A marine EM survey of the Scarborough gas field, Northwest Shelf of Australia

David Myer, Steven Constable[*] and Kerry Key of the Scripps Institution of Oceanography describe the first fully academic marine CSEM and MT survey of a hydrocarbon reservoir.

The first tests of the marine controlled source electromagnetic (CSEM) method over hydrocarbon reservoirs were carried out 10 years ago offshore Angola by Statoil and ExxonMobil (see Constable and Srnka, 2007, for a review). These companies relied heavily on academic instrumentation for both the EM transmitter and receivers, as well as academic expertise for help with data collection, processing, and some interpretation. However, neither of these surveys represented academic research as such, and the data have been published in summary form only. The rapid expansion of contractor capability in early 2002 meant that academic help in carrying out surveys was no longer needed (or at least that was the perception), and while industry has been fairly generous in supporting research into the method in general, all subsequent data collection over actual reservoirs has been conducted by contractors and with few exceptions is proprietary. Lack of experience in collecting such data sets and lack of access to high quality CSEM data has significantly limited academia's ability to contribute to the continued development of the method. The physics behind marine CSEM is sound, but we believe that limitations in instrumentation, data collection, and (especially) interpretation tools are limiting the commercial application of the method.

The survey we describe here is a breakthrough in this regard. With funding from BHP Billiton Petroleum, we have been able to carry out a comprehensive survey of the Scarborough gas field, on the Exmouth Plateau about 250 km offshore northwestern Australia (Figure 1). Although BHP provided assistance with the experimental design, and gave us access to a large amount of existing geological and geophysical data, the survey was carried out entirely under academic direction, using the research vessel *Roger Revelle*, an 83 m ship operated by Scripps Institution of Oceanography, and a fleet of academically built instruments. We have a number of objectives we wish to address with this experiment: (a) Obtain a calibration data set over a known structure, with control from five wells and excellent 3D seismic data coverage, in order to develop our ability to interpret data with 1D, 2D, and 3D forward and inverse modelling tools; (b) Collect a data set suitable for joint magnetotelluric (MT), CSEM, and seismic interpretation; (c) Investigate the effect of shallow, confounding resistors (Scarborough has regions of shallow gas and gas hydrate, as well as a resistive stratigraphic layer above the reservoir); (d) Understand how to optimize the density and geometry of CSEM receivers and transmitter tows; (e) Examine how well CSEM data can differentiate between various reservoir thicknesses and saturations; and (f) Examine noise and repeatability in CSEM data collection.

Instrumentation and experimental design

Besides taking 50 conventional ocean-bottom EM (OBEM) recorders and two fully redundant 500 A transmitters, we also successfully tested a number of new instrument systems on this project. We had two long-antenna EM receivers (LEMs) configured to measure electric field gradients across two 100 m antennae, which we deployed a total of three times each; a new inverted long baseline (iLBL) acoustic navigation system to locate the position of the transmitter; and two 3-axis electric field receivers designed to be towed at a fixed offset behind the transmitter antenna (Vulcans). Also, 40 of the OBEM instruments were configured to measure vertical electric fields as well as horizontal electric and magnetic fields. All OBEM instruments were equipped with external recording compass/tiltmeters for orientation, and we carried out dedicated LBL acoustic surveys to determine receiver positions to about 3 m accuracy. Most of the data were collected using a transmitter antenna 250 m long and a current of 300 A, except for a profile designed to target gas hydrate, which used a 50 m antenna and 200 A current, behind which we towed two Vulcans at 250 m and 500 m offsets.

The Scarborough gas field is approximately 20 x 30 km in lateral extent, 1000 m below seafloor in 900–950 m water. Well logs peak at about 25 Ωm in a series of stacked reservoirs extending over about 100 m thickness. The Gearle Formation, expressed as a 100 m thickness of claystones and siltstones, sits about 400 m above the reservoir and at 3 Ωm is somewhat more resistive than the surrounding 1–2 Ωm sediments of the Barrow Group. Being about 100 m thick, the transverse resistance of this formation is perhaps comparable to that of the reservoir.

