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Special Section — Marine Controlled-Source Electromagnetic Methods

An introduction to marine controlled-source electromagnetic methods for hydrocarbon exploration

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ABSTRACT

Early development of marine electromagnetic methods, dating back about 80 years, was driven largely by defense/military applications, and use for these purposes continues to this day. Deepwater, frequency-domain, electric dipole-dipole, controlled-source electromagnetic (CSEM) methods arose from academic studies of the oceanic lithosphere in the 1980s, and although the hydrocarbon exploration industry was aware of this work, the shallow-water environments being explored at that time were not ideally suited for its use. Low oil prices and increasingly successful results from 3D seismic methods further discouraged investment in costly alternative geophysical data streams. These circumstances changed in the late 1990s, when both Statoil and ExxonMobil began modeling studies and field trials of CSEM surveying in deep water (around 1000 m or deeper), specifically for characterizing the resistivity of previously identified drilling targets. Trials offshore Angola in 2000–2002 by both these companies showed that CSEM data can successfully be used to evaluate reservoir resistivity for targets as deep as several thousand meters. Both companies leveraged instrumentation and expertise from the academic community to make swift progress. The resulting rapid growth in the use of marine EM methods for exploration has created a demand for trained personnel that is difficult to meet; nevertheless, at this time, CSEM data represent a commercial commodity within the exploration business, and acquisition services are offered by three companies. The ability to determine the resistivity of deep drilling targets from the seafloor may well make marine CSEM the most important geophysical technique to emerge since 3D reflection seismology.

INTRODUCTION

Marine controlled-source electromagnetic (CSEM) surveying has been transformed recently from a relatively obscure academic discipline to a promising new tool for remotely detecting and mapping offshore hydrocarbon reservoirs. This transformation has been driven in large part by the technical and economic challenges associated with exploration in the deepwater environment. For example, seismic hydrocarbon indicators lack perfection, and deepwater exploration wells are expensive; therefore, collecting additional data sets makes sense if they add information that can provide new insights and significantly reduce risk. Early indications are that marine CSEM data may provide some risk reduction in this regard. Currently, the industry is in the process of assessing this new technology. It is fair to say that oil and gas companies, and the national licensing entities, hold views on marine CSEM varying from cautious observation, through judicious use, to enthusiastic embrace. In this paper, we review some of the history of the method and present some early examples of the technology in use. No attempt is made here to review all CSEM technology for hydrocarbon applications or to discuss onshore applications, which are receiving some renewed interest from the industry. For this we refer the reader to Strack (1992), Strack and Vozoff (1996), and Hobbs et al. (2006). For a recent review of academic marine EM studies, see Baba (2005).

Figure 1 introduces the basic method we discuss. A horizontal electric-field transmitter is towed close to the seafloor to maximize the energy that couples to seafloor rocks. Although other source con-

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figurations have been used, such as vertical electric and horizontal magnetic dipoles (e.g., Edwards, 2005), the long horizontal electric bipole offers a number of practical and theoretical advantages; hence, it is the only source currently used in the industry. A series of seafloor electromagnetic receivers spaced at various ranges from the transmitter record the time-varying source signal over source-receiver ranges from zero to several tens of kilometers, depending upon source waveform period and the conductivity below the seafloor. Data processing — including time-domain stacking (binning in time windows), Fourier transformation, and merging with navigation and position — converts these recordings into amplitude and phase of the transmitted signal as a function of source-receiver offset and frequency (which is typically between 0.1 and 10 Hz). Because the electromagnetic skin depth is almost always smaller in seawater than in subseafloor rocks, at sufficient source-receiver offset, the electric and magnetic fields measured by the receiver instruments have propagated almost entirely beneath the seafloor. This desired sensitivity to subseafloor geology can be significantly weaker in shallow water and at higher frequencies, where the air layer exerts a proportionately stronger influence on the data. This so-called airwave effect arises from an unfavorable ratio of skin depths, where the source signal up through the water column and back down to the receivers is comparable or larger than the signal through the geology. Equipped with magnetic as well as electric sensors, the receivers can recover the natural source magnetotelluric (MT) signals, which can be viewed either as a source of noise for CSEM or useful data for recovering geologic structure.

In geophysics, electric and electromagnetic (EM) methods are used to measure the electric properties of geologic formations. At the low frequencies used in marine CSEM, rock resistivity accounts for almost all of the electromagnetic response. Because replacement of saline pore fluids by hydrocarbons (gas, gas condensate, or oil) increases the resistivity of reservoir rocks, EM methods are clearly important exploration tools. Until recently, the main application of electric methods in the oil and gas business has been well logging. The MT method has been used on land since the 1950s (Vozoff, 1972) and in the marine environment since the 1980s (Key et al., 2006) to image geologic structure as part of the exploration process. The MT method is particularly useful for mapping salt, volcanics, and carbonates that present challenges to seismic methods. However, because MT currents within the earth are generated mostly in the horizontal plane, thin subhorizontal resistive formations are almost invisible to the MT method, and so the technique alone is not useful for hydrocarbon fluid detection. On the other hand, the dipole transmitters used in marine CSEM generate vertical electric fields that sense horizontal resistors of sufficient size.

