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Mapping shallow geological structure with towed marine CSEM receivers

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SUMMARY

Marine controlled-source electromagnetic (CSEM) surveying using nodal ocean-bottom recorders has become a standard tool for offshore hydrocarbon exploration. A combination of low-noise receivers and transmitters emitting 1,000 amps or more allows data collection at source–receiver offsets of up to 10 km, with depths of investigation reaching several kilometers. However, characterization of shallow geological structure (less than several hundred meters below mudline) is limited by the typical node spacing of 500 m or more. A 3-axis electric field receiver has been developed that is towed behind the EM transmitter in order to collect continuous constant-offset data, either as a stand-alone surveying technique or as a supplement to a node-based survey. Low frequency noise on the towed receiver is significantly higher than that for sea-floor nodes, but at 10–100 Hz approaches that of sea-floor instruments when the shorter (1–2 m) antenna length is considered. Early applications of this new technology were limited to source–receiver offsets of a few hundred meters, for fear of the array fouling on the sea-floor. To address this we have developed a telemetry protocol that can be used on twisted-pair copper cables to distances of up to 4 km, allowing real-time monitoring of the array depth during towing. By careful trimming of the buoyancy we are able to "fly" an array of four receivers with offsets of up to 1,000 m at an altitude of 100 m above the seafloor, with only a few meters variation in depth across the array during level flight. Tests were carried out in the San Nicolas Basin, offshore southern California, over an area where a seismic bottom-simulating reflector (BSR) had been identified in heritage seismic data. Increases of 30% in amplitude and 20° in phase were observed when the array was over the BSR, suggesting minor amounts of hydrate above the BSR or free gas accumulation below the BSR.

INTRODUCTION

Node-based marine CSEM, in which a line or array of electric and magnetic recorders is deployed on the sea-floor and a deep-towed EM transmitter is flown over the receivers, has become a standard part of the exploration toolkit. Because the sea-floor is an extremely low noise environment, and electric dipole transmitters can be made with moments of order 100,000 Am, source–receiver offsets of around ten kilometers are possible before the instrument noise floor is reached. Since the depth of resolution is of order one third of source–receiver spacing, these data are capable of detecting resistive hydrocarbons and other geological structure at depths of several kilometers below mudline.

Typical receiver spacing for node-based CSEM is 500–2,000 m, which means that much of the shallow sea-floor geology is under-sampled. This can be a problem in two situations. The first is if the shallow structure is of interest, such as in the study of gas hydrates, shallow gas, and groundwater. The second is if there are variations in shallow resistivity that confound the interpretation of the deeper resistivity structure. Since a large component of the electric CSEM signal is galvanic, the signature of shallow structure can easily mimic the signature of deep structure in a single CSEM component. Although multi-frequency, multi-component data (amplitude and phase of both magnetic and electric fields) can help distinguish shallow/deep ambiguities, high resolution at shallow depths will only be obtained with densely spaced, short offset data, since there is such a strong geometrical component in the marine CSEM method.

To address this problem in the context of gas hydrate mapping, we developed a three-axis, continuously towed receiver that is neutrally buoyant and can be flown some hundreds of meters behind a CSEM transmitter. The first version of this instrument, nicknamed "Vulcan", was used in a fairly extensive node-based gas hydrate study in the Gulf of Mexico in late 2008 (Weitemeyer and Constable, 2010). In the work described here, we re-designed the Vulcan instrument to allow multiple units to be towed behind the CSEM transmitter and increased the source–receiver offsets to 1,000 m or more. This was partly motivated by that fact that deploying and recovering ocean-bottom nodes is a time consuming enterprise. The ability to tow an array with multiple source–receiver offsets and a maximum offset of a kilometer or more would allow shallow surveys to be carried out without sea-floor nodes being deployed. Alternatively, the nodes can be deployed in a sparse array and the Vulcan system used to interpolate structure between nodes. In either case, the cost of CSEM surveying is decreased.

