Marine Electromagnetic Survey of the Deep San Andreas Fault and North American Continental Margin Structure

R/V New Horizon, November 15-22, 2008
R/V R.G. Sproul, January 3-9, 2009
Cruise Report

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A Research Project Funded by a Combination of UCSD/Scripps Institutional Ship-time and Discretionary Funds Associated with Our Industry Activities

SUMMARY

Between November 2008 and January 2009 we conducted a research experiment involving the collection of marine magnetotelluric (MT) and controlled source electromagnetic (CSEM) data along a survey line approximately perpendicular to both the Central Californian coast, near Estero (Morro) Bay, and the central segment of the San Andreas Fault, near Cholame. The objectives of the experiment were to image the deep (upper mantle scale) structure of the San Andreas Fault and the adjacent continental margin using the MT method, as well as image the near surface (crustal scale) structure of offshore Central California using the CSEM method. A total of 38 seafloor EM recorders were used which measured both the electric and magnetic fields along two instrument-horizontal orthogonal axes. An EM transmitter was used for the CSEM, which operated at 200 A emission on a 162 m dipole for a source dipole moment of 32.4 kAm. The source waveform was a newly designed binary sequence that provides a dense array of harmonics that share more power with the fundamental frequency than those of a simple square wave. The standard long baseline (LBL) acoustic system was used to locate the seafloor recorders, while acoustic relays between the transmitter's head, the transmitter's tail, the seafloor receivers and the ship were used to track the position of the transmitter.

This project was divided between two cruises. During the first cruise, aboard the New Horizon in November 2008, the seafloor recorders were deployed and acoustically ranged upon at 38 distinct sites, after which the transmitter was towed along the entire line of sites. The transmitter tow lasted a little more than 2 1/2 days. The first cruise lasted 8 days, after which, the recorders were left on the seafloor for slightly over 6 weeks to record the magnetotelluric fields. During the second cruise in January 2009, we returned to the survey line aboard the Scripps research vessel Robert Gordon Sproul, performed some additional acoustic locating of the seafloor receivers and then recovered them all. The second cruise lasted 7 days.

In order to provide power for such a long deployment a new battery circuit board was developed specifically for this cruise. It turned out that the boards were designed with a pernicious defect that affected some instruments but not others. Therefore, of the 38 instruments deployed, only 23 came back with any usable data. Preliminary inspection of the data from the 23 unaffected instruments shows good MT responses between 10 s and 30,000 s period. The CSEM signal is seen above the noise floor between source-receiver ranges of 0 to 5 km. Noise floors on the electric field sensors (5×10^{-14} V/Am^2) and magnetic field sensors (5×10^{-17} T/Am) are a slightly higher than normal possibly due to tidal currents near-shore.

No health, safety, or environmental incidents occurred during the experiment.

INTRODUCTION

The overarching objective of this research is to investigate to crustal and upper-mantle scale conductivity structure of the continental margin in Central California. This area is of particular interest because it lies adjacent to a well studied segment of the San Andreas Fault that exhibits a transition between locked behavior, south of Cholame, and freely slipping behavior, north of Parkfield. In addition, this portion of continental margin underwent active subduction during much of the last 200 million years. The most recent subduction episode ceased approximately 22 mya, and active seismic studies have imaged the oceanic crust underplating the continental shelf of Central California to a depth of 28 km, and possibly extending as far east as the San Andreas fault (e.g., *Miller et al.*, 1992; *Lafond and Levander* , 1995). Terrestrial magnetotelluric (MT) studies conducted across the adjacent segment of the San Andreas fault have imaged a large lower crust/upper mantle conductive zone west of the fault (e.g. *Becken et al.*, 2008). *Becken et al.,* a group from the GFZ German Research Center for Geosicences in Potsdam, proposed that this deep conductive zone is related to fluids in the lower crust and upper mantle. It is hypothesized that the presence of subducted oceanic crust beneath this region may provide a source of the deep fluids, as oceanic crust can hold significant amounts of water through sediment saturation and serpentinization. *Becken et al.* have also imaged along strike variation of this deep conductive zone. They have shown that to the north, near Parkfield, the deep conductor connects to a upper crustal conductor east of the San Andreas via a sub-vertical corridor of high electrical conductivity, whereas to the south, near Cholame, the deep conductor is isolated from the shallow conductive zone near the fault. This suggests that a varying level of interaction between these imaged deep fluids and the shallow fault zone may influence the change in behavior of the San Andreas Fault in this region. Other offshore faults in Central California, such as the Hosgri and the Santa Lucia bank, provide interesting targets for this survey. Our survey line was designed to extend the MT study of *Becken et al.* 200 km offshore, and relate to existing offshore seismic profiles. The stated goals for this research are:

1. Image the conductivity structure of the entire continental margin transition from the deep ocean to the continental shelf. This will be highly complementary to the regional seismic profiles since the EM studies will be able to constrain porosity, permeability and the presence of fluids in the seismically imaged accretionary complex and subducted oceanic crust, from the shallow sediments to the upper mantle.