Pre-cruise 2D forward modelling (Figure 2) showed that frequencies around 1 Hz would be most sensitive to the

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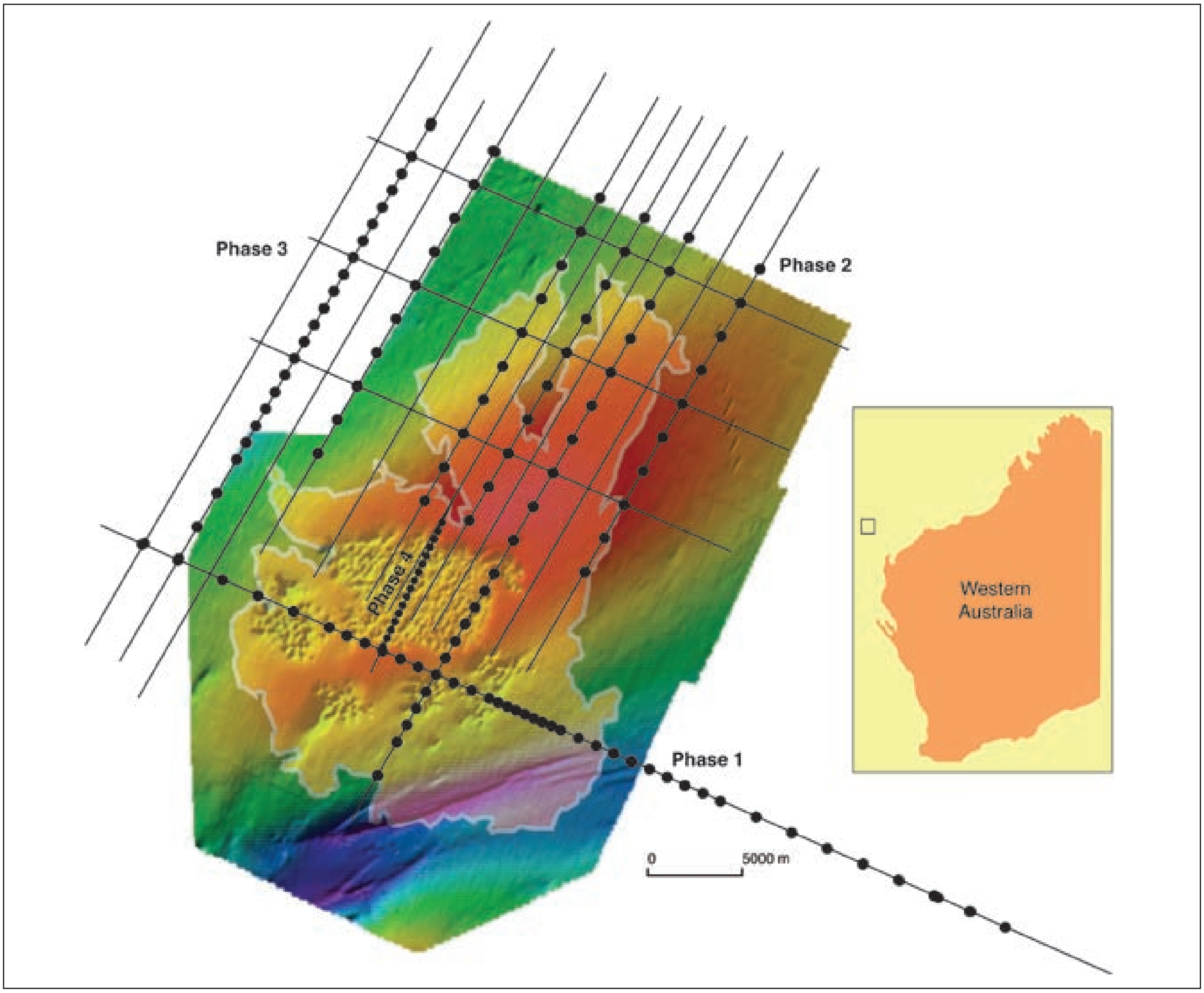

