MARINE ELECTROMAGNETIC METHODS FOR GAS HYDRATE CHARACTERIZATION

A proposal submitted to members of the Seafloor Electromagnetic Methods Consortium
by
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SUMMARY

Following successful trials of the marine controlled-source EM (CSEM) and magnetotelluric (MT) methods over Hydrate Ridge, offshore Oregon, USA, we propose further field tests of the marine EM method for hydrate mapping in the Gulf of Mexico (GoM). Gas hydrates present complications during offshore drilling, issues of slope stability during development, and for some countries a possible resource. Further, resistive features in the shallow section, such as gas hydrates, need to be considered during EM exploration for deeper hydrocarbon reservoirs.

Although hydrate is often evident in seismic surveys as a bottom-simulating reflector (BSR), this is not always the case. In particular, the GoM is notorious for a lack of BSR in areas of known hydrates. Furthermore, it is difficult to quantify the volume fraction of hydrates in the shallow section from seismic data alone. However, because hydrates are more resistive than the host sediments they will have an electromagnetic signature that increases with hydrate volume fraction. Indeed, well logs indicate increased resistivity in zones of gas hydrate, although this effect is sometimes modest.

Marine EM methods have long been proposed as an effective way to map and characterize gas hydrates, notably by Nigel Edwards at University of Toronto. Rob Evans at Woods Hole has a towed EM system suitable for shallow (top few 10's of meters) seafloor study. The SIO Hydrate Ridge work represents the first attempt to apply the EM methods recently developed for oilfield characterization to the hydrate question. The data are promising, but this survey was a pilot study with less than 4 days of shiptime available on station. Furthermore, the physical characteristics of *in situ* hydrate vary considerably, and Hydrate Ridge, while a good test of the method because of the extensive seismic and drilling data sets available, may not be characteristic of hydrates in more commercially relevant areas, such as the GoM.

Issues associated with obtaining ship time, sponsors, and choosing a target location have resulted in a long gestation period for this project. However, several meetings with current and prospective sponsors resulted in a firm plan to survey three locations in the GoM: AC 818, MC 118, and GC 955. We had 22 days of time reserved on the R.V. Cape Hatteras starting June 10th, 2007, but this cruise had to be cancelled at the last moment because issues arose about the use of concrete anchors in the Gulf of Mexico. However, the permitting problems have been resolved, and we now have MMS permits for all three sites. We have also been able to find replacement ship time for this project, on extremely good terms. Scripps Institution of Oceanography will provide shiptime on one of our most capable vessels (the R.V. Roger Revelle) under a sort of ship-swap deal that effectively halves the cost of the vessel. We are on the Revelle's schedule for 7–26 October 2008 out of Miami, Florida (load on the 6th, unload on the 27th). One of the many advantages of the larger vessel is that we will be able to take a number of industry observers.

The delays in getting this project to move forward have been frustrating, but not wasted. During the past year we have developed significant new capabilities, which include a 3-axis towed electric field receiver and a novel long baseline navigation system for the transmitter. Between now and October we will improve

these systems further, as well as commission a second 500 A transmitter. The latter will allow us to take advantage of the larger vessel and have 100% redundancy for our transmitter system.

Using a funding model that resulted in the development of the broadband marine MT method and the highly successful SIO CSEM/MT receiver instrument, we invite companies to support our efforts by contributing $50k each. While it is the long-term intention to put our research into the public domain, supporters of this project will benefit from early access to data, results, and methodology. To date we have six companies funding this work - the extra time will allow us to obtain four more, in order to support the increased cost of shiptime.

INTRODUCTION

Submarine gas hydrates are of considerable importance to the global energy industry for a variety of reasons:

- Although extraction is not feasible with current technology, hydrates represent a considerable energy resource; of order 10^{15} m^3 of methane are estimated to be bound up in gas hydrates. However, estimates of total world-wide hydrate volume vary by four orders of magnitude.

- Hydrate represents a potential hazard to offshore drilling, since sediments could become unstable if warmer drilling muds and fluids initiate decomposition.

- Similarly, seafloor installations are at risk if they are situated at the base of slopes containing significant hydrate concentrations and there are changes in the hydrate stability field driven by variations in seawater depth or temperature.

- Methane is a potent greenhouse gas, and if released from hydrate reservoirs in significant quantities could exacerbate global warming and climate change.

In addition to the above, we note that marine controlled source EM (CSEM) has become a useful tool to characterize hydrocarbon reservoirs, but resistivity anomalies in the shallow section, as created by hydrates and shallow gas, can mimic or mask the signature of deeper resistors if care is not taken in survey design.

For all of these scenarios, the actual concentration and total volume of hydrate is more important than the mere presence. We thus need techniques to estimate hydrate concentration and volumetric extent in situ. As in many other geophysical applications, the seismic method provides structural information with exquisite detail but often fails to provide bulk properties. Electrical methods, on the other hand, provide excellent estimates of bulk porosity and fluid resistivity (which is why they are so popular for well logging). The downside of electrical methods is that resolution diminishes with increased source–receiver–target separation, but this is a well understood and manageable phenomenon.