2. Detect any high conductivity zone associated with detachment faulting and ductile flow along the boundary between underplated oceanic crust and the overlying and deformed continental shelf. If detachment faulting occurs along serpentinized oceanic crust, there should be a detectable conductivity anomaly. This will help constrain models for the source of deep fluids beneath the San Andreas fault zone, as well as kinematic models for deformation along the plate boundary.

3. Detect the depth and lateral extent of conductivity anomalies, if they exist, associated with the Hosgri and Santa Lucia bank fault zones on the continental shelf. Seismicity suggests that these faults are active and electrical conductivity images from the seafloor to the upper mantle will allow us to determine the relationship between faulting, seismicity and crustal fluids in the offshore region.

4. Extend the land MT data into an amphibious transect of over 300 km total length, which will provide a comprehensive electrical image of the subducted oceanic crust, any associated fluids and conductive mineral phases, and allow us to constrain their role in the behavior of the San Andreas fault zone.

MOBILIZATION

The research was carried out on two different ships: the Research Vessel New Horizon from 15 November to 22 November 2008, and the Research Vessel Robert Gordon Sproul from 3 January to 9 January 2009. The R/V New Horizon is 31 years old, owned by the University of California, San Diego, and operated by Scripps. It is 170‘ long, 36‘ wide, with a 797 ton gross displacement. It has 19 berths for the scientific crew, and 12 for the ship's crew. The R/V New Horizon has an endurance of 40 days and can sustain a 10 knot cruising speed. There are 1,265 sq. ft of laboratory space, and 1,730 sq. ft of deck working space on the New Horizon. It is equipped with P-code GPS navigation and a Knudsen Sub-Bottom Profiler. It has an A-frame and winch suitable for use with a deep tow transmitter. The R/V R.G. Sproul is 28 years old, owned by the University of California, San Diego, and operated by Scripps. It is 125‘ long, 32‘ wide, with a 355 ton gross displacement. It has 12 berths for the scientific crew. The R/V R.G. Sproul has an endurance of 14 days and can sustain a 9 knot cruising speed. There are 350 sq. ft of laboratory space, and 1,854 sq. ft of deck working space on the R.G Sproul. It is equipped with P-code GPS navigation.

The Scripps Marine EM lab supplied the following equipment for this project:

- 38 SIO Mark III seafloor electromagnetic field recorders, with two horizontal axes each for the E and B fields.
- 1 SUESI EM transmitter, with a peak current capability of about 500 amps and a GPS controlled waveform, with a topside power unit.
- 1 transmission antenna, of 200 A capability and 160 m dipole length.
- 40 concrete anchors for the deployment of seafloor recorders
- All necessary topside support equipment.

Mobilization commenced the 14th of November at the Scripps operated Nimitz Marine Facility (MARFAC) in Point Loma, CA, with the loading of the scientific equipment onto the ship and the termination of the 0.680 deep tow cable to enable it to mechanically and electrically connect to the SUESI transmitter. On the 15th of November we finished loading the R/V New Horizon and pushed-off at 0830.

We returned to port at MARFAC at 0800 on the 22nd of November 2009. Since the New Horizon would stay in port for maintenance through the rest of the year, the demob took place the following Monday, November 24.

EXPERIMENTAL DESIGN

The plan for this experiment was to collect 38 sites of MT and CSEM data by way of two separate cruise legs: the deployment leg and the recovery leg.

