Marine Electromagnetic Methods for Gas Hydrate Characterization, Gulf of Mexico

R.V. Roger Revelle, October 7th – 26th 2008

Sponsors: CGG-Veritas, Chevron, emgs , ExxonMobil, Fugro, Shell, Statoil, WesternGeco Electromagnetics UC Shipfunds, DoE NETL

Cruise Report
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http://marineemlab.ucsd.edu/Projects/GoMHydrate/

photo courtesy Alex James

Summary

As part of a comprehensive study to develop marine electromagnetic methods for gas hydrate detection and mapping, we carried out an 18-day cruise on the R.V. Roger Revelle in the Gulf of Mexico from 7th–26th October 2008. During this experiment we deployed 30 ocean bottom electromagnetic (OBEM) recorders a total of 94 times at four survey areas (Alaminos Canyon block 818, Walker Ridge block 313, Green Canyon block 955, and Mississippi Canyon block 118) and towed the Scripps Undersea Electromagnetic Source Instrument (SUESI) a total of 103 hours. Transmission was 200 A on a 50 m dipole antenna at heights of 70–100 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.

Research Objectives

Submarine gas hydrates are of considerable importance 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 can become unstable if cements or 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. Also, continental shelf landslides initiated by hydrate decomposition could generate damaging tsunamis.

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

For all of the scenarios quoted above, 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. Although hydrate is often evident in seismic surveys as a bottom-simulating reflector (BSR), this is not always the case. In particular, the Gulf of Mexico (GoM) is notorious for a lack of BSR in areas of known hydrates. 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.

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. Edwards, Rob Evans at Woods Hole, Katrin Schwalenberg of Federal Institute for Geosciences and Natural Resources (BGR), Germany, and Tada-nori Goto of JAMSTEC all have towed EM systems suitable for shallow (top few 10's of meters) seafloor studies. A study by SIO at Hydrate Ridge in 2004 represented the first attempt to apply the EM methods recently developed for oilfield characterization to the hydrate question. The results were promising, but this survey was limited to 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.

Following the successful trials of the marine controlled-source EM (CSEM) and magnetotelluric (MT) methods over Hydrate Ridge, offshore Oregon, USA, we wrote proposals to a variety of funding entities to carry out further field tests

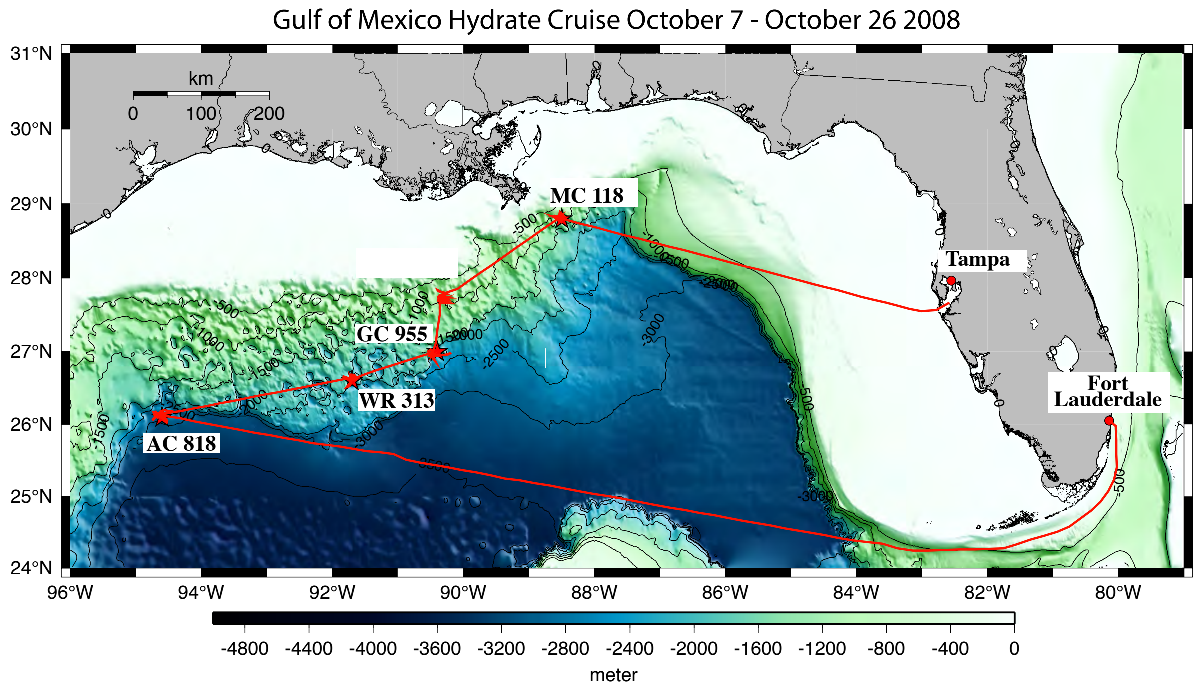

Figure 1. Map of survey areas, with ship trackplot in red.

of the marine EM method for hydrate mapping in the Gulf of Mexico (GoM). Funding was obtained from a consortium of oil companies and oilfield service companies, SIO/UCSD Shipfunds, and the US Department of Energy.

The original plan was to carry out a comprehensive 3D EM survey at a location of known and well-documented sub-seafloor hydrate at a single location in the GoM. Discussions with sponsors made it clear that no such location exists, and so the strategy of the current experiment was to carry out 2D and 3D surveys at as many sites as possible. The original plan was for three sites, but good weather and the use of a more capable ship carrying more OBEM receivers meant that four locations could be surveyed, two with 3D coverage and two with intersecting 2D lines.

The areas studied during the cruise are in different water depths and have different geologic controls on the way hydrate is thought to be distributed:

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 Ohm.m) 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 after 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 remains a high priority for our own studies. We deployed 30 receivers and made four transmission tows, centered on the Chevron well. Two instruments failed to record data. We were planning two more tow lines over this area, through sites 27/15/22 and sites 28/16/21, but decided that the large overhead associated with the need to make a wide turn onto these lines with the transmitter, and the desire to conserve time to fit WR 313 into the program, argued against these.

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). 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 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.

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. Again, we had 100% data recovery.

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). We supplemented the deployed instruments with a receiver ("Vulcan") towed at a constant offset of 300 m behind the transmitter antenna, to provide short-offset data for all transmitter positions. 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.

Funding History

Issues associated with obtaining ship time, funding, choosing a target location, and permitting have resulted in a long gestation time for this project. First proposals were circulated in early 2005 with funding from several industry sponsors committed shortly after. The initial plan was to survey one area in October 2005 using the R.V. Pelican, but no single site could be found where unequivocal evidence for hydrate in the sub-section existed. Several meetings with current and prospective sponsors resulted in a firm plan to survey three locations in the GoM in summer 2007 over blocks AC 818 (where Chevron had recently intersected hydrate in a well), MC 118 (an MMS designated hydrate observatory), and GC 955 (prospective based on proprietary seismic data and seafloor features). We originally requested R.V. Pelican time for this project, but UNOLS assigned us 22 days of time on the R.V. Cape Hatteras starting June 10th 2007. However, we were instructed to request Minerals Management Services (MMS) permits for this project both by MMS and our industrial sponsors. We requested permits in May 2007 but MMS failed to grant permits in time for the Hatteras cruise, which we had to cancel at some cost to the project. We continued to pressure MMS for permits, which we obtained in December 2007.

At this point we had modest funding and no ship. The presence of the Revelle in the GoM area in early 2008 presented a unique opportunity for us to use the most capable vessel in the US fleet for a highly exciting and societally relevant project. However, for a cruise that originally budgeted 2005 shiptime on the Pelican at $5,800/day, the Revelle was well beyond our means, and so we approached UC Shipfunds with a request for ship time. UC Shipfunds agreed to support half the cost of the vessel, and encouraged us to seek further funding. An RFP from the Department of Energy was then announced which included a call for hydrate mapping using marine EM methods, and so we submitted a proposal, using the existing industry funds and UC Shipfunds as matching support. This proposal was successful, and was funded about one week before the Revelle cruise pushed off.

During the contract approval process, DoE program managers asked if it was possible to relocate our survey sites to accommodate a survey at the Walker Ridge location. A DoE-funded Joint Industry Project (JIP) plans to drill prospective hydrate locations in the GoM in 2008/2009 at AC 818, GC 955, and WR 313, and adding Walker Ridge would provide CSEM data at all three JIP sites. However, we did not want to lose our survey at the MC 118 MMS hydrate observatory, so we sketched out an ambitious program which included all four locations.

As part of normal behavior at SIO, and because of the significant institutional commitment of ship time, we put out a call for student participation in the cruise. One student, John Blum, noted that our plans took us very close to an area he had been studying while an intern with BP. He had been examining a magnitude 5.3 earthquake recorded February 10th 2006 which had a source mechanism consistent with a submarine landslide. He broached the possibility of collecting a high resolution seafloor bathymetry map to test this idea. BP was approached and agreed to pay for half a day of shiptime and John's expenses to carry out such a survey.

Mobilization and Logistics

The Revelle mobilized from Port Everglades, Fort Lauderdale, Florida. We were able to ship all the scientific equipment in one 40' air ride truck with 0.5" to spare, departing from the Marine EM Laboratory at SIO on the 29th September arriving Port Everglades 4th October. The equipment included:

30 seafloor electric and magnetic receivers (OBEM)
2 SUESI deeptowed EM transmitters
2 power supplies for SUESI
1 SUESI antenna winch with two 50 m antennas
1 towed 3-component electric field receiver (Vulcan)
2 racks of e-field antenna arms for the OBEMs
5 boxes of magnetic sensors for the OBEMs
2 stacks of 5 anchors each
2 deck-mounted electric capstans for the barracuda navigation system
1 crate of miscellaneous equipment
5 pallets of approximately 60 Zarges boxes containing support equipment

We also had 87 concrete anchors stored at Cocodrie, Louisiana, which had been shipped there in 2007 in expectation of carrying out this cruise on the R.V. Cape Hatteras. We arranged for these to be trucked to Port Everglades to arrive at the same time as the main shipment.

Jacques Lemire, Cambria Colt, Chris Armerding and Jake Perez of SIO EM Lab flew out to Port Everglades on the 3rd to carry out loading on the 4th and 5th. All equipment was on deck by the end of the 4th. Arnold Orange, Karen Weitemeyer, John Souders, and Steven Constable flew on the 5th to assist in instrument setup on the 6th. The balance of the science party arrived on the afternoon and evening of the 6th for push-off at 16:00 on the 7th.

Efficient use of ship time was achieved by dividing personnel into two 12 hour shifts for around-the-clock operations (see shift list appendix). Each shift included a deck operations supervisor/crane operator (Langer or Colt), a technician familiar with the equipment operations (Perez or Armerding), a scientist familiar with the project objectives (Myer/Wheelock or Weitemeyer), and at least four other personnel to assist with instrument deployments and recoveries. Constable and Souders worked variable hours in order to supervise and assist with all SUESI deployments, operations, and recoveries.

Instrumentation

Receivers

Thirty modern, state of the art, seafloor electromagnetic recorders constituted the core facility for this project. These instruments were developed and built over the last decade or so with energy industry sponsorship, and have a shared heritage with the Scripps ocean-bottom hydrophone now in the NSF's Ocean Bottom Seismometer Instrument Pool.