This proposal is to develop and test marine electromagnetic techniques for gas hydrate characterization. Since hydrates may occur up to several hundred meters below mudline, the shallow EM system of Rob Evans (Woods Hole), while useful for delineating near-surface occurrences, is not sufficient to explore the whole section. We have tested a system at Hydrate Ridge, Oregon, that combines the CSEM methodology as applied to deep oil exploration, in which an EM transmitter is towed across discrete seafloor EM/MT receivers, with the towed fixed offset transmitter/receiver array as employed by Nigel Edwards.

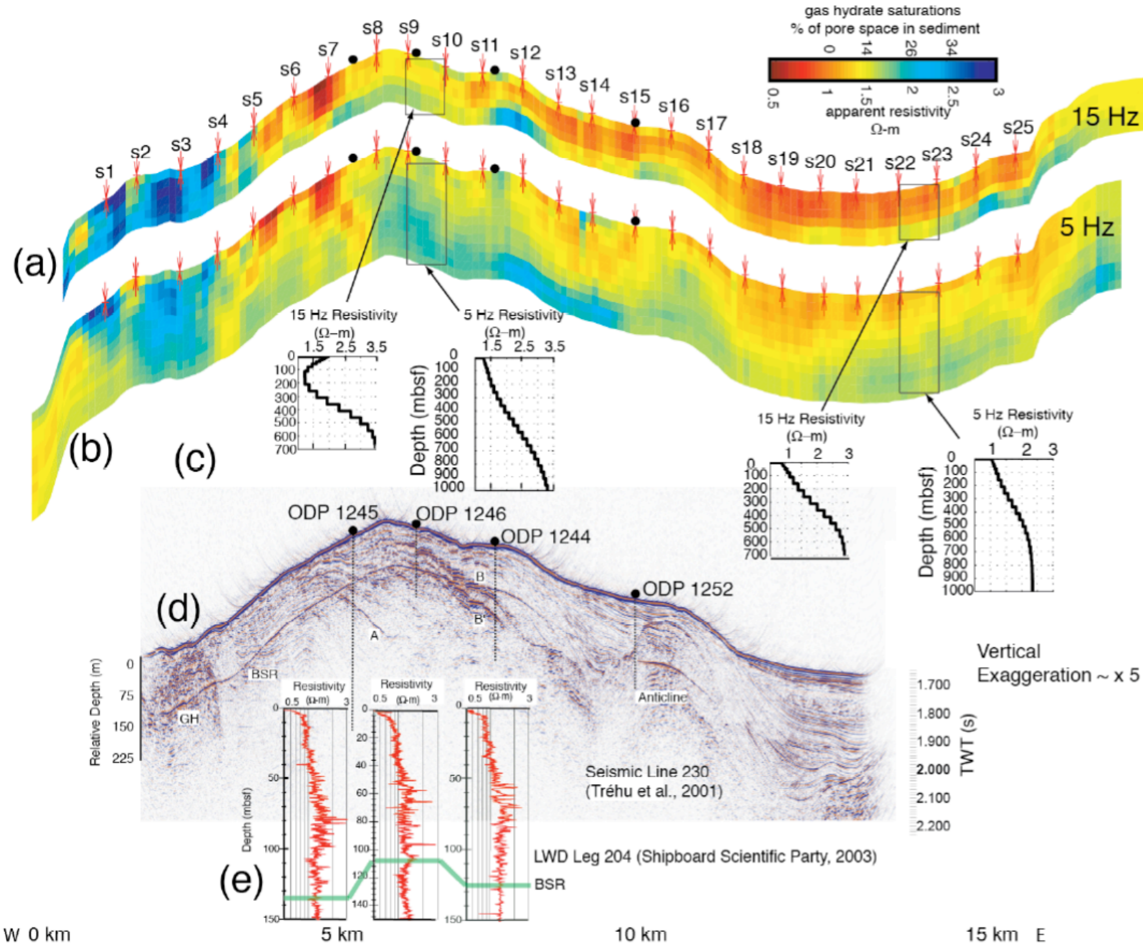

Figure 1. Apparent resistivity pseudosections (a and b) from the Hydrate Ridge pilot study, along with seismic line 230 extracted from the 3D seismic volume (d), and positions of and logs from (e) ODP leg 204 boreholes. The pseudosections show sensible resistivities that vary between that of seawater saturated sediment (0.5 Ωm) and logged values associated with hydrate (3 Ωm). Although the depth scale is not quantitative, 1D inversions (c) show that the 5 Hz data are sensitive to a maximum depth of about 1 km and the 15 Hz data to about 500 m. We see higher resistivities in the 15 Hz data near the summit (S), and on the western flank where there are high hydrate concentrations based on seismic analysis (GH). Although there appears to be a BSR under the anticline on the eastern flank, ODP hole 1252 did not intersect hydrate and the 15 Hz data show no evidence of a resistor here. The deep, resistive feature in the 5 Hz data suggest a resistive core to the anticline, possibly associated with a change in lithology.

