the Beaufort, we have completed a draft manuscript for submission to JGR-Solid Earth which we are currently circulating between co-authors. The draft describes the results mentioned above and in previous quarterly reports for this study in significantly greater detail. In particular it shows that (1) ocean temperatures in the Beaufort Sea are steadily rising at intermediate water depths and are are partially responsible for destabilizing methane hydrate; (2) it provides the first comprehensive heat flow map across the Beaufort margin, and (3) it demonstrates that non-steady state conditions extend across much of the Beaufort Margin. We anticipate submission within the next few weeks and will inform DOE when it is submitted. Additionally, the USGS will submit a final research vessel scoping report to DOE by August 31st, 2014.

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EXECUTIVE SUMMARY

In October 2012, Southern Methodist University in close partnership with The United State Geological Survey at Woods Hole and Oregon State University, began investigating methane hydrate stability in deep water (>100 mbsf) environments below Alaskan Beaufort Sea. This research is part of a three-year study funded by the Department of Energy's (DOE) National Energy Technology Laboratory (NETL). Key goals of this study include integrating and processing marine seismic data collected at the USGS with dynamic 2D/3D/4D heat flow models developed at SMU to determining the depth, location, and dynamics of methane hydrate stability along the Alaskan Beaufort Margin. A key component of this study is to constrain how the methane hydrate stability zone is changing with time. Additional goals of this study include determining areas where concentrated methane hydrate might exist in the subsurface and to understand the role methane hydrate plays in slope stability along the Alaskan Margin.

The third quarter of this project was dedicated primarily to (1) 3D development of heat flow models for assessing hydrate stability in the subsurface that enable tight constraints on the depth of methane hydrate stability in the Beaufort Sea and (2) using model results to complete a manuscript detailing both regional heat flow and methane hydrate stability across the margin. In particular, we focused our efforts on parallelizing the 3D heat flow code with the goal of improving model run time by an order of magnitude. We are pleased to report that using cGPU code parallelization techniques, we were able to increase 3D model run-time by as much as ~100x, and this improvement allowed us to produce several high-resolution (m-scale) heat flow models for the US Beaufort Sea in a matter of weeks (as opposed to months using the standard code). We have used results from these models to generate a detailed 3D hydrate stability map across the U.S. Beaufort. The results demonstrate that the hydrate stability zone is anomalously deep along the feather edge of the Beaufort Sea, and is particularly deep along the western boundary near the Canada Beaufort Sea. Recent ocean temperature warming provides an explanation for the anomalously deep BSRs observed below the eastern US Beaufort; however, ocean temperature warming alone cannot explain the anomalously deep BSRs along the western US Beaufort, near the US/Canada Border. We suggest glaciation/permafrost, downward fluid advection, unanticipated changes in regional heat flow, or anomalously cold temperatures in the Canada Beaufort as possible explanations for the anomalously deep BSRs observed in the western Beaufort. Combining results with those of the past two quarters, we have spent the past month writing a manuscript for submission to JGR-Solid Earth outlining heat flow, ocean temperature variability, and hydrate stability along the U.S. Beaufort margin. We will submit a final version to JGR-Solid Earth during the 4th Quarter, likely within the next week or two.

The USGS is on target to meet an August 2013 deadline to submit a scoping report on the research vessel to be used for the summer/autumn 2014 coring cruise. The USGS has also advanced the processing of the MCS data from Summer 2012, which has been delayed by Pat Hart's participation in a Gulf of Mexico cruise and obligations to other USGS projects. The USGS recently reconstituted its pore water processing capabilities in support of an unrelated hydrates-related fluids project in the Atlantic and is now well-prepared to support core processing for the 2014 cruise.

PROGRESS

Primary project goals for the third quarter of this project, as outlined in figure 1 of the project management plan (PMP) include the following:

TASK 1—continue to develop numerical models for the 1977 USGS data and submit peer-reviewed paper by Quarter #3

TASK 2—Continued scoping of the R/V Noreseman II for 2014 Coring/Heat-flow research.

We continue progressing on Tasks 1 and 2 stated in the PMP and have experienced no significant delays. Our goal, as outlined in the PMP, was to complete a draft of a paper for submission to a peer-reviewed journal this quarter outlining our initial results for hydrate stability in the US Beaufort using legacy 1977 DOE seismic data and newly developed 3D heat flow models. We have completed a draft manuscript and will submit the paper in the matter of weeks pending final approval by co-authors. The USGS was recently in communication with DOE about the scoping report for use of the research vessel for the 2014 coring cruise, and we are on target to have that submitted in August 2013, the date that is recorded for this milestone in DOE's internal system. The USGS has also been in brief communication with Andy Fisher about the heat flow instrumentation. The USGS will not be permitted to send anyone to the Fall AGU meeting, and we are therefore identifying a different time when Ruppel can visit UC Santa Cruz to review heat flow instrumentation with USGS coring technicians from the USGS Santa Cruz office.

Below, we discuss in greater detail each of the accomplishments for this Quarter.