Each instrument is fitted with a pair of horizontal orthogonal 10 m dipoles for electric field measurements, a vertical 1.5 m electric dipole, and a pair of orthogonal induction coil magnetometers. A brief list of specifications follows:

Channels	8
ADC	24 bit
ADC noise floor	10^{-13} V^2/Hz at 0.01 Hz to nyquist
Power consumption	450 mW (4 channels at 32 Hz sampling)
Maximum sample rate	1,000 Hz on 2 channels
Time base drift	1 - 5 ms/day, correctable to < 1 ms
E and B amplifiers	Chopper-stabilized
Bandwidth	10,000 s to 1,000 Hz
E sensors	AgCl electrodes
Voltage noise floor	10^{-18} V^2/Hz at 1 Hz
E-field noise floor on 10m antenna	10^{-10} V/m/$\sqrt{\text{Hz}}$ at 1 Hz
B sensors	Multi-turn, mu-metal core
B noise floor	10^{-8} nT^2/Hz at 1 Hz
Weight of assembly in air	125 kg
in water	-14 kg
Endurance on one set of Li batteries	2 months
Flashcard capacity	2 Gbyte
Depth rating	6,000 m
Acoustic navigation/release	custom (SIO)
Long term loss rate	<1% per deployment
Deployments to date	>1,000

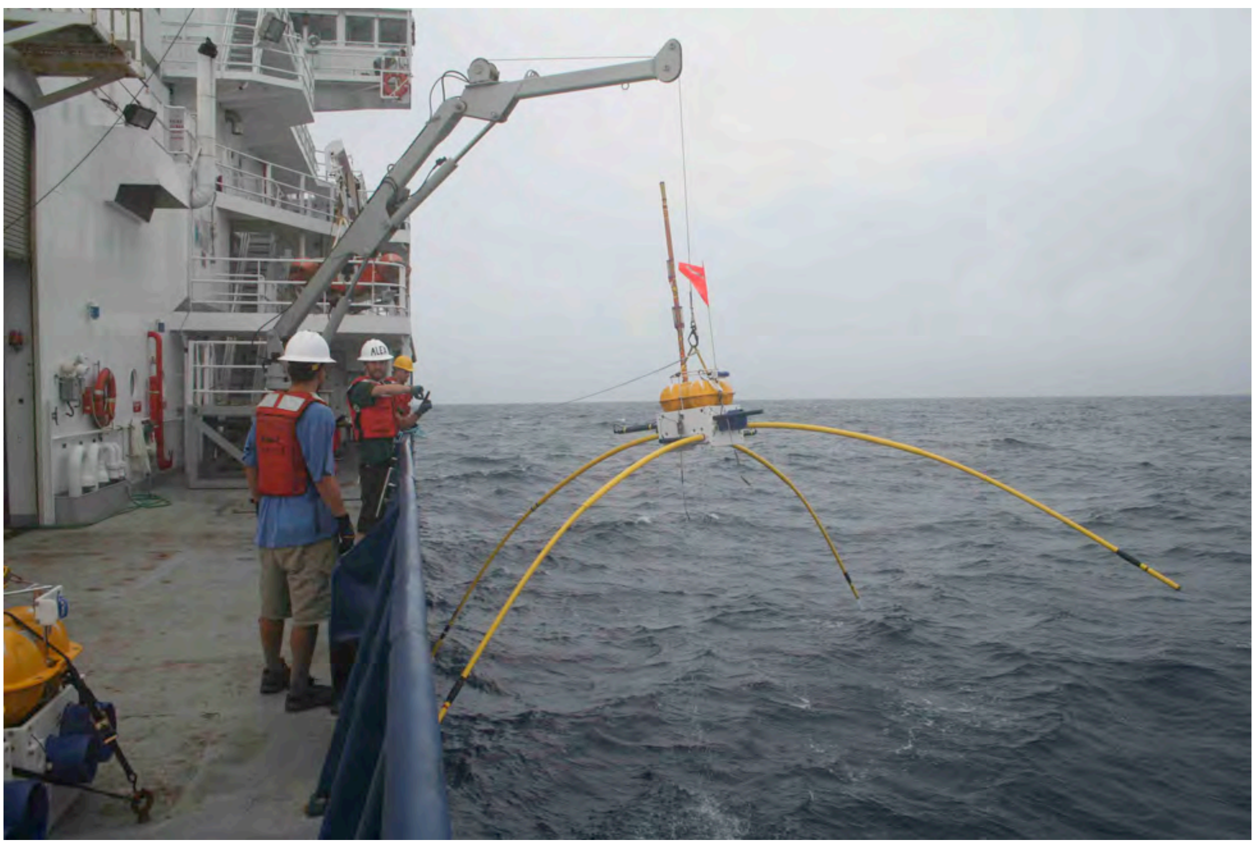

Figure 2. Seafloor EM receiver being recovered on the starboard side of the Revelle.

We have two versions of seafloor receiver in operation at this time, termed the Mk-II and Mk-III instruments. Although they share the same frame, sensors, acoustics, and basic electronic circuits, they differ in several ways. The Mk-III instrument has a more recent version of the Real Time Systems data logger and ADC board, housed in a smaller pressure case. The ADC has a slightly different least count and has 8 channels compared to the 4 channels of the Mk-II instrument. The logger electronics can be run off 7 V (c.f. 14 V) for some savings in power. In particular, since we wanted to collect both horizontal magnetics and electrics as well as vertical electric fields (5 channels total), this experiment was carried out with a uniform fleet of thirty Mk-III instruments. We carried along two spare logging systems and one for the towed receiver (Vulcan, described below). The two spare systems were equipped with prototype e-field amplifiers manufactured by Quasar Federal Systems, for deployment and comparison with the SIO amplifiers.

Scripps Undersea Electromagnetic Source Instrument

The transmitter instrument used on the original Hydrate Ridge project was SUESI-200, the first version of our new-generation EM source instruments. Output current was kept between 100 and 150 A for that experiment since it was the first use of the transmitter and we wanted to be conservative. Since then we have built a second version of this transmitter rated to 500 A (SUESI-500). In the past we have taken one of our two SUESI-200 instruments along as a spare, but for this cruise we built a second SUESI-500 to provide redundancy, partly because we needed a second 500 A system to provide redundancy in future projects, and partly because, like the receivers, there are small differences between the two versions besides output current. In particular, the 500 A instruments have much better cooling systems.

For this hydrate project the 200 m long 500 A antenna that we use with SUESI-500 for deep crustal sounding was replaced with a much smaller, 50 m antenna, in order to better approximate a dipole field and increase resolution at short source-receiver offsets. This smaller antenna and its connections to SUESI were only rated at 200 A, which is the current we used for all four surveys.

We had a tail buoy which included an acoustic relay transponder and a recording depth meter attached to the end of the 50 m transmission antenna. SUESI itself has a depth gauge, altimeter which works over the range 0–200 m, water temperature/sound velocity/conductivity meter, and heading/pitch/roll sensors. Data from all of these sensors are telemetered to the ship over a 9600 baud bi-directional FSK link on the deeptow cable. SUESI also monitors output current and 12 temperatures, and includes a Benthos DS-9000 intelligent acoustic transponder which is used to range on seafloor instruments or the Barracuda navigation buoys (see below). Note that acoustic reply pings add noise to the EM data recorded on the receivers.

Specifications for SUESI-500 are as follows:

Dipole moment at full power	100 kAm
Square wave zero- peak current	500 A
Tow cable	Standard 0.680” (17 mm) UNOLS copper coaxial
Tow cable voltage	2000 V RMS/400 Hz
Input power supply	30 kVA, 208 - 480 VAC, 3-phase
Telemetry	9600 baud bidirectional on copper
Noise floor of system with SIO recorder	10^{-15} V/m per Am
Output frequency	DC to 100 Hz, GPS stabilized
Depth rating:	6,000 m
Top-side interface	Serial port / Labview GUI

One important feature of SUESI is that the topside power supply, which takes ship’s 3-phase 60 Hz power and creates 400 Hz, 0–2,000 V power for transmission down the tow cable, uses a control signal generated from a 400 Hz square wave output from a Zypher GPS timebase. Since the SUESI output waveform is created by counting half-cycles of the 400 Hz power after transformation and rectification, the output waveform has a phase that is stable to GPS precision.

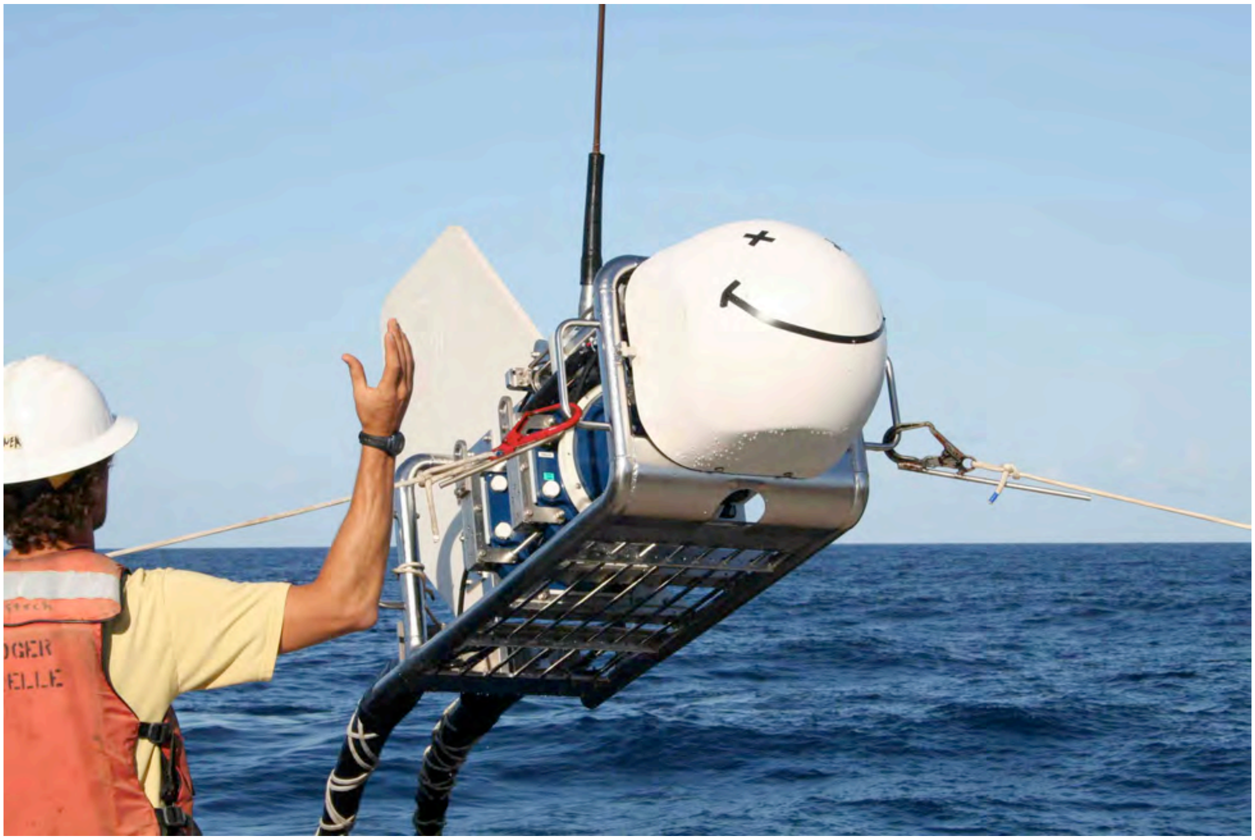

Figure 3. Scripps Undersea Electromagnetic Source Instrument, being recovered.