HISTORICAL CONTEXT

Beginnings

The use of electromagnetic methods in hydrocarbon exploration dates back to the beginning of the twentieth century (e.g., Rust, 1938) and on land continues to this day, mainly through MT surveys carried out to provide structural constraints. Marine electrical methods started with DC resistivity surveys carried out over water within only a few years of the method's inception (Schlumberger et al., 1934). For DC methods to have any great sensitivity, seafloor resistivity has to be less than seawater resistivity (which is 0.25 to 0.3 Ωm, depending on salinity and temperature); thus the main application was prospecting for sulfide ores. Work carried out over 80 years ago, off the Cornish coast, was reviewed by Francis (1985). A Wenner survey in the same area of England was reported by Francis (1977). In the context of current marine CSEM practices, it is interesting to note that this early surface-towed array had an emission current of 2000 A, provided by the generators of a minesweeper. Wynn (1988) developed a marine induced-polarization system to explore for mineral sands. However, because these are all shallow-water systems and the market for offshore mineral mining is small, little commercial activity in marine DC methods has developed.

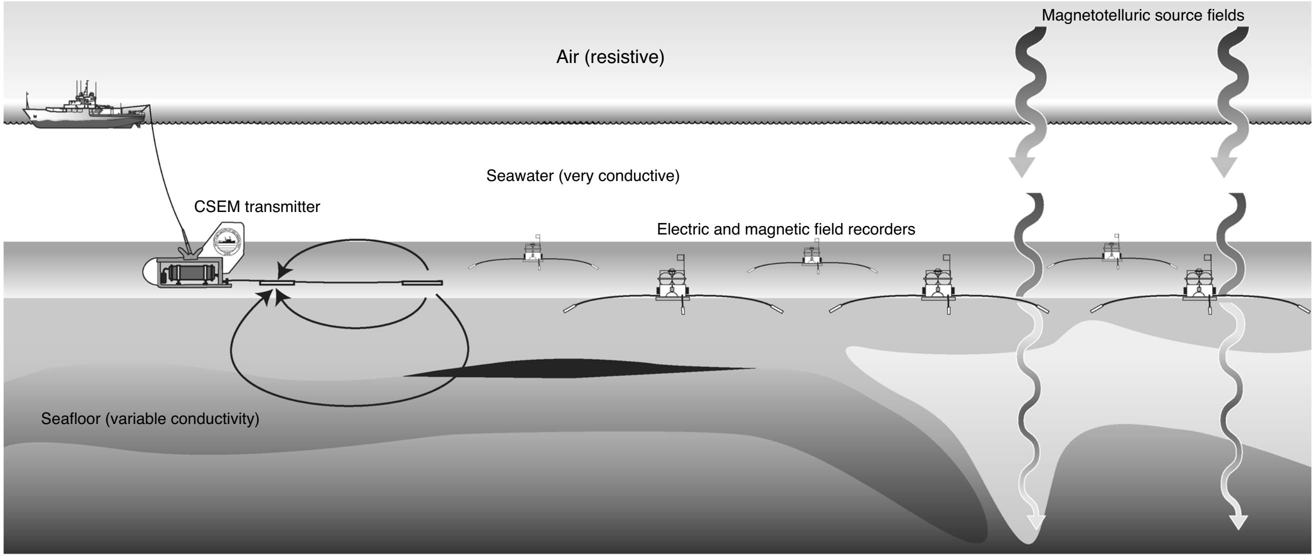

Figure 1. Schematic representation of the horizontal electric dipole-dipole marine CSEM method. An electromagnetic transmitter is towed close to the seafloor to maximize the coupling of electric and magnetic fields with seafloor rocks. These fields are recorded by instruments deployed on the seafloor at some distance from the transmitter. Seafloor instruments are also able to record magnetotelluric fields that have propagated downward through the seawater layer.

Some of the earliest work on AC marine electromagnetic methods involved military applications, dating back to early in the last century with work on submarine cables and ship guidance (Drysdale, 1924). The use of electric and magnetic fields for vessel detection and characterization continues to the present time, although given the nature of the applications, publications are hard to find. The proceedings of the various MARELEC conferences probably provide the best unclassified view of this field.

