Oil & Natural Gas Technology

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Quarterly Research Performance Progress Report (Period ending 06/30/2016)

Mapping Permafrost and Gas Hydrate using Marine CSEM Methods

Project Period (10/1/2012 – 09/30/16)

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EXECUTIVE SUMMARY

Last quarter we presented preliminary inversions of all the lines collected in 2015, and prepared a manuscript for submission to *Geophysical Research Letters*. Sadly, *GRL* declined to send the manuscript out to review, citing the nature of the paper and number of figures. This quarter we expanded the paper somewhat and submitted it to *Earth and Planetary Science Letters*.

The inversion we showed last quarter was for amplitudes only. We collected excellent phase data in 2015, but we have been having trouble fitting amplitude and phase simultaneously. We suspected a timing error in the processing, but could not find such a thing. This quarter we extended the inversions to include anisotropy, and this has largely eliminated the problem of fitting amplitude and phase. Furthermore, the highly anisotropic resistivities required to fit the data occur exactly where we expect permafrost to be located. High horizontal conductivities, which contribute to the high anisotropies, are consistent with a mechanism of brine exclusion associated with permafrost forming in a horizontally layered/stratified medium.

ACCOMPLISHMENTS

Major goals of project

Permafrost underlies an estimated 20% of the land area in the northern hemisphere and often has associated methane hydrate. Numerous studies have indicated that permafrost and hydrate are actively thawing in many high-latitude and high-elevation areas in response to warming climate and rising sea level. Such thawing has clear consequences for the integrity of energy infrastructure in the Arctic, can lead to profound changes in arctic hydrology and ecology, and can increase emissions of methane as microbial processes access organic carbon that has been trapped in permafrost or methane hydrate dissociates. There has, however, been significant debate over the offshore extent of subsea permafrost.

Our knowledge of sub-seafloor geology relies largely on seismic data and cores/well-logs obtained from vertical boreholes. Borehole data are immensely valuable (both in terms of dollar cost and scientific worth), but provide information only about discrete locations in close to one (vertical) dimension. Seismic data are inherently biased towards impedance contrasts, rather than bulk sediment properties. In the context of mapping offshore permafrost and shallow hydrate, seismic methods can identify the top of frozen sediment through the identification of high amplitude reflections and high-velocity refractors but simple 2D seismic surveys do little to elucidate the bulk properties of the frozen layers, particularly the thickness. However, permafrost and gas hydrate are both electrically resistive, making electromagnetic (EM) methods a complementary geophysical approach to seismic methods for studying these geological features. Deep ocean EM methods for mapping gas hydrate have been developed by both academia and industry, but the deep-ocean techniques and equipment are not directly applicable to the shallow-water, near-shore permafrost environment. This project addresses this problem by designing, building, and testing an EM system designed for very shallow water use, and using it to not only contribute to the understanding of the extent of offshore permafrost, but also to collect baseline data that will be invaluable for future studies of permafrost degradation.

We will use the new equipment to carry out a pilot project to map the contemporary state of subsea permafrost on part of the U.S. Beaufort inner shelf, reoccupying seismic lines acquired in 2010 to 2012. We will combine the interpretation of EM data with seismic data through a no-cost collaboration with Carolyn Ruppel of the USGS. Modeling suggests that a 500 m long EM array will be adequate to sense the top of permafrost in many of the areas where the USGS has completed mapping, although our receiver array is now 1,000 m long. The towed array will be supplemented by the deployment of 2 to 4 seafloor recorders that will be retrieved after the cruise so that nothing remains in the area. The use of a small number of seafloor recorders will allow us to collect data at larger offsets, providing insight into deeper structure.

We are exploiting the close association of hydrate and permafrost at high latitudes, and in particular their common response to changing climate. By using a second geophysical method to supplement seismic data, we will be able to better map the current extent of permafrost and so better understand the impact of past sea level rise on the hydrate stability field, and provide a critical baseline for studies which target the effects of current climate change.