Vulcan and Barracudas

The OBEM and SUESI instrument systems have become somewhat routine aspects to our marine EM experiments. On this cruise we also deployed two new instrument systems; Vulcan, a 3-axis electric field recorder which is towed at constant offset behind SUESI, and Barracuda, a deeptow navigation system consisting of two paravanes flown behind the vessel and containing acoustic transponders, GPS receivers, and radio modems. Both of these systems have undergone testing offshore San Diego, but this was the first time they were deployed in an operational sense.

Vulcan (Figure 5) was attached to the 50 m SUESI antenna behind the far electrode (25') by means of 250 m of 3/8" amsteel blue tow line. Directly in front of Vulcan was a 20 m length of amsteel through which a length of 22 gauge telflon single conductor wire was threaded and terminated at both ends with underwater connectors. A single electrode was taped on at the front end of this line, with its pair mounted on the tail stinger of Vulcan at the 1.5 m mark to form a 22 m long Ey antenna. Vulcan itself consisted of a standard Mk-III data logger, three 10" glass floatation balls, a vertical stabilizer fin with a pair of electrodes spaced 1 m apart (Ez), two horizontal stabilizers with an electrode on each spaced a total of 2 m (Ex), and a 3 m 'stinger' of 2" diameter spun kevlar supporting an inline pair of electrodes 2 m apart (Ey). On previous tests the noise floor of Vulcan was comparable to the seafloor instruments when the shorter antennae was considered, and inspection of data from this cruise suggests that this will again be the case. The Ex and Ez data have approximately 10 s period noise associated with ship's pitch being transmitted down the deeptow cable to SUESI and then along Vulcan's tow cable. These two channels cut Earth's magnetic field during towing, unlike the Ey channels.

Vulcan also contained two serial logging devices that time stamped and recorded output from a Paroscientific depth gauge and a heading, pitch, and roll sensor.

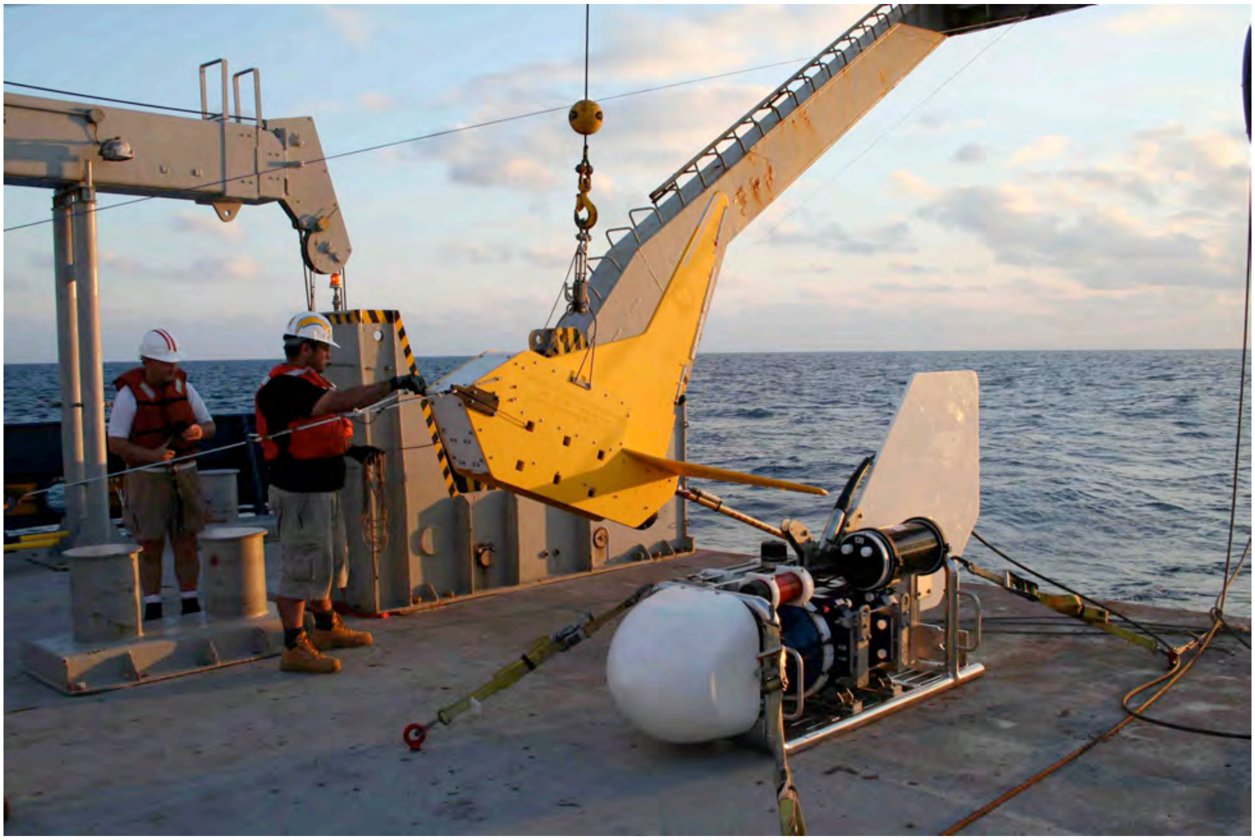

Figure 4. Vulcan, the three-axis constant-offset receiver being deployed.

Instrument performance

SUESI

Our pre-cruise modeling had shown that we wanted to capture as broad a range of frequencies as possible for hydrate surveying. Sensitivity analysis showed a peak in the CSEM response to near-surface hydrates at greater than 10 Hz, associated with induction at short source-receiver offsets, and at less than 0.1 Hz, associated with a DC-like galvanic effects. We have thus been experimenting with switched frequency waveforms in which we transmit several minutes at 0.1 Hz, several minutes at 1 Hz, and one minute at 10 Hz. However, recent work in processing data collected this way has revealed complications associated with transient effects during frequency switching and the very long (5 minute) true periodicity of this waveform. In response to this, we developed a new, compact waveform having an unusually broad spectrum (Myer *et al.*, manuscript in preparation). This waveform is shown in Figure 5, along with its amplitude and phase periodogram. Note that we have nearly two decades of frequency for which the harmonics are above 0.1 times the peak current, and that the five largest harmonics are only a factor of three different is size and span more than one decade. For comparison, a square wave has only a little more than one decade of frequencies greater than one tenth peak current, and the two lowest harmonics differ by a factor of three and only cover a factor of three in frequency. The new waveform was used throughout the Gulf of Mexico experiment.

Although brought along as a backup, we decided to deploy the new SUESI-500 system as the primary transmitter for this cruise, in order to get some operational time on the new instrument. Unfortunately, this transmitter failed after about one hour of operation. We suspect a custom 2000/110 V transformer which provides power for the non-switchframe electronics – we had to replace this part when the first transmitter was commissioned. We replaced the new transmitter with the older, mature unit and discovered that the read/write lines on the Valeport CTD were swapped. Just before this cruise we had replaced the Valeport unit on the older transmitter with same (newer) model as on the new transmitter to

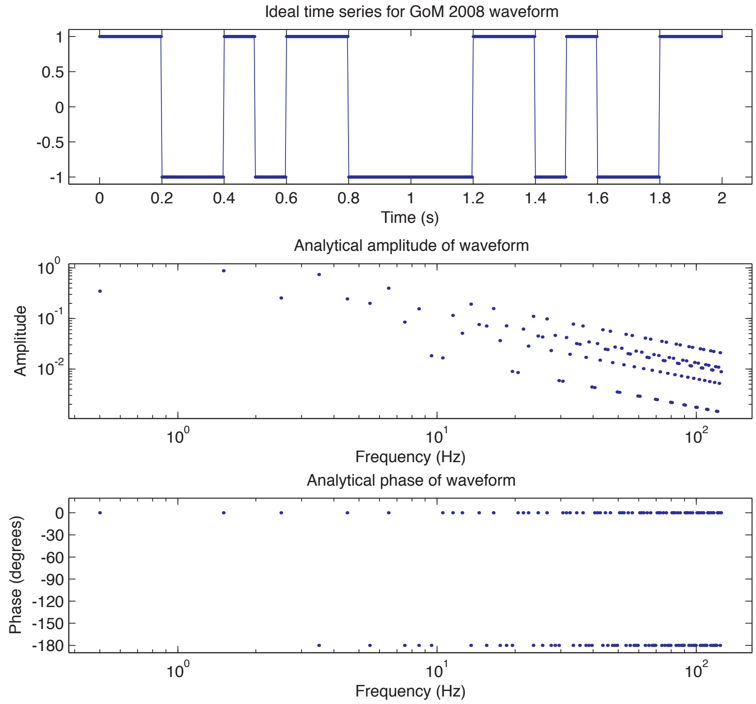

Figure 5. Waveform used for all the GoM 2008 hydrate surveys, along with amplitude and phase periodograms. Note the broad range of frequencies (nearly two decades) that are larger than 0.1 times the peak current, and the very flat envelope in the lowest decade of frequencies.

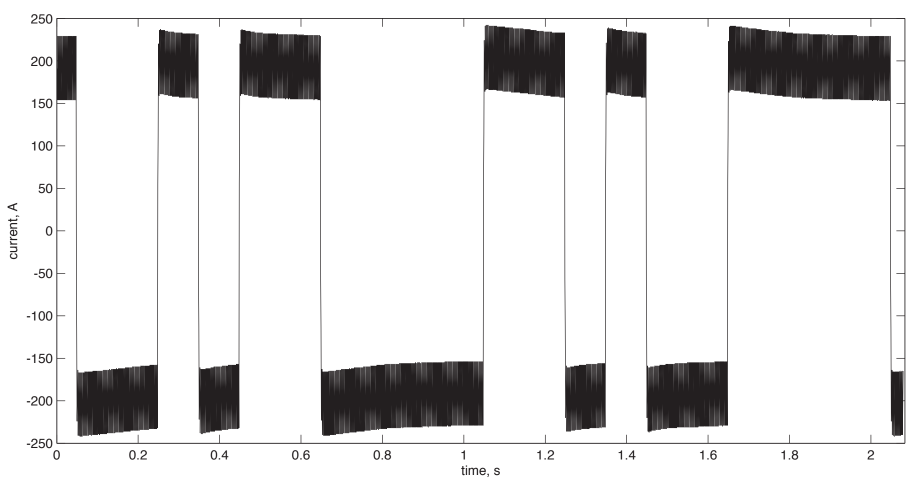

Figure 6. SUESI waveform, as measured at 1200 Hz on the output current meter. The dark bands are the 800 Hz ripples associated with the rectified 400 Hz power. They are rapidly filtered by seawater (skin depth is 10 m) and would be removed by the anti-alias filters in the receivers if not.

make the two units compatible, and had not noticed that I/O lines were not compatible. After re-making the cable the system came up perfectly and performed flawlessly for the rest of the cruise, operating at 200 A for a total of 103 hours on the four surveys. Figure 6 shows an example of the output waveform as measured by the on-board current meter.

