Marine EM Studies over Scarborough Gas Field

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Background

Scripps Institution of Oceanography is a world leader in the development of marine electromagnetic methods, starting with the pioneering work of Charles Cox and Jean Filloux in the 1970's (e.g. Cox, Filloux, and Larsen, 1971), continuing from the early 1980's with the work of Steven Constable, and now with the recruitment of Kerry Key onto the permanent scientific staff. Initially marine EM methods were developed for the study of the deep seafloor and mid-ocean ridges in particular, and this application continues to this day, but in the mid 1990's Constable and Key (then a graduate student) started to apply marine EM methods to offshore exploration problems. Initially the research focussed on the development of marine magnetotelluric (MMT) methods to assist interpretations in seismically difficult terrane such as salt, basalts, and carbonates (Constable *et al.*, 1998; Key, Constable, and Weiss, 2006). Later, Scripps played a critical role in the development of marine controlled-source electromagnetic (MCSEM) sounding for direct detection of hydrocarbons (Ellingsrud *et al.*, 2002; Constable, 2006; Constable and Srnka, 2007). Most recently, Scripps is developing equipment and methodology to use EM to map shallow hazards such as gas hydrate and shallow gas (Weitemeyer *et al.*, 2006; Weitemeyer, Constable, and Key, 2006). Future applications may include the monitoring of oil and gas reservoirs during production using marine EM methods (Orange, Key, and Constable, 2009).

One of the unfortunate side-effects of a rapid and successful transfer of academic marine EM expertise and technology to industry is that three commercial contracting companies were formed very early in the development cycle. Contractor resources were initially focussed on replicating existing academic equipment and expertise, and are now applied to weathering the economic downturn, a situation exacerbated by various patent disputes. They have little capacity for pure research and development. Although the industry leveraged academic expertise heavily to establish a successful and vigorous marine EM capability, to this day no fully academic public domain data set over a hydrocarbon reservoir exists. This represents a severe impediment to further development of the equipment and processing, modeling, and interpretation codes by the academic community, as well as restricting an objective evaluation of various common practices, free of contractor bias and conflict of interest. This research project is aimed squarely at remedying this situation by collecting a rich and diverse marine EM data set over a known structure.

Proposed Research

We have been given access to the Scarborough gas field, jointly operated by BHP Billiton Petroleum and ExxonMobil (Figure 1). This large gas field on the Northwest Shelf is well studied by drilling and 3D seismic surveying, providing excellent ground truth for the calibration of marine EM methods. Our premier research vessel, the R.V. Roger Revelle will be in the Indian Ocean this year, and we have carried out several highly successful studies using this platform. On a recent experiment to study gas hydrate in the Gulf of Mexico we achieved very high data collection rates using this vessel.

Questions that will be addressed during this project include:

i) What is the repeatability of MCSEM surveys with respect to repeat transmitter tows? Little has been done to quantify the error structure of MCSEM data, and calculations show that navigation of the transmitter/antenna is one of the largest contributions to data error. Model simulations of repeat MCSEM surveys over reservoirs during production show that data error needs to be held to 1% or less, yet it is not clear that such low errors can be achieved even during repeated tows over fixed seafloor instruments. We will address this question by making several transmitter passes over seafloor receivers, spaced many days apart (so ocean currents have time to change).

ii) What does the noise environment look like; instrumental, oceanographic, geomagnetic, and "geological"? Again, this addresses questions of noise in MCSEM and MMT data. Although these questions will mostly be addressed during the data processing stage, having a large number of instruments deployed for a relatively long time (up to three weeks) with a high level of redundancy will facilitate addressing this problem.