Our work will not only expand our geophysical tool-kit but also expand our understanding of the geological and hydrological systems associated with gas hydrate. Instrumentation and analytical methods developed for this project can be easily applied for future permafrost and hydrate mapping elsewhere, and also other applications such as groundwater exploration and engineering studies associated with near-shore infrastructure development, and most recently offshore geothermal exploration.

Work accomplished during the project period

We are using the MARE2DEM code of Kerry Key (http://mare2dem.ucsd.edu/), to invert the data. This code uses adaptive refinement of a 2-dimensional unstructured finite element mesh to ensure that the forward model calculations are accurate. Such inversions are computationally demanding, running for significant fractions of a day on 100-core clusters, and many runs are required to ensure that (a) the data errors are appropriately scaled, (b) the data are free of outliers, (c) the model domain is large enough, (d) and the model domain is adequately discretized.

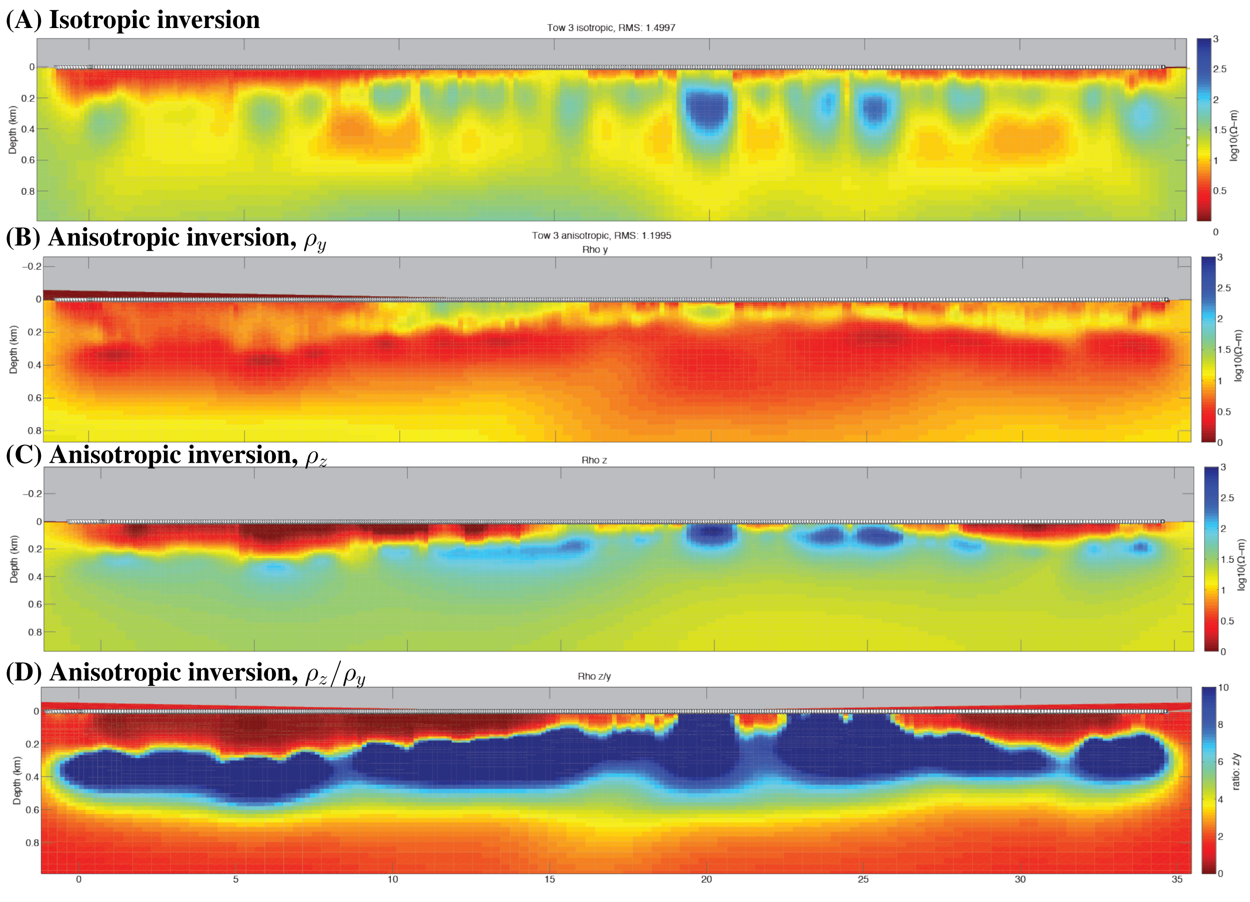

Figure 1. (A) Isotropic inversion presented in the last quarterly report. (B) Horizontal resistivity of anisotropic inversion. (C) Vertical resistivity of anisotropic inversion. (D) Anisotropy ratio.

Last quarter we presented an isotropic inversion of tow 3 from 2015, shown here in Figure 1(A). This inversion showed resistors consistent with permafrost in the area of the Sag River outflow, but only moderate resistivities elsewhere, even though permafrost is thought to extend throughout this region. This inversion was for amplitudes only, because we had been having trouble fitting both amplitudes and phase, and suspected that a timing error had corrupted the phase data. However, our receivers and transmitter are all clocked with GPS time, and we could not find any processing error that would introduce a timing shift.