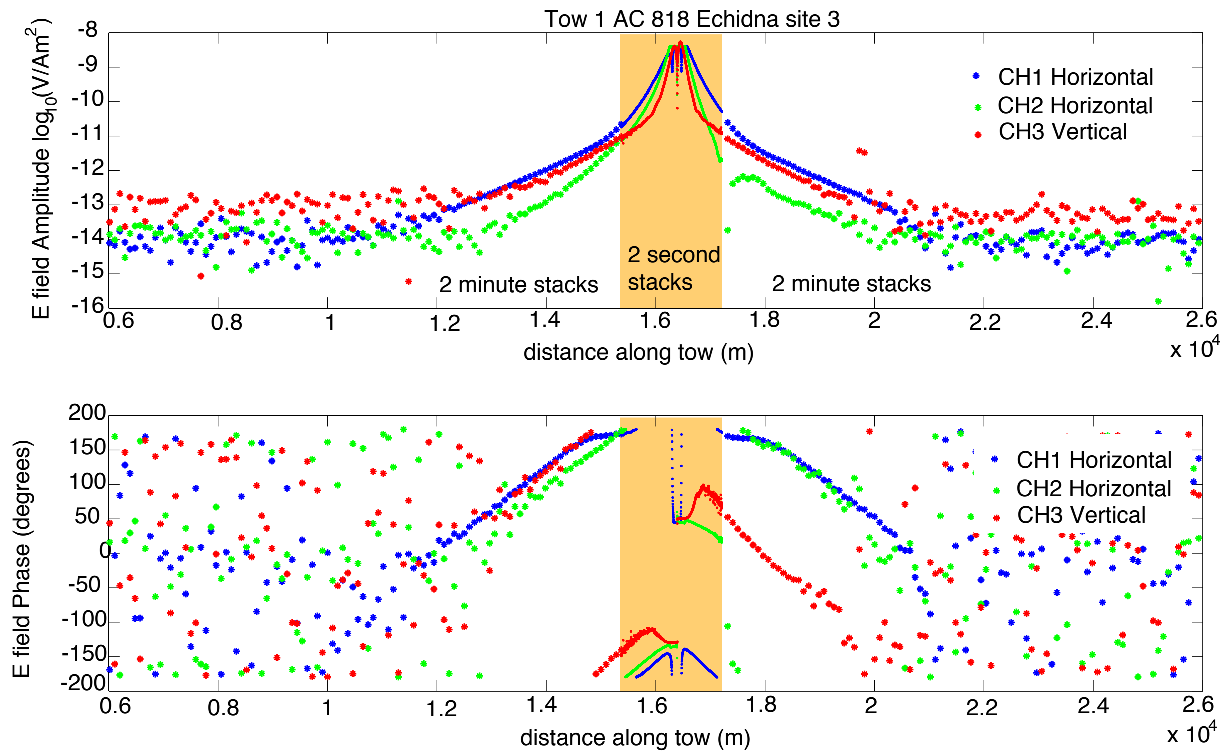

Figure 7. Example of CSEM horizontal and vertical 1.5 Hz E data collected on an instrument deployed at AC818.

Receivers

The OBEM receivers performed extremely well. We had a 100% instrument recovery rate over 94 deployments, with only 5 instruments requiring the use of the secondary release. Of these several were a matter of misinterpretation of the acoustics, which were quite noisy. We lost only two data sets; one instrument failed to record data during the first deployment on AC818 because the ADC did not initialize properly. The instrument tested OK before and after the cruise, and we have since discussed this problem with Real Time Systems, who think that it may be a statistically rare problem with initializing the ADC. Nevertheless, we took this instrument out of service for the subsequent surveys. One instrument failed to record past a few hours because a rechargeable battery failed either because it had reached the end of its useful life or had not been charged properly. This is an occupational hazard associated with using rechargeable batteries, which we try to mitigate with a rigorous battery management protocol. Vendor delays in filling an order for new batteries meant that we were using older batteries for some of the AC818 (only) deployments, including this one.

The noise floor on first inspection (Figure 7) is exceptional – 10^{-15}V/Am^2. This is comparable to, or better than, industry data collected with dipole moments that are an order of magnitude larger than the one we used. We had put a lot of effort before the cruise into optimizing amplifier performance and quality control of the receiver system, which appears to have paid off. Figure 8 shows example spectrograms for the horizontal field sensors from one instrument deployment.

Vulcan

Vulcan performed well and collected data sets on all four surveys, with the exception of the pitch and roll logger for the last survey (MC118) (of all the data streams, this was the least important). On the first deployment (AC118), Vulcan flew about 50 m higher than SUESI, which was better than flying low but somewhat excessive. We had trimmed the instrument to be slightly buoyant so that it would not foul on the seafloor and would float to the surface if it came loose. We established that the high flying on AC818 was a result of float testing it with 2 battery packs but deploying

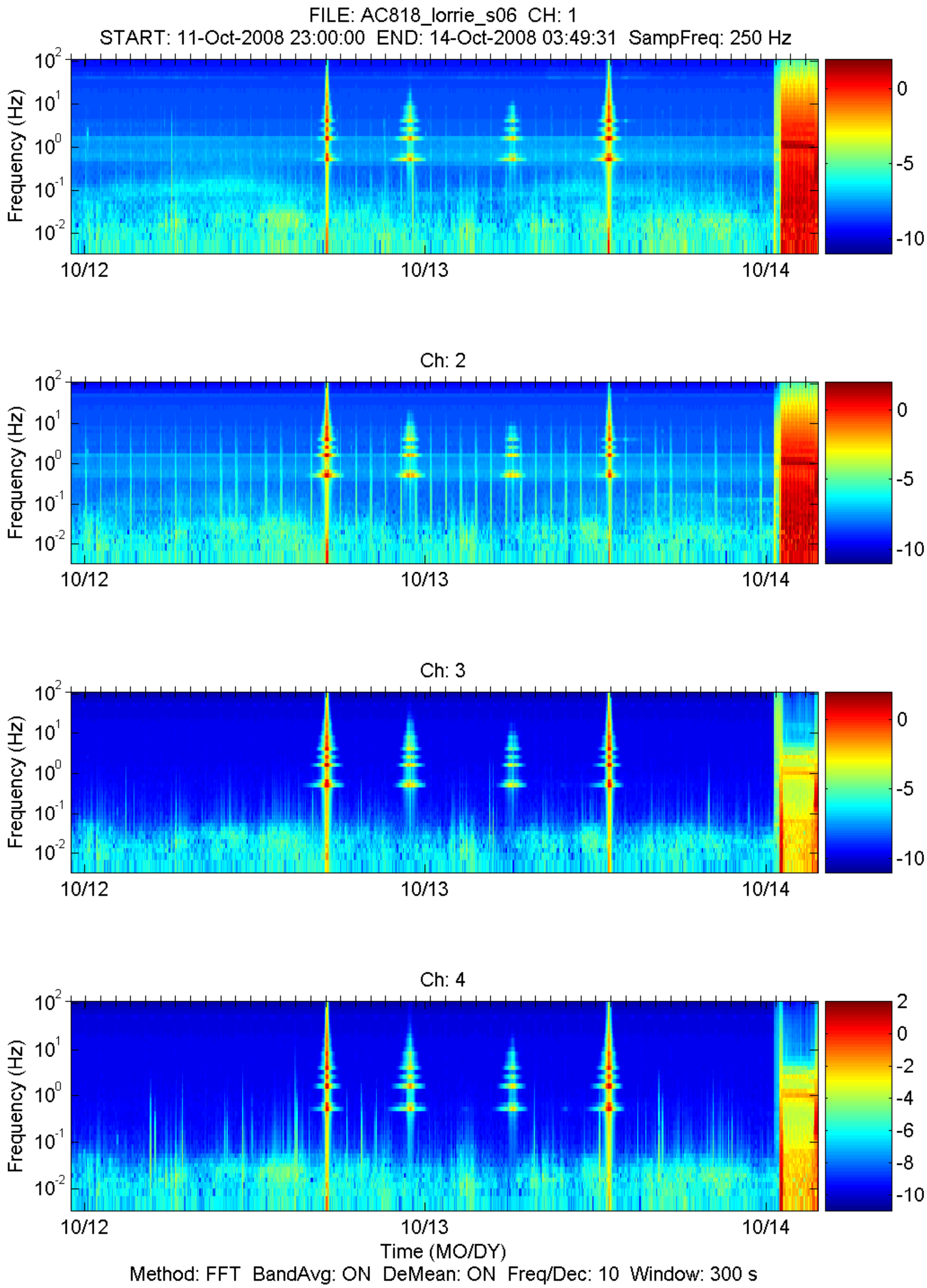

Figure 8. Spectrogram from an instrument deployed on AC818, showing horizontal magnetic (top two panels) and horizontal electric (bottom panels) channels. Vertical stripes on the magnetic channels are associated with writing to the flash card at known times denoted by the tick marks. The four passes of the transmitter are clearly visible. (Units are counts^2/Hz, essentially from saturation (red) to the noise floor (blue).)

it with only one. For the other three surveys we used two battery packs and Vulcan then flew about 20 m high, which is a comfortable safety margin.

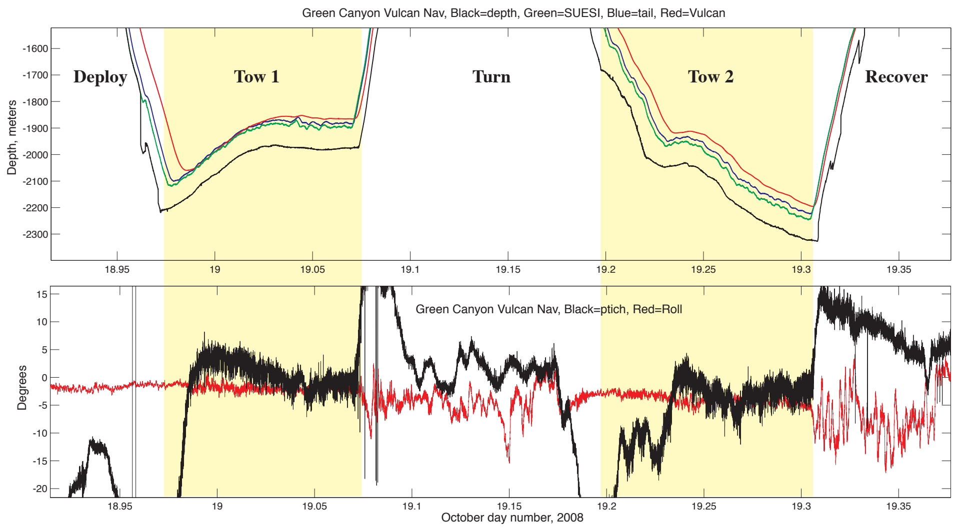

Figure 9. Navigation parameters collected during the two Green Canyon tows. SUESI depth (green, upper panel), seafloor depth (black), antenna tail buoy depth (blue) and Vulcan depth (red). The bottom panel shows pitch (black) and roll (red) for Vulcan.