RESULTS & DISCUSSION

SMU Task 1, Component 1—parallelize/finalize 3D heat flow model

A major impediment to 3D gas hydrate stability analysis is the computational time required to model heat-flow for thousands of square kilometers below the US Beaufort Margin. We completed a preliminary 3D heat flow model in May 2013; however, this model, with a resolution of deca-meters, required more than 4 weeks of run-time to complete. Because of this, researchers at SMU spent approximately one month during the 3rd quarter developing, benchmark testing, and implementing a parallel version of the heat flow code that improves model run time while simultaneously enhances model resolution (meter scale).

We are pleased to report that we have now finalized a new forward time, center space, finite difference heat flow model that utilizes parallel processing on a computational/CUDA graphics processing unit (cGPU). This new code takes advantage of GPU-accelerated applications that run the sequential part of their workload on the CPU (optimized for single-threaded performance) while accelerating parallel processing on the GPU, a.k.a. GPU computing. Integrating our heat flow model with the GPU computing code on a NVIDIA Tesla c2075 cGPU we are able to dramatically increase the computational speed of our codes. Specifically, initial benchmarks show a ~100 times faster computational time improvement over our conventional heat flow model in 3D. This means a 3D model that initially took ~30 days to run, now takes ~7 hours to complete. Additionally, our high resolution 2D finite difference models show a computational time improvement of ~70 times. The difference in the computational time improvement is due to the time spent moving the data from the CPU to the cGPU versus the amount of time spent actually computing temperatures in the cGPU. The more time spent computing, the greater the computational time improvement. As a result, we see the most time improvement for both 3D modeling applications and higher resolution models, since in both cases, a larger number of nodes exist (resulting in more computation time in the cGPU as opposed to a single thread CPU, and therefore, a larger computation time improvement).

As one might expect, our development of a parallelized heat flow code has led to tremendous improvements in model run-time efficiency, including rapid analysis of hydrate stability across thousands of square kilometers below the US Beaufort. Due to the improvement in model run-time, we have now been able to run multiple 3D heat flow models at varying resolutions for the US Beaufort and have been able to assess hydrate stability across the region using 3D techniques at multiple scales. As opposed to waiting a month as we did for the first initial 3D run, we now typically run additional, higher resolution 3D models overnight and check results in the morning. We have used results from these model runs to spend the past several weeks completing a manuscript defining the state of methane hydrate stability throughout the entire US Beaufort Sea (with results discussed in the next section). We have also ordered a cGPU upgrade for our computer systems using DOE equipment funds. This upgrade will be used to extend 3D heat flow analysis and coverage into the abyssal plain of the US Beaufort Sea, and, where needed, provide sub-meter resolution analysis for the DOE-funded, USGS-collected 2012 sparker data in the Beaufort Sea. We will use results from these models to pin-point coring/heat-flow sites for our upcoming 2014 cruise.

SMU Task 1, Component 2—write initial manuscript on US Beaufort Sea hydrate stability

During the past quarter, researchers at SMU have compiled results from the past three quarters into a comprehensive manuscript for submission to JGR-Solid Earth. This manuscript integrates heat flow measurements/modeling results with long term (decadal scale) ocean temperature changes to assess in 3D the methane hydrate stability for the US Beaufort margin. The analysis provides a first to-date heat flow map extending from the north slope of Alaska to the US Beaufort abyssal plain. We anticipate this map will be extremely valuable for future hydrate stability modeling (as well as oil and gas exploration) in this region. Additionally, the manuscript provides a long-term (decadal scale), statistically robust analysis of ocean temperatures in the Beaufort Sea that we use to constrain gas hydrate stability modeling boundary conditions. The ocean temperature analysis indicates clear and consistent (greater than 2-sigma certainty) ocean temperature warming at intermediate water depths across the region. Finally, the analysis, using 3D hydrate stability models, demonstrates that the gas hydrate stability zone along the feather edge of the margin is consistently too deep, and therefore not in equilibrium across the entire margin.

Our analysis demonstrates that this observation of hydrate instability is ubiquitous across the margin with the most extreme instability along the western edge of the margin, near the Canada border. We can explain hydrate instability in the Eastern Beaufort Sea via ocean temperature warming. Specifically, using expected extreme ocean temperature values of approximately -2 deg. C (the minimum temperature of salt water before freezing occurs), we can reproduce the hydrate stability zone. This implies that previously colder ocean temperatures in the eastern Beaufort Sea can in theory explain the anomalously deep hydrate stability zone in the Eastern Beaufort Sea. In the western Beaufort Sea, however, the anticipated minimum temperature that ocean temperature can exist without freezing is not cold enough to explain the anomalously deep BSR. The cause of the anomalously deep BSR in the western Beaufort therefore requires either unrealistically cold ocean temperatures, a change in the gas composition (a higher proportion of higher order hydrocarbons), significantly higher seismic velocities than we expect perhaps due to more significant permafrost in this region, significantly higher hydrate concentrations impeding downward heat flow due to endothermic reactions, or significantly colder subsurface surface temperatures in the western Beaufort to explain our observations. Regardless of the cause, our analysis implies that the feather edge of the US Beaufort Sea is not in equilibrium and currently destabilizing.

