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Gas Hydrate Characterization in the GoM using Marine EM Methods

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EXECUTIVE SUMMARY

As part of Phase 1 of this project we collected marine controlled source electromagnetic (CSEM) data at four sites in the Gulf of Mexico (GoM) from 7th–26th October 2008, using the Research Vessel Roger Revelle, operated by Scripps Institution of Oceanography. The CSEM data have been processed, merged with navigation, and modeled to generate apparent resistivity pseudosections, which provide an initial assessment of data quality and information content.

The original proposal was to survey three GoM locations with indications of sub-seafloor hydrate accumulations; Alaminos Canyon block 818 (AC 818) where Chevron had encountered hydrate in a well, Mississippi Canyon 118 (MC 118) where the Minerals Management Services had designated a hydrate observatory, and Green Canyon 955 (GC 955) where seismic data suggested hydrate in a channel sand. During initial project discussions with DoE it was suggested that we add a fourth location at Walker Ridge block 313 (WR 313), a target for a Joint Industry Program (JIP) drilling campaign. By generating several contingency plans to take maximum advantage of the time available and what turned out to be very good weather, we were able to accomplish surveys over all four areas. We deployed 30 ocean bottom electromagnetic (OBEM) recorders a total of 94 times at the four survey areas and towed the Scripps Undersea Electromagnetic Source Instrument (SUESI) a total of 103 hours. SUESI transmission was 200 A on a 50 m dipole antenna at heights of 50–100 m above the seafloor. We also towed a newly developed 3-axis electric field recorder ("Vulcan") behind the SUESI antenna at a constant offset of 300 m. Only two seafloor deployments failed to collect data, and quality was excellent on all the rest. We also carried out a multibeam survey over a suspected landslide in the Green Canyon area for a student project, funded by BP America.

Several aspects of our work differentiate it from earlier studies. The deployment of large numbers of seafloor receivers results in an expanded set of transmitter–receiver offsets and extends the depth of investigation from the seafloor to the base of the hydrate stability field, and even deeper. Seafloor recorders collected every EM component except the vertical magnetic field (Ex, Ey, Ez, Bx, and By) supplemented the fixed-offset Vulcan receiver. By towing the transmitter at altitudes of 50–100 m above the seafloor, rather than dragging it in contact with the sediments and rocks, we can operate in areas with seafloor infrastructure or rough terrain. Instead of transmitting a single fixed frequency, we transmitted a binary waveform with about two decades of frequency content, from 0.50 Hz to about 50 Hz.

During discussions at the kick-off meeting held in January 2009 it was concluded that a first priority for the project should be to obtain a rapid result to assist the DoE-NETL/JIP in their upcoming spring drilling compaign. Two of four sites surveyed, WR 313 and GC 955, are relevant to the JIP drilling campaign and so analysis of AC 818 and MC 118 data was delayed. The WR 313 data were processed first because the CSEM survey targeted most of the proposed JIP wells, while the GC 955 CSEM survey was unable to target the proposed JIP wells due to the presence of a drill rig at this site during our operations. We initially focussed our attention on the Vulcan data collected at Walker Ridge 313, reasoning that the fixed offset data would be simpler to process and interpret. Unfortunately the novel nature of this instrument, combined with significant seafloor topography, resulted in some uncertainty in the early results, and we did not want to distribute them publicly until we were able to confirm them by independent examination of the OBEM data.

One of the biggest problems with the marine CSEM method as currently practiced is estimating the position of the transmitter antenna. During the GoM cruise we deployed a novel long-baseline acoustic navigation system to track the transmitter, but unfortunately we did not get this system working until the very end of the surveys. This method worked spectacularly well on a subsequent project, demonstrating that the approach was sound, but left us with needing to estimate transmitter position using a Marquardt inversion program written as part of Weitemeyer's PhD thesis. Processing navigation data has taken a substantial amount of time during the first phase of this project. The navigation code uses the short range (<1000 m source-receiver offset) electromagnetic fields recorded at the receivers to invert for the position and orientation of the transmitter.

A total of 18 CSEM tow lines were processed using the navigation program and apparent resistivity pseudosections have been generated to create data images. Although it will take subsequent work using 1D and 2D inversion to quantify the resistivities seen in these images, there is enough internal consistency and agreement with the JIP drilling to be cautiously optimistic about the success of this experiment. There is general agreement between the Vulcan data processed at Walker Ridge and the OBEM pseudosections from that area, suggesting that features seen in the data projections are interpretable.

Part of this project is also aimed at quantifying hydrate conductivity using laboratory measurements, but progress in this area has been delayed due to the efforts to get pre-drilling results from the field data, as well as the extra time the navigation processing has taken. We held a meeting in Menlo Park on December 14th 2008 to discuss the design of the conductivity cell with Laura Stern, Jeff Roberts, John Pinkston, Steve Kirby, and Heather Watson. Bill Durham participated by phone. At that time the decision was made to construct a conductivity cell in which hydrate could be grown in situ, rather than transferring hydrate into the cell after synthesis, as proposed. A follow-up meeting at Menlo Park is scheduled for November 6th this year to get this part of the project going again.

Raw data were distributed to industrial sponsors in February 2009 and a presentation was made at our two day annual consortium meeting in March 2009. Talks have also been given at the MARELEC meeting in Stockholm and the RAEG meeting in Kyoto. We generated a web site for the project, providing real-time updates during the October cruise. This site generated a lot of traffic, with 1037 views during the month of October alone. We have since posted a cruise report on the site.

PROGRESS, RESULTS, AND DISCUSSION

Phase 1.

Task 1.0: Project Management Plan. On November 5th 2008 the Principal Investigator (PI) revised and resubmitted the Project Management Plan (PMP), incorporating comments from the DOE Project Officer. This plan outlines the research to be preformed during the entire three-year project.

Task 2.0: Technology Status Assessment. This is embodied in the original proposal.

Task 3.0: Collect Marine CSEM Field Data. The data were collected as proposed, with the addition of a fourth survey over Walker Ridge. The only aspect of the data collection that did not proceed as anticipated was that the new Barracuda long baseline acoustic navigation system could not be made to work until the final survey over Mississippi Canyon.

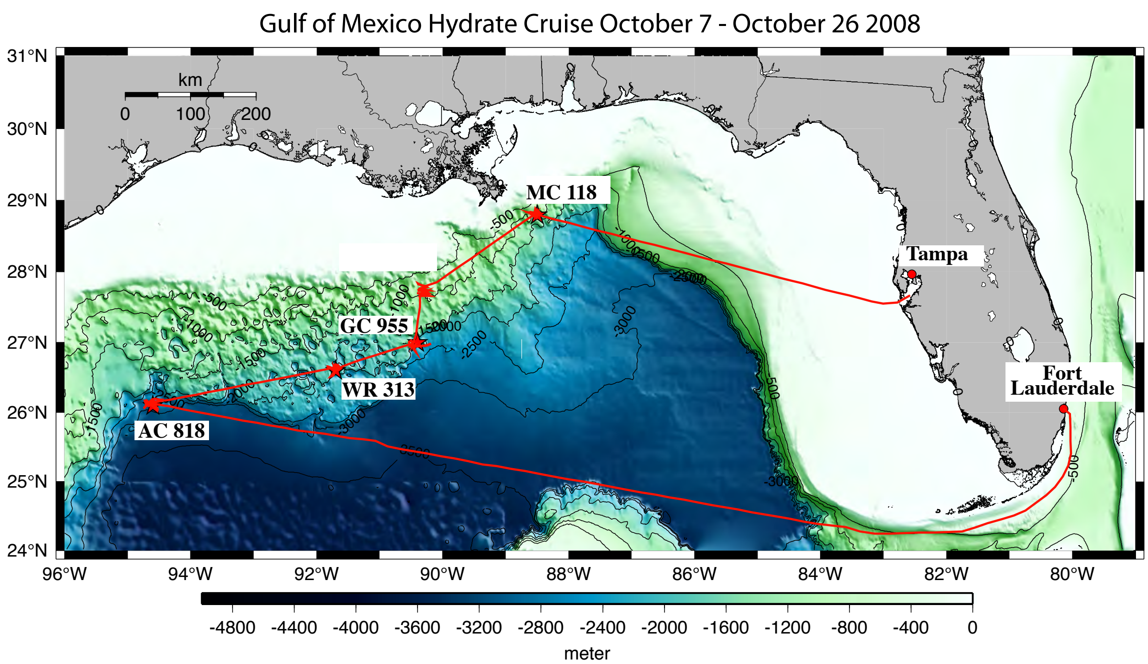

Figure 1. Map showing the three proposed survey locations in Alaminos Canyon (AC 818), Mississippi Canyon (MC 118), and Green Canyon (GC955), along with the extra location added at DoE's request, Walker Ridge 313 (WR 313).