Figure 9 shows the navigation parameters for SUESI and Vulcan during the Green Canyon survey. Both the antenna and Vulcan are trimmed slightly positive to ensure no untoward encounters with the seafloor, and fly about 10 and 30 m higher than SUESI respectively over level ground (e.g. the latter half of Tow 1). During the tows Vulcan's roll is about 1.5 degrees $\pm$1–2 degrees. The pitch also varies $\pm$2 degrees at short time scales, but can be offset up to 5–15 degrees during tows up and down slopes.

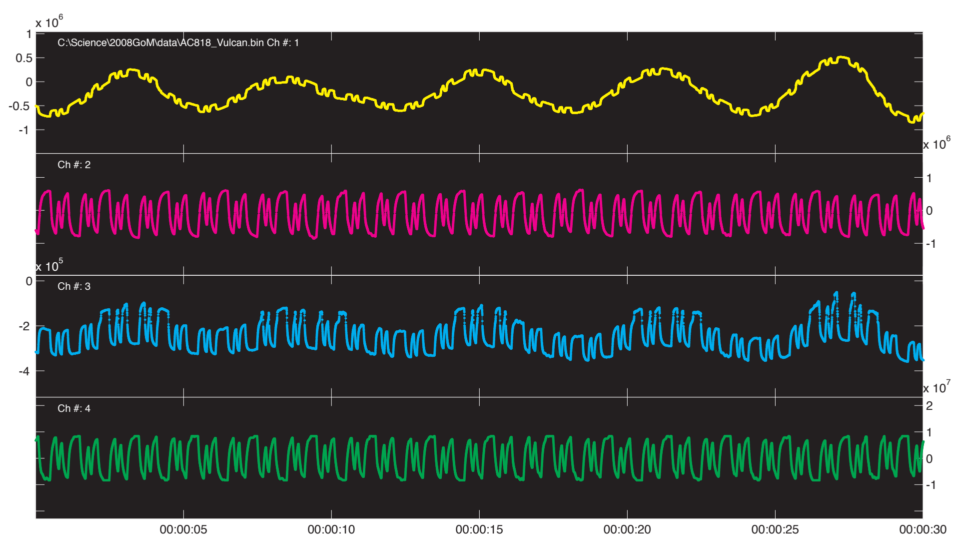

Figure 10. Thirty seconds of data collected on Vulcan. Yellow is 2 m crossline E, red is 2 m inline E collected on the rigid stinger, blue is 1 m vertical E , and green is inline E collected on the 22 m lead-in rope. The units are counts on the ADC; least count is 4×10^{-7} V and we have a gain of 10,000, so full scale on the two top panels is about 80 μV, the third panel is about 16 μV, and the bottom panel is about 2 mV.

Figure 10 shows a screen-shot of 30 s of Vulcan data. Crossline E (Ch1, yellow) has the smallest signal, which for perfect geometry and a 1D earth conductivity would be zero. The non-zero signal is an indication of higher dimensional conductivity or, more likely, small deviations in geometry of the transmitter or Vulcan, both of which have been measured. Signal to noise ratio is high on all channels.

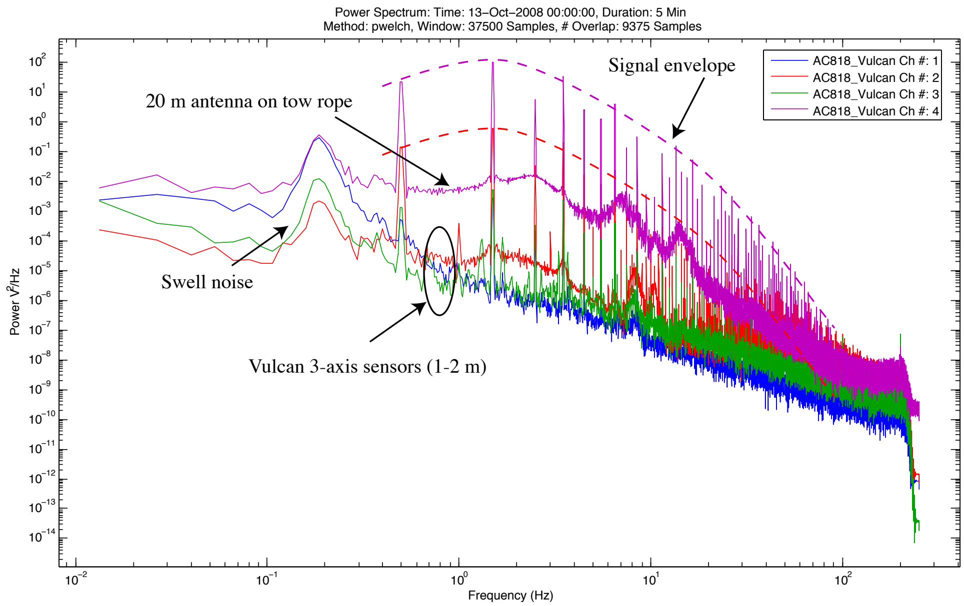

Figure 11. Spectrum of Vulcan data. Here blue is crossline E, green is vertical E, red and magenta are inline E with magenta the 22 m antenna on the tether (apologies for the change in color code). This is a power spectrum in V^2/Hz.

The low frequency signal in the crossline E and vertical E (Ch 3, blue) is a result of the fact that both these axes cut Earth's magnetic field B with a tow velocity V, generating an electric field $E = V \times B$ associated with the Lorentz force. Here V is being modulated slightly at the swell period (around 6 s) as the ship's motion is transferred down the tow cable to SUESI and along the tether to Vulcan. This effect is exaggerated in the figure because the vertical axis is scaled by the transmitter signal, which is also smallest in these two channels.

Figure 11 shows a spectrum of a 5 minute section of Vulcan data, clearly showing the harmonics of the transmitted signal. One sees that while the 22 m inline E antenna on the tether provides a ten times larger signal than the stinger inline E (or 100 times in power), between about 0.5 and 10 Hz the tether noise is larger by this amount or more. This is probably a result of the tether vibrating in Earth's magnetic field, again creating an electric field. The broad peak at around 0.17 Hz is motional noise associated with swell as mentioned above, and it is now clear that it exists in all channels, although proportionally strongest in the crossline and vertical.

Navigation and Barracudas

Our experience at Hydrate Ridge taught us that for short-offset hydrate studies, navigation of receivers and transmitter is very important. Although the industry standard for navigation is to use short baseline (SBL) acoustics, there are a number of reasons we chose to pursue long baseline (LBL) solutions to navigation of both the transmitter and receivers. First is reliability; while permanently installed and calibrated SBL systems work well, our experience with bolt-on portable systems (necessary for work on a variety of vessels) is that they are unreliable – two out of three attempts to use them have failed. Second is accuracy; angular uncertainty translates to error in position that increases with range. The consensus opinion from end-users is that industry-provided SBL-derived positions of CSEM transmitters can be inaccurate by as much as 50 m. During early work with ExxonMobil where we had both SBL and LBL systems on seafloor receivers, both systems could reduce the uncertainty in receiver position to a few meters, but only after we had collected a redundancy of SBL data using the same sort of survey as for an LBL system (i.e. steaming in a pattern over the instrument). Finally, there is cost in money and time; rented equipment usually requires the inclusion of an operator for the duration of the cruise, while the capital cost of the equipment (of order $100k) needs to be augmented by the training of all potential users. More importantly, every installation needs time spent calibrating the system before and during use.

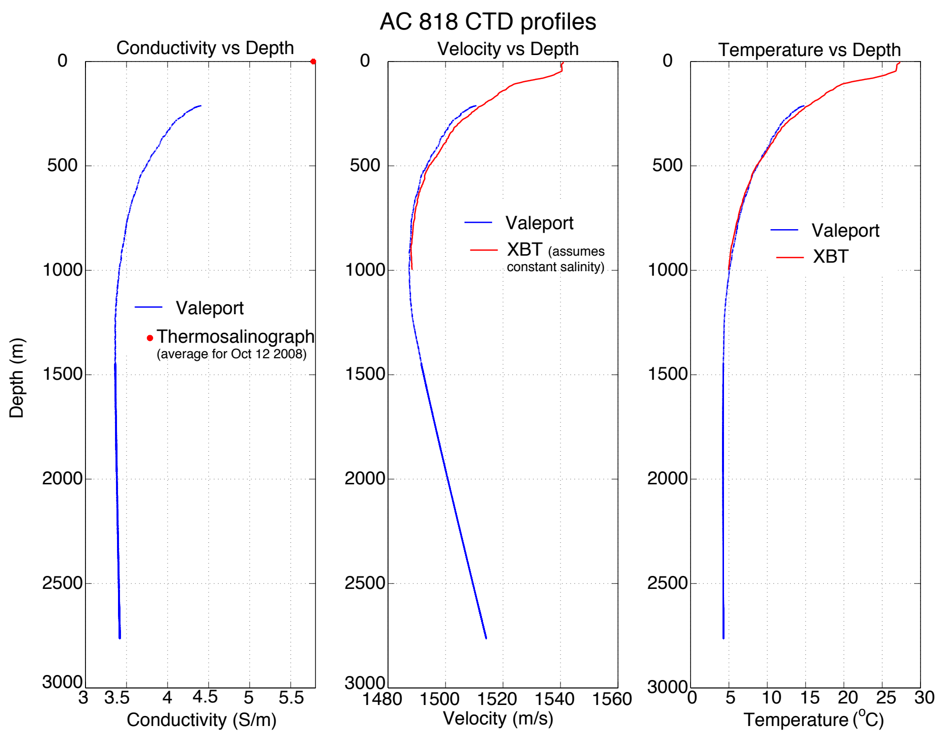

Figure 12. Sound velocity, temperature, and conductivity as a function of depth collected by the Valeport CTD/sound velocity sensor on SUESI during the AC818 survey, as well as temperature and computed velocity from an expendable bathy-thermograph (XBT). The sound velocity profiles are used to carry out the long baseline navigation of the receivers. The conductivity profile will be used in modeling the EM data.

For receiver instruments, which have SIO-made LBL transponders installed as part of the deployment and recover system, LBL navigation is straightforward. We use a Benthos DS-9000 intelligent acoustic transponder connected to the vessel's 12 kHz hull transducer to range on the instruments from a variety of ship positions (located by GPS). (A newly acquired Benthos ranging unit 'fried' during bench testing on this cruise, but we were able to use the underwater unit from the spare SUESI in its stead.) We carry out a Marquardt parameter estimation to recover (x, y, z) for the instruments using sound velocity profiles as collected by the CTD/sound velocity sensor on SUESI (e.g. Figure 12). These were augmented by XBT (expendable bathy-thermograph) casts during the surveys. The positions for all instrument deployments listed in the Appendix are navigated positions using the LBL system.

We also have a Benthos DS-9000 installed on SUESI, done initially in order to range directly on the seafloor instruments to provide real time LBL navigation of the transmitter. However, each receiver reply ping puts a near-saturation noise pulse on the electric and magnetic field records, and we also discovered that the near-seafloor geometry favors the receivers replying on the surface bounce of the interrogation pulse. We aim to solve both these problems by towing transponders behind the vessel on the surface using paravanes. The transponders have GPS receivers and radio modems, providing real-time estimates of position. This is the Barracuda system, shown along with the other LBL systems is shown in Figure 13. The relay transponders on the tail buoy and Vulcan provide an LBL solution based on replies from either Barracuda or seafloor instruments.