HYDRATE RIDGE PILOT STUDY

In August 2004 we obtained 4 days of R.V. New Horizon time on station at Hydrate Ridge, Oregon, and carried out a pilot study to examine the feasibility of using marine EM methods to map hydrates. This area has been well studied using 3D seismics, ODP leg 204, and seafloor characterization. We deployed 25 EM receivers and towed the Scripps Undersea Electromagnetic Source Instrument (SUESI) for about 24 hours, before recovering the array. Figure 1 presents an apparent resistivity pseudosection for two of the frequencies transmitted. It must be emphasized that pseudosections are an extremely qualitative way of presenting data (more rigorous 2D inversion is the subject of ongoing work), but realistic resistivities were recovered and several features are evident that correspond to known structure.

Although the Hydrate Ridge experiment demonstrated the feasibility of the methodology, and although we will get more out of the data with more processing and interpretation, this experiment was limited for a number of reasons. Firstly, the short time on station limited us to a single profile which will allow 2D interpretation at best. Second, the conditions of the Cascadia subduction zone are not necessarily those of the Gulf of Mexico and other exploration environments (for example, GoM hydrates are not typically characterized by a seismic bottom simulating reflector, or BSR). Third, our first effort at towing a fixed-offset tandem receiver behind the transmitter failed as a result of a technical glitch (and the short amount of station time prevented re-deployment).

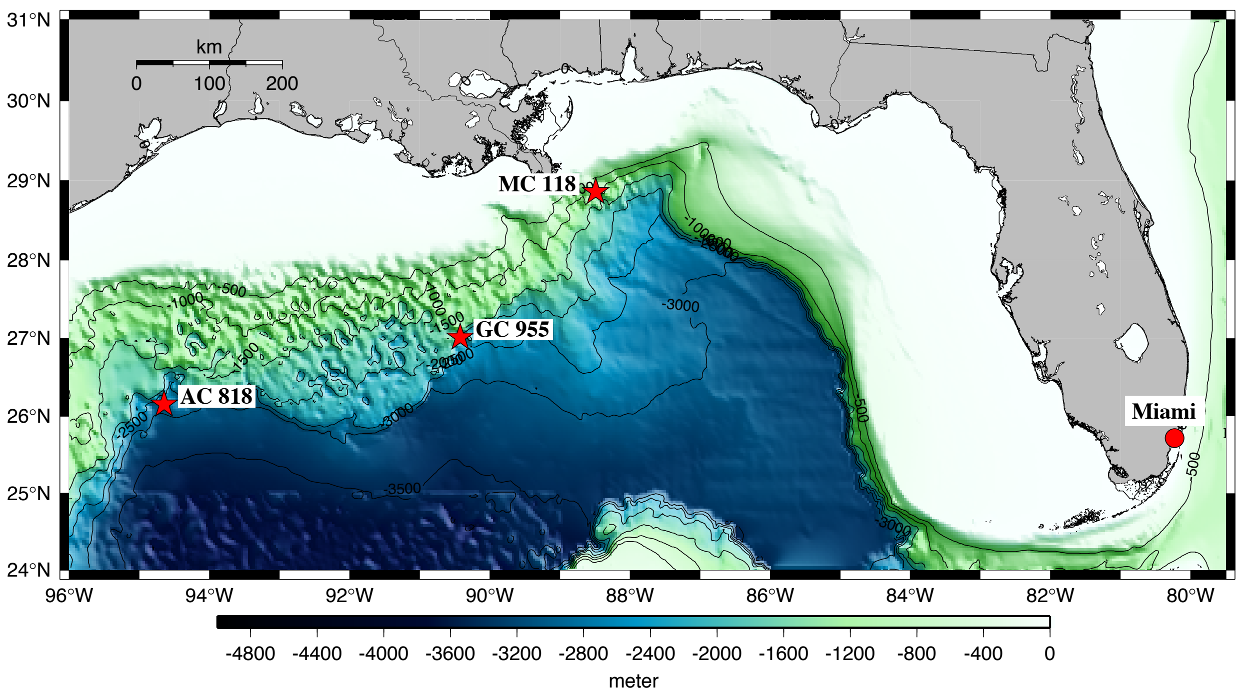

Figure 2. Map showing the three proposed survey locations (AC 818, MC 188, GC955).