DEPLOYMENT LEG

In this leg of the experiment we deployed 38 seafloor receivers over a 187 km line starting from 23 km from the shore of Estero Bay and extending and extending 93 km past the base of the continental shelf (Figure 1). The receiver spacing is 3.5 km for the shallowest 29 sites, 7 km for the next 7 progressively deeper sites, and 15 km for the final 2 sites. The receiver spacing is tight over the continental shelf and slope where we hope to image near-surface structure with higher resolution, and looser out in the abyssal plain where the near-surface structure is simpler and we can therefore afford the diminished resolution. This survey was designed to collect a 2D data set in hope that the overall geoelectric structure is also 2D. The survey line is oriented at N 47º E. The goal with the orientation was to make the survey line perpendicular to the prominent 2D structure in the area. The San Andreas fault trends approximately N 43º W in this area of central California, perpendicular to our survey line. The coast and continental shelf trend roughly N 35º W so our survey is close to being perpendicular to these large features as well. The receivers were deployed starting with the near-shore sites and moving toward the deep ocean sites.

Between the deployment of each receiver, the ship followed a slight zig-zagged path between sites to allow for acoustic ranging along two orthogonal horizontal directions. This enables full 3D location of the receiver on the seafloor. The transmitter tow had a 15 km run-in from the deep-ocean end of the line. The tow line was parallel to the line of receivers but shifted a quarter mile to the south. The run-out of the tow was only 5 km on the shallow end of the receiver line. During the tow we used SUESI's Benthos unit and and transponder relay on the transmitter's tail to get a range to the instruments as we passed them. This will help us navigate the transmitter position and orientation during the tow.