We considered the possibility that the amplitude/phase incompatibility was a result of anisotropy in the sediments, and so started experimenting with anisotropic inversions. Indeed, this has largely removed the problem with fitting phase (a bias of 1° remains for the lowest frequency inverted, 3 Hz – see Figure 2). Furthermore, relatively large (greater than a factor of 10) anisotropies develop in the inversions, and the resistivity structure is much more laterally consistent (Figure 1). Increased resistivities (assumed permafrost) persist at the Sag River outflow, but high vertical resistivities (about 100 Ωm) extend to other parts of the model at a depth of 100–200 m. These high vertical resistivities are associated with low horizontal resistivity, about 3–10 Ωm, which is why we see large anisotropy ratios. If we plot the anisotropy ratio, we see low anisotropies in the regions interpreted to be surface sediments, underlain by a large and abrupt jump to high anisotropy. The anisotropy returns to normal values at a uniform depth across the section of about 600 m, which is where the base of permafrost is thought to be. It appears, quite convincingly, that anisotropy is an excellent proxy for mapping permafrost.

This raises the question, of course, as to what is causing the high horizontal conductivities. It is not too far-fetched to propose that in a horizontally stratified sediment permafrost might preferentially form in beds of one lithology, perhaps sands, and that salts excluded during ice formation might reside in fluids associated with other layers, perhaps silts. As is well known from T and S equivalence in DC resistivity methods, vertical resistivity will be the average of the resistivities of the layers, and thus dominated by the high resistivity of the frozen ground, and horizontal resistivity will be given by the average of conductivities of the layers, dominated by unfrozen ground containing briny or brackish water.