We carried out the 18-day cruise on the R.V. Roger Revelle in the Gulf of Mexico from 7th–26th October 2008 (Figure 1). During this experiment we deployed 30 ocean bottom electromagnetic (OBEM) recorders a total of 94 times at the four survey areas and towed the Scripps Undersea Electromagnetic Source Instrument (SUESI) a total of 103 hours. SUESI transmission was 200 A on a 50 m dipole antenna at heights of 50–100 m above the seafloor. We also towed a 3-axis electric field recorder behind the SUESI antenna at a constant offset of 300 m. Only two seafloor deployments failed to collect data, and data quality was excellent on all the rest. We also carried out a multibeam survey over a suspected landslide in the Green Canyon area for a student project, funded by BP America.

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Our transmitter and towed receiver operate at altitudes of 50–100 m above the seafloor, allowing us to operate in areas with seafloor infrastructure or rough terrain, rather than being dragged in contact with the sediments and rocks. The towed receiver records all three axes of electric field instead of just the inline Ey field, and because it is not in contact with the seafloor has much lower noise levels. Instead of transmitting a single fixed frequency, we transmitted a binary waveform with about two decades of frequency content, from 0.50 Hz to about 50 Hz.

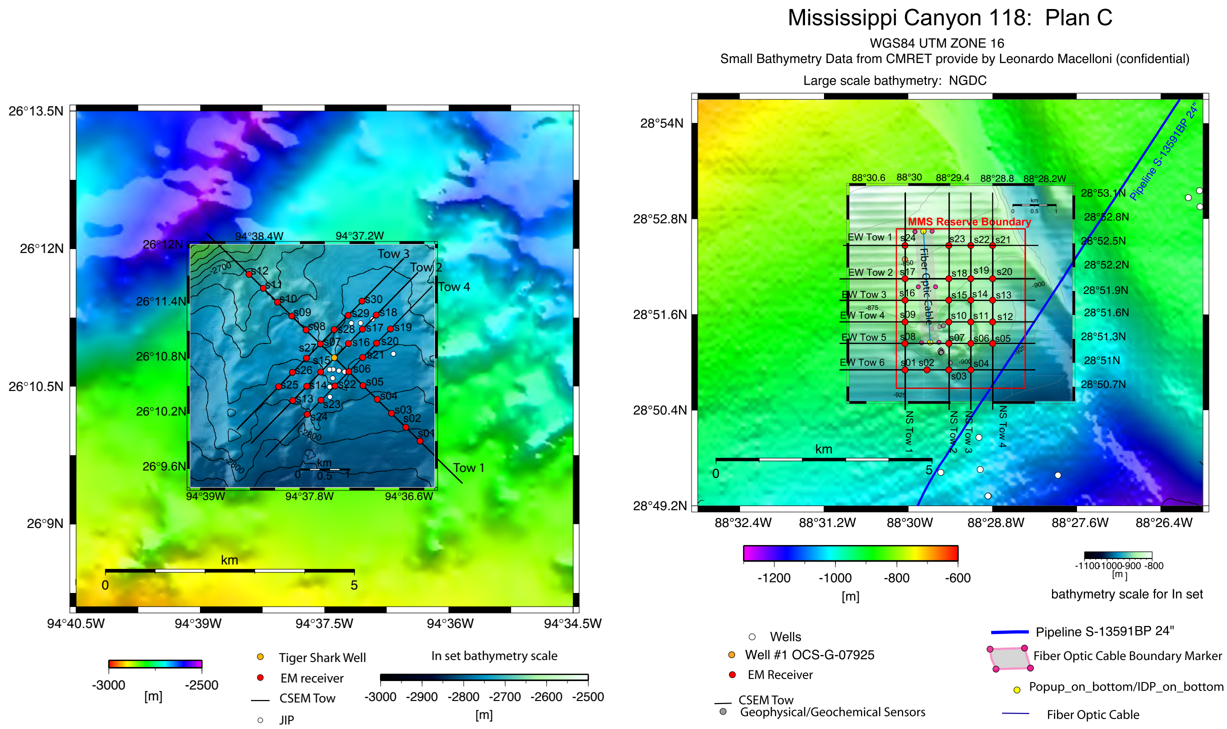

Figure 2. Left: Map of Alaminos Canyon 818 CSEM survey area. Large scale map from Chevron 2007 Dave Bartel and inset map from AOA Geophysics. Right: Map of Mississippi Canyon 118 CSEM survey area. Large scale bathymetry from NGDC and small scale map from CMRET (Leonardo Marcelloni).

Alaminos Canyon 818. Chevron encountered a thick hydrate-bearing section (20 m) a few hundred meters below seafloor in an exploration well on this block, with high resistivities (30-40 Ωm) evident in the logs. Water depth is around 3,000 m, which is deep for exploration but easily within the 6,000 m operating depth of our equipment. Initially we were hoping to impact future Joint Industry Project (JIP) drilling plans, but shortly before the cruise we heard that AC 818 was dropped from the JIP program. However, as one of the few places in the Gulf where hydrate has been found in the sub-section (c.f. the seafloor), this area remained the highest priority for our own studies. We deployed 30 receivers and made four transmission tows, centered on the Chevron well (Figure 2). Two instruments failed to record data.

Mississippi Canyon 118. This block has been designated as a Minerals Management Services observatory. Large outcrops of hydrate occur on the seafloor in relatively shallow water depths of 800-900 m, but there is yet no direct evidence of hydrate at depth. This area provides the opportunity to coordinate and collaborate with many other ongoing scientific programs, including shallow resistivity surveying. We deployed 24 receivers in a 6 x 4 array and towed 10 transmitter lines in a grid pattern (avoiding the already installed seafloor equipment) (Figure 2). All receivers recorded data.

Green Canyon 955. This prospect is in intermediate water depth (2200 m) and shows evidence of gas accumulation in a channel sand near the base of the hydrate stability field, based on examination of seismic data. It is targeted by the JIP program, but unfortunately current exploration drilling prevented us from carrying out our planned survey. We