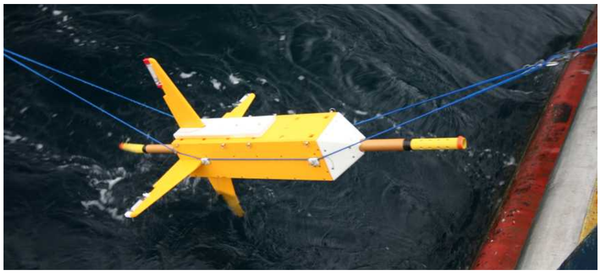

Figure 1: Towed 3-axis electric field recorder ("Vulcan" Mk II) being deployed. The split line allows instruments to be clipped in and out of the array without having to transfer load.

THE VULCAN INSTRUMENT

The Vulcan Mk I instrument used in the Gulf of Mexico was built using an electric field logger from a standard sea-floor node, adding externally mounted depth and pitch/roll/heading

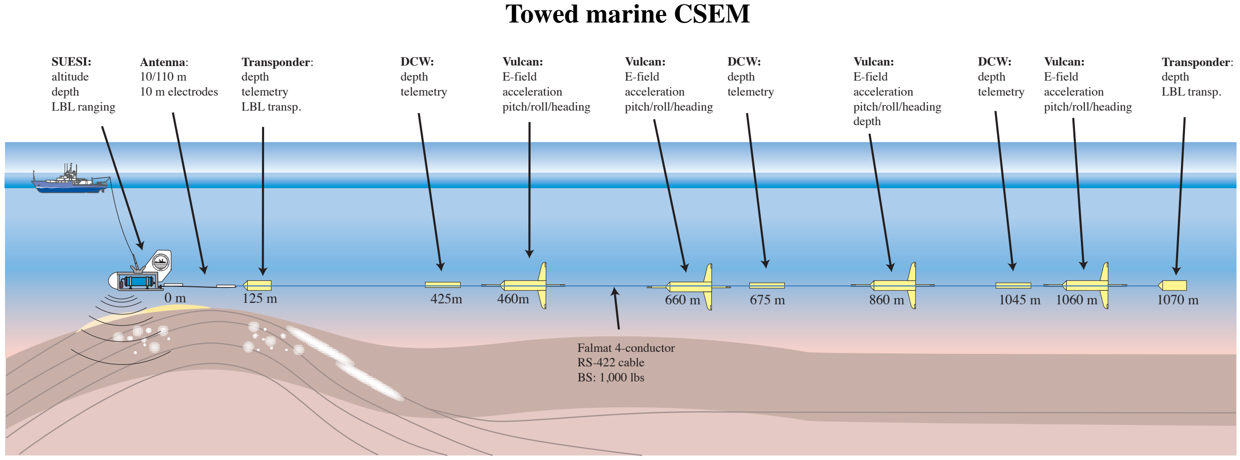

Figure 2: The array of 4 Vulcan Mk II instruments and 3 depth communication widgets (DCW) used in the San Nicolas Basin tests.

sensors, along with a long base line (LBL) acoustic transponder. Flotation was two oceanographic glass spheres. While this instrument demonstrated the concept and produced excellent data, it does not ideally lend itself to being used in a multi-receiver array, being about 2 m in height and width and about 4 m long, with an air weight of about 200 kg. For the Vulcan Mk II instrument described here we incorporated the depth and pitch/roll/heading sensors into the main logger pressure case, removed the acoustic transponder, and replaced the glass flotation spheres with a rectangular slab of syntactic foam. This made the instrument smaller by a factor of 2 in every direction and resulted an air weight of about one third the original instrument (Figure 1). The pitch/roll sensors, which are logged at one-second intervals by a separate serial data logger, were supplemented by a 3-axis accelerometer logged at the same rate as the electric field (typically 250 Hz).