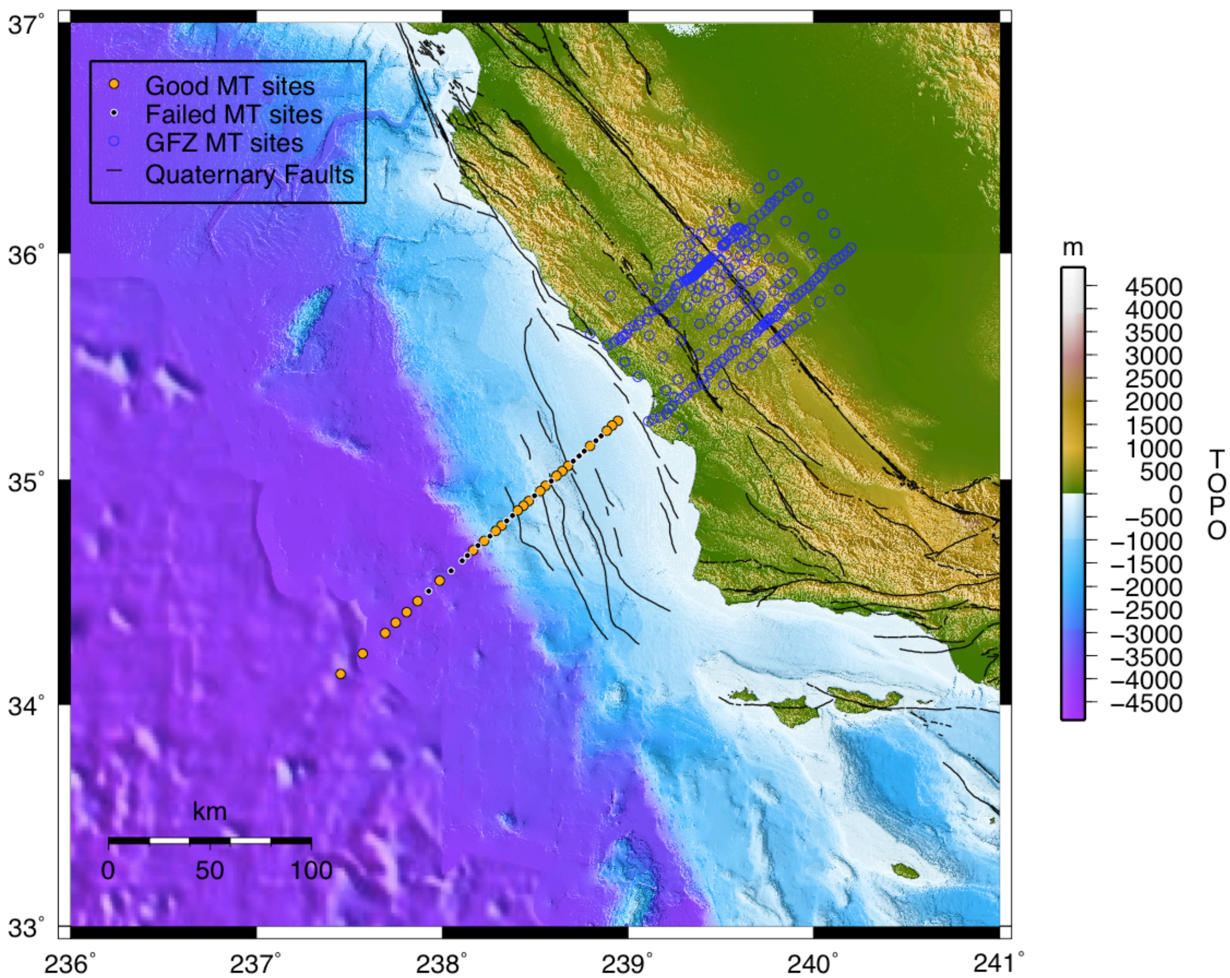

Figure 1. Survey layout. Symbols depict MT sites collected during this experiment as well as those collected by the group from GFZ, Potsdam. The 15 sites which failed to collect any data were spread quite evenly along our survey line.

RECOVERY LEG

After deployment, the receivers were left on the seafloor for a total 6 weeks to maximize the opportunity to collect strong long period MT signal. In the recovery leg of the experiment, we returned to the survey site in a smaller vessel to locate and recover the receivers. Before releasing an instrument from the seafloor, we again drove the ship in a zig-zag pattern over each site while gathering more acoustic range data, thereby increasing the accuracy of the instrument's estimated seafloor location.

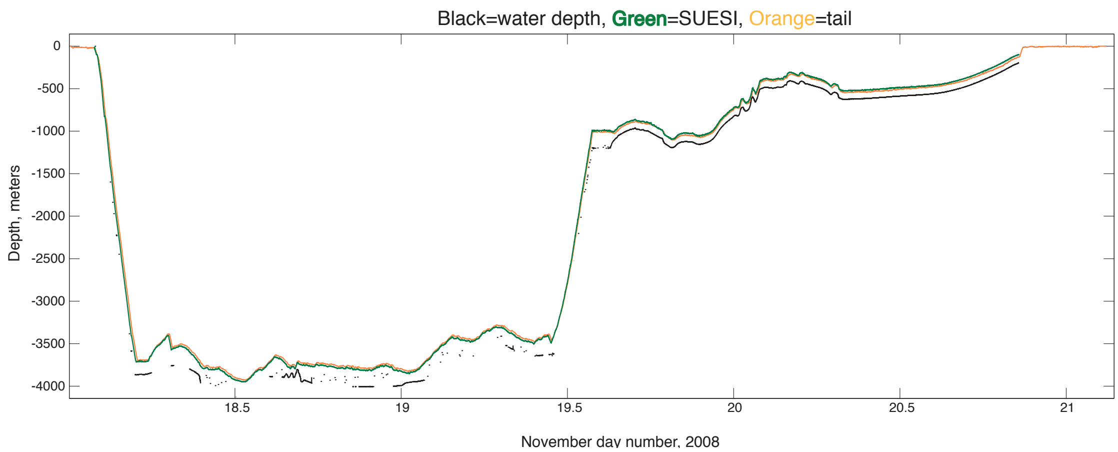

Figure 2. Water depth profile of the CSEM tow. SUESI depth, and antenna tail depth plotted along with pseudo-bathymetry calculated from SUESI depth + SUESI altimeter readings. Note the tail flew slightly higher than SUESI in the deep water, but then reversed to flying below SUESI in the shallow water.

SURVEY PARAMETERS

An attempt was made to carry out the CSEM tow at a flying height of 100m above the seafloor. Due to the large variations in bathymetry in the area, 100m was chosen as a safer alternative to the usual 50m height, despite a small sacrifice in seafloor coupling (Figure 2). We were unable to hold the 100m height for the entire tow. On the deeper end of the our line where water depths were over 4 km; over 5,600 m of .680 wire was payed out in order to reach a flying height of 150m. With that much payout, the winch began to make unnerving noises and the chief engineer required that no more wire be paid out. Once we towed up the continental shelf, the wire out fell below 1000m and the winch returned to its normal performance. From that point onward in the tow we were able to hold the tow package at 100m above the seafloor.

Transmitter waveform. The waveform used for the SUESI transmissions was a compact broadband binary waveform recently developed by David Myer. The single free parameter for this waveform is the pattern's duration, which determines the fundamental frequency of the output. A 4 second duration was chosen for this experiment which gave us 0.25 Hz for the lowest CSEM frequency (Figure 3). This binary waveform spreads more power into the harmonics than a simple square wave of the same fundamental frequency (Table 1). The trade-off is a loss of power at the fundamental frequency. However, the fundamental, being the lowest frequency, is least attenuated by the seawater, and so one can usually afford the loss of power in the fundamental in favor of more power at higher frequencies.