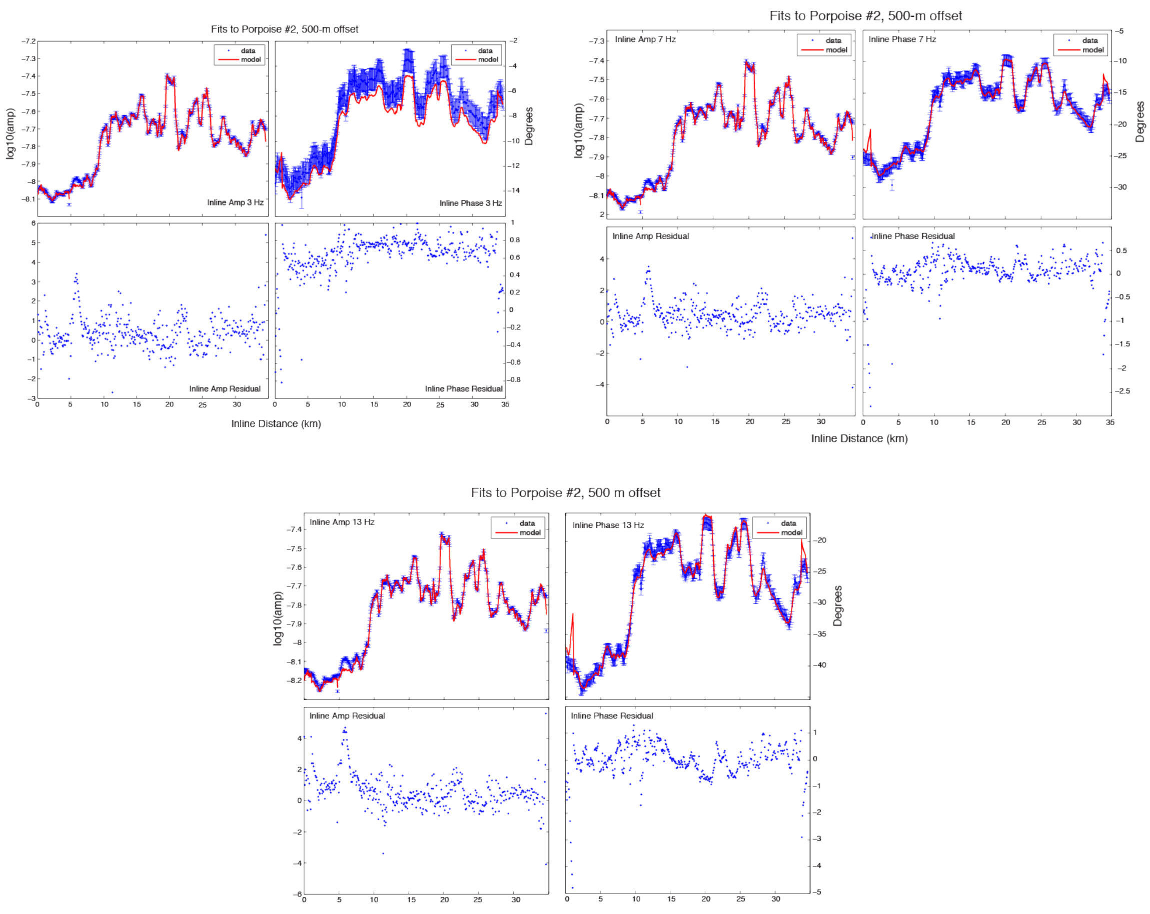

Figure 2. Data (amplitude and phase) and anisotropic model response for the second receiver at the three frequencies inverted. Fits are excellent, with the minor exception of a 1° phase bias at 3 Hz.