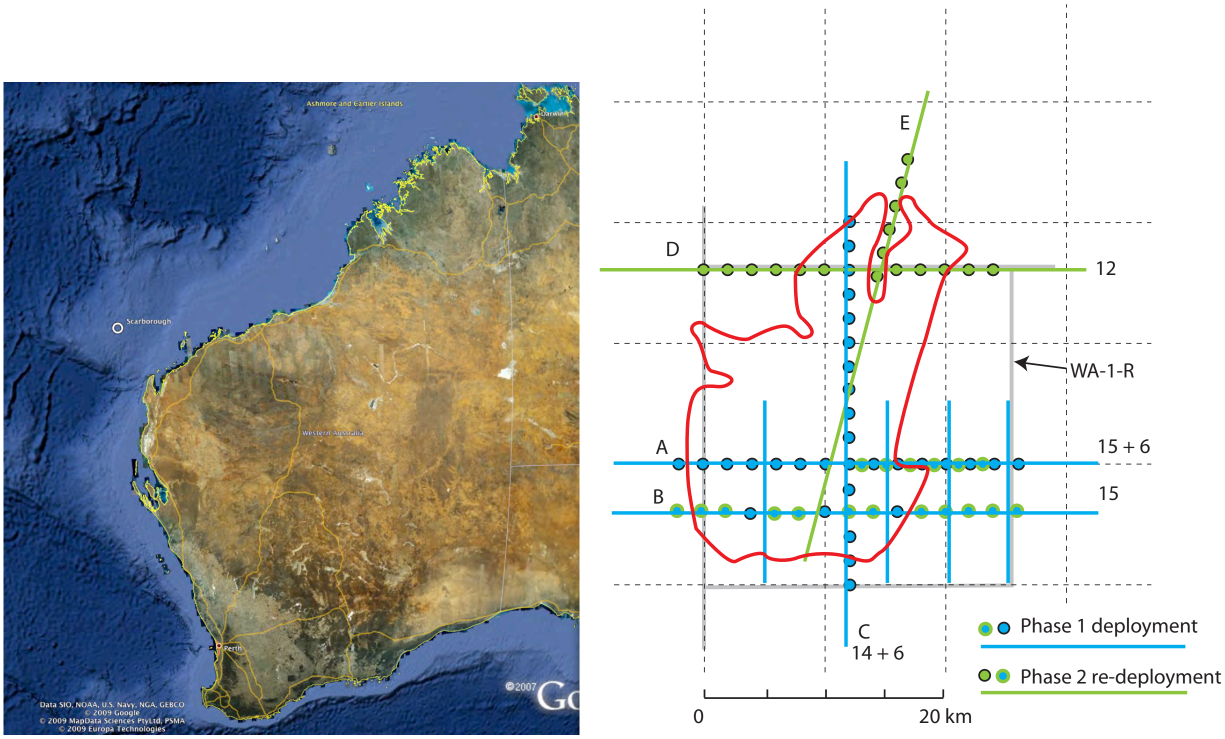

Figure 1. Location of the research area (left) and schematic layout of study (right). The approximate reservoir location is in red and the broken dashed lines are a 10 km grid. The project calls for three deployments, initially of 50 instruments (Phase 1), and then the movement of 18 instruments, first to extend the survey to the "ears" (Phase 2) and then to carry out a localized survey over the area identified as having shallow gas. The remaining 32 instruments would continue to collect MT and some CSEM data during the Phase 2 and shallow hazards studies.

iii) What is the lateral sensitivity to structure broadside to a 2D receiver/transmitter line? Unlike MMT, in which case one is sensitive to structural contrasts many kilometers outside the survey area, the resolution kernels of MCSEM are concentrated between the source and receiver. Most MCSEM data is currently collected using single transmitter tows along lines of seafloor receivers. It is important to know how sensitive these 2D data sets are to off-line structure, because (a) one might want to carry out 2D interpretations under the assumption that there is little sensitivity to off-line 3D structure and (b) one might want to be able to choose a line spacing that would not fail to detect a structure of a certain size. We will use several 2D lines laid out over the "rabbit ears" of Scarborough to address these questions.

iv) What is an optimum receiver spacing for MT and CSEM? Contractors offering MMT and MCSEM surveys have an interest in deploying more, rather than fewer, seafloor recorders. While safe and conservative, as the methods mature it is important to understand the tradeoffs between resolution and number of instruments (and thus cost). Over-sampling some of the MCSEM and MMT lines will allow several levels of decimation and re-interpretation to understand this tradeoff.

v) How effective are "scanning" methods? On approach to MCSEM exploration being touted is the deployment of broadly spaced seafloor receivers and the towing of multiple transmitter lines, under the assumption that any targets in the area will be detected by one or two source-receiver pairs. While it is easy to run model simulations of this approach, such simulations do not account for realistic instrument noise (which tends not to be uniform or stationary), nor "geological" noise associated with variations in seafloor resistivity not associated with target structures. We will lay out such broad arrays of receivers in order to examine these issues.