PROPOSED WORK

Our initial plan was to pick a well-characterized site and carry out a very dense, comprehensive survey over it. However, it became clear that a single ideal site did not exist. On the 5th January 2007 at a meeting in Austin, Texas, a group of 20 current and potential sponsors discussed candidate sites for our project (see Appendix 1) under a revised philosophy that no single, ideal, target existed in the GoM and that as many locations as possible will be surveyed. The following 3 sites were chosen:

MC 118. This is as an MMS designated observatory, and there are some shallow resistivity studies being carried out in this area. There are large outcrops of hydrate on the surface, and other features associated with hydrate. The relatively shallow water depth (800–900 m) complements AC 818.

AC 818. This site yielded high resistivities (30–40 Ohm.m) in recent well logs from an interpreted thick hydrate section (20 m) a few hundred meters below seafloor. Water depth is greater than average (around 3,000 m). The opportunity to influence future JIP plans would give the project a large impact in the broader community. There is less infrastructure in this area and it is also of current exploration interest.

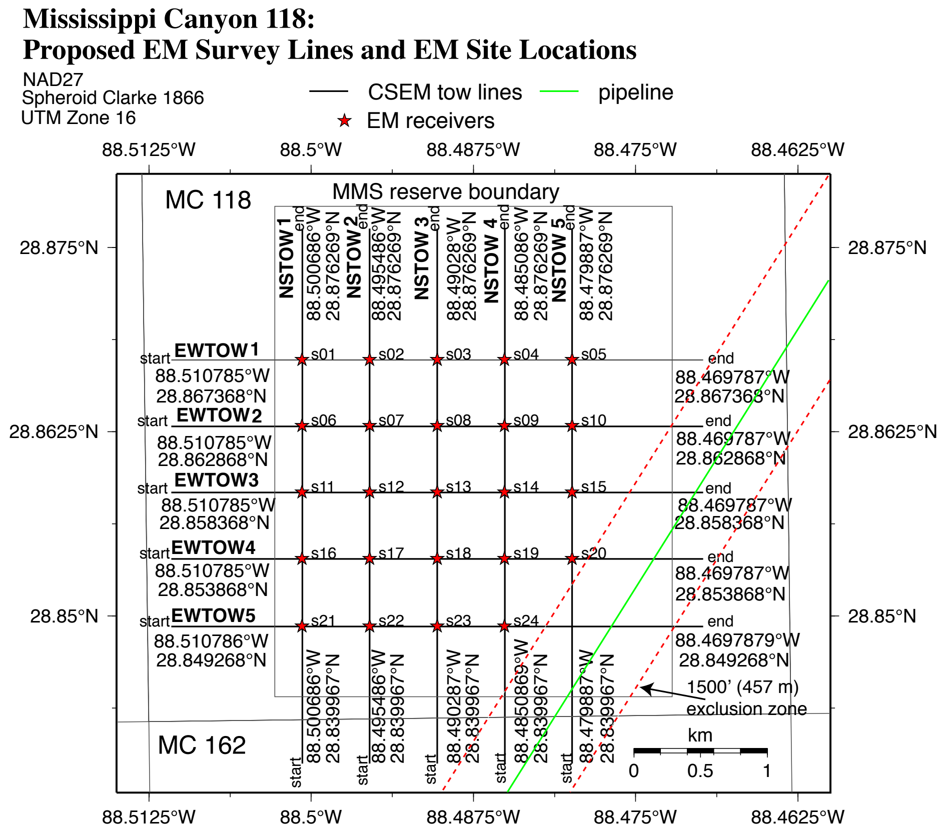

Figure 3. Survey layout planned for MC118, as permitted. Some sites have been re-located slightly to increase the standoff from a pipeline in the southeast, and we will adjust as necessary the remaining sites to avoid any other instrumentation that is on the seafloor during the time of our survey.

GC 955. A prospect in intermediate water depth (2200 m) and with surface evidence of features often associated with hydrate (mud volcanoes, etc.). The target is a channel sand that is well defined in seismic data and shows evidence of gas accumulation near the base of the stability field, and so a CSEM survey here could be carried out using a smaller, targeted survey.

With 22 days of ship time on the R.V. Roger Revelle, we can survey the 3 areas in reasonable detail. When we were planning to carry out this work on a smaller vessel, we had to include time to re-supply anchors during the cruise. With the Revelle, we will be able to load enough anchors for the entire project (85), for a more efficient use of time.

Transit from Miami to MC 118 is about 624 nm, or about 2.5 days steam. For MC 118, where we would like 3D coverage over the target area, we propose to deploy a 2D array of 25 instruments (5×5 with a 750 m spacing) (1 day), tow ten 4 km lines across the array (3 hours each with turns for a total of 2 days), and recover the receivers (1 day) for 4 days total work.

Transit from MC118 to GC 955 is about 150 nm, or about 0.75 days steam. For GC 955, where we have a target structure identified, we propose to deploy two quasi-orthogonal lines of about 10 seafloor instruments each across the target (more or less depending on how time is going) and make two simple transitter tows along these lines. We then recover the instruments, for about 3 days work.