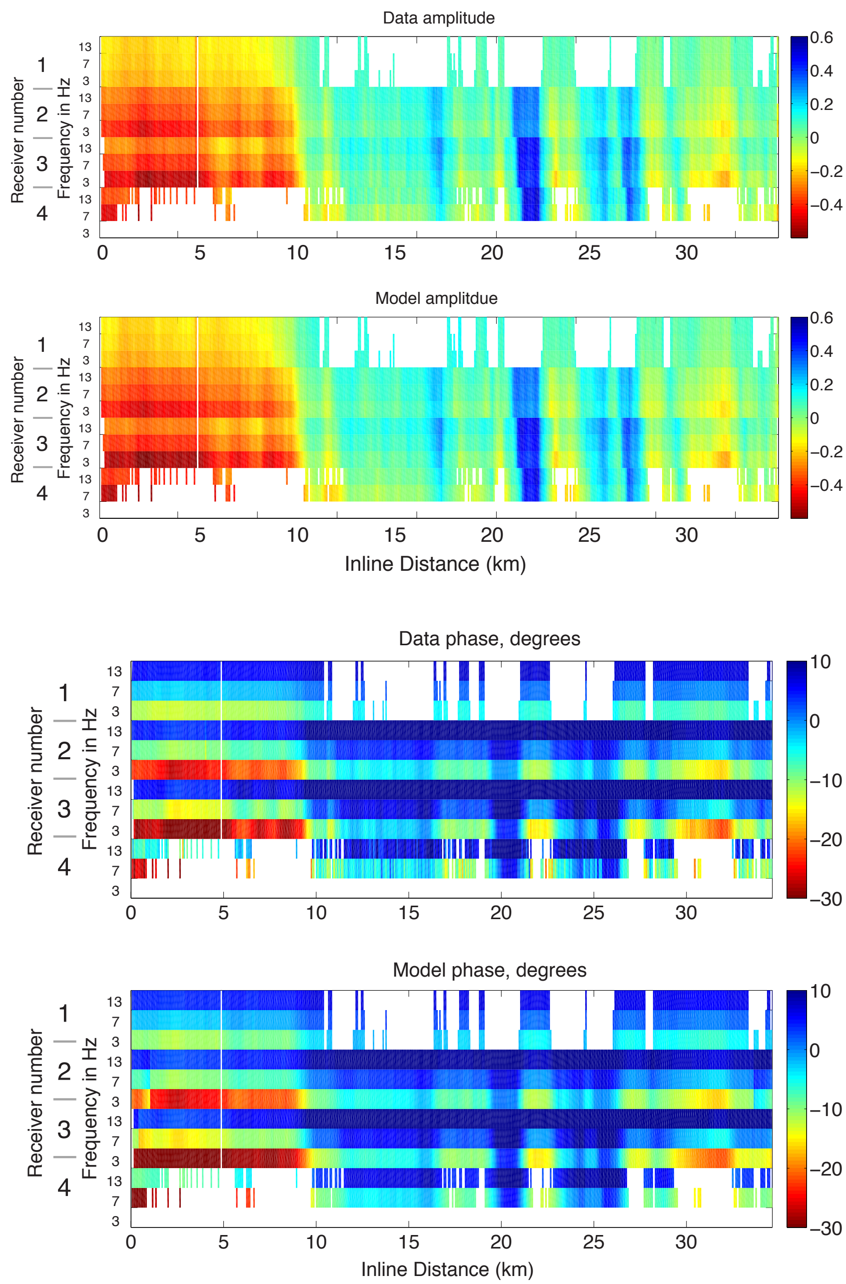

Figure 3. Data amplitude and phase compared with model response (median amplitude and phase for each receiver has been subtracted).

Figure 2 shows a comparison of the model response and actual data for the second receiver, to show the fidelity of the model fits. With the exception of a 1° phase bias for the lowest frequency (3 Hz), the fits are excellent. Figure 3 shows the data and model response for the entire data set, and Figure 4 shows normalized residuals. Ideally, residuals should average to zero and be randomly scattered across the data set. There is some clustering of positive residuals in the amplitude at about 6 km, but mostly the residuals look well behaved.

Training and professional development.

Dallas Sherman, PhD student, is now the student working on this project, and has carried out all the processing and