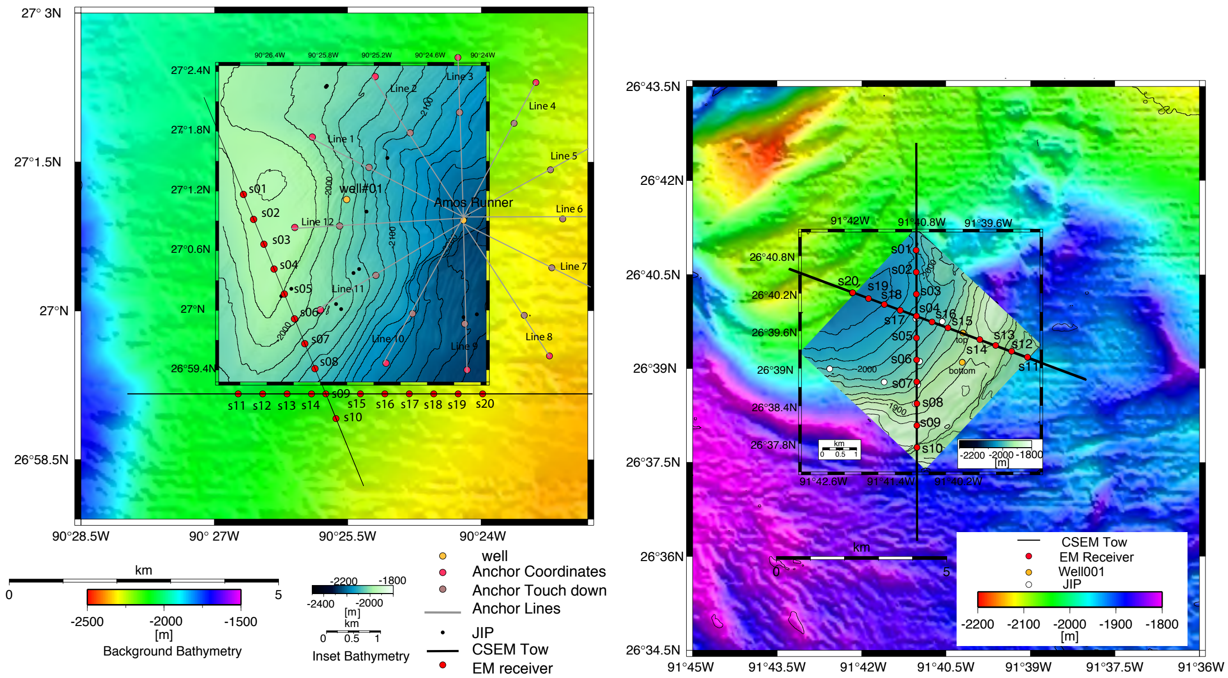

Figure 3. Left: Map of Green Canyon 955 CSEM survey area. Right: Map of Walker Ridge 313 CSEM survey area. Large scale maps from the NGDC and small scale map from AOA Geophysics.

deployed 20 seafloor instruments (all of which collected data) along two transmission lines as close as possible to the anchor patten of the drill rig (Figure 3).

Walker Ridge 313. This fourth prospect was added at the request of NETL to the 3 sites above selected in consultation with our industry sponsors. It is in intermediate water depths on the lower slope of the northern Gulf of Mexico, within a tabular salt minibasin province and having a very low geothermal gradient (hence a very thick gas hydrate stability zone). Evidence for hydrate comes from seismic data, gas mounds, and focused fluid expulsion sites. WR 313 is the third location chosen for the JIP (along with GC 955 and AC 818), and so clearly it is desirable to have marine EM data for comparison with the drilling results. We decided that if we had cooperative weather (we did) and scaled back the GC 955 survey by a few sites it would be possible to carry out a two-line survey similar to the one at Green Canyon. We deployed 20 receivers in two intersecting lines and towed the transmitter and vulcan over top of the receivers (Figure 3). Again, we had 100% data recovery.

Task 4.0: Preliminary Field Data Interpretation. Originally Task 5.

The receiver positions have been navigated and located with acoustic sounding and a Marquardt inversion program. CSEM data from all receivers have been processed; we have merged the EM data with navigation and generated apparent resistivity pseudosections for all four surveys.

A total of 18 CSEM tow lines were processed through the total field navigation program. Total field navigation uses the near field (< 1000 m) EM data to solve for the transmitter position and orientation. This technique was used sucessfully in Weitemeyer's PhD thesis (2008). At each receiver the dipole field of the transmitter is measured and the amplitude and phases of the EM fields are distorted from what one would get for a pure horizontal electric dipole. These distortions directly relate to the position and orientation of the transmitter and can be modeled.

The starting transmitter model for the inversion assumes the transmitter is located behind the ship at a distance calculated from the wire out and depth, which leaves ambiguity in the transmitter's X, Y and θ. The transmitter's dip is measured and so this parameter is fixed; receiver locations are also fixed and are based on acoustic triangulation done while on station and receiver orientations are measured by an external compass. The forward code for the total field navigation program is Key's (2009) Dipole1D which allows one to make layered 1D models of the transmitters and receivers in a cartesian coordinate system. A layered seawater electrical conductivity profile, as measured from the transmitters CTD (conductivity-temperature-depth) gauge during the CSEM tow, and a terminating half-space resistivity is used for the model. The half-space seafloor resistivity, ρ_a, is allowed to vary for each transmitter, and so the inversion parameters become transmitter X, Y, θ, and ρ_a. Since Dipole1D is a 1D solution all receivers and transmitter positions must obey this assumption by being modeled at the same sea depth. As a first attempt the transmitter's depth and altitude readings were used to set the depth for the model space, but this trapped the inversion program into a relatively high misfit. A constant altitude and depth were used for each tow (based on an average depth and average altitude for that tow) and allowed progression of the inversion. After the first inversion run we examined the misfits and locations with higher than average misfit were re-run using a different starting apparent resistivity – in most cases this would reduce the misfit considerably. Once we were satisfied with the first navigation model this was smoothed and then this smoothed model was used as the starting model for a second inversion process. This step might repeat an additional time before the final model was smoothed and used as the navigation model for the transmitter to generate apparent resistivity pseudosections for each CSEM tow. In most cases an RMS of about 10 was obtained for the final transmitter model of each CSEM tow given an error of about 2 percent.

The final transmitter model was used to generate 1D half-space resistivity forward models of 0.3, 0.5,1, 2, 3, 4, 5, and 10 Ωm using the same Dipole1D modeling code of Key (2009). Here it was necessary to use the real transmitter altitude and the correct seawater depth for each receiver, otherwise the forward modeled phase disagreed with the real phase data. Thus, each receiver had to be modeled seperately; this meant 8 forward models were generated for each receiver at each CSEM tow – totaling to over 2000 1D forward models for the entire Gulf of Mexico CSEM experiment. For simplicity, the major axis of the polarization ellipse was used in selecting the "best" half-space forward models that matched the recorded data. In this way each transmitter-receiver pair has an apparent resistivity value assigned to it. Then the pseudosection projection technique was used to make a general image of the data. This process was carried out for all surveys and are shown in Figures 1 to 5.

Preliminary pseudosections have been generated for all survey areas; these pseudosections may change as further improvements are made to the transmitter navigation. In addition, 2D and 3D analysis is the only way to get depth constraints and accurate geometries for the resistivity variations. The pseudosections have been assigned the same color scale, between 0.5 Ωm (red) and 3 Ωm (blue), to allow for comparison between the different surveys. The pseudosections are generated by mapping the ranges into a depth by projecting the midpoint between the transmitter and receiver 45 degrees below the seafloor. The larger the range between transmitter and receiver the deeper that resistivity value is projected. The depth scale is not to be taken literally as CSEM depths are not truly geometric and furthermore pseudosections are prone to producing artifacts such as "pant-leg" features whereby surface conductors or resistors may be mapped deeper than is realistic. The pseudosections allow one see lateral changes in heterogeneity across the CSEM tow line. Two frequencies have been choosen for this first analysis, the 0.5 Hz fundamental and the 6.5 Hz harmonic, which is plotted above the fundamental for all pseudosections displayed in Figures 1 to 5. The 6.5 Hz pseudosection is similar to the top of the 0.5 Hz pseudosection; the higher frequency has a skin depth attenuation of 196 m in 1 Ωm sediment and so does not image as deeply as 0.5 Hz, which has a skin depth attenuation of 707 m in 1 Ωm sediment.

Alaminos Canyon 818.

Figure 4 shows the 0.5 Hz and the 6.5 Hz pseudosections for Alaminos Canyon 818. The top pseudosection is for Tow 1 which runs from the SE to the NW going across 15 receivers spaced approximately 250 m apart and intersects with the AC 818 'Tigershark' well at the center of the tow line. The three bottom pseudosections are for the three other SW to NE tows that are perpendicular with the first tow. Tow 2 also intersects the AC 818 well (middle), Tow 3 (right) crosses with site 6 from Tow 1 and Tow 4 (left) crosses with site 7 from Tow 1. Observing the three SW to NE tows there is a general trend of a deep resistive area to the south and a shallow conductive region to the north. There is a lot of variation in electrical conductivity within the shallow surface of all pseudosections; further analysis is required to determine the validity of these features. The approximate location of the well is marked in Tow 1 and Tow 2, and straddles a transition zone of conductive and resistive sediment. There is evidence for a resistive zone consistent with