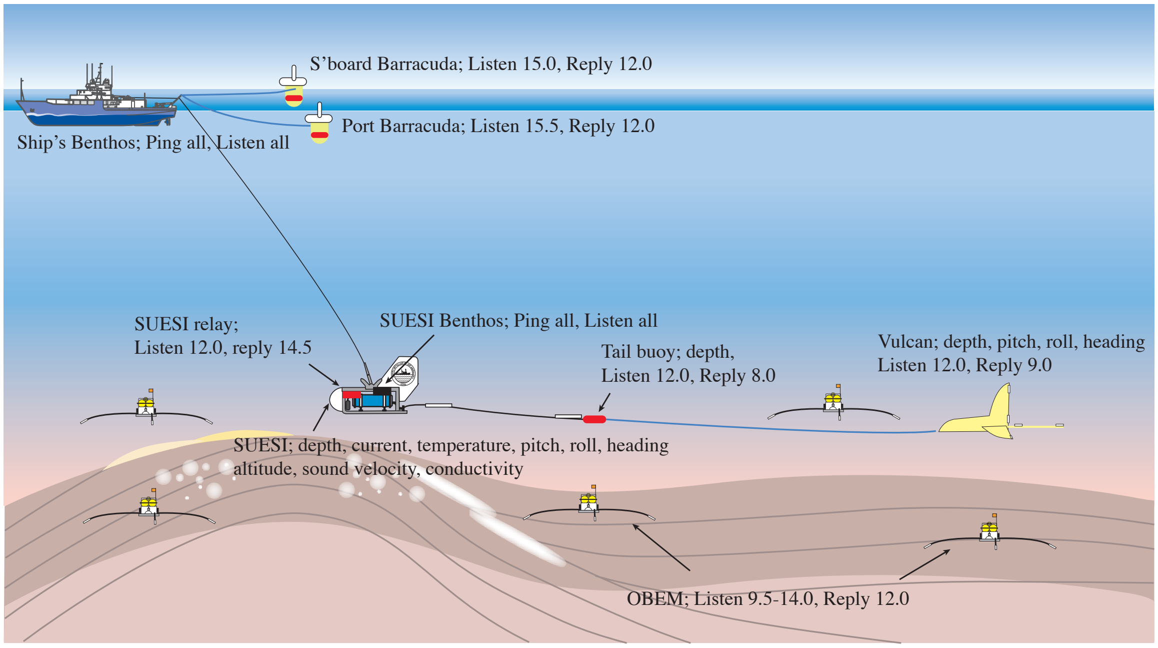

Figure 13. Diagram of the LBL systems used during the surveys.

The Barracuda system was perhaps the most disappointing aspect of instrument performance on the cruise. We had various issues which included a loose cable in the SUESI-mounted Benthos acoustic ranging unit, a new transponder system which may be weaker than our older ones, intermittent failure of the GPS units in the paravanes, and collapse of the towing bridle in turns resulting in the paravanes failing to fly properly and even flying underwater. One unit flooded as a result of this, but we had a spare. However, this was a new instrument system and some startup problems often occur. We did get the system working for the majority of the MC 118 survey, and will have enough data to test its viability, and for a time we had real-time locations for the deeptow transmitter during the survey, which is our objective. Since we have ship's position, wire out, SUESI depth, and antenna depth, the only critical parameters we do not have are the offline set and the antenna azimuth. The seafloor instruments are all well navigated using long baseline ranging from the ship (standard errors in the positions are typically 1-2 m) and the recording compasses worked very well (accurate to a few degrees), so we will recover these parameters using a method developed by Karen Weitemeyer during her thesis work which uses the close-range geometry of the electromagnetic fields.

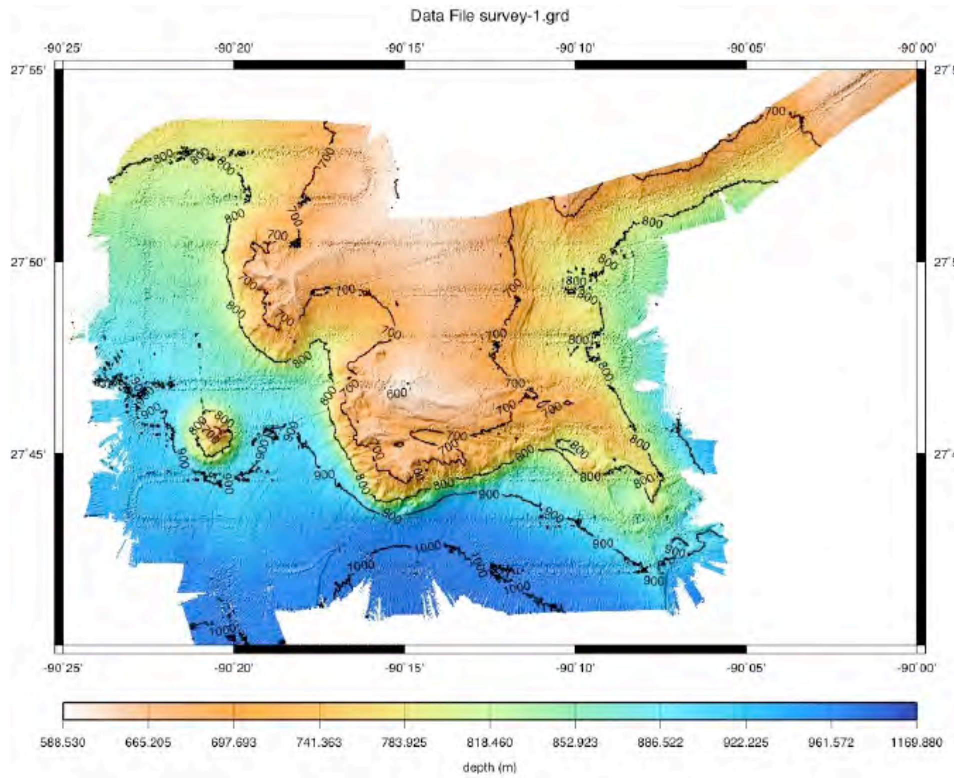

Figure 14. Multibeam survey carried out by John Blum under BP sponsorship.

Multibeam Survey

A half-day of shiptime was scheduled during the transit from Green Canyon to Mississippi Canyon for a multibeam survey at the location of a recently recorded earthquake. The source mechanism for the earthquake was consistent with a seafloor landslide, and so the objective was to carry out a multibeam survey to (a) try and identify features consistent with slope failure and (b) compare the new bathymetry to previous seafloor maps to see if there were any differences. We carried out the survey successfully on the 20th October. Figure 14 shows a preliminary version of the seafloor map.

Acknowledgments. It takes help from a lot of people to make a project as successful as this one. We would like to thank our industrial sponsors, ExxonMobil, WesternGeco, Chevron, emgs, Fugro, CGG/Veritas, Shell, and StatoilHydro, as well as the NETL program at the US Department of Energy and the UC Shipfunds Committee for funding this work. Thanks to the captain and crew of the R.V. Roger Revelle for their fine sailing, excellent cooking, engineering support, good cheer; without them this cruise would not have been anything close to as successful as it was. Thanks to the resident technicians Frank Delahoyde and David Langner. Thanks to the weather gods. And Jacques, of course, who does so much to make everything happen.

Carolyn Ruppel has been extremely supportive of this work, providing bathymetry data, site locations for all drill JIP drill sites, and literature, as well as answering questions, organizing telephone conferences, and being generally available for discussions. Emerys Jones provided data for GC 955 and AC 818, and helpful contact infrormation for the GC 955 drilling operation. Carol Lutken, Ken Sleeper, Andy Gossett, and Leonardo Macelloni all provided data from MC 118. Dan McConnell and Hunter Danque provided bathymetry data and discussions about JIP sites. David Bartel provided large scale bathymetry data for AC 818.

Appendix

Cruise Personnel

Steve Constable	Scripps Inst. Oceanography	Chief Scientist
Karen Weitemeyer	Scripps Inst. Oceanography	Graduate Student, Co-I
Arnold Orange	Scripps Inst. Oceanography	Scientist
Steve Reese	CGG/Veritas	Scientist/observer
Christian Herisson	Fugro	Scientist/observer
Katrin Schwalenberg	BGR Germany	Scientist/observer
Joachim Depp	BGR Germany	Scientist/observer
David Myer	Scripps Inst. Oceanography	Graduate Student
Brent Wheelock	Scripps Inst. Oceanography	Graduate Student
John Blum	Scripps Inst. Oceanography	Graduate Student
Chris Takeuchi	Scripps Inst. Oceanography	Graduate Student
Ashlee Henig	Scripps Inst. Oceanography	Graduate Student
Alex James	UCSD	Graduate Student
John Souders	Scripps Inst. Oceanography	Engineer
Chris Armerding	Scripps Inst. Oceanography	Technician
Cambria Colt	Scripps Inst. Oceanography	Technician
Jake Perez	Scripps Inst. Oceanography	Technician
Dave Langner	Scripps Inst. Oceanography	Resident Technician
Frank Delahoyde	Scripps Inst. Oceanography	Computer Technician

Shift List

12pm-12am	**12 am -12 pm**	**Floating**
Colt	Langer	Constable
Wheelock	Weitemeyer	Souders
Myer	Perez	
Henig	Blum	
James	Reese	
Takeuchi	Orange	
Armerding	Deppe	
	Herisson	

Daily Log

3rd Oct.	Revelle arrives Port Everglades.
4th	Loading.
5th	Tie-down and setup.
6th	Tie-down and setup.
7th	Setup. Push off 16:00.
8th	In transit, instrument prep.
9th	In transit, instrument prep.
10th	Arrive on station AC818 at 16:15. Deployed S01–S12.
11th	00:00 Deployed S13–S30.
	11:00 End deployments. Navigate receivers.
	20:15 Deployed SUESI #2.
	22:50 Recoved SUESI #2 with fault.

12th	05:00 Deploy SUESI #1.
	08:45 Tow lines 1, 2, and 3.
13th	Tow line 4. Finish SUESI ops 13:30.
	13:30 Finish SUESI ops.
	15:10 Start recoveries. Recover S01–S06, S22.
14th	00:00 Recover S07–S21, S23–S30.
	19:00 Finish recoveries. Transit to WR313.
15th	09:30 Arrive on station. Deploy S01–S20.
	29:20 SUESI in water.
16th	01:35 tow lines 1.
	10:06 tow line 2.
	19:00 recover SUESI, nav.
	23:30 Start recovery.
17th	01:36 Recover S01–S20.
	16:50 finish recoveries. Transit to GC955.
	23:00 start deployments. Deploy S01, S02.
18th	00:00 Deploy S03–S20.
	09:20 Start receiver navigation.
	14:30 deploy SUESI.
	18:27 start line 1.
19th	00:32 start line 2.
	07:00 SUESI recovered.
	08:20 Recover instruments S06–S20.
20th	00:00 Recover S01–S05.
	02:15 Transit to Blum survey Green Canyon.
	06:00 Start multibeam survey.
	22:30 Finish multibeam. Transit to MC118.
21st	08:25 Deploy instruments S01–S24.
	15:55 Navigate receivers.
	19:15 Deploy SUESI.
	21:50 – 02:10 Tow line 1
22nd	03:18 – 04:40 Tow line 2.
	06:45 – 08:20 Tow line 3.
	09:40 – 12:25 Tow line 4.
	14:38 – 15:59 Tow line 5
	18:00 – 19:45 Tow line 6.
	22:25 – 23:30 Tow line 9.
23rd	02:41 – 04:15 Tow line 8.
	06:40 – 07:40 Tow line 7.
	09:30 – 13:20 Tow line 10.
	15:05 SUESI recovered.
	16:30 Recover S1–3, S7–10, S15–17.
24th	00:20 Recover S4–6, S11–14, S18–24
	07:30 Transit to Tampa.
25th	Tie up 16:00.
26th	Offload and ship.