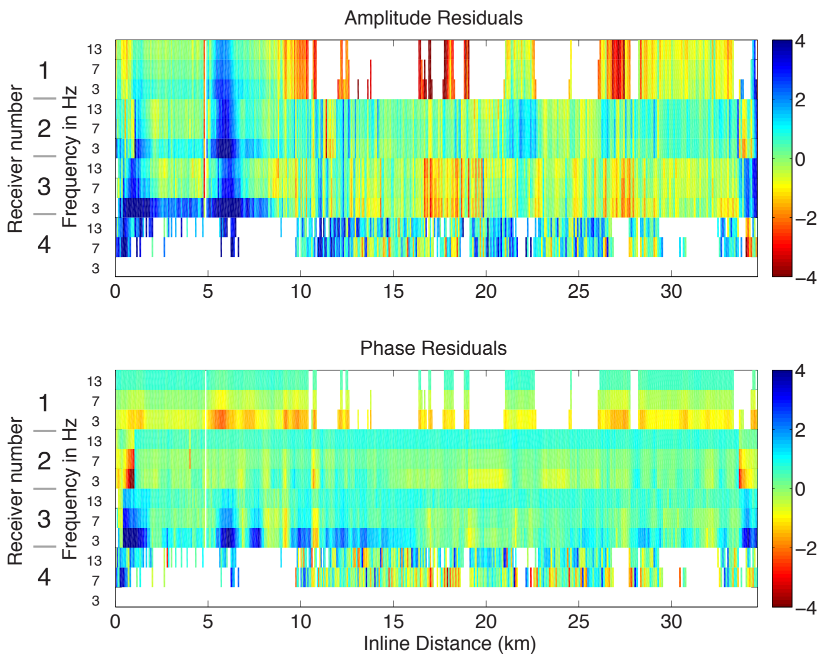

Figure 4. Weighted residuals for both amplitude and phase.

inversion presented in the past year's quarterly reports. She has taken the lead on writing the manuscript we are submitting for publication.

Plans for next project period.

During the next project period we will continue to invert the 2014 and 2015 data sets. We also hope to meet with USGS scientists and compare the inversion results to seismic refraction data collected by them.

Milestone status report.

Milestone Title	Planned Completion Date	Actual Completion Date	Verification Method	Comments on progress
Equipment design approved	5/1/2013	5/1/2013	Internal review	
Equipment passes tests	12/6/2013	12/1/2013	Internal review	delayed one quarter
Y2 data collection	9/1/2014	7/22/2014	Internal review	
Y2 data processing	9/30/2014	9/30/2014	Internal review	
Y3 data collection	9/1/2015	7/7/2015	Internal review	
Y3 data processing	9/30/2015	9/1/2015	Internal review	
Publications(s) submitted	4/1/2016	5/20/2016	Internal review	Submitted to *EPSL*
Publications(s) accepted	9/30/2016			

PRODUCTS

Project Management Plan. The revised Project Management Plan was accepted on 19 November 2012.

The following abstracts are relevant to this and past DoE funded research:

Gordon Conference Abstract, 2016: Surveying hydrates in the California Borderlands using electromagnetic methods. Presented at the Natural Gas Hydrate Systems Gordon Research Conference. Galveston, Texas. Peter Kannberg and Steven Constable.

AGU 2015 Fall Meeting: Resistivity structure of the Del Mar methane seep, Peter Kannberg and Steven Constable.

AGU 2015 Fall Meeting: Surface towed CSEM systems for shallow water mapping, Joanna Sherman, Steven Constable, and Peter Kannberg.

AGU 2015 Fall Meeting: Water and electricity do mix: Studying plates, petroleum, and permafrost using marine electromagnetism, Steven Constable (invited Bullard Lecture).

AGU 2014 Fall Meeting: Hydrates in the California Borderlands revisited: Results from a controlled-source electromagnetic survey of the Santa Cruz Basin, Peter Kannberg and Steven Constable.

Gordon Conference Abstract, 2014: Hydrates in the California Borderlands: Results from controlled-source electromagnetic surveys, Peter Kannberg, Steven Constable, and Kerry Key.

AGU 2013 Fall Meeting: Hydrates in the California Borderlands: 2D inversion results from CSEM towed and seafloor arrays, Peter Kannberg, Steven Constable, and Kerry Key.

AGU 2012 Fall Meeting: Mapping methane hydrate with a towed marine transmitter-receiver array, Peter K. Kannberg; Steven Constable, presented in *GP33A. Advances in Electromagnetic Induction: From the Near Surface to the Deep Mantle III Posters.*

AGU 2012 Fall Meeting: Mapping marine gas hydrate systems using electromagnetic sounding, Steven Constable; Karen A. Weitemeyer; Peter K. Kannberg; Kerry W. Key, presented in *OS34A. Marine and Permafrost Gas Hydrate Systems III.*

AGU 2012 Fall Meeting: Electrical conductivity of lab-formed methane hydrate + sand mixtures; technical developments and new results, Laura Stern; Wyatt L. Du Frane; Karen A. Weitemeyer; Steven Constable; Jeffery J. Roberts, presented in *OS43B. Marine and Permafrost Gas Hydrate Systems IV Posters.*

The following papers acknowledge this or past DoE funded research:

Constable, S., P. K. Kannberg, and K. Weitemeyer, 2016. Vulcan: A deeptowed CSEM receiver. *Geochemistry, Geophysics, Geosystems*, **17**, doi:10.1002/ 2015GC006174.