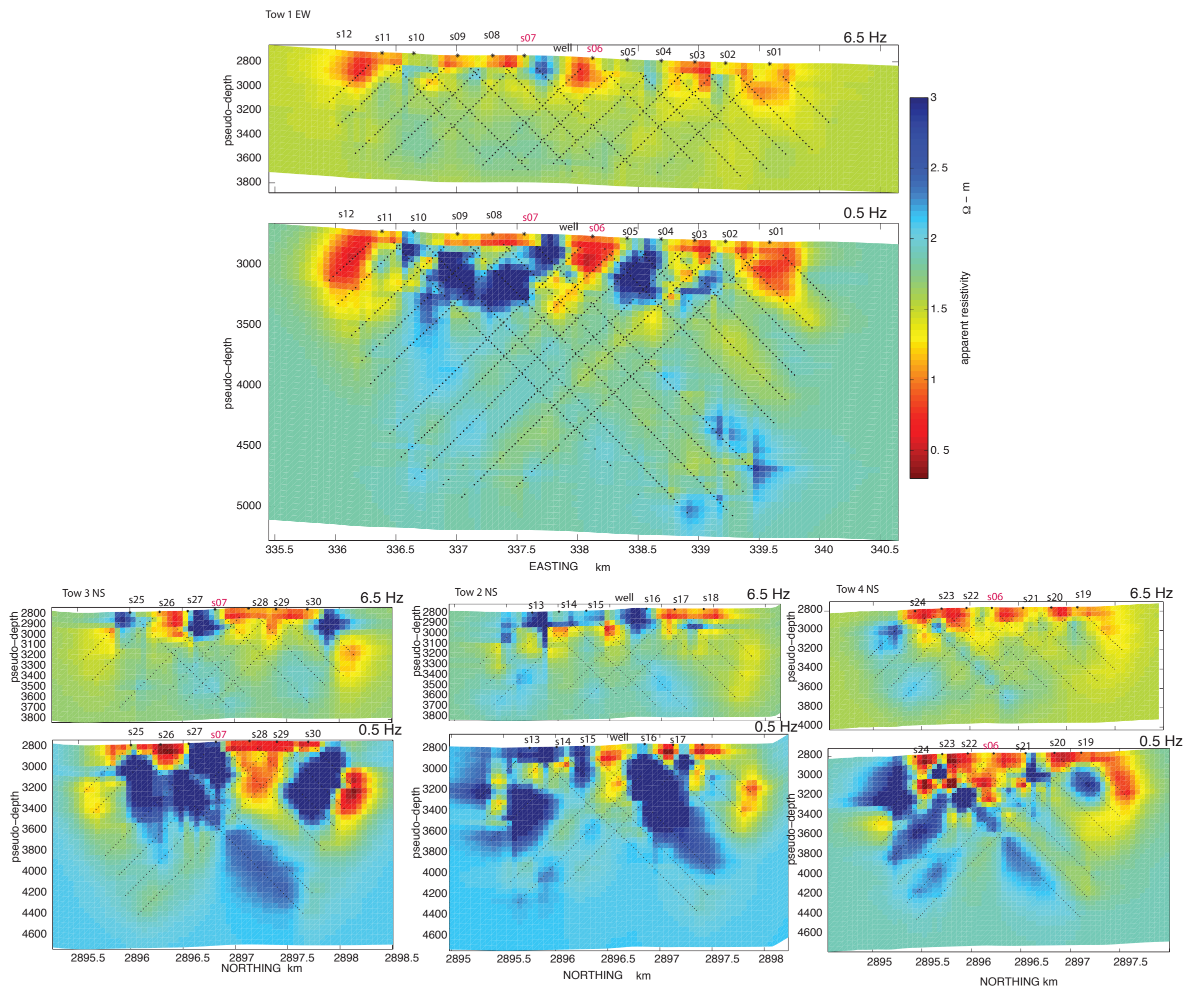

Figure 4. Alaminos Canyon 818 pseudosections of 6.5Hz and 0.5 Hz for the main SE to NW tow and three smaller SW to NE tows given in the three panels below.

resistivity in the well log, but, further analysis (2D) is required before more detailed comparisons are made. One can look for consistency at the crossing points of Tow 1 with Tow 3 and 4 by looking at sites 6 and 7. Site 7 in both Tow 1 and Tow 3 is straddling a resistive and a conductive zone for the two frequencies. Site 6 in Tow 1 and Tow 4 is sitting above a conductive feature in both tows for the 0.5 Hz pseudosection. However, the 6.5 Hz pseudosections give an indication of another conductive/resistive surface variation that is present in both tows. Data from receivers 12 and 27 could not be used because in one case there was a bad ADC and in the latter a bad electric field channel.

Walker Ridge 313.

Figure 5 shows the two Walker Ridge 313 pseudosections and the crossing point for these two tows is site 4. In both tows site 4 is sitting above a more conductive region that becomes more resistive at depths similar to the resistive zone from JIP drill site ‘G’. The EW tow intersects with the same ‘G’ drill site as well as the ‘H’ JIP drill site which is located between sites 16 and 15 we also observe an increase in resistivity at these locations that may coincide with the resistive zone from JIP site ‘H’. At Walker Ridge 313 there is a salt wall to the south and a north south trending salt diaper to the east (Hutchinson et. al. 2009) which are intersected by the NS and EW CSEM tows. There is evidence for a resisitor at sites 9 and 8 to the south and sites 14 to the east possibly associated with these salt occurrences. The 0.5 Hz pseudosections give evidence of resistive sediments at depth for the WR 313 survey. Site 18 could not be used because the instrument battery died and no data was recorded.

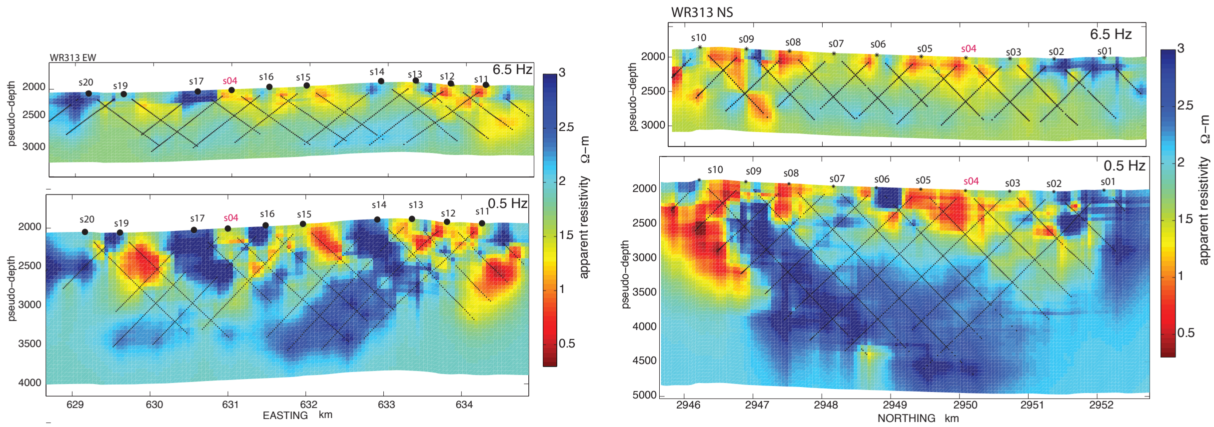

Figure 5. WR313 pseudosections for the east-west (left) and north-south (right) CSEM tows.

The Walker Ridge 313 survey has been the focus of most of this year's work, having identified this prospect as being of highest priority for DoE/NETL. This began with an examination of the Vulcan data (Figure 6 and 7). The amplitude and phase data for Vulcan across the east-west and north-south lines of WR313 are shown in Figure 6 along with the bathymetry profile across the two tows and the depths to the transmitter and towed receiver. The 1D Dipole forward modeling code of Key (2009) was used to model the electric fields for each transmitter (X,Y,Z, dip, azimuth from north) and the receiver (X,Y,Z, dip, pitch, azimuth from north) position over seafloor half-space models of various resistivities (0.3, 0.5, 1, 2.5, 5, 10, 100 Ωm). A stratified seawater layer is used based on the conductivity data recorded by the transmitter. Seven frequencies were selected that have the largest signal spread over a decade (0.5, 1.5, 3.5, 6.5, 13.5, 23.5, 33.5 Hz). Frequencies above 33.5 Hz appear to be too noisy to be useful and so were not considered in this analysis.