Figure 1 *Locations of OBEM deployments (filled circles) and CSEM tow lines (black lines) overlain on shaded relief of bathymetry and the outline of the reservoir. Water depths on this figure vary from 900 m (red) to 990 m (blue).*

target reservoir, with about a factor of two enhancement of horizontal radial electric fields. Frequencies of 0.25 Hz and lower were not expected to have significant sensitivity to the target. Inversions using the 1D OCCAM algorithm (Key, 2009) showed that the reservoir could be recovered from multi-frequency, multi-component data with 1% random noise added. Our transmitter signal was a newly designed binary waveform which has about two orders of magnitude of usable frequency content (defined as harmonics with power above 0.1 times the peak current). The other useful feature of this waveform is that the frequency of the most powerful harmonic is three times the fundamental frequency, and so we chose a fundamental of 0.25 Hz, which placed peak power at 0.75 Hz, thus allowing us to test our predictions about 0.25 Hz sensitivity without compromising the signal to noise at the preferred frequency.

Data

We had 32 days of shiptime available for the project, which included the *Revelle*'s seven day transit from Perth to Darwin. We divided data collection up into four phases (Figure 1), the first being a long line across the largest part of the reservoir with a smaller crossed line to collect data amenable to 1D and 2D interpretation. We then moved all instruments to a 2D grid across the more complicated, northern part of the target, and towed the transmitter in a pattern which included a number of lines between instruments, to provide a data set suitable for testing 3D modelling. We re-occupied two Phase 1 sites (on the north side of the Phase 1 cross line) and towed them a second time to test repeatability. We then moved about half the Phase 2 instruments to a dense line to the west of the target to examine another, deeper structure. Finally, after recovering all the Phase 2 and 3 instruments, we just had time to carry

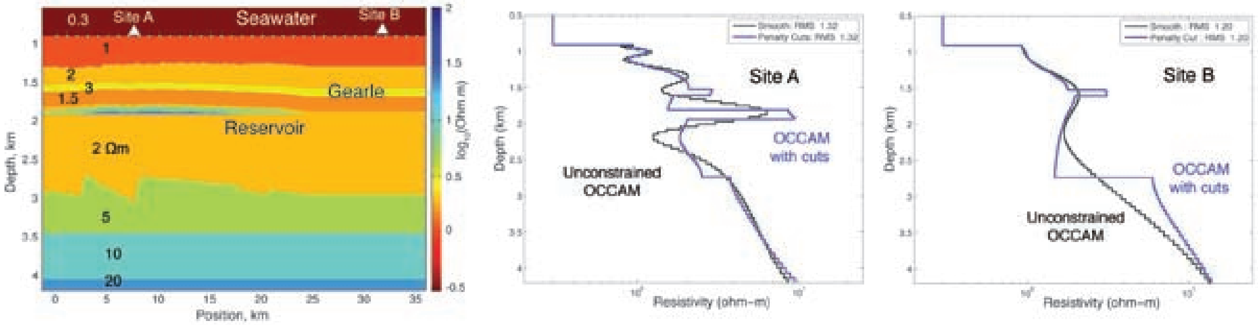

Figure 2 Two-dimensional experimental design study. The left panel shows the 2D model slice that was used to compute CSEM responses with and without a simplified reservoir layer. The other panels show unconstrained smooth inversions of the synthetic data with 1% noise added, along with inversions with cuts at the Gearle and reservoir, both for sites on (A) and off (B) the target structure.