Du Frane, W., L.A. Stern, S. Constable, K.A. Weitemeyer, M.M. Smith, and J.J. Roberts, 2015. Electrical properties of methane hydrate + sediment mixtures. *Journal of Geophysical Research*, **120**, 4773–4787, doi:10.1002/2015JB011940.

Weitemeyer, K., and S. Constable, 2014. Navigating marine electromagnetic transmitters using dipole field geometry. *Geophysical Prospecting*, **62**, 573–593, doi: 10.1111/1365-2478.12092.

Du Frane, W.L., L.A. Stern, K.A. Weitemeyer, S. Constable, J.C. Pinkston, J.J. Roberts, 2011. Electrical properties of polycrystalline methane hydrate. *Geophysical Research Letters*, **38**, doi:10.1029/2011GL047243.

Weitemeyer, K.A., S. Constable, S. and A.M. Trehu, 2011. A marine electromagnetic survey to detect gas hydrate at Hydrate Ridge, Oregon. *Geophysical Journal International* , **187**, 45-62.

Weitemeyer, K., G. Gao, S. Constable, and D. Alumbaugh, 2010. The practical application of 2D inversion to marine controlled-source electromagnetic sounding. *Geophysics*, **75**, F199–F211.

Weitemeyer, K., and S. Constable, 2010. Mapping shallow geology and gas hydrate with marine CSEM surveys. *First Break*, **28**, 97–102.

PARTICIPANTS AND OTHER COLLABORATING ORGANIZATIONS

Name:	Steven Constable
Project Role:	PI
Nearest person month worked:	1
Contribution to project:	Management, scientific direction
Funding support:	Institutional matching funds
Foreign collaboration:	Yes
Country:	United Kingdom
Travelled:	No

Name:	Dallas Sherman
Project Role:	PhD student
Nearest person month worked:	3
Contribution to project:	Processing and inverting data. Writing manuscripts.
Funding support:	This project, federal plus matching funds
Foreign collaboration:	No

CHANGES/PROBLEMS

No changes or problems to report at this time.

BUDGETARY INFORMATION

Table 2a: Spend profile

	Budget Period 1							
baseline	10/1/12 – 12/31/12		1/1/13 – 3/31/13		4/1/13 – 6/30/13		7/1/13 – 9/30/13	
	Q4		Q1		Q2		Q3	
	Q4	Cum. Total	Q1	Cum. Total	Q2	Cum. Total	Q3	Cum. Total
Baseline cost:								
Federal	$49,969	$49,969	$33,192	$83,161	$19,810	$102,971	$18,771	$121,742
Non-federal	$9,897	$9,897	$9,897	$19,794	$9,897	$29,692	$29,897	$59,589
Total	$59,866	$59,866	$43,089	$102,955	$29,707	$132,663	$48,668	$181,331
Actual cost:								
Federal	$19,027	$19,027	$8,160	$27,187	$17,444	$44,631	$43,370	$88,001
Non-federal	$10,874	$10,874	$9,514	$20,388	$3,500	$23,888	$24,215	$48,103
Total	$29,901	$29,901	$17,674	$47,575	$20,944	$68,519	$67,585	$136,104
Variance:								
Federal	-$30,942	-$30,942	-$25,032	-$55,974	-$2,366	-$58,340	$24,599	-$33,741
Non-federal	$977	$977	-$383	$594	-$6,379	-$5,804	-$5,682	-$11,486
Total	-$29,964	-$29,964	-$25,415	-$55,380	-$8,763	-$64,144	$18,917	-$45,227