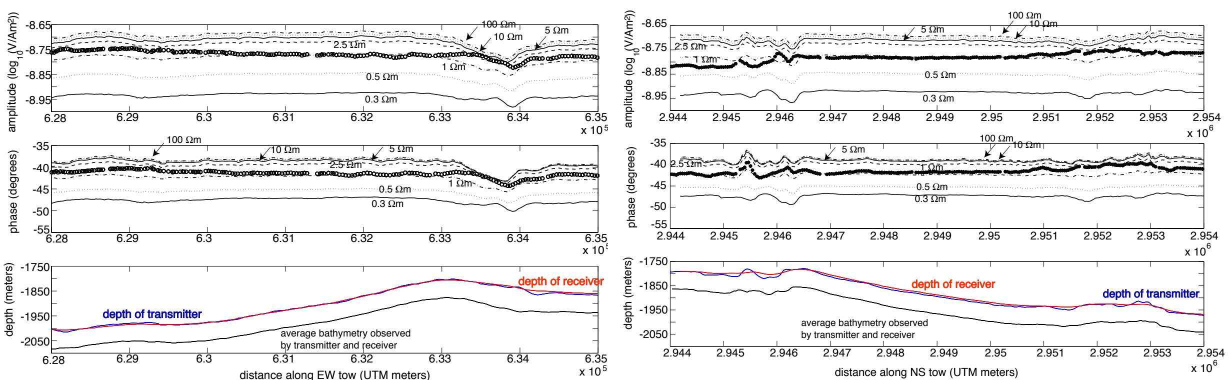

Figure 6. The in-line amplitude and phases for 1D forward models (lines) and data (dots) at a frequency of 1.5 Hz shown for the east-west and north south Vulcan data from WR 313. Although only on frequency is shown here, this analysis was done for all seven frequencies to obtain apparent resistivities.

The amplitude and phase of the forward models show effects associated with bathymetry and variations in the height of the transmitter relative to the receiver. These same effects are evident in the field data. While there are some inconsistencies in the phase data which we have yet to understand, the amplitude data can be used to make a preliminary apparent resistivity image of the Vulcan data.

The electric field data at each data point can be fit to a half-space resistivity value from the 1D forward models using an interpolation to match the data, yielding apparent resistivity values across the tow lines for the seven frequencies considered (shown in Figure 7). The apparent resistivities can be mapped into a pseudo-depth by using the skin

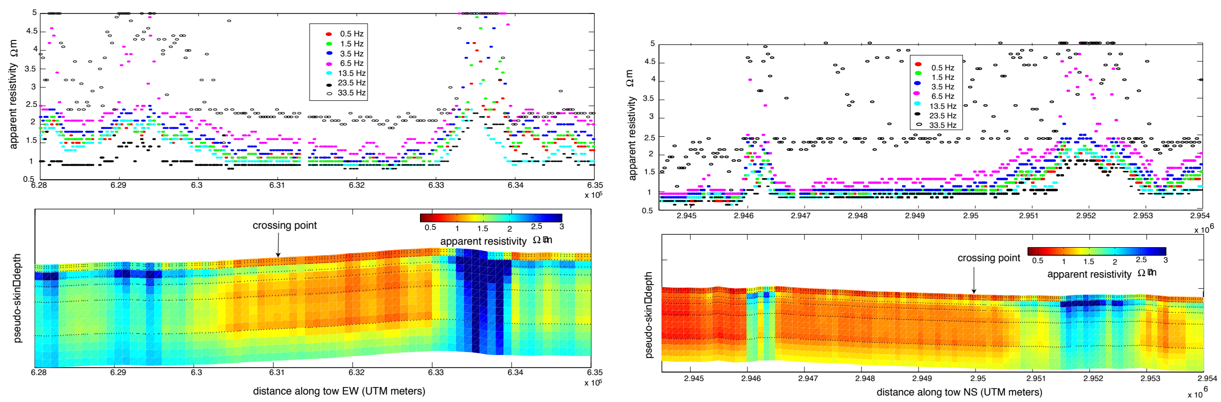

Figure 7. Amplitude 1D forward modeled apparent resistivity values from Vulcan data for the north south and east west tows at WR 313 for frequencies 0.5, 1.5, 3.5, 6.5, 13.5, 22.5, and 33.5 Hz. The skin depth of the frequencies can be used to project the resistivites into an approximate depth. Future work will involve 1D OCCAM inversions across the tow line.

depth attenuation; high frequencies will map shallower and low frequencies will map deeper, allowing us to image the heterogeneity across the two tow lines. We have not put a depth scale on the figure since such imaging projections do not provide quantitative depths. A 1D frequency inversion will be carried out to obtain an accurate depth scale when the inconsistency in the phase data is resolved. Meanwhile, the crossing point of the north-south and east-west tows are consistent, which is encouraging.

The near surface resistivity changes observed in Vulcan are consistent with the seafloor resistivity pseudosections shown in Figure 5. The north-south tow at 2946 km and at 2952 km both the Vulcan and the seafloor pseudosections give a resistive zone. The EW tow at 629 km and at 633 km roughly agree with resistors for both the Vulcan and seafloor pseudosections that are slightly offset probably because there the transmitter navigation available was inadequate when the Vulcan pseudosections were generated, updated Vulcan pseudosections will be one of the next steps taken. There are other variations in the near surface that are not observed by Vulcan but are present in the seafloor pseudosections.

Green Canyon 955.

Green Canyon pseudosections are shown in Figure 8 for the north south and east west tows. At the crossing point, site 9, is sitting above more resistive sediments for both the NS and EW tows. These two tow lines had to be adjusted to accomodate the presence of a drill rig in the area while we conducted our CSEM survey and so we could not target the JIP drill locations. However, the NS tow does intersect with the JIP well ‘Q’ and is in close proximately the JIP well ‘H’. These JIP sites are in the area of four-way closure that coincides with an uplifted mound cored by allochthonous salt (Hutchinson et al., 2008, JIP scientific Party, 2009). The NS tow is much more resistive then the EW tow, likely associated with this allochthonous salt. Site 5 and JIP well ‘Q’ which had gas flow problems and high hydrate concentrations are both resistive. In the EW tow the east side is more conductive then the west; this could be associated with unconsolidated sediments associated with slumping from the young slump scarp to the north discussed in Hutchinson et al. (2008).

Mississippi Canyon 118.

Pseudosections are given for all ten towlines at Mississippi Canyon 118 in Figures 9 and 10. There are still some inconsistencies in the navigation for the Mississippi Canyon 118 survey that are yet to be resolved. It is unclear why the total field navigation program is having difficulty for this survey; it could be from the short CSEM tow lines and the lack of data density and site overlap – where a single transmitter is observed by multiple receivers along the tow line at once. At MC 118 the most overlap is 4 receivers or less along an EW tow and 6 receivers or less along a NS tow. This location is also in much shallower water and the transmitter was towed closer to the seafloor then any other survey (about 65 m above the seafloor compared to 95 m at AC 818, 80 m WR 313 and 80 m at GC 955) and the

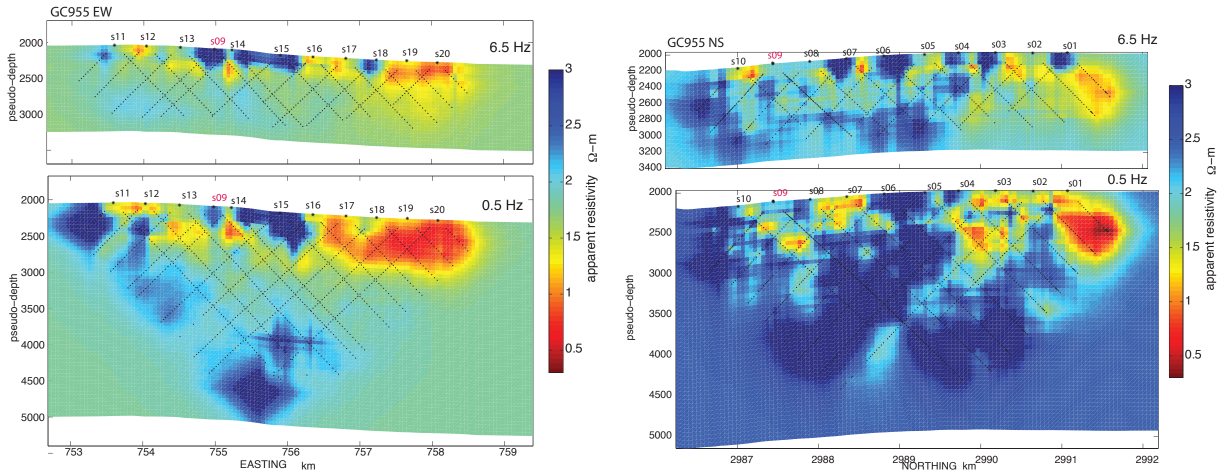

Figure 8. GC955 pseudosections for the east-west (left) and north-south (right) CSEM tows.

proximity of the transmitter to the seafloor makes it more sensitive to surface resistivity variations. MC 118 has very diverse geology with supersaline waters to carbonate pavements with outcropping hydrate (McGee et al. 2008), these lithologic variations are reflected in measurements of resistivity that are not accounted for in the total field navigation program, which assumes a half-space resistivity. Nevertheless, a consistent image arises for all the pseudosections – MC118 has much more conductive sediments then any of the other survey locations. This is consistent with the fact that this is an active fluid flux area that contains three craters with varying degrees of fluid flux venting methane and brines into the water column (McGee et al. 2008). There is also evidence from a pore fluid array of supersaline waters 5 times more conductive then seawater (compare 0.3 Ωm for seawater to 0.06 Ωm for these supersaline waters) (McGee et al. 2008).