INSTRUMENT PERFORMANCE

Instrument performance for this cruise represents an anomalous amount of data loss (approximately 40%) compared to the average rate over the last few cruises for our lab (approximately 1%). Of 38 deployed receivers, all were retrieved, but only 23 had any usable data. The reason for this lies behind the experiment's extreme demands on receiver endurance. The six week deployment required a reconfiguration of the data logger's power pack. This had to be done at the last moment as we had only just retrieved our instrument fleet from the preceding cruise in the Gulf of Mexico. The battery capacity was nearly doubled, and a new diode board was used to connect the extra batteries in parallel to the data logger circuitry. The locus of failure was between two traces on the diode board that were too close together and shorted-circuited upon wake-up in nearly 2 out of 5 instruments. Pressed for time, we had only been able to test a few of these new boards before sending them out to sea, and, as luck would have it, the few we tested turned out to be some of the good ones. This unfortunate loss of data, due to a minor change in equipment, underscores the experimental nature of academic research. The continuous advancement of the cutting-edge, is invariably met with the occasional setback. Luckily the incidence of these failed instruments was more or less spread evenly along the survey line; no one area is severely diminished in resolution relative to the rest (Figure 1).

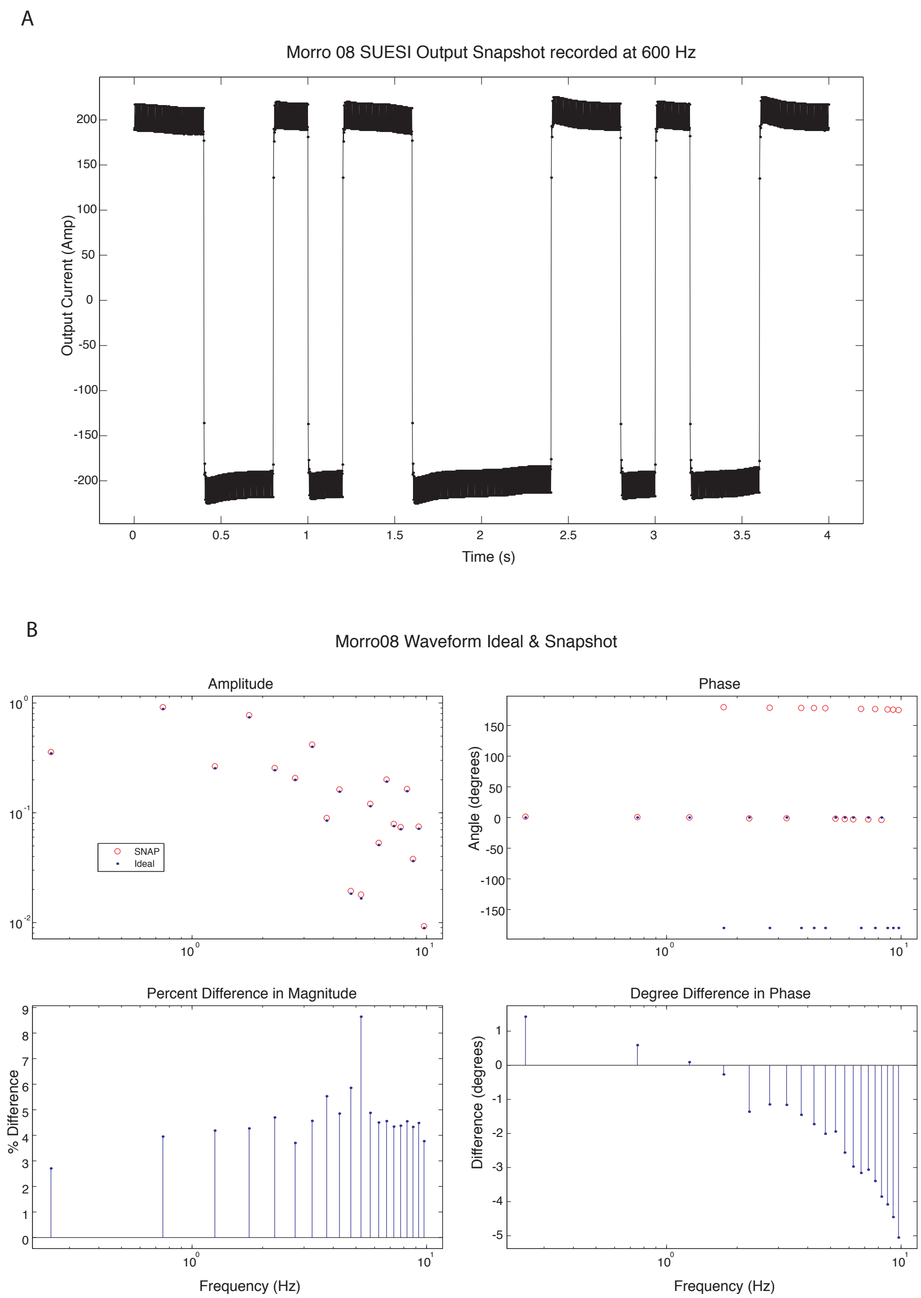