Table 2b: Spend profile

	Budget Period 1		Budget Period 2					
baseline	10/1/13 – 12/31/13		1/1/14 – 3/31/14		4/1/14 – 6/30/14		7/1/14 – 9/30/14	
	Q4		Q1		Q2		Q3	
	Q4	Cum. Total	Q1	Cum. Total	Q2	Cum. Total	Q3	Cum. Total
Baseline cost:								
Federal	$0	$121,742	$10,588	$132,330	$160,134	$292,464	$16,705	$309,169
Non-federal	$0	$59,589	$9,899	$69,488	$14,854	$84,341	$14,854	$99,196
Total	$0	$181,331	$20,487	$201,818	$174,988	$372,360	$31,559	$408,365
Actual cost:								
Federal	$18,959	$106,960	$12,002	$118,962	$144,084*	$263,046*	$35,382	$298,428
Non-federal	$11,486	$59,589	$3,247	$62,836	$36,360	$99,196	$0	$99,196
Total	$30,445	$166,549	$15,249	$181,798	$180,444*	$362,242*	$35,382	$397,624
Variance:								
Federal	$18,959	-$14,782	$1,414	-$13,368	-$16,050	-$29,418	$18,677	-$10,741
Non-federal	$11,486	$0	-$6,652	-$6,652	$21,506	$19,300	-$14,854	$0
Total	$30,445	-$14,782	-$5,238	-$20,020	$5,456	-$14,563	$3,823	-$10,741

* = estimate, includes ship time liened for 2014 field work.

Table 2c: Spend profile

	Budget Period 3							
baseline	10/1/14 – 12/31/14		1/1/15 – 3/31/15		4/1/15 – 6/30/15		7/1/15 – 9/30/15	
	Q4		Q1		Q2		Q3	
	Q4	Cum. Total	Q1	Cum. Total	Q2	Cum. Total	Q3	Cum. Total
Baseline cost:								
Federal	$18,842	$328,011	$18,842	$346,853	$48,842	$395,695	$111,322	$507,017
Non-federal	$9,900	$109,096	$9,900	$118,996	$9,900	$128,896	$9,900	$138,796
Total	$28,742	$437,107	$28,742	$465,849	$58,742	$524,591	$121,222	$645,813
Actual cost:								
Federal	$6,397	$ 304,825	$35,075	$339,900	$72,796	$412,696	$104,030	$516,726
Non-federal	$9,900	$109,096	$9,900	$118,996	$9,900	$128,896	$9,900	$138,796
Total	$16,297	$413,921	$44,975	$458,896	$82,696	$541,592	$113,930	$655,522
Variance:								
Federal	-$10,741	-$23,186	$16,233	-$6,953	$23,954	$17,001	-$7,292	$9,709
Non-federal	$0	$0	$0	$ 0	$0	$0	$0	$0
Total	-$10,741	-$23,186	$16,233	-$6,953	$ 23,954	$17,001	-$7,292	$9,709

Table 2d: Spend profile

	Budget Period 4							
baseline	10/1/15 – 12/31/15		1/1/16 – 3/31/16		4/1/16 – 6/30/16		7/1/16 – 9/30/16	
	Q4		Q1		Q2		Q3	
	Q4	Cum. Total	Q1	Cum. Total	Q2	Cum. Total	Q3	Cum. Total
Baseline cost:								
Federal	$18482	$525,499	$24,596	$550,095	$24,596	$574,691		
Non-federal	$9,900	$148,696	$10,719	$159,415	$10,719	$170,134		
Total	$28,382	$674,195	$35,315	$709,510	$35,315	$774,825		
Actual cost:								
Federal	$8,810	$525,536	$4,338	$529,874	$36,945	$566,819		
Non-federal	$9,900	$148,696	$10,719	$159,415	$10,719	$170,134		
Total	$18,710	$674,232	$15,057	$689,289	$47,664	$736,953		
Variance:								
Federal	-$9,672	$37	$-20,258	$-20,221	$12,349	$-7,872		
Non-federal	$0	$0	$0	$0	$0	$0		
Total	-$9,672	$37	$-20,258	$-20,221	$12,349	$-7,872		