The ten pseudosections are examined from north to south progressing through all of the EW tows (Figure 10) and simultaneously looking at the variations along the NS tows (Figure 9). At each crossover point we examine the shared receiver for the EW and NS tows. Data from sites 23 and 3 could not be used because one of the horizontal electric field channels was bad at both of these sites. Most of the more resistive regions to not appear to have any significant depth extent except for the northern most EW tow line. The NS tow lines indicate a trend of a central conductive region (NS Tow 2 and 3) and slightly less conductive on the two bounding tows (NS Tow 1 and 4). The EW tow lines progressively become more conductive to the south at EW Tow 6. It is interesting to note that site 6 is in the middle of the southeast crater and is resistive corresponding nicely the geologic observations of a pavement of methanotropic clam shells with no active venting (McGee et al. 2008). Site 10 is in close proximity to the pore fluid array in the northwest crater where supersaline waters have been observed, the CSEM pseudosections for the NS and EW give a shallow resistive region in the 6.5 Hz, but more conductive in the 0.5 Hz; this could be a real effect from the resistive carbonate cement at the crater site and the very conductive supersaline pore water present here.

The following paragraphs go through each of the EW tows.

EW Tow 1 intersects with NS Tow 1, 3, and 4, at sites 24, 22, and 21. Site 24 is above a resistor in both NS and EW tows, however the NS tow is much more conductive then the EW direction. Site 22 is slightly more resistive in the 6.5 Hz pseudosection and is conductive in the 0.5 Hz pseudosection for both the NS and EW tows. Site 21 consistently sits over a resistor in both the NS and EW tows. For comparitive purposes we can compare NS Tow 2 with this tow and find similar resistivity values at their intersections.

EW Tow 2 intersects with NS Tow 1, 2, 3, and 4 at sites 17, 18, 19, and 20. Here we observed some discrepencies at the cross over points of site 17 which sits over a resistor in the EW tow and a conductor in the NS tow. Site 18 consistently sits on a resistor in both the EW and NS tows. Site 19 sits on a resistor for the 6.5 Hz data for both EW and NS tows, but for the 0.5 Hz data site 19 sits on a conductor for both NS and EW tows. Site 20 has another discrepency were the

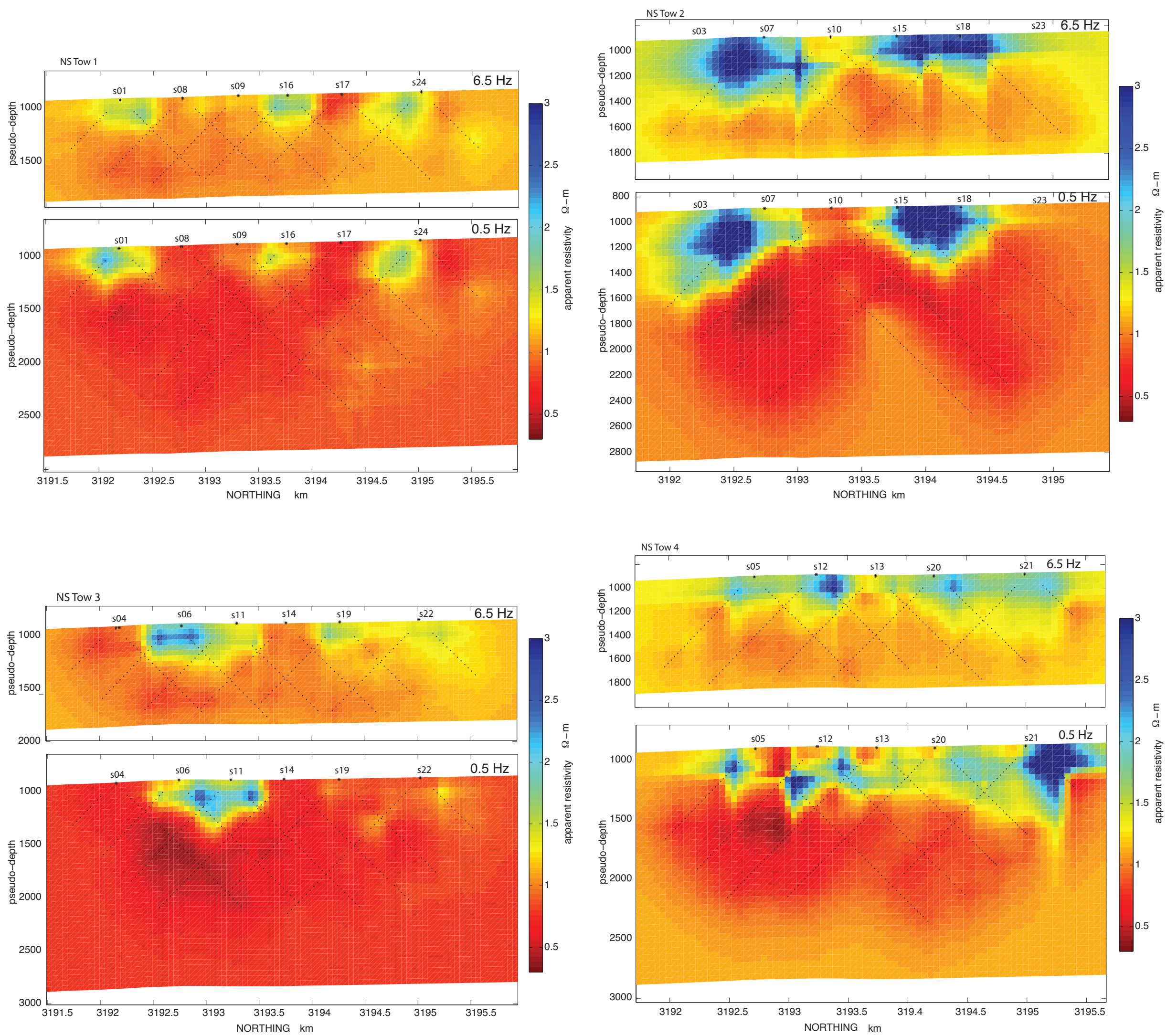

Figure 9. MC118 pseudosections north south

NS tow is it more resistive and the EW tow it is more conductive.

EW Tow 3 intersects with NS Tow 1, 2, 3, and 4 at sites 16, 15, 14, and 13. There is a discrepancy at site 16 were NS is more resistive and EW is more conductive although the extent of the resistor is not great. Site 15 consistently sits over a resistor in both the NS and EW tows. Site 14 sits in a transition zone of conductive and resistive for the EW tow and is conductive for the NS tow. Site 13 is siting over a resistor in both EW and NS tows although the NS tow indicates it is slightly less resistive then in the EW.

EW Tow 4 intersects with NS Tow 1, 2, 3, 4 at sites 9, 10, 11, and 12. There is no agreement of the resistivites at the intesections points for the NS and EW tows. There is only slight agreement at site 10 which is generally more resistive in the 6.5 Hz then the 0.5 Hz for both NS and EW tows.