In order to safely increase the source–receiver offset while flying close (about 100 m) to the seafloor, we need real-time monitoring of the array depth. The Scripps undersea electromagnetic source instrument (SUESI) avoids the use of fiber optic communication systems in order to reduce cost and complexity; communication between the ship and the transmitter is carried out using frequency-shift-keyed (FSK) telemetry over the coaxial copper tow cable. To extend telemetry back to the array instruments we developed a packet-based, multi-drop error detecting communication protocol which uses the RS422 standard on a twisted pair of copper conductors. We have tested this communication system on oceanographic conductivity/temperature/depth (CTD) cables to distances of 4 km. For the Vulcan array we used a 1070 m long tow cable consisting of two pairs of 22 gauge stranded copper wire and a Kevlar strength member. At intervals along the cable we mounted communication devices which incorporated Paroscientific Inc. Digiquartz pressure sensors, accurate to about 10 cm depth. Figure 2 shows the layout of the final array used in the experiment described in the next section. The first depth sensor was position immediately after the transmitter antenna, to provide real-time information on the antenna dip. Three more devices were distributed along the array. We separated the communication devices from the Vulcans in order to avoid noise on the electric field sensors.

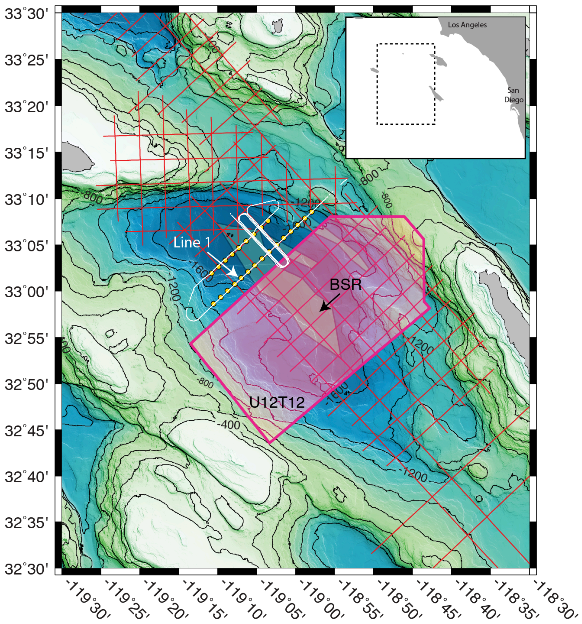

Figure 3: Bathymetry of the San Nicolas Basin, offshore southern California. Yellow dots show the location of deployed conventional nodal electromagnetic receivers and white lines show the path of the transmitter tow and Vulcan array. The outline of the BSR, determined from seismic data collected along the red lines, is shaded. The area marked U12T12 is a US Navy testing range having restricted access.

SAN NICOLAS BASIN TESTS

We tested the Vulcan array offshore southern California in December 2011. The Bureau of Ocean Energy Management had identified a bottom simulating reflector (BSR) in open file seismic data collected in 1983. A BSR is an indicator of gas accumulation at the base of the gas hydrate stability field, and could provide a suitable target for tests of our electromagnetic profiling system. We derived the areal extent of the BSR from the seismic data (Figure 3). Unfortunately, most of the BSR is in a US Navy test range, which has very restricted access, but we were able to get permission to work off the NW edge of the range. We deployed 25 standard sea-floor receivers and towed the EM transmitter and Vulcan array for about 140 km over a period of about 50 hours. The tow pattern consisted of two NE/SW lines across the basin and a series of 6 lines spaced 200 m apart to demonstrate our ability to carry out dense surveys with the array. The transmission used the Waveform D described in Myer *et al.* (2011), broadcast on a 100 m antenna with a peak current of 200–300 A. The fundamental frequency was 0.5 Hz on line 1 and 0.25 Hz for the other lines.

Figure 4 shows a power spectrum of receiver data collected while the transmitter is off. Power at frequencies above 1 Hz represents instrument noise – below this there may be some contamination from magnetotelluric signal. At the highest frequency (100 Hz), noise on the towed receiver is comparable to that of the sea-floor instrument when the shorter receiver dipoles lengths are considered (1–2 m versus 10 m), but at 1 Hz is about 1,000 times the amplitude of the sea-floor instrument. However, the transmitter signal is still large at an offset of 1 km, and so the higher noise does not prevent useful data collection.