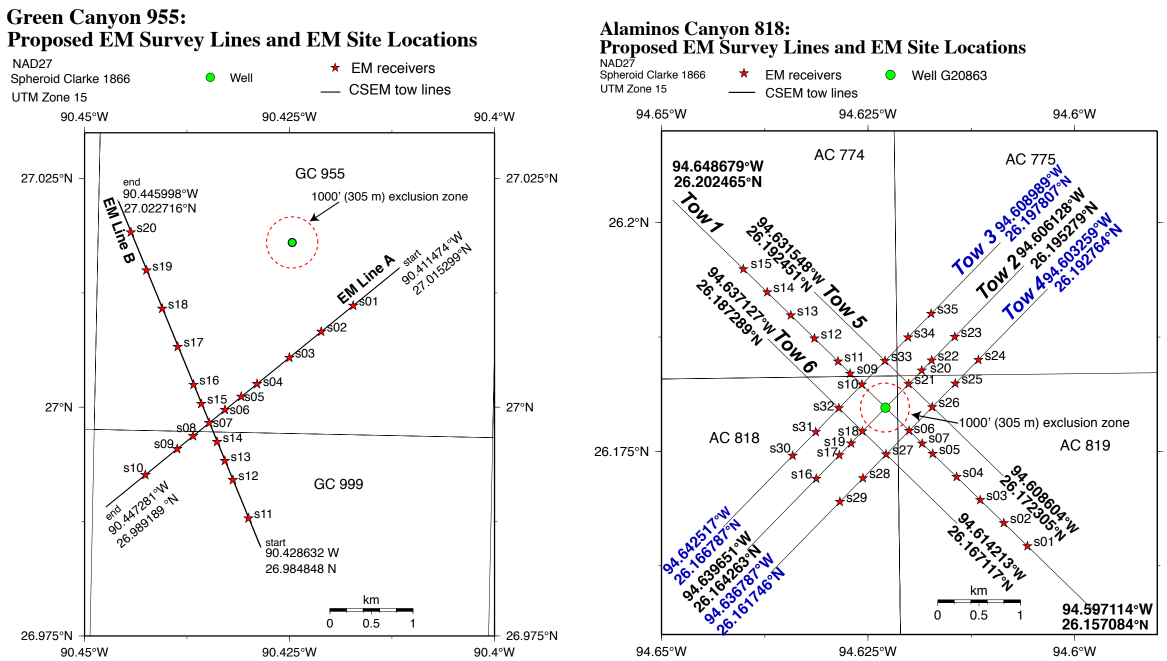

Figure 4. Sites and tow lines for planned GC955 and AC818. Some sites at AC818 have been re-located slightly to increase the standoff from the wellhead (show in green).

Transit from GC 955 to AC 818 is about 624 nm, or about 1 day steam. The original plan for AC 818, when we were limited by the deck space of the smaller vessel, was to deploy 25 instruments in a line across the well, tow over it with the transmitter, and then move 15 receivers in a sparse array around the well and tow again, for 5 days work. With the larger vessel, we will be able to take 30–35 instruments along and deploy all at once (1.5 days), tow for 2 days, and then recover all instruments (1.5 days).

Transit from AC 818 to Miami is about 858 nm, or about 3.5 days steam. Total operations time is thus about 20 days, with two port days makes 22 days of shiptime total. The fact that the targets are spread across most of the Gulf of Mexico, and the ship is operating out of Miami (necessary because of scheduling considerations), means that we have a large ratio of transit days (8) to operational days (12), an unfortunate necessity. However, the large aperture of our operations will be to our advantage if a hurricane becomes a problem during our cruise, since we will be able to re-schedule to work around the storm.

Our instrument capability is comparable to current industrial operations. Our transmitter (Scripps Undersea Electromagnetic Source Instrument, SUESI) is rated and tested at 500 A on a 200 m antenna, but for this operation we have already built and tested a custom 50 m antenna which is more suited to the shallower targets, which we expect to operate at 250–300 A (because of the shorter electrodes). Our transmitter waveform control is excellent, and the low noise floor of the SIO receivers is as good as or better than commercial instruments. Because there is no contingency time in the schedule, we will take advantage of the delays in getting this cruise going to build a second SUESI and have full redundancy in our transmitter system.

For all surveys we will also tow a tandem receiver behind the transmitter to collect continuous fixed offset radial electric field data. Our modeling shows that we want a combination of a very low frequency (less than 1 Hz) to carry out what is essentially a galvanic resistivity survey, along with very high frequency (around 10 Hz plus harmonics) to generate inductive currents in the shallow section, and the towed receiver will allow us to maximize the use of the higher frequency transmissions. Our modeling also indicated that collecting vertical electric field data was important if the hydrate formed in steeply dipping dikes, and this led us to develop a towed receiver which incorporated a vertical electric field sensor (Figure 5). We have tested this 3-axis electric field receiver, and the noise floor is as good as for a seafloor instrument if the shorter dipoles (1 m instead of 10 m) are accounted for. The pitch and roll of the device was measured at only a couple of degrees. Between now and the planned cruise in October, we may be able to add a feature which would allow the device to fly at a constant depth or altitude.