EW Tow 5 intersects with NS Tow 1, 2, 3, 4 at sites 8, 7, 6, and 5. Site 8 is conductive in both the NS and EW tows. Site 7 is conductive for the EW tow and resistive for the NS tow. Site 6 is resistive for both the EW tow and the NS tow. Site 6 is located in the middle of the south east crator which has a pavement of methanotropic clam shells with no active venting (McGee et al. 2008) . Site 5 is at a transition zone from resistive to conductive between frequencies

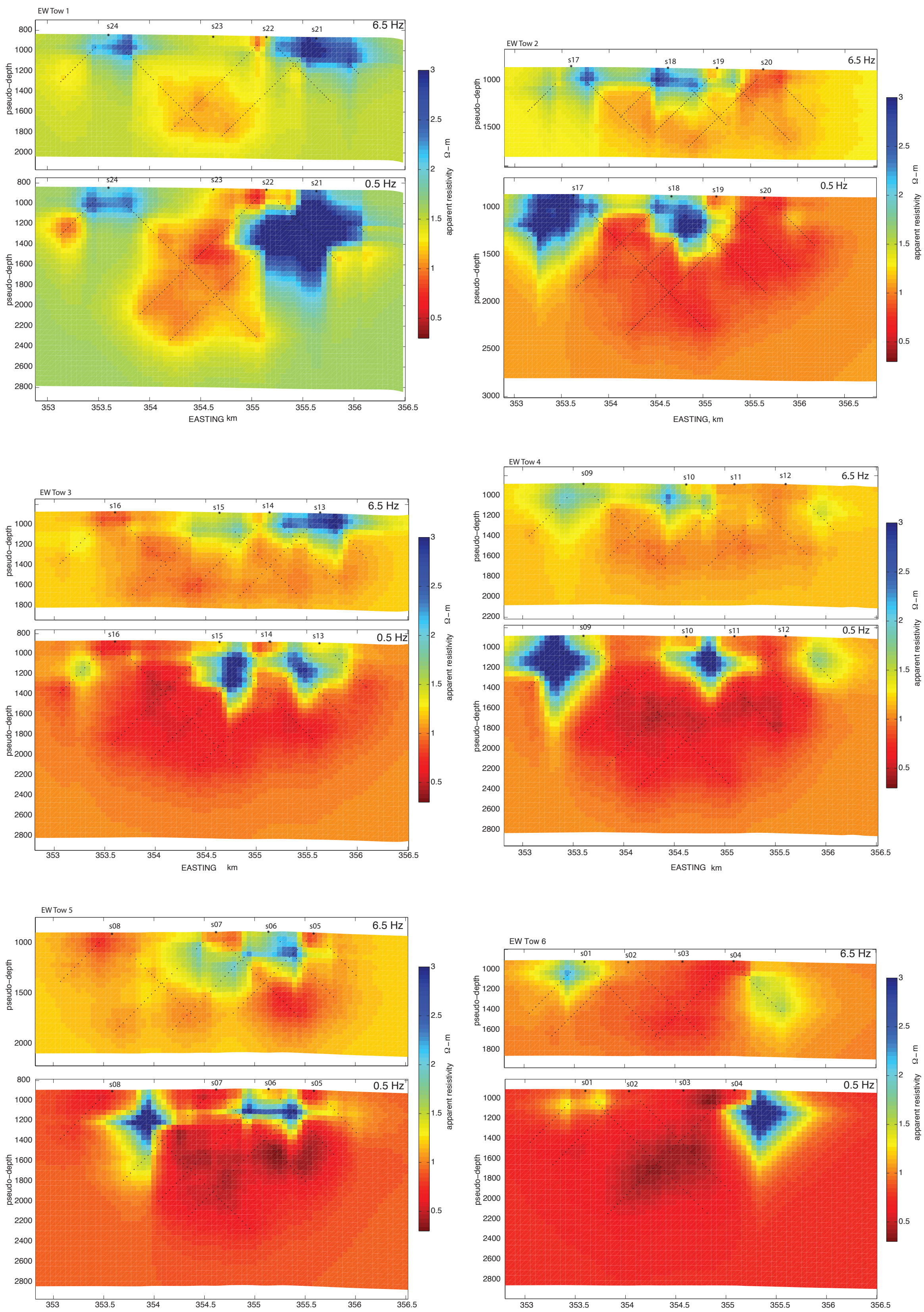

Figure 10. MC118 pseudosections east west

and between tows.

EW Tow 6 intersects with NS Tow 1 and 4 at sites 1 and 4. Site 1 is resistive for both the EW and NS tow. Site 4 is conductive for both NS and EW tows.

References

McGee, T., J.R. Woolsey, L. Lapham, R. Kleinberg, L. Macelloni, B. Battista, C. Knapp, S. Caruso, V. Goebel, R. Chapman, and P. Gerstoft. 2008. Structure of a carbonate/hydrate mound in the northern Gulf of Mexico. *Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008),* Vancouver, British Columbia, Canada, July 6-10, 2008.

Latham, T., D. Shelander, R. Boswell, T. Collett, M. Lee. 2008 Subsurface charactization of the hydrate bearing sediments near Alaminos Canyon 818. *Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008),* Vancouver, British Columbia, Canada, July 6-10, 2008.

Hutchinson, D. R., D. Shelander, J. Dai, D. McConnell, W. Shedd, M. Frye, C. Ruppel, R. Boswell, E. Jones, T. Collett, K. Rose, Brandon Dugan, W. Wood, T. Latham. 2008. Site Selection for DOE/JIP gas hydrate drilling in the northern Gulf of Mexico. *Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008),* Vancouver, British Columbia, Canada, July 6-10, 2008.

JIP scientific Party, 2009, *http://gomhydratejip.ucsd.edu/JIP_LWD_Cruise/Daily_Cruise_Log/* Daily Report April 18 WR313-G; Daily Report April 19 WR313-G; Daily Report April 20 WR313-G; Daily Report April 25 GC955-H; Daily Report April 26 GC955-Q; Daily Report April 27 GC955-Q; Daily Report April 28 GC955-Q; Daily Report April 30 WR313-H;

Task 5.0: Design and Build Conductivity Cell. Originally Task 4. We held a pre-AGU meeting (Sunday December 14th 2008) at Menlo Park to introduce Constable, Weitemeyer, and Jeff Roberts to the facility and to Laura Stern's group. The USGS facility has a well established method to produced synthetic hydrate. Also in attendance at the meeting was Steve Kirby and John Pinkston of USGS, and Heather Watson of LLNL. This initiated discussions on the design of the conductivity cell. A second meeting took place in mid-March with Steven Constable and Jeff Roberts at LLNL. This task has been delayed, and is being moved into Phase 2. A planning meeting is scheduled for November 6 2009.

Task 6.0: Make Hydrate and Hydrate/Sediment Conductivity Measurement. This task is scheduled for later this year and Budget Period 2.

Task 7.0: Modeling and Inversion of Field Data. The bulk of this task is scheduled for Budget Period 2. However, we have made some progress in understanding inversion of hydrate CSEM data through our continued work on the Hydrate Ridge data set, which we inverted in collaboration with Schlumberger (see Figure 11).

Task 8.0: Estimate Quantitative Hydrate Volumes from Field Models and Laboratory Studies. This task is scheduled for Budget Period 2.

Task 9.0: Technology Transfer. We have maintained a web page and a daily cruise log during the cruise. Initial results were presented to sponsors meeting during the SEG Annual Conference, November 2008. Cruise report was released in January, 2009. The data have been distributed to the sponsors (February, 2009) and preliminary results were presented at the Seafloor Electromagnetics Consortium annual meeting March 18 and 19, 2009. A meeting with Ken Greene of Exxon Mobil (March 20, 2009) took place with a discussion of possible collaboration in the near future. Constable attended the SEG meeting and the Vulcan data was well received with the potential for further research in developing Vulcan type systems for third parties.

Task 10.0: Final Publication. This task is scheduled for Budget Period 3.