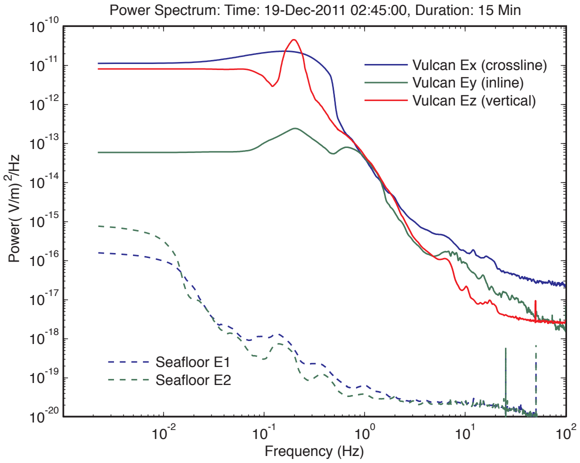

Figure 4: Power spectrum of the fourth Vulcan (1,000 m offset, solid lines) and a sea-floor receiver (broken lines) during transmitter off time.

The CSEM processing scheme of Myer *et al.* (2011) allows the computation of a variance in the mean over the stacking window, here 60 seconds. Figure 5 shows the standard error in CSEM data at the various transmission frequencies for the third Vulcan during line 1, when the peak transmission current was 200 amps. As one would expect from the noise spectra, noise tends to be lower at higher frequency, although there is variation in the transmitter power at the various frequencies in Waveform D: the largest amplitudes are at 1.5 and 3.5 Hz. Although about a factor of 100 larger than for seafloor instruments, the stacking errors of 10^{-13} V/Am^2 are well below the amplitudes of the CSEM signals at a source–receiver offset of 1,000 m (10^{-11} V/Am^2). The spikes in the variance plot suggest that occasional motion of the receiver results in increased noise levels. The stacking variance was slightly higher at 0.5 Hz for the fourth Vulcan, suggesting that this instrument was moving more that the others and that increased drag on the far end of the array might have improved things.

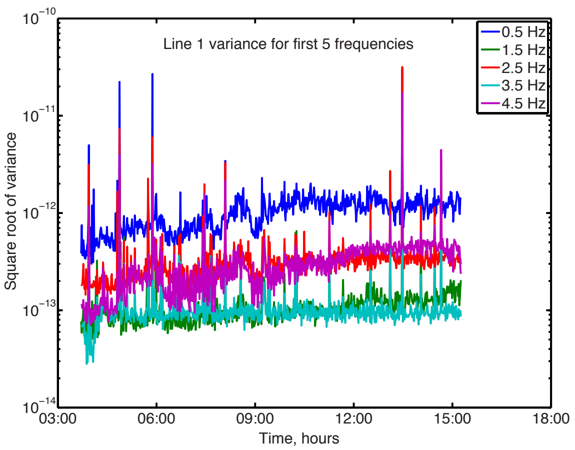

Figure 5: CSEM stacking variance for the third Vulcan (800 m offset) at various frequencies over a 60 second window.

A sample of towed CSEM data is shown in Figure 6. We have plotted total field amplitude and vertical phase at a frequency of 1.5 Hz for the Vulcan with the greatest source–receiver offset (1,000 m). Data are for the first tow line, the NE/SW trending line to the south-east of the array in Figure 3. The line was towed from NE to SW, so we have reversed the distance axis to match the convention that right is to the north or east. Amplitudes and phases are elevated over the BSR, by about 30% in amplitude and 20 degrees in phase. Until we carry out quantitative modeling, we cannot say whether this is a result of gas accumulation below the BSR or hydrate in the sediment above.

The figure also shows the depths of the transmitter and array, along with the pitch and roll of the receiver instrument. There may be some correlation between the CSEM data and the navigation parameters, but it appears weak. We have chosen total field amplitude and vertical phase because they both should be relatively immune to instrument orientation. The peak in amplitude and phase over the center of the BSR at a distance of -20 km is over the flat center of the basin where the array is flying without much variation in navigation. The scatter in the data is about an order of magnitude higher than the stacking variance shown in Figure 5, indicating that these are actual variations in the data. The slight correlation with the size of the pitch and roll variations suggests that the source of the scatter is instrument motion, and future work will investigate this further. The target height of the transmitter tow was 100 m. A miscalculation in the buoyancy of the far electrode and antenna termination resulted in the antenna flying about 10 m lower than the transmitter, but over flat bathymetry the array of Vulcan receivers flew within a few meters of level, or within a fraction of a percent of the total array length.