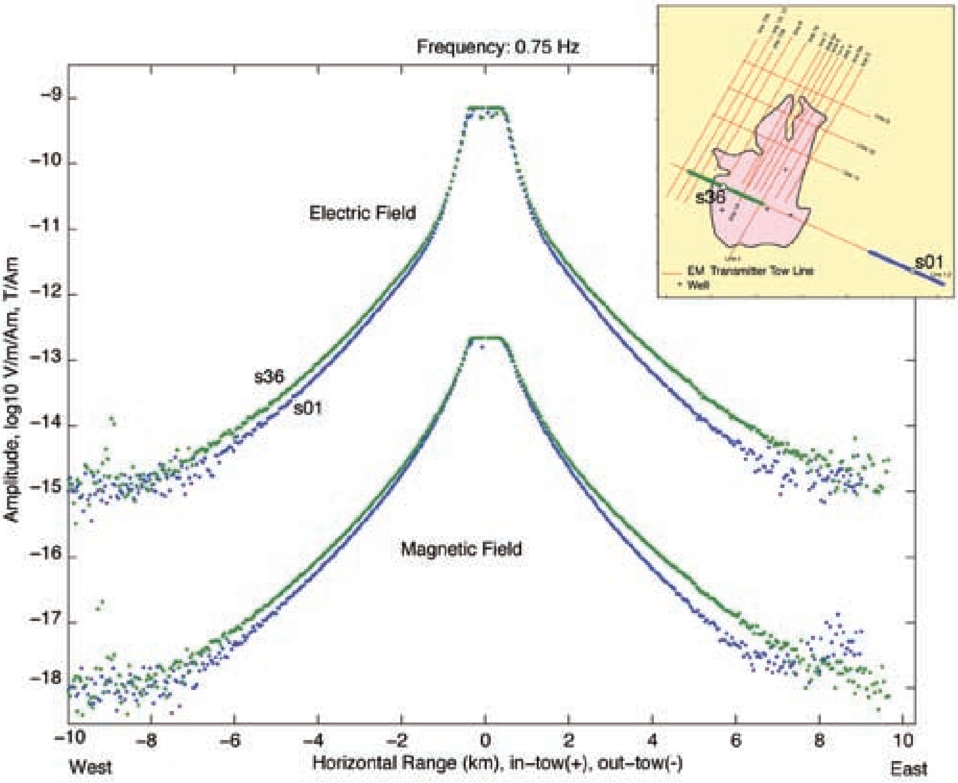

***Figure 3** Example of horizontal electric and magnetic field amplitudes from two sites on (s36) and off (s01) the reservoir at a frequency of 0.75 Hz. As predicted by the experimental design study, on-target responses are about a factor of two larger than off-target responses. These are 60 s stack frames; the noise floor is respectable, but analysis shows that the dominant noise source is environmental electric and magnetic fields associated with water currents, rather than instrumental noise.*

out a 15-site survey to look for hydrate near the center of the structure.

Examples of two sets of horizontal amplitude data are shown in Figure 3. These are 60 s stacks and qualitatively show the response of the reservoir quite clearly, and confirm our predication of a factor of two increase in amplitude. The noise floors for both the electric and magnetic field data are respectable (10^{-15} V/(Am^2) and 10^{-18} T/(Am) respectively), but examination of data from the LEM instruments shows that noise floor is not limited by instrumental noise. Rather, we are limited by environmental noise caused by water motion associated with tidal currents, which were quite strong in this area (see Constable et al., 2009). Further stacking and processing should reduce the noise floor somewhat.

An overview of all the electric field amplitude data for the main Phase 1 line can be obtained by constructing a normalized amplitude pseudosection (Figure 4). Here we can see confirmation of our prediction that 0.25 Hz would have little sensitivity to the target. Our peak frequency of 0.75 Hz shows amplitudes increased by a factor of two over the target structure, with off-target fields still elevated by about 25%, presumably because of the Gearle Formation. Higher frequencies also respond to the target (as expected), but with noise floors reached at shorter ranges (indicated by the blue parts of the plots). We are not supporters of interpreting anomaly plots, particularly when data from a seafloor recorder, rather than a sensibly chosen model, is used for the normalization, but these figures provide a graphic illustration of the sensitivity of the data to the reservoir.

Our pre-cruise modelling showed that we should try to collect data with errors approaching 1%, and we have spent considerable effort with our processing algorithms, navigation, and noise models in order to reduce systematic errors in the data and get as close to this value as possible. Figures 5 and 6 show 1D inversions and data fits of five frequencies of out-tow horizontal electric and magnetic field amplitudes for two sites, one on and one off the reservoir. All data are inverted jointly and fit to RMS 1.0 with about 2% error bars at the lower frequencies/shorter ranges.