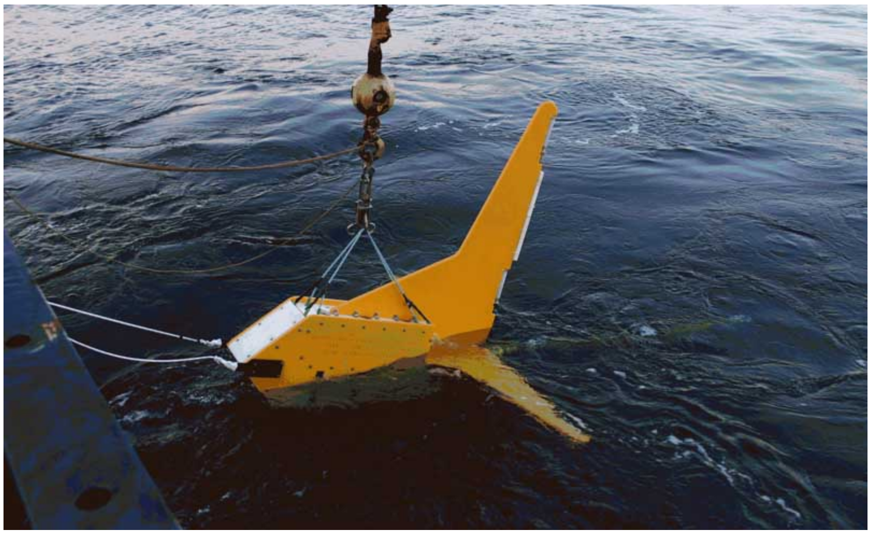

Figure 5. Our towed, 3-axis electric field receiver being deployed behind our EM transmitter. The horizontal axis 'stinger' can just be seen in the water behind the package.

We have also recently tested a long-baseline acoustic navigation system designed to improve the location of the EM transmitter (Figure 6). Two acoustic transponders equipped with GPS positioning are towed behind the ship with paravanes to fly them apart. Their locations are continuously sent back to the ship using 900 Mz radio modems. We have equipped our EM transmitter with a Benthos intelligent acoustic ranging system, which collects travel times to the surface transponders, as well as the ship and seafloor receiver instruments, and telemeters this information (along with depth, altitude, etc.) up the tow cable. This provides accurate, real-time, navigation of the transmitter which is largely independent of water depth. The far electrode has a recording depth meter as well as a relay transponder, which allows us to locate this as well.

ANALYSIS AND INTERPRETATION

The Hydrate Ridge results show the value of pseudosections when appropriately dense data coverage is available, and so we expect that rapid assessment of the results will come from a similar treatment of the GoM data. Selective 1D inversions may help quantify the apparent resistivity data. We have a 2D finite element CSEM forward code and we anticipate that by early next year will will have the capability of carrying out 2D inversions of the data. Meanwhile, we have been provided access to Schlumberger's finite difference inverse code, and have been testing its use to invert the Hydrate Ridge data set (results were presented at the Fall 2007 AGU meeting).

BUDGET JUSTIFICATION

The increasing costs of ship time (larger vessel, higher diesel prices) have pushed our budget up to $500k.