vi) How does the transmitter tow height and waveform affect the quality of CSEM data? The current choice of waveform and transmitter height has evolved little since the first surveys. Mostly a 0.25 Hz square wave is used with a transmitter towed at constant height as close as is practical to the seafloor (25–100 m) in order to maximize coupling. Harmonics (up to about the 9th) of the square wave are processed, and one of the few innovations has been to use more complicated binary waveforms which boost the amplitude of selected harmonics, still being restricted to about the 9th harmonic. One area of research we have been pursuing is the development of waveforms with nearly two orders of magnitude of useful frequency content, as well as time domain signals. Also, in areas of significant seafloor bathymetry, one might want to tow the transmitter at constant depth (rather than height), in order not to drive continuous variations in transmitter pitch. Such tows would include data 100–300 m above the seafloor, and so it is important to know how sensitivity and resolution falls off with transmitter height. Simply, we will tow some lines at various transmitter heights and with various waveforms.

vii) Can various parts of a large structure be inverted as separate problems? Full 3D inversion of MCSEM data is one of the largest computational problems encountered in science and engineering (ExxonMobil used a dedicated IBM "Blue Gene" computer, the fastest in the world between November 2004 and June 2008, to carry out inversions of its data sets). Obviously, if inversion of a large structure can be broken into several smaller inversions, there will be a computation efficiency. Our data sets, collected over known parts of the Scarborough structure, will allow us and other groups to test these questions.

viii) How do strike lines and dip lines compare? Placing MCSEM surveys along the long axis of structures will maximize the coupling and sensitivity of EM signals, but place few constraints on the geometry of the target. Lines across the short axis will have higher resolution, but lower signal. We will use the "rabbit ears" to test this comparison.

ix) How relatively effective are 1D, 2D, and 3D modeling, and what are the data requirements of each? Again, computational effort increases as one goes from 1D to 3D modeling and inversion. A great deal of current routine commercial MCSEM data are interpreted using 1D modeling, and so it is extremely important to understand the limitations of this approach. Scarborough is sufficiently large that we expect the MCSEM response to be largely 1D near the center, and so our data sets will be rich enough to test the limitations of the lower dimensional inversions as one progresses from 1D structure near the center to 2D/3D structure in the ears.

x) How effective is vertical electric field data for resolving structure? Modeling shows that vertical electric MCSEM responses are preferentially sensitive to lateral variations in resistivity. Scripps has developed an effective vertical E-field sensor, with a sensitivity comparable to the horizontal sensors, but has no data over typical oil-field targets.

xi) How does MMT data quality depend on noise environment and acquisition time? In MMT processing, a time series of electric/magnetic fields is used to generate a frequency-dependent transfer function related to earth impedance. The length of an MMT time series determines not only the quality of the impedance estimates but also the high and low frequency limits. Since time is money, one needs to understand the tradeoffs in a quantitative way to optimize data collection. We will leave a subset of MMT recorders down for the entire 3 weeks on station to give us a rich data set to examine this tradeoff.

xii) How important is the collection of "broadside" (azimuthal) MCSEM data? Early work in MCSEM made much of the observation that the radial, or in-line, MCSEM mode was sensitive to both thin (reservoir-type) and thick (non-reservoir geology) resistive structures, while the azimuthal, or broadside, mode was only sensitive to thick structures (and thus could be used as a target discriminant). More recent modeling shows that use of in-line MCSEM phase, MMT data, and a broader MCSEM frequency range can all be used as similar discriminants. We will test these modeling-derived concepts with real data sets.

xiii) How effective is CSEM for identifying shallow hazards, and what frequencies, source–receiver spacings, survey geometries are necessary for this application? Scripps has been working on the development of specialized equipment and techniques for identifying resistive structures in the shallow section, such as those associated with shallow gas and gas hydrate. We recently carried out a successful cruise to map gas hydrate in the Gulf of Mexico (see http://marineemlab.ucsd.edu/Projects/GoMHydrate/), and Scarborough offers a great opportunity to try similar techniques over the known area of shallow gas. We will deploy dense arrays of receivers over the shallow gas areas, and also tow a 3-axis receiver at a constant offset behind the transmitter. For shallow hazards studies we use a smaller transmitter antenna (50 m compared with 300 m) than for deep target detection, and transmit much higher frequencies (up to 100 Hz).

xiv) Does the accurate measurement of seafloor electric field gradients provide superior detection and delineation for deep resistive targets? Model simulations (again) show that deep reservoir targets are manifest as lower gradients in amplitude and phase of the MCSEM signals. We have built and tested a sensitive electric field gradiometer (a "G-LEM") designed to provide superior resolution to conventional MCSEM/MMT recorders, and will be able to test this instrument for the first time over a hydrocarbon target.