That we can invert multi-component data over nearly a decade of frequency with a 1D model and achieve this level of misfit is a remarkable achievement, but we have been somewhat selective in order to accomplish this. We have neglected the 0.25 Hz data, which may be sensitive

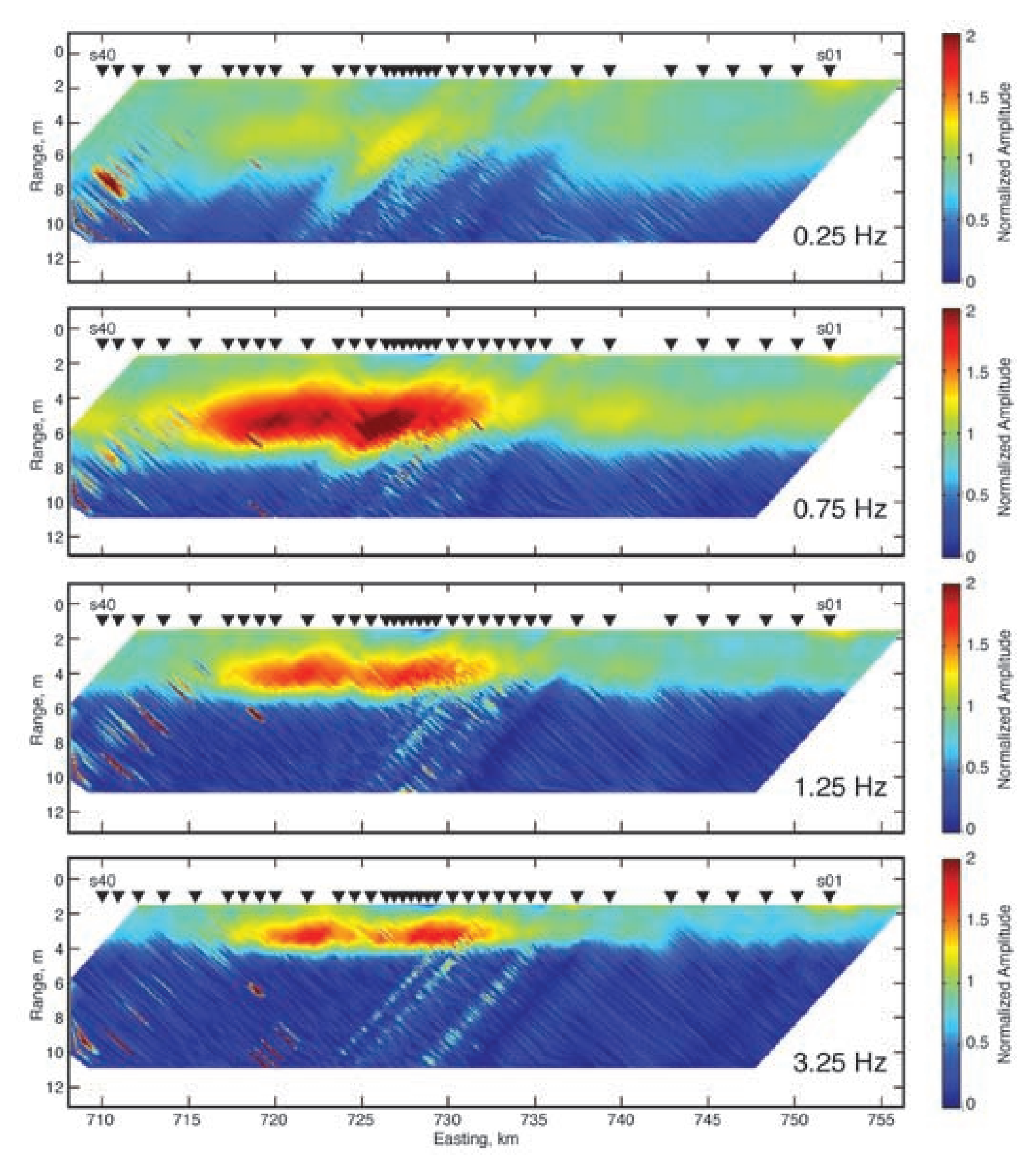

Figure 4 *Phase 1 (see Figure 1 for location) normalized out-tow electric field amplitude pseudosections at three frequencies (0.25 Hz, 0.75 Hz, 1.25 Hz, and 3.25 Hz). The fields have been normalized by the top two layers of the experimental design model shown in Figure 2 (i.e., 300 m of 1 Ωm underlain by 2 Ωm). As predicted by the experimental design, 0.25 Hz is not particularly sensitive to the target structure.*

to non-1D structure at depth. Inverting both the in-tow and out-tow data together produces similar models but increases the misfit to about 4%, again probably because of breakdown in 1D assumptions as one expands the transmitter footprint from 8 km to 16 km. Finally, while we have excellent quality phase data, fitting both amplitude and phase doubles the misfit and, of most concern, produces systematic amplitude and phase residuals, with amplitude residuals about +5 to +10% and phase residuals about -5 to -10°. We have attempted to rule out problems in receiver calibration and source signature, and do not think it a processing error. Rather, modelling shows that this may be caused by anisotropy, which normally can be ignored in radial field interpretations, but perhaps not when fitting to the 1–5% level. We are carrying out more work to explore this.