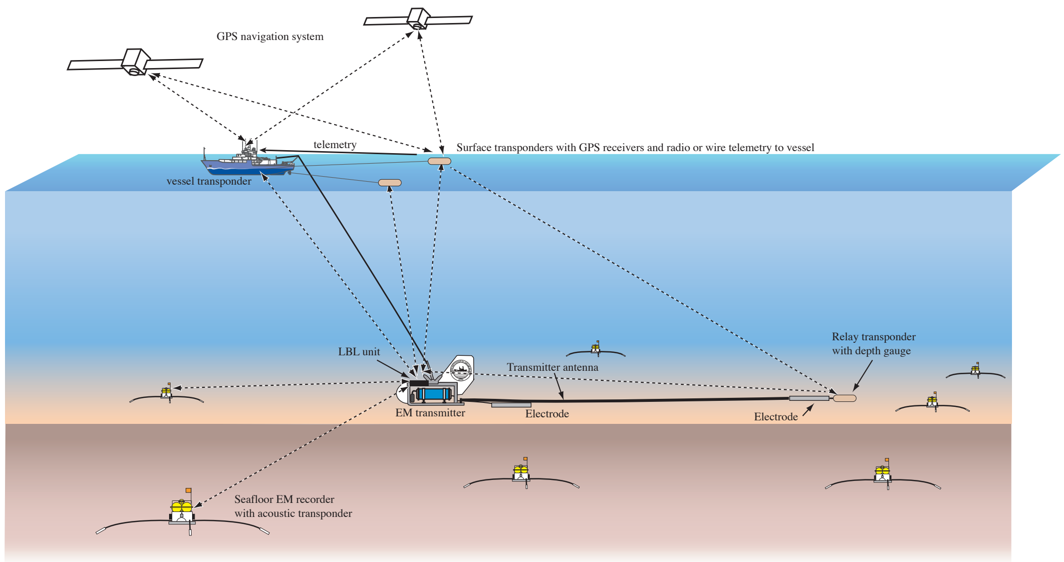

Figure 6. Our novel long baseline acoustic navigation system. Two acoustic transponders equipped with GPS positioning are towed behind the ship with paravanes to fly them apart. The EM transmitter ranges on these transponders, as well as seafloor receiver instruments, to provide accurate, real-time, navigation. A relay transponder on the far electrode allows us to locate this as well. We also equip the far electrode with a recording depth meter.

With individual contributions from each sponsor at $50k each, we will need 10 sponsors by October. The key item is shiptime. Deployment supplies and shipping amount to a little more than $50k (with overhead), which covers anchors, batteries, and other expendables for the instruments as well as trucking equipment to and from Scripps.

Instrumentation owned by SIO (seafloor receivers and deeptowed transmitter) is being made available free of charge for this experiment, having been developed and built under previous industry support.

We have some flexibility in the funding amount. If we fall short of 10 sponsors, we will endeavor to support salaries from other sources, and it is possible that SIO can provide more support for the ship. If we exceed 10 companies, we will be able to fund the salaries other personnel who will be supporting this operation, in particular Karen Weitemeyer. However, we are confident that we have used the delays in this project to good effect, and that when we finally go to sea we will collect 3 completely novel and state of the art data sets, so many companies should want to benefit from this highly leveraged project.

DELIVERABLES

The sponsors will receive a cruise report from the experiment within two weeks of the operation, and immediate access to all data collected. As the data are processed and interpreted, sponsors will be provided with updates of progress. Any papers produced from the work will be made available in preprint form to the sponsors before publication and distribution to the public. We will present the results to the sponsors through workshops held in SIO and/or Houston. We will endeavor to make equipment and techniques developed for this project available to the sponsors for proprietary surveys in an appropriate way.

APPENDIX 1
Minutes from Austin Meeting, 5th January 2007

Attendance (in no particular order):

Bob Kleinberg	Schulmberger	kleinberg@slb.com
Len Srnka	ExxonMobil Research	len.j.srnka@exxonmobil.com
Nathan Bangs	University of Texas	nathan@ig.utexas.edu
Mark Wilkinson	EMGS	jmw@emgs.com
Dave Ridyard	EMGS	dr@emgs.com
Marianne Mulrey	AOA Geophysics	mkm@aoageophysics.com
Michael Tompkins	Shell EPT	michael.tomkins@shell.com
David Bartel	Chevron	dbartel@chevron.com
Betty Johnson	Chevron	bjohnson@chevron.com
Jeff Paine	UT-BEG	jeff.paine@beg.utexas.edu
Dan McConnell	AOA	dan_mcconnell@aoageophysics.com
Eric Potter	BEG	eric.potter@beg.utexas.edu
Bill Ambrose	BEG	william.ambrose@beg.utexas.edu
Bob Hardage	BEG	bob.hardage@beg.utexas.edu
Arnold Orange	SIO	aorange1@compuserve.com
Karen Weitemeyer	SIO	kweitemeyer@ucsd.edu
Mike Taylor	BP	mike.taylor4@bp.com
William (Bill) Shedd	MMS	william.shedd@mms.gov
Stewart Sandberg	AGO	ssandberg@slb.com
Lesli Wood	BEG	lesli.wood@beg.utexas.edu
Steven Constable	SIO	sconstable@ucsd.edu

The meeting opened at 08:00 with introductions. The various interests expressed by the attendees included:

1) Hydrate mapping as a new market for CSEM technology.
2) Hydrates may become part of the permitting process for GoM blocks.
3) An interest in hydrate reservoir architecture, anisotropy, and morphology.
4) Hydrate as a shallow geohazard.
5) Hydrates can be confounding influence on CSEM data for deeper reservoir detection.
6) Hydrates as a potential energy resource.
7) A better understanding of seismic bright spots.