Figure 3. Transmitted Waveform. A) snapshot of the 4 second waveform pattern during transmission. The average output current is seen to dither around 200A, and the actual transmitted waveform deviates slightly from the ideal square shape. B) the amplitude and phase spectra of the recorded snapshot compared with the idealized binary sequence. Percent differences between these two are plotted below.

Table 1.

	Amplitudes	
Freq.	**Binary**	**Square**
0.25	0.3481	1.2732
0.75	0.8818	0.4244
1.25	0.2546	0.2546
1.75	0.7417	0.1818
2.25	0.2442	0.1414
2.75	0.1998	0.1157
3.25	0.3993	0.0979
3.75	0.0848	0.0848
4.25	0.1556	0.0748
4.75	0.0183	0.0670
5.25	0.0165	0.0606
5.75	0.1150	0.0553
6.25	0.0509	0.0509
6.75	0.1922	0.0471
7.25	0.0758	0.0439
7.75	0.0709	0.0410
8.25	0.1573	0.0385
8.75	0.0363	0.0363

Of the instruments that did not have shorted batteries, the data recovery is good. Four of these instruments had problem channels. One instrument, (Croc, site M14) had a B channel with amplitudes nearly an order of magnitude less than those of its other B channel and those of B channels from adjacent instruments. Further investigation of this instrument led to the discovery of a single non-standard resistor which depressed that particular B channel's sensor voltages. Luckily, this error can be corrected with

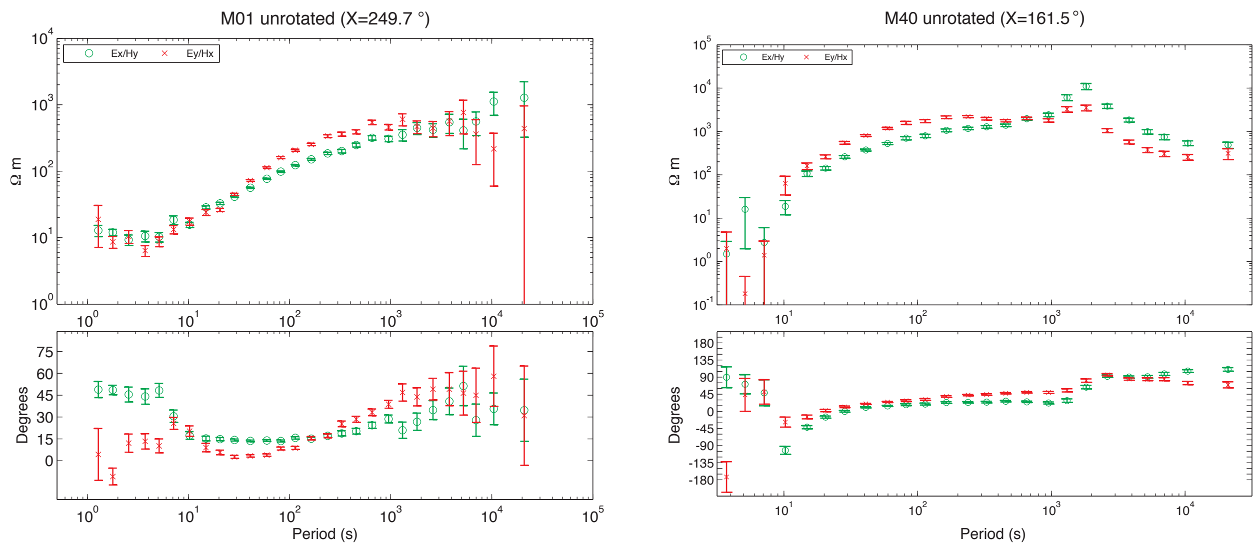

Figure 4. Shallow (M01, 320m depth) and deep (M40, 3,870m depth) water examples of MT apparent resistivity and phase data from this experiment. While the shallow sites experienced a fair bit of noise interference (waves, cultural, etc.), the deep sites past the continental shelf exhibit very clean MT responses between 10 and 30,000 s.