Field program.

We have sketched out a program shown in Figure 1 based on qualitative consideration of our objectives. It is anticipated that this program will evolve as quantitative modeling (currently underway) is carried out, but it provides a strong basis for understanding how the the project will look. Also, our recent experience on the R.V. Roger Revelle in the Gulf of Mexico suggests that we will be able to carry out up to 120 deployments and recoveries, rather than the 86 in the original proposal.

Preliminary work plan:

Deploy 50 instruments in Phase 1 locations: 3 days
Deploy 2 G-LEMs, 0.5 days
Tow Line A, 40 km (22 nm), 50 m height, 1 day
Tow Line B, 40 km, 1 day
Tow 'scanning' lines, 45 km plus turns, 2 days
Tow Line A, 50 m height for repeatability tests, 1 day
Tow Line A, 100 m height, 1 day
Tow Line A, different waveform, 1 day
Recover 18 instrument for Phase 2 locations 2 days
Deploy 18 instruments for Phase 2, 1 day
Tow line D, 40 km, 1 day
Tow line E, 40 km plus turns, 2 days
Recover 18 instrument for shallow hazard study, 2 days
Deploy 18 instruments for shallow hazard study, 1 day
Tow shallow hazard study, 2 days
Recover 50 instruments, 4 days.
Contingency, 2.5 days.

Total on station, 28 days. Total number of deployments 86.

Facilities

Scripps Institution of Oceanography (SIO) is one of the oldest, largest, and most important centers for marine science research, graduate training, and public service in the world. Research at SIO encompasses physical, chemical, biological, geological, and geophysical studies of the oceans. With more than a century of exploration and discovery in global sciences, SIO is the world's preeminent center for ocean and earth research, teaching, and public education. SIO operates one of the largest research fleets in the world, with 2 ocean-class, 1 regional-class, and 1 local-class vessels. For this project we will use the R.V. Roger Revelle (Figure 2).

Though the support of industrial sponsors, the Marine EM Laboratory at Scripps has designed and built a state-of-the-art fleet of 50 EM receivers, all capable of being equipped with magnetotelluric and vertical electric field sensors, and even hydrophones (Figure 3). This instrument system is at least as capable as those used by industry. Indeed, one of the contractors licenses the SIO technology and uses either identical instruments or instruments based closely on this design. Another contractor started business in marine EM using a clone of the SIO instrument obtained from a

Figure 2. The Scripps Research Vessel Roger Revelle, operated under charter agreement with the U.S. Navy, will be used for the proposed research. It is only 18 years old, and is 273' long and 52.5' wide, with a 3,512 long ton displacement. It berths 37 scientists, has an endurance of 52 days, and can cruise at a speed of 12 knots. There is 4,000 square feet of laboratory space and a working deck space of 4,070 square feet. It is equipped with P-code GPS navigation, dynamic positioning, and the standard suite of oceanographic instrumentation. It has an A-frame and winches suitable or use with the deep-tow transmitter.

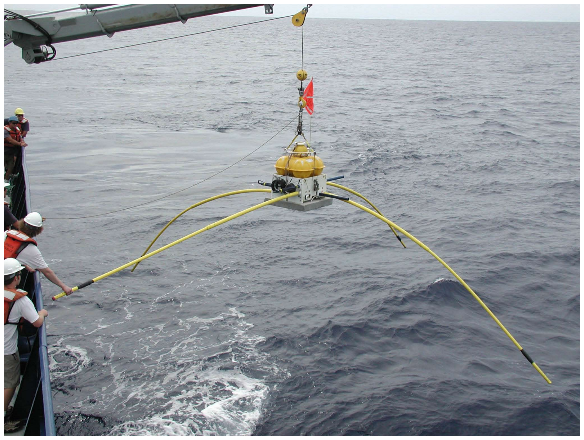

Figure 3. Seafloor electric and magnetic field recorder, right being deployed from the R.V. Roger Revelle. These instruments have performance capabilities comparable to, or better than, current industry equipment. They are capable of recording up to 8 channels of data at speeds of up to 1 kHz (but with total data rate restrictions of about 2,000 Hz–channels). Electric field sensors extend from DC to nyquist, while magnetic field sensors extend from about 10,000 seconds to nyquist.