USGS Task #1: numerical modeling support: Processing new USGS MCS seismic data.

The USGS is continuing processing of the summer 2012 MCS data, although progress has been impeded in part by other commitments (Gulf of Mexico seismics; non-hydrate project commitments in the USGS) on the part of Pat Hart. The USGS is undertaking an advanced type of analysis of the Beaufort MCS data using some new approaches pioneered for hydrates studies at the USGS Woods Hole office. The USGS has a commitment that this work, which should take about 2 weeks, will commence after the 15 August, 2013 proposal deadline for the National Science Foundation. This analysis will be the last step required to complete the first manuscript on these data. We anticipate the processed MCS data being available to SMU sometime in the first quarter of FY2014.

The USGS has met several times with L. Keigwin of WHOI and provided him with background information on the US Beaufort margin and insight about prime targets for coring of potentially continuous sequences. In the first few weeks of August 2013, just prior to Keigwin's departure for Dutch Harbor to meet the USCG Healy for his NSF-funded cruise in the Mackenzie Delta area, Ruppel will supply Keigwin with maps, high-resolution seismic images, coring coordinates, and other information that will enable him to target upper slope sequences in the US Beaufort during his transit from Mackenzie back to Barrow in early September. The core that Keigwin obtains in this area will provide excellent guidance for the Summer 2014 cruise and determine whether it is worthwhile for us to spend time coring apparently intact sequences on the upper continental slope. Ruppel has also facilitated Keigwin's access to certain MITAS cores. Keigwin's analysis of the paleoceanographic information stored in these cores will be the first from the upper continental slope in the US Beaufort and may prove critical to reconstruction of the history of this margin.

TASK 2--Scoping of the R/V Norseman II for 2014 Coring/Heat-flow research (USGS)
The USGS is taking the lead on investigating the suitability of Alaskan vessels for summer 2014 coring on the upper continental slope. During Quarter #2, the USGS has interacted with the ship operator, obtained ship drawings, and determined the configuration of coring equipment that will work with this vessel. This information will be used to formulate a short scoping report that will be submitted to DOE in August 2013 to honor the milestone in DOE's internal project tracking system.

COST STATUS

costs incurred so far at SMU is
--RA support for Hornbach's graduate student, Ben Phrampus who was the primary person who worked towards developing the parallel code. Not including fringe, this cost comes to ~$6,120 for the quarter.
--Research Support for Hornbach (research support for summer). ~ $26,000.
--Equipment support: Purchase of dual-core Tesla cGPU system from code parallelization speed-up. $6000 from DOE (total cost of the system was ~$15,000—SMU provided $9000 additional in "matching" to cover the full cost of this computer upgrade).

Total approximate expenditures for SMU in Quarter #2: ~$38,120(not including overhead).

PROBLEMS OR DELAYS

Small delays related to personnel availability (Pat Hart) for USGS seismic component, otherwise none.

PRODUCTS

(1) A new, parallelized finite-difference heat flow code that accelerates run time for 3D heat flow modeling by a factor of ~100.
(2) A draft manuscript outlining results for the past three quarters or research. Results from this analysis include the following deliverables:
    (a) A new, and to our knowledge first to-date, heat flow map extending from the north slope of Alaska to the US Beaufort Sea abyssal plain that reveals a complex subsurface heat-flow regime across the Beaufort Margin.
    (b) A detailed assessment of ocean temperatures and ocean temperature changes in the Beaufort Sea for the past 30 years documenting progressive ocean temperature warming at intermediate water depths across the Beaufort Sea during the past several decades. We use these temperatures as upper boundary conditions for our numerical model to assess methane hydrate stability across the margin.
    (c) A high resolution 3D heat flow model for the US Beaufort margin that reveals widespread hydrate instability beneath the feather edge of the US Beaufort margin.

(d) Evidence that ocean temperature warming alone can explain hydrate instability along the eastern edge of the margin. In contrast, ocean temperature changes alone cannot explain hydrate instability along the western edge of the Beaufort margin (near the US/Canada border), where the most extreme hydrate instability appears to exist.
(e) Importantly, the analysis implies hydrate instability along the feather edge of the Beaufort sea is likely irreversible for the short term (next few 100 years) for the foreseeable future as the system equilibrates and ocean temperatures continue to warm. This result likely has important implications for slope stability along the feather edge of the margin.

CONCLUSIONS AND FUTURE DIRECTIONS

In Summary, we have completed the 3D numerical model development, and have tangible results in manuscript form. We therefore continue to make clear and steady progress with this research. We anticipate submitting our manuscript to JGR-Solid Earth within the next two weeks, and we will inform DOE directly when we do so; we will have a final research scouting report provided by the end of the month, and we look forward to beginning work on initial heat flow analysis of sparker data collected in 2012 during the next quarter in preparation/planning for coring/heat flow sites for the 2014 cruise.

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