Steven Constable briefly reviewed the earlier Hydrate Ridge work, the history of the current project and the rationale for targeting the Gulf of Mexico, instrument modifications that are planned for the upcoming project, and the importance of texture on the way hydrate will affect bulk conductivity (citing some unpublished GeoTek results from AGU and recent calculations using HS bounds). He presented a candidate list of potential sites and explained that collective thinking has progressed from carrying out an extensive 3D survey over one site to surveying as many sites as possible. Candidate sites are:

Green Canyon 184/185, ‘Bush Hill’
Green Canyon 204/237, associated with Genesis field
DSDP Hole 618 (hydrate in shallow section)
Missisipi Canyon 118, future hydrate observatory
Alaminos Canyon 818, ‘Tiger Shark’, possible future JIP site, good hydrate in logs
Alaminos Canyon 856/857, ’Great White’, another possible JIP site

Bill Shedd presented the MMS perspective and said a few words about permitting for CSEM. He also discussed the MMS interest in recoverable hydrate reserves, which he assumes will have to come from sands with intrinsic permeability that are saturated or nearly saturated with hydrate.

Bob Hardage presented some background information for MS 118 in lieu of Bob Woolsley being able to attend the meeting. He then reviewed some well log compilations he had collected around the GC 204 area. Handouts were provided to speed up the discussion; two handouts pertaining to MC 118 and one handout detailing a compilation of resistivity well logs in the Green Canyon area.

Bob Kleinberg discussed his views on hydrate emplacement, outlining different scenarios depending on methane flux and presenting the case for steeply dipping hydrate dikes using borehole data. It is an open question whether or not hydrate dikes can be exploitable sources of natural gas. Even if they are only relic gas conduits that fed horizontal sand bodies, they constitute a good target for CSEM seafloor surveys.

Dan McConnell presented some background data for a new site, GC 955.

Discussion commenced on the ranking of sites. Bob Kleinberg suggested adding the previous JIP site KC 151 to the list. The sites were considered with respect to existence of hydrate in logs, hydrate on the seafloor (recognizing that emplacement mechanisms for exposed seafloor hydrate and hydrate in the section are probably different), water depth, existence of infrastructure, political impacts, geology (presence of salt/carbonate), logistics, prior/other data, etc. Betty Johnson suggested that the list of sites should represent a range of water depths to provide a useful variable associated with pressure changes and the extent of the stability field.

The final candidates were AC 818, MC 118, and GC 955. The resistivity contrasts in logs from the GC 204/237 area are very low and do not present encouraging targets from a CSEM point of view. At GC 184/185 BP's examination of the available seismic data suggests that hydrate is not prevalent in the subsection.

AC 818 was considered a prime target because of the high resistivities (30–40 Ohm.m) in the well logs and an interpreted thick hydrate section (20 m) at reasonable depth below seafloor (a few hundred meters). Water depth is greater than average (around 3,000 m), but it was verified that the Pelican's deeptow cable is long enough (4,700 m). The opportunity to influence future JIP plans would give the project a large impact in the broader community. There is less infrastructure in this area and it is also of current exploration interest.

MC 118, as an MMS designated observatory, provided another popular choice. Carrying out the EM now, before too much infrastructure is in place, would be an advantage. There are some shallow resistivity studies being carried out in this area. Although there are large outcrops of hydrate on the surface, and other features associated with hydrate, there is no direct evidence of hydrate at depth. The proximity to a salt body makes the area structurally interesting. The relatively shallow depth (800–900 m) complements AC 818.

GC 955 presents an intermediate water depth (2200 m) and with surface evidence of features often associated with hydrate (mud volcanoes, etc.). The target would be a channel sand that is well defined in seismic data and shows evidence of gas accumulation near the base of the stability field, and so perhaps a CSEM survey here could be carried out using a smaller, targeted survey. GC 955 would present a good test for the existence of hydrates in permeable sands, and was supported by Bill Shedd, who pointed out that there are resistivity data available from a well in the area.

There was some discussion of survey design, 2D lines versus 3D arrays of instruments. Although it puts pressure on time and instruments, 3D arrays were a consensus favorite because of the current poor understanding of hydrate distribution in the subsurface, although the final layout will depend on the target.

For example, at AC 818 a 2D line through the well may be useful to get maximum density of interpretable data where there is good prior information, coupled with a redeployment as a 3D array to evaluate extent and geometry and perhaps provide input to the JIP. MC 118 might best be targeted with a simple 3D grid, since no prior drilling exists, and GC 955 might be evaluated with a targeted 2D array across the BSR-type structure.

There was also discussion about what frequencies to use. Constable pointed out that his group are generally moving towards higher sample rates and a broader frequency spectrum in the transmission waveforms.

The three targets are distributed across a large section of the GoM, and EMGS volunteered to support resupplying the research vessel with anchors using a supply boat.

The next steps include the designation of industry and academic ‘champions’ for these sites and design of surveys using input from pre-existing seismic data and well log resistivity data. For survey design we will need bathymetry data with locations of seafloor infrastructure. For modeling purposes we will need the approximate extent of GHSZ (based on water depth, seafloor geothermal gradient, type of hydrate (thermogenic versus biogenic), and stress models for the regions to approximate fault structures. Presence of salt and carbonates in the region will also be important.