company which had previously licensed the SIO instrument, and is now using a second-generation instrument based on that experience. A third contractor used expertise from an academic group which had developed much of its marine EM instrumentation through collaboration with Scripps. The specifications of the SIO receiver instrument are:

8 Channels of data
Ex, Ey, Bx, By, Ez sensors, with optional hydrophone
MT between about 5 s (1 km water depth) and 5,000 s period
24 bit ADC
5 GB data capacity on removable solid state memory
Power < 500 mW
External recording compass on all instruments
Long baseline acoustic navigation
Timing accuracy 2 ms/day correctable to 0.2 ms/day
Battery endurance 12 – 60 days, depending on chemistry
Maximum sample rate 1 kHz (250 Hz on 5 channels).
E-field noise 10^{-20} $(\mathrm{V/m})^2$/Hz at 1 Hz (10^{-18} $(\mathrm{V/m})^2$/Hz on Ez)
B-field noise 10^{-8} nT^2/Hz at 1 Hz

We have fully tested 200 A and 500 A EM transmitters with GPS stabilized waveform control capable of operating on any standard coaxial deeptow cable (Figure 4). These transmitters generate about half the output current (and dipole moment) of commercial systems, at a fraction of the power and weight. A factor of 2 in signal to noise ratio is not significant, and is easily made irrelevant if receiver instrument noise is low. Most importantly, transmitter reliability is high, and the output waveform is fully configurable as any binary or ternary waveform, is stable, and synchronized with GPS time.

Because the transmitter system is such a critical element of CSEM operations, we recently constructed a second, identical, 500 A transmitter (both deeptowed unit and topside power supply and control system) which will be taken along on all cruises, providing 100% redundancy for every part of the system except the winch and cable.

The specifications of the SIO transmitter are:

-500–500 A at DC–50 Hz on 200 m dipole
30 kVA power supply with 200-500 VAC 3-phase input
Navigation by long baseline acoustics
9600 baud telemetry over co-ax.
Altitude, depth, sound velocity, tilt, roll, and heading sensors
Any binary or ternary waveform available synchronized to GPS time
Depth rating 6,000 m

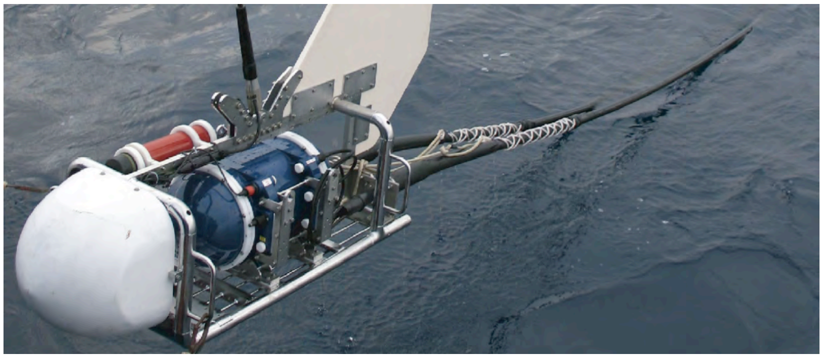

Figure 4. Left is the SIO 500 A transmitter being deployed. Although only about half the size in terms of dipole moment compared with industry transmitters, it is also half the size physically and has features such as a fully configurable binary or ternary waveform with GPS phase stabilization.

Our laboratory staff presently includes 2 engineers and 3 technicians all trained to build and operate this equipment, and 5 students and postocs all with seagoing experience. We have extensive computing resources, including access to the San Diego Supercomputer Center, along with a dedicated 30-node X-serve cluster.

Figure 5. Prototype 3-axis electric field receiver being deployed behind the SIO EM transmitter. The noise floor before transmitter switch-on is comparable to that of sea floor instruments when the shorter antenna length (1 m versus 10 m) is considered.

One piece of equipment developed specifically for a shallow hazards research project is a towed, three-axis electric field recorder, shown in Figure 5. We tested this instrument in early 2007 offshore San Diego and it performed flawlessly, and used it to collect about 20 lines of CSEM data in the Gulf of Mexico in October 2008. Surprisingly, even while being towed at 2 knots through the water behind our transmitter, the noise levels are comparable to those of seafloor instruments when the shorter dipole lengths were considered. This instrument is designed to tow behind the transmitter at a fixed offset of about 400 m to collect continuous data sensitive to near-surface structure.

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