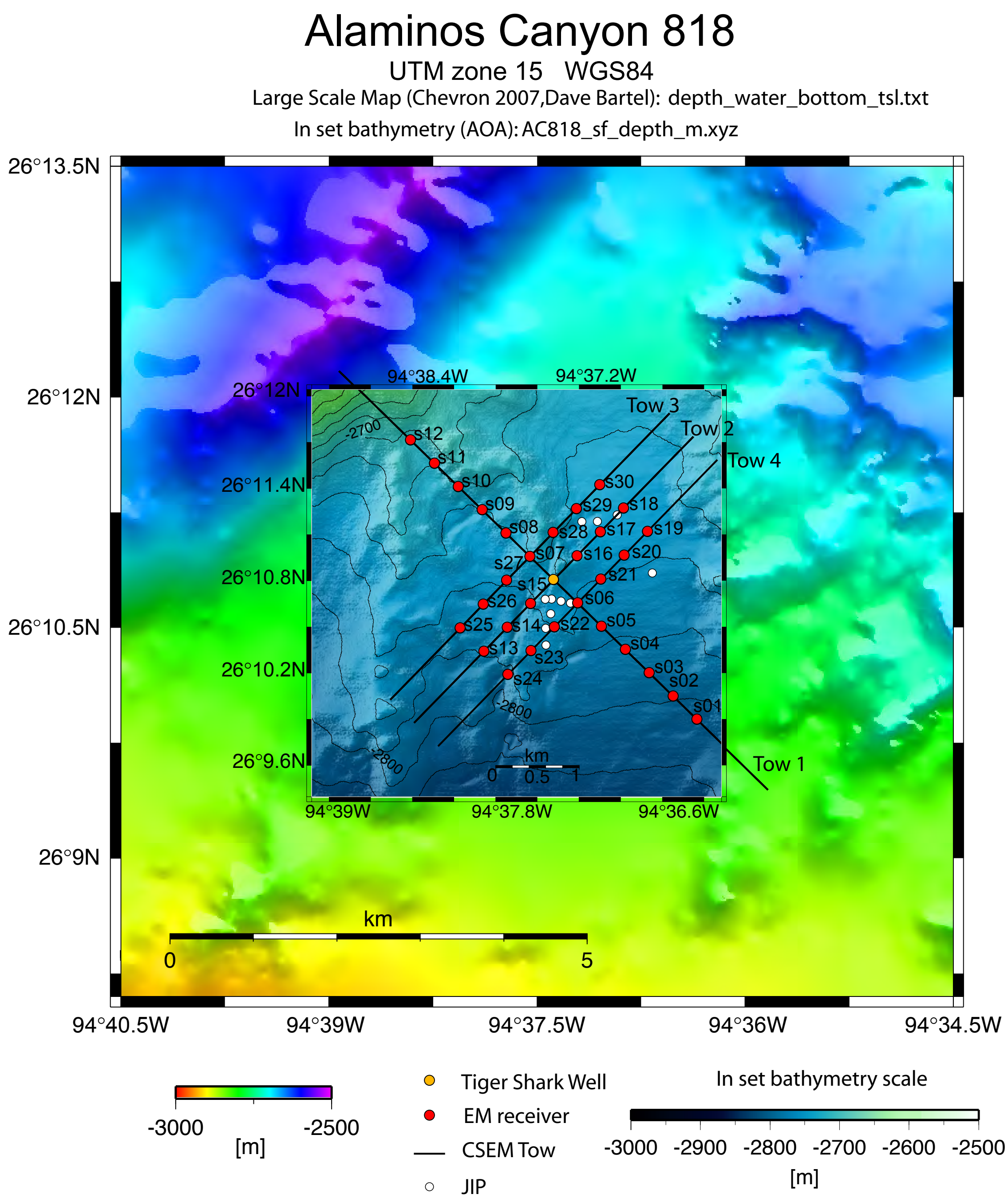

Figure 15. OBEM positions and SUESI tow lines on AC 818 as deployed. This survey was centered on a well that intersected 20 m of hydrate sand at a depth of about 500 m below the seafloor. A long 2D line was positioned across structural strike, and a quasi-3D array was stepped out in the direction of suspected hydrate. White dots show proposed drilling locations for the JIP.

AC 818 instrument positions as navigated:

AC818:

Site ID	Instrument	Longitude	Latitude	Depth
s01	Numbat	-94.60500	26.16396	2816
s02	Quokka	-94.60868	26.16643	2810
s03	Echidna	-94.61124	26.16893	2800
s04	Rosella	-94.61406	26.17151	2790
s05	Croc	-94.61691	26.17411	2782
s06	Lorrie	-94.61979	26.17638	2768
s07	Roo	-94.62552	26.18162	2748
s08	Goanna	-94.62816	26.18408	2747
s09	Cocky	-94.63110	26.18665	2747
s10	Glider	-94.63476	26.18977	2729
s11	Mozzie	-94.63742	26.19224	2726
s12	Kooka	-94.64020	26.19471	2714
s13	Brumby	-94.63142	26.17195	2785
s14	Penguin	-94.62853	26.17432	2776
s15	Budgie	-94.62567	26.17673	2767
s16	Cuscus	-94.62033	26.18204	2748
s17	Skink	-94.61735	26.18453	2755
s18	Ibis	-94.61475	26.18709	2752
s19	Corella	-94.61176	26.18445	2760
s20	Occie	-94.61463	26.18198	2762
s21	Mantis	-94.61736	26.17932	2765
s22	Stingray	-94.62308	26.17398	2767
s23	Koala	-94.62589	26.17162	2774
s24	Rabbit	-94.62891	26.16912	2800
s25	Camel	-94.63459	26.17418	2778
s26	Bunyip	-94.63195	26.17677	2772
s27	Marron	-94.62905	26.17923	2765
s28	Brolga	-94.62338	26.18454	2739
s29	Taipan	-94.62036	26.18694	2746
s30	Shark	-94.61768	26.18966	2747

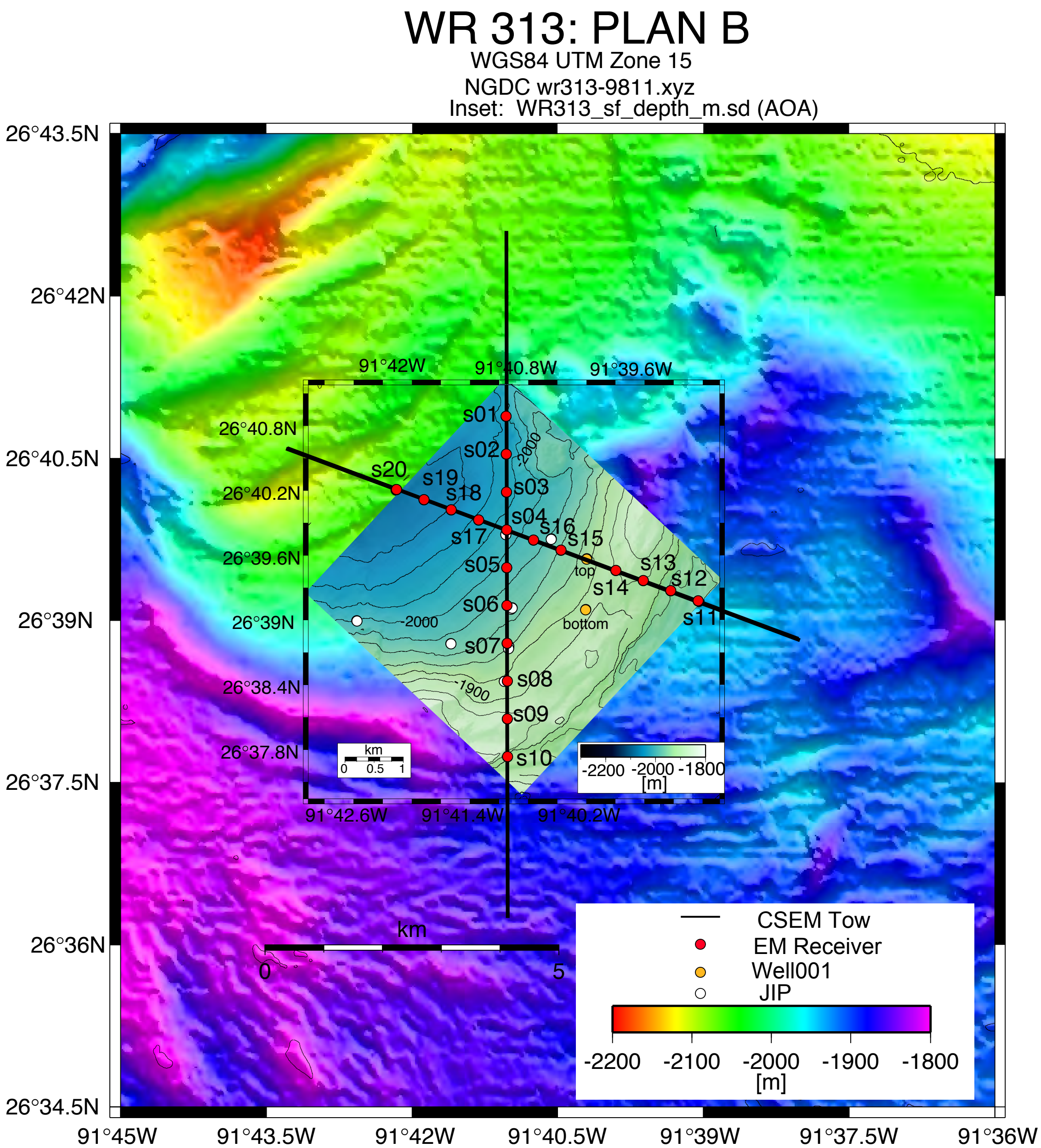

Figure 16. OBEM positions and SUESI tow lines on WR 313 as deployed. This survey was included in the cruise plan at the last moment at the request of DoE because it will be one of the JIP drilling locations, and so we deployed two simple reconnaissance lines to span several of the proposed sites.