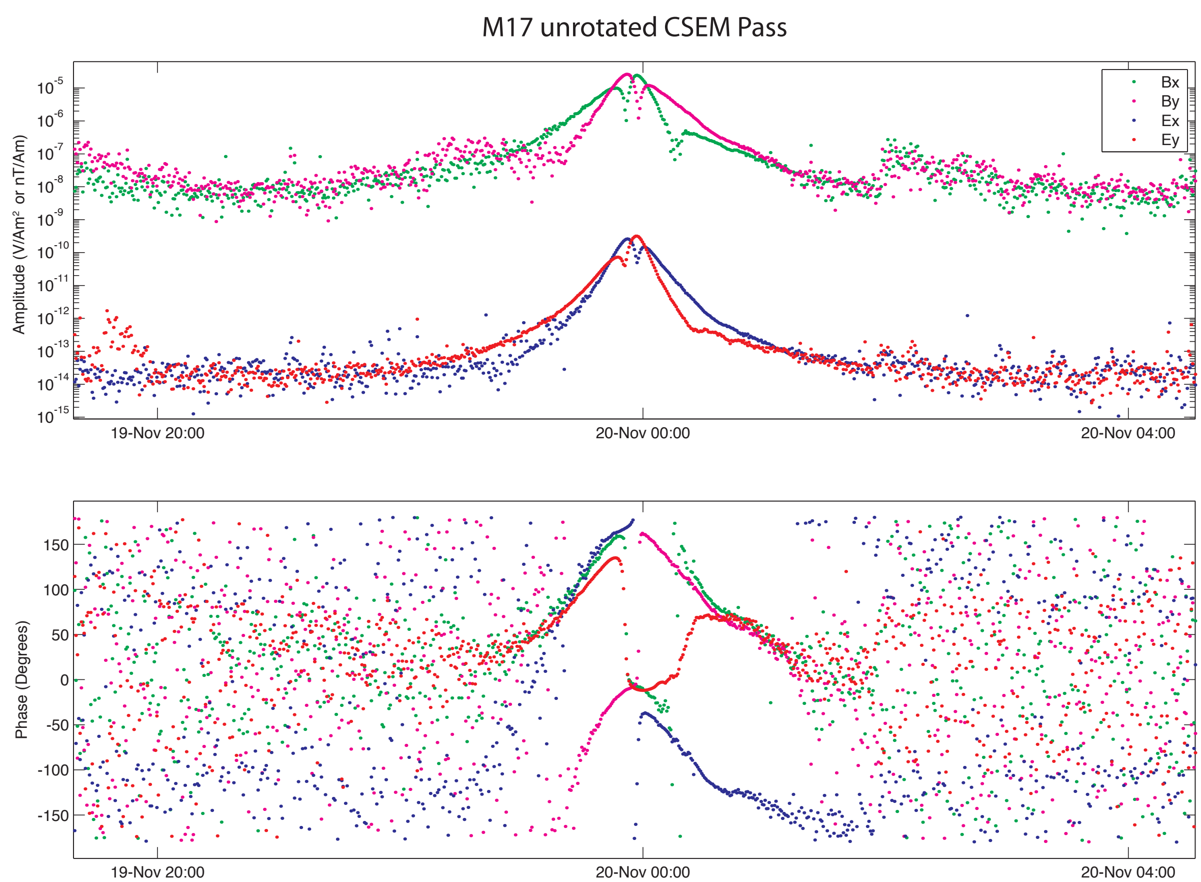

Figure 5. An example of some CSEM data collected during this experiment. The abscissa in these plots is time, but if we take into account the 1.5 kt speed of that tow, we can see that there is good CSEM signal out to about 5 km source-receiver offsets. Note the non-stationary noise in the CSEM noise-floor.

only a minor loss in resolution, by means of a new calibration. Another instrument, (Cuscus, site M15) had an E channel that seemed to be dead for most of the deployment except, strangely, for a few days in the middle (November 30, 2008 - December 3, 2008). A decent MT signal may be recoverable from these few days of good data. Two other instruments (Occie, site M22, and Cocky, site M38) each had one bad E channel which seems to have no recoverable data. This renders these site useless for MT, but their working channels may contain some useful CSEM information. In summary, we set out to collect 38 sites of MT data and came out with 21 sites with good MT data. If we exclude the instruments that had the battery board failure, leaving 23 instruments with 4 channels each, of which only 3 channels of data were lost, then the rate of data loss for this experiment dips below the standard data loss rate of 5% for marine free-vehicle experiments.