CONCLUSIONS

We have successfully demonstrated that the source–receiver offset in towed marine CSEM instruments can be increased to at least 1,000 m without serious compromise in signal to noise ratio and without fouling on the sea-floor. The instrument systems described here could be used for a stand-alone survey to characterize the upper few hundred meters of the seabed, or in conjunction with deployed sea-floor nodes.

ACKNOWLEDGMENTS

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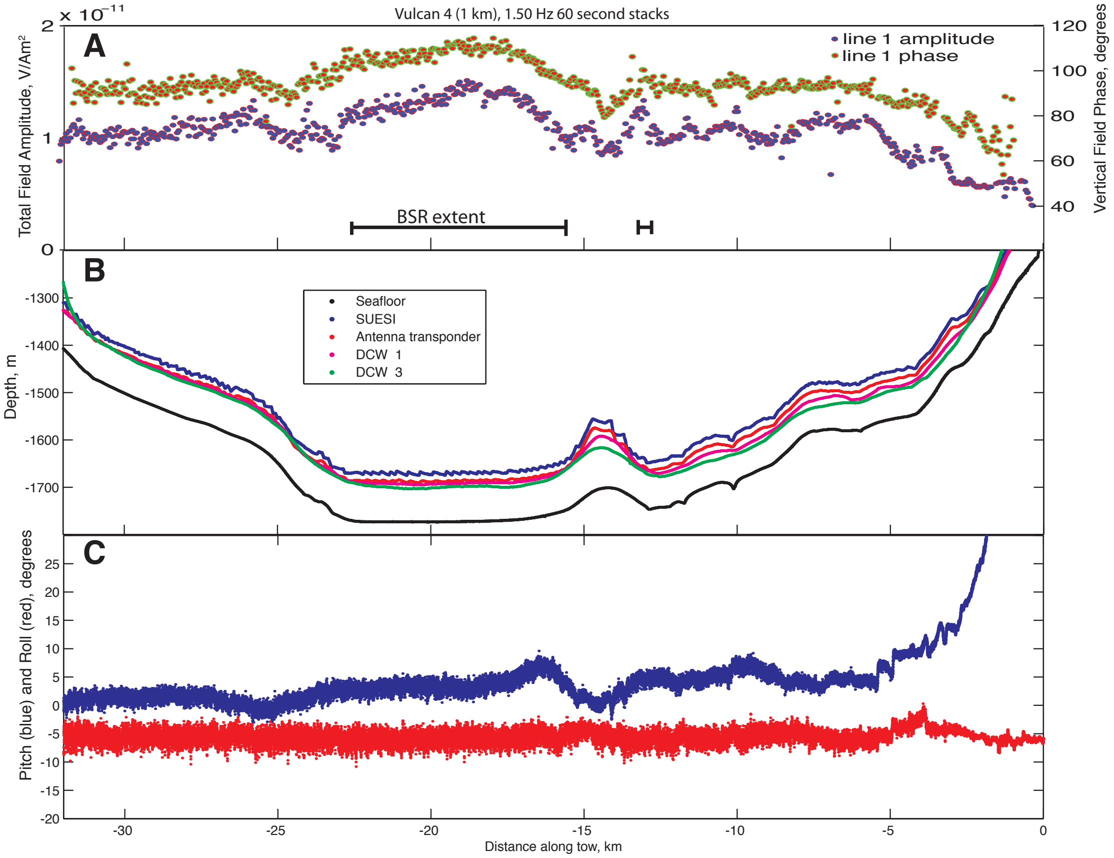

Figure 6: A: Total electric field amplitude and vertical field phase along line 1 for the Vulcan at a 1 km source–receiver offset. B: Depths of the sea-floor, transmitter (SUESI), antenna far end transponder, and two depth communication widgets. C: Pitch and roll of the Vulcan instrument.