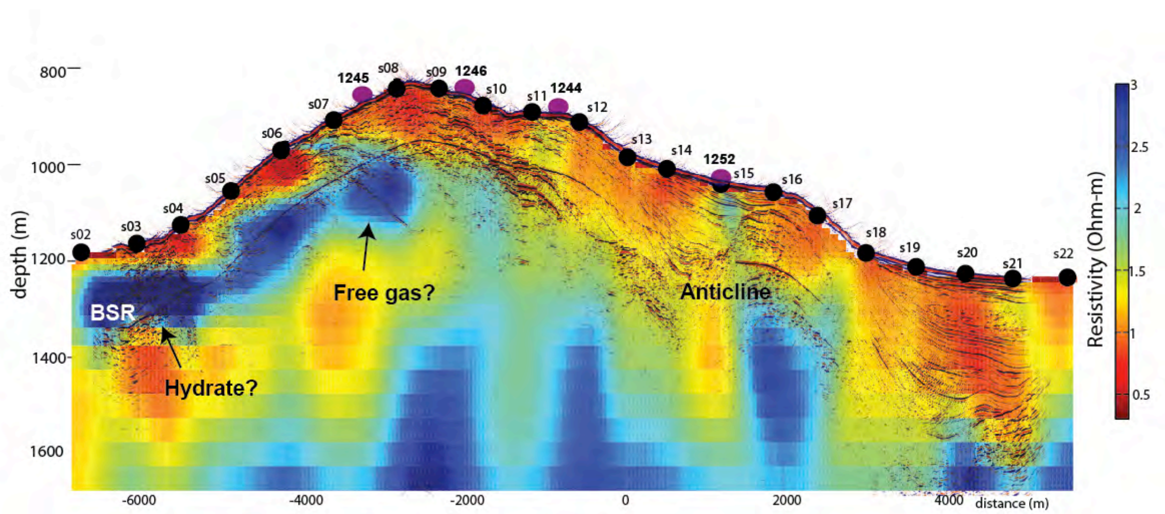

Figure 11. Inversion of Hydrate Ridge CSEM data set, done in collaboration with Guozhong Gao and David Alumbaugh of Schlumberger/EMI Technology Center. Resistive material (blue) is interpreted as gas hydrate above the BSR, and free gas below.

CONCLUSION

This project is off to a great start with the successful Gulf of Mexico data collection cruise commencing within a week or two of funding. All the proposed objectives of the cruise were met, with the addition of a fourth survey area added at the request of NETL. The updated project management plan was provided in November, after the cruise but within the time frame requested. However, the need to concentrate on the field project right from the beginning has resulted in some delays to the design and construction of the conductivity cell, although we had a fruitful design meeting with the whole team just prior to AGU in December.

The desire to produce a quick result for the DoE/NETL JIP drilling timeline led us to attempt a less rigorous treatment of the data, which in our opinion has proven to be inadequate. This year has been a useful period for learning the complexities of Vulcan-type CSEM data, but it became clear that reliable results would not be obtained until we carry out total field navigation to obtain an accurate location and orientation for the transmitter.

All of the CSEM survey data have been processed using the total field navigation program to obtain a more accurate location and orientation for the transmitter. In some cases the navigation appears to be adequate, but for MC 118 further work needs to be done to determine the discrepencies in the pseudosections and resolve navigation issues that are still present in the data. Preliminary pseudosections have been produced for all surveys with some initial interpretations carried out.

MILESTONE STATUS

Milestone log for Budget Period 1.

Milestone 1: Revised Project Management Plan. Task 1.0, completed 3 November, 2008.

Milestone 2: Submission of Technology Status Assessment. Task 2.0, embodied in the original proposal.

Milestone 3: Preparation of marine instrumentation for shipping. Task 3.0, completed 30 September, 2008. Equipment was tested in the laboratory and trucked to Fort Lauderdale. Critical milestone for tasks 5,7,8,9,10.

Milestone 4: Carry out field program in GoM. Task 3.0, completed 26 October, 2008. Field program was completed more than successfully, with one extra survey area covered and 15 more stations than proposed. Critical milestone for tasks 5,7,8,9,10.

Milestone 5: Produce initial cruise report Task 3.0, completed 30 January, 2009.

Milestone 6: Design conductivity and pressure cell. Task 5.0, work underway. Critical milestone for tasks 6, 8, 9, 10.

Milestone 7: Generate merged EM/navigated data set. Task 4.0, work completed. Critical milestone for tasks 7, 8, 9, 10.

Milestone 8: Construct conductivity/pressure cell Task 5.0, work underway. Critical milestone for tasks 6, 8, 9, 10.

Milestone 9: Make calibration tests of cell using water standard Task 5.0, work not yet started. Critical milestone for tasks 6, 8, 9, 10.

Milestone 10: Install cell in Menlo Park and make initial hydrate measurements Task 5.0, work not yet started. Critical milestone for tasks 6, 8, 9, 10.

Milestone 11: Preliminary interpretation of field data Task 4.0, work completed.

Milestone 12: Webpage updated Task 9.0, January 30 2009.

Milestone 13: Produce Phase 1 Report Tasks 1-4, completed 2 November 2009.

ACCOMPLISHMENTS

• Collection of the Marine CSEM Field Data

• Conductivity cell design underway.

• Processing of the data is completed.

• A Fire in the Ice article was published.

• Participated in a "Spot Light on Research" article for Fire in the Ice.

• Data distributed to sponsors.

• Generated merged transmitter navigation with the CSEM data using the Total field navigation program

• Generated pseudosections for the 0.5 Hz and 6.5 Hz CSEM data transmissions for all 18 tows of the 4 areas surveyed in the Gulf of Mexico.

PROBLEMS OR DELAYS

The design and construction of the conductivity cell is progressing more slowly then anticipated. The reasons are a combination of a later than proposed funding of the project, the large amount of work that went into the highly successful field work, the diversions of the year-end holiday and conference (AGU, SEG) season, and other ongoing projects competing for attention, along with our focus on obtaining a quick result for the JIP hydrate drilling campaign. However, the pre-AGU meeting went well and we have a plan for moving ahead with this part of the project, moving the work into Phase 2.

Generating merged EM/navigated data sets has also progressed more slowly due to the failure of our Barracuda navigation system while at sea. As a first step, and in order to obtain a quick result for the JIP, we used wire out, pressure and altimeter data in the transmitter to project back the position of the transmitter, but the treatment of the data in this way was inadequate, resulting in significant inconsistencies for in tows and out tows at each receiver. Instead we have modifed the total field navigation code used for Weitemeyer's PhD thesis to solve for transmitter position and orientation. It has been applied to all of the surveys from the Gulf of Mexico with varying degrees of success, further improvements are planned to ensure good quality navigation is used in future analysis.

PRODUCTS

• Revised Project Management Plan.

• A project website was set up:

http://marineemlab.ucsd.edu/Projects/GoMHydrate/index.html

Cruise Report is available for download.

• Project Summary:

project summary outlining project goals and objectives on the NETL project Web site.

• Collection of Marine CSEM data in the Gulf of Mexico:

Data distributed to sponsors early February.

• Fire in the Ice article published Winter 2009.

• NETL kick off meeting, Morgantown, WV - January 6, 2009

The PI delivered a project overview presentation.

• Talked at the 2009 MARELEC Meeting - Stockholm, Sweden - July 7-9 2009

The PI will present a talk entitled *Applying marine EM methods to gas hydrate mapping*

• Submitted the first quarter report February 2 2009.

• Invited talk at LLNL in mid March

Steven Constable delivered a presentation:

Marine Electromagnetic Methods for Mapping Gas Hydrate

• SIO Seafloor Electromagnetics Consortium annual meeting, La Jolla, CA - March 18-19, 2009

Karen Weitemeyer delivered two presentations:

Marine EM for gas hydrate studies, with first results from the Gulf of Mexico

Using Near field data to navigate controlled source electromagnetic data

• Two Invited Seminars in Canberra, ACT, Australia:

1) Research School of Earth Sciences, Australian National University, June 25 2009

2) Australian Society for Exploration Geophysicistst at Geoscience Australia, June 26 2009

Karen Weitemeyer presented a talk entitled:

Marine Electromagnetic Methods for Gas Hydrate Characterization

• Steven Constable and Karen Weitemeyer participated in NETL Project Phase Transition Meeting, August 8, 2009.

• Invited talk in Japan

Steven Constable delivered a presentation

• Submitted a paper to Geophysics entitled *The practical application of 2D inversion to marine controlled source electromagnetic data* by Weitemeyer, Gao, Constable, and Alumbaugh.

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