As for the data from the functioning channels, the quality appears good (see Figures 4 & 5). A couple of storms came through the area during the deployment and their passing effects can be seen in a spectral time series. The data collected during these discrete storms are simply removed from the MT processing. As expected, shallow water sites are noisier that the deep water sites due to their proximity to civilization, wave movement at the surface, stronger bottom currents, and microseism sources. The noise floors seen in the electric field sensors (5×10^{-14} V/Am^2) and magnetic field sensors (5×10^{-17} T/Am) are slightly higher than other recent experiments; this is assumed to be due to the aforementioned environmental factors.

SUMMARY AND CONCLUSIONS

Even though we set out to collect a nearly two-fifths larger data set, the 21 instruments of MT and CSEM data that we did collect will provide plenty of fodder for research. We have learned from the instrument failure and have implemented more stringent testing procedures for instruments before future deployments. The data that we did collect has yielded clean MT and CSEM responses. The modeling of the MT and CSEM data is in progress and will provide constraints on the composition of the upper mantle and crust of the continental margin in Central California. Ultimately the results extracted from this experiment will complement the research into the evolution and current state of the central California segment of the San Andreas fault.

ACKNOWLEDGEMENTS. First, we'd like to thank the UC Ship Funds Program for making this cruise possible. Also we would like to thank the scientists, students, technicians, and engineers of the Scripps Marine EM Laboratory for their help on- and off-board preparing the instruments and carrying out the experiment. Finally, we would also like to thank the crew of R.V. New Horizon and R.V. Gordon Sproul for maintaining safe and effective vessels without which our research would be impossible.

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Appendix 1: Personnel

Steven Constable	Chief Scientist (NH only)
Chris Armerding	Technician
Cambria Colt	Technician
Dave Jabson	Observer (RGS only)
Kerry Key	Scientist (Chief Scientist on RGS)
David Langer	Resident Technician
Josh Manger	Resident Technician (RGS only)
Arnold Orange	Scientist (NH only)
Jake Perez	Technician
Karen Weitemeyer	Student
Brent Wheelock	Student (data from this cruise will constitute his Ph.D work)

Appendix 2: Navigated Positions for all Instruments

Site	Longitude, W	Latitude, N	Depth
M01	-121.053913	35.262266	329.9
M02	-121.084316	35.240677	436.6
M03	-121.114181	35.217975	496.2
M04	-121.143916	35.195739	564.0
M05	-121.172926	35.173006	591.2
M06	-121.202873	35.150958	607.0
M07	-121.233445	35.128917	610.5
M08	-121.263617	35.106580	628.8
M09	-121.293098	35.084632	636.6
M10	-121.322524	35.062130	659.1
M11	-121.352930	35.039426	528.2
M12	-121.382523	35.018050	465.9
M13	-121.413490	34.996335	402.7
M14	-121.442342	34.973503	529.7
M15	-121.472486	34.952098	515.0
M16	-121.502870	34.930103	779.3
M17	-121.532873	34.908018	887.7
M18	-121.562728	34.886655	1034.4
M19	-121.592874	34.864238	1182.7
M20	-121.621911	34.842345	1189.4
M21	-121.651987	34.819780	1151.1
M22	-121.681351	34.796991	1037.7
M23	-121.711675	34.774346	1046.1
M24	-121.742460	34.751857	1434.8
M25	-121.773156	34.731311	2277.6
M26	-121.805953	34.709549	3656.4
M27	-121.833266	34.688377	3901.9
M28	-121.863026	34.665556	3926.5
M29	-121.892806	34.642953	3924.4
M30	-121.952189	34.597149	3752.8
M31	-122.012508	34.552362	3750.8

M32	-122.073233	34.507112	3906.2
M33	-122.132174	34.460768	4006.2
M34	-122.191382	34.413572	4023.4
M35	-122.249832	34.366587	4034.8
M36	-122.308036	34.320343	4027.3
M38	-122.427240	34.228256	4178.7
M40	-122.545942	34.135671	3872.0