WR 313 instrument positions as navigated:

WR313:

Site ID	Instrument	Longitude	Latitude	Depth
s01	Roo	-91.68350	26.68389	2004
s02	Mantis	-91.68345	26.67732	2027
s03	Glider	-91.68331	26.67152	2021
s04	Rosella	-91.68366	26.66573	2011
s05	Goanna	-91.68367	26.65986	1991
s06	Cocky	-91.68362	26.65404	1969
s07	Lorrie	-91.68338	26.64840	1948
s08	Rabbit	-91.68280	26.64257	1912
s09	Echidna	-91.68297	26.63691	1881
s10	Camel	-91.68317	26.63080	1856
s11	Stingray	-91.65081	26.65510	1938
s12	Brumby	-91.65528	26.65668	1928
s13	Mozzie	-91.65983	26.65827	1882
s14	Penguin	-91.66432	26.65971	1886
s15	Corella	-91.67402	26.66279	1958
s16	Ibis	-91.67873	26.66427	1986
s17	Bunyip	-91.68783	26.66735	2031
s18	Cuscus	-91.69301	26.66878	2053
s19	Koala	-91.69751	26.67114	2061
s20	Occie	-91.70206	26.67207	2051

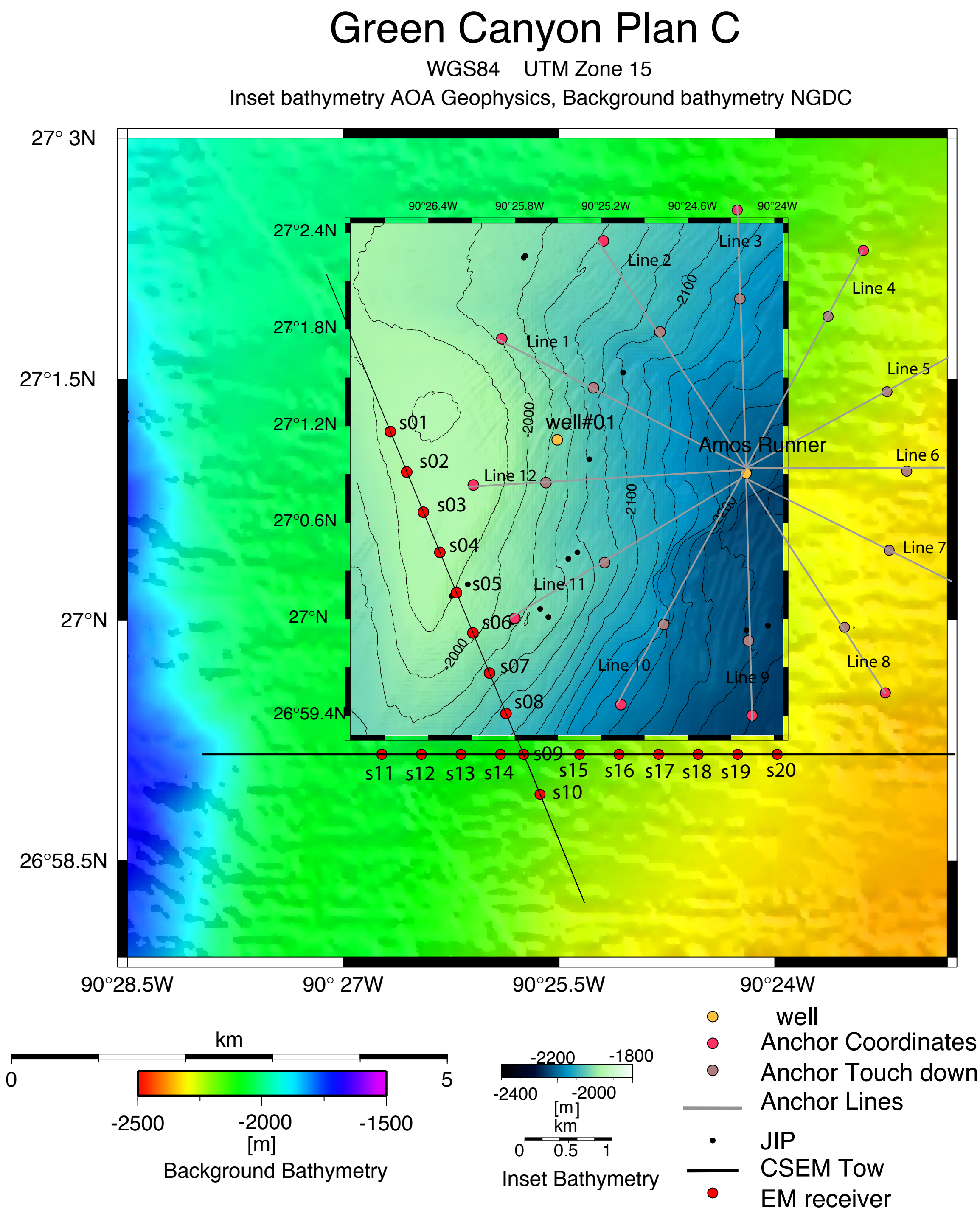

Figure 17. OBEM positions and SUESI tow lines on GC 955 as deployed. The original plan for this survey included a line orthogonal to the N–S line, crossing the strike of a suspected hydrate bearing channel sand. Unfortunately, drilling operations during our experiment made that impossible, and so we re-located the second line to lie just outside the anchor pattern of the rig.

GC 955 instrument positions as navigated:

GC955:

Site ID	Instrument	Longitude	Latitude	Depth
s01	Lorrie	-90.44449	27.01864	1971
s02	Roo	-90.44197	27.01476	1974
s03	Glider	-90.44036	27.01055	1970
s04	Echidna	-90.43860	27.00640	1973
s05	Cocky	-90.43595	27.00260	1993
s06	Rosella	-90.43413	26.99804	2010
s07	Goanna	-90.43235	26.99386	2043
s08	Brumby	-90.43033	26.98973	2077
s09	Penguin	-90.42840	26.98560	2107
s10	Taipan	-90.42711	26.98166	2163
s11	Occie	-90.44485	26.98561	2040
s12	Skink	-90.44038	26.98565	2052
s13	Camel	-90.43563	26.98571	2071
s14	Corella	-90.43087	26.98562	2097
s15	Mantis	-90.42165	26.98530	2183
s16	Ibis	-90.41707	26.98516	2204
s17	Bunyip	-90.41247	26.98543	2223
s18	Koala	-90.40821	26.98547	2245
s19	Rabbit	-90.40393	26.98565	2256
s20	Stingray*	-90.39967	26.98607	3000

* drop location

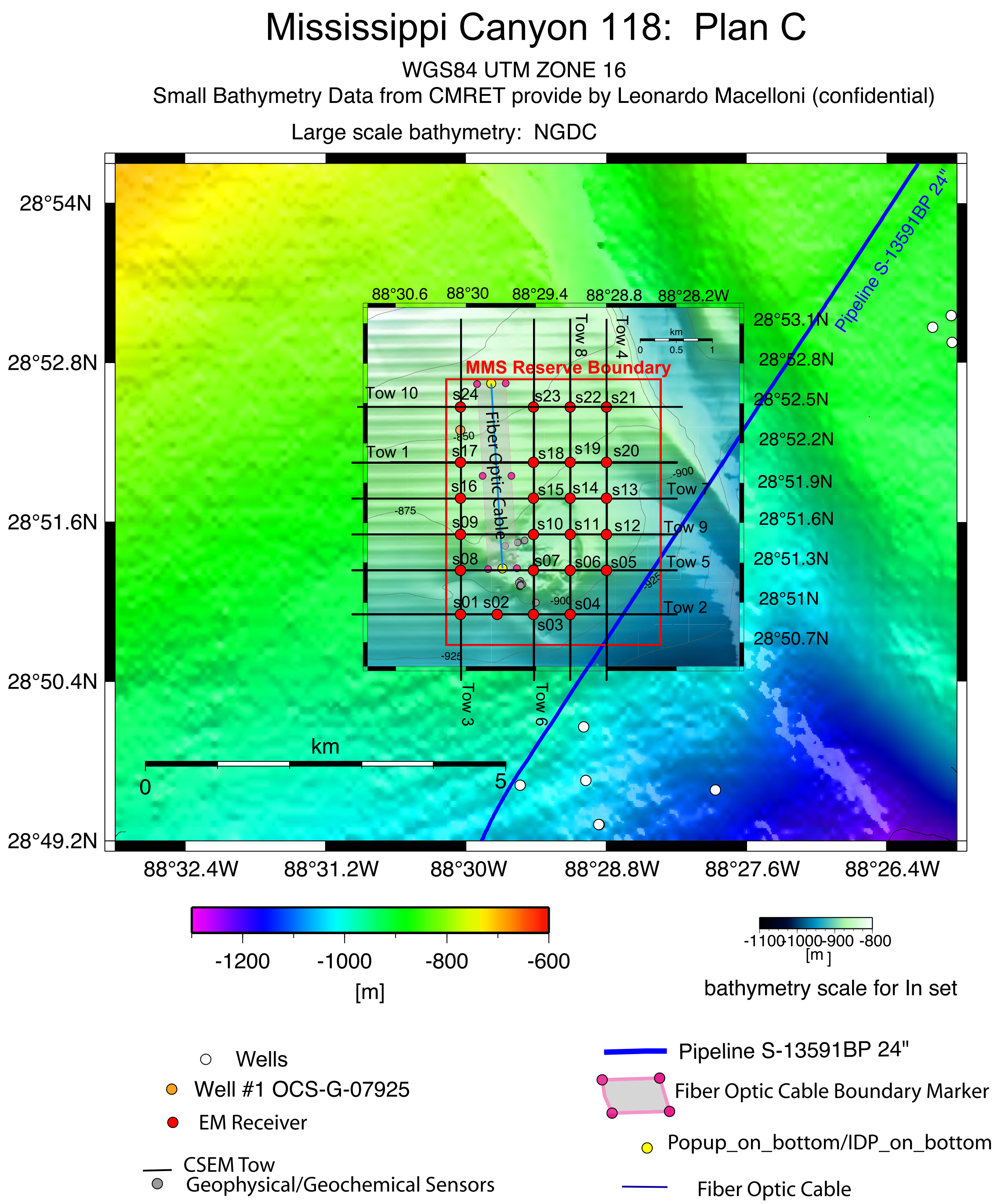

Figure 18. OBEM positions and SUESI tow lines on AC 818 as deployed. This site is a MMS observatory, and unfortunately during the delays associated with our project other groups started their own operations, limiting our access to the area. In particular, a seafloor fiber optic cable that will be used from acoustic arrays was considered vulnerable to our OBEM anchors. In this area we tested the 3D grid approach, carrying out a total of 10 SUESI tow lines both E–W and N–S.

MC 118 instrument positions as navigated:

MC118:

Site ID	Instrument	Longitude	Latitude	Depth
s01	Taipan	-88.50081	28.84905	922
s02	Koala	-88.49635	28.84882	926
s03	Occie	-88.49081	28.84907	919
s04	Roo	-88.48560	28.84888	915
s05	Camel	-88.48053	28.85407	902
s06	Bunyip	-88.48513	28.85424	885
s07	Mantis	-88.49047	28.85416	889
s08	Skink	-88.50106	28.85434	906
s09	Stingray	-88.50094	28.85907	880
s10	Glider	-88.49051	28.85886	887
s11	Rosella	-88.48562	28.85866	884
s12	Penguin	-88.48043	28.85877	883
s13	Rabbit	-88.48025	28.86326	894
s14	Corella	-88.48531	28.86319	877
s15	Ibis	-88.49040	28.86352	881
s16	Brumby	-88.50100	28.86325	877
s17	Echidna	-88.50080	28.86784	869
s18	Cuscus	-88.49015	28.86801	879
s19	Goanna	-88.48527	28.86788	880
s20	Lorrie	-88.48007	28.86768	896
s21	Brolga	-88.48034	28.87457	879
s22	Croc	-88.48535	28.87481	865
s23	Numbat	-88.49069	28.87494	863
s24	Mozzie	-88.50121	28.87458	845