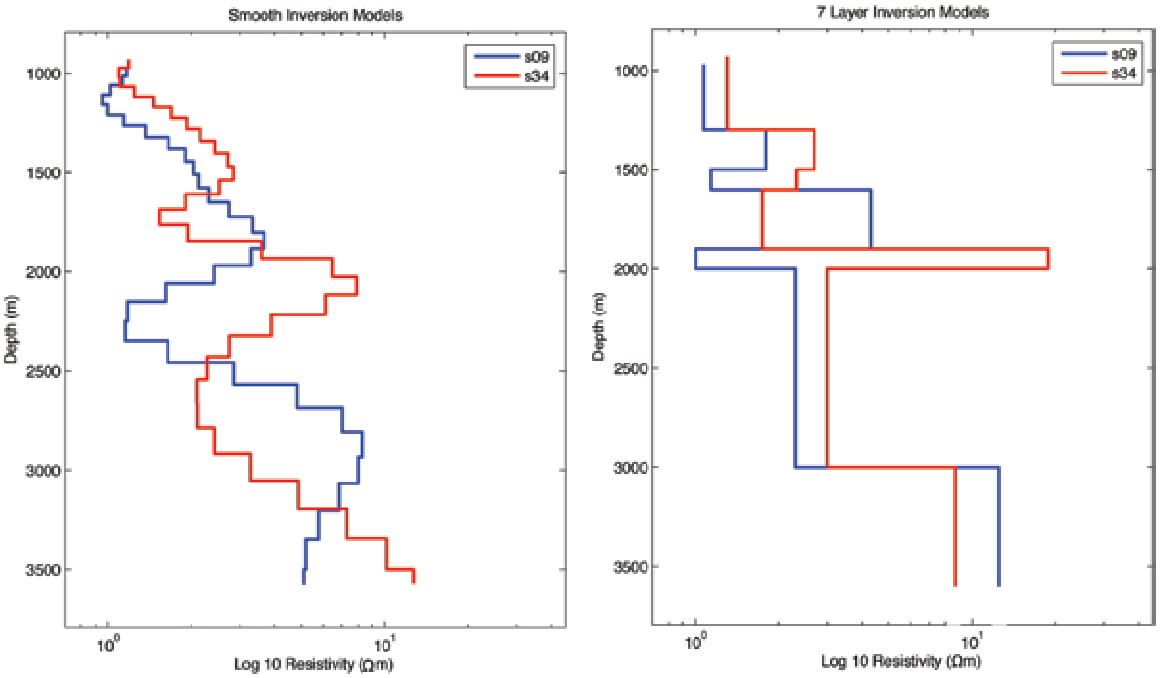

Figure 5 *Unconstrained smooth 1D inversions of out-tow multi-frequency electric and magnetic field amplitudes at two sites, on (s34) and off (s09) the reservoir (left), and similar inversions where the layer structure has been reduced to seven layers with thicknesses given by the experimental design study (right). The on-target inversions (red) show a response from both the Gearle and the reservoir, with some attempt to differentiate between them. The off-target smooth inversion shows a single response from the Gearle, but the seven layer inversion produces an oscillatory model, probably because the reservoir layer is not required to fit the data.*

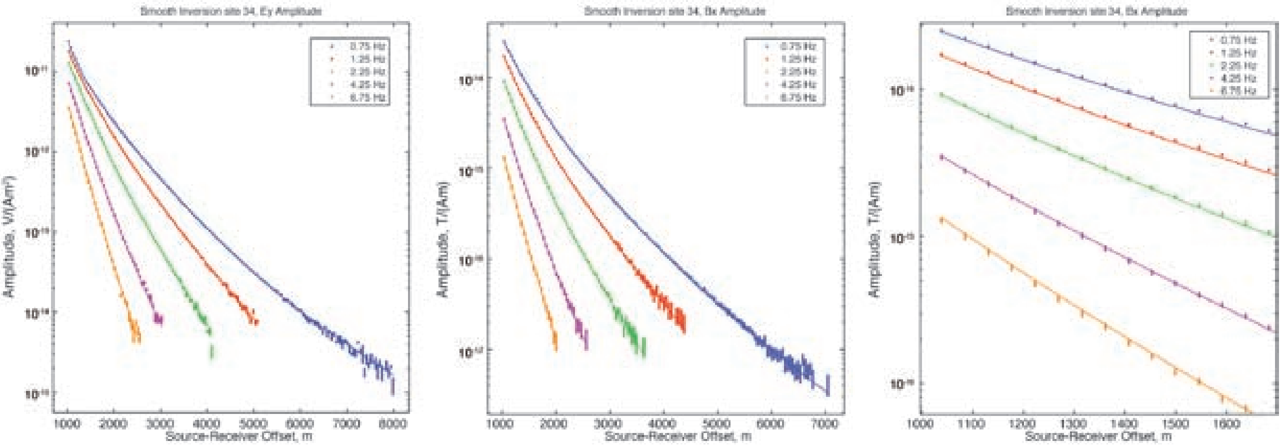

Figure 6 *Fits of the smooth on-reservoir model shown in Figure 5 to the electric (left) and magnetic (center) field amplitudes. On the right is a close-up of the short-range magnetic field data. Low frequency, short-range data error bars are about 2%, but the error model propagates navigational errors into larger error bars at higher frequencies, and longer ranges are also subject to larger errors associated with the noise floor. The fit is to RMS 1.0.*

The unconstrained smooth models shown in Figure 5 are remarkably similar to the ones generated from synthetic 2D data in the design study. We can 'lead' the inversion by making the layered structure similar to the known lithological boundaries, also shown in Figure 5, which sharpens up the reservoir model but confuses the off-reservoir model with more layers than it requires. Clearly, much further work is required in terms of inversion, but these initial results serve to illustrate the quality of the data we have collected and confirm that for this large target, 1D inversion is valid and useful.

Conclusions

We made a total of 144 CSEM/MT receiver deployments and carried out 12 days of CSEM transmitter tow (about 800 km including turns, 630 km of which generated usable on-line data) over the Scarborough gas field, an area well studied with 3D seismic and five exploration wells. Although beyond the scope of this short article, we have also processed marine MT data of reasonable quality from most sites. This large amount of high quality, multi-component, multi-frequency data will allow us, and others, to test a wide variety of inversion and interpretation techniques, up to and including joint seismic-CSEM inversion. It is our intention to release these data to the public as we publish our own studies, in order to facilitate progress in marine EM interpretation.

Acknowledgements

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