Academic development of CSEM

The deepwater marine CSEM method used today for hydrocarbon exploration was developed by Charles Cox of Scripps Institution of Oceanography in the late 1970s (Cox, 1981), and the first experiment was carried out on a mid-ocean ridge in the Pacific in 1979 (Spiess et al., 1980; Young and Cox, 1981). Cox had been working on seafloor magnetotelluric equipment and methodologies for a while (Cox et al., 1971). The original motivation for his CSEM experiments was to study the shallow and resistive parts of the oceanic lithosphere by replacing the relatively high frequency energy lost to magnetotelluric fields with a deep-towed man-made transmitter. Early funding for instrument development came from the U. S. Defense Advanced Research Projects Agency (DARPA), which was interested in the effect of the seafloor on submarine communications. Support also came from the U. S. Office of Naval Research (ONR), which wanted to learn more about the seafloor noise environment. Several early experiments (e.g., Webb and Constable, 1986) involved combined deployments of a sensitive broadband pressure variometer (known as the differential pressure gauge, or DPG; Cox et al., 1984) and sensitive electric-field recorders (Webb et al., 1985). Because of the funding agencies' interest in the resistivity structure of normal oceanic lithosphere, the next few experiments moved away from the ridges to more representative crust (Cox et al., 1986; Constable and Cox, 1996). The oceanic lithosphere proved to be remarkably resistive; the lower crust and upper mantle approaches 10^5 Ωm, and the resistivity-thickness product of the lithosphere exceeds 10^9 Ωm^2. Combined with the high conductivity-thickness product of the ocean (10^4 S), the effect of such a resistive lithosphere is to trap horizontal electric currents associated with MT fields or horizontal water flow in the ocean for very large distances.

As useful as this information is about the normal seafloor, geologic interest then (and now) is biased toward areas of tectonic activity, such as the mid-ocean ridges that provided the initial target for CSEM studies. Martin Sinha and his group from the University of Cambridge started to develop a marine CSEM system in the mid-1980s (Sinha et al., 1990). Their equipment was largely based on the Scripps system, but with one very important improvement, the use of a neutrally buoyant transmitter antenna that allowed the deep-towed transmitter to be "flown" about 100 m above the seafloor. This approach was necessary for working over the rough terrain of the ridge axis and proved to be desirable later in the hydrocarbon exploration environment. First trials of the Cambridge system were carried out in 1987 and 1988, and were followed by collaborative Cambridge/Scripps experiments on the East Pacific Rise (Evans et al., 1991), the Reykjanes Ridge (MacGregor et al., 1998), and the Valu Fa Ridge (MacGregor et al., 2001). In mid 2000, the Cambridge group moved to Southampton University.

Although the deepwater frequency-domain horizontal electric dipole-dipole system appears to be the most appropriate tool for exploration, other marine CSEM techniques have been tested, notably by Nigel Edwards's University of Toronto group. Cheesman et al. (1988) deployed a horizontal magnetic dipole-dipole time-domain system, and Edwards et al. (1985) tested a variation of his land magnetometric resistivity technique in the ocean by utilizing a vertical low-frequency electric transmitter that hangs from the ship to the seafloor. Both of these techniques are currently being used for geophysical surveys (e.g., Evans et al., 2000; 2002), although neither method propagates deeply enough to be useful for hydrocarbon detection. Yuan and Edwards (2000) developed a short-offset time-domain electric dipole-dipole system for gas hydrate characterization.

Collection of data sets cannot proceed far without supporting theory and numerical modeling algorithms. Early work depended on the asymptotic solutions of Kraichman (1970) and Bannister (1968, 1984). The first widely available layered-model solution for the frequency-domain electric dipole method was published by Chave and Cox (1982), and some discussion developed around the issue of quadrature versus digital filtering for the solution of the Hankel transforms involved in 1D calculations (Anderson, 1984). One-dimensional solutions for time-domain methods were produced by the Toronto group (Edwards and Chave, 1986; Cheesman et al., 1987). Flosadottir and Constable (1996) implemented the fast Hankel transform of Anderson (1989) along with the OCCAM inversion algorithm of Constable et al. (1987) into the Chave and Cox algorithm to produce a rapid 1D inversion code. Numerical finite-element solutions to the 2D electric dipole problem were developed for the time domain by Everett and Edwards (1993) and for the frequency domain by Unsworth et al. (1993). Unsworth and Oldenburg (1995) demonstrated a subspace inversion method using the frequency-domain code, but as far as we know this method was never tested on real data. The first 2D inversion of real data was published by MacGregor et al. (2001), who modified the Unsworth forward code to handle experimental geometries and bathymetry and implemented the OCCAM inversion algorithm.

Three-dimensional analytic solutions do not exist for the general marine CSEM case, although approximate solutions exist for simple shapes (disks and spheres) in a uniform or layered background. However, modern 3D numerical algorithms are flexible enough to include a water layer, and sometimes an air layer, as part of the model, particularly if they have been developed for borehole applications, in which the source and receiver are both within the conductive structure. One code that is used extensively within the marine exploration community is the finite-difference algorithm of Newman and Alumbaugh (1995). Badea et al. (2001) describe a 3D finite-element algorithm.

Early industry involvement

Exxon (now ExxonMobil) was aware of work being carried out by Scripps and others and investigated the use of marine EM for exploration in the early 1980s: a patent was issued in this regard (Srnka, 1986). By following a series of numerical and physical (graphite) model experiments, Exxon scoped a field test using a naval minesweeper (like Francis) and both seafloor and towed electric sensors under development at Scripps. Scripps held a meeting in April 1984 to generate support for the development of exploration CSEM, which resulted in a small project being funded by Amoco, Arco, Elf, and Sohio. The result of this work is reported in Constable et al.

(1986) and Chave et al. (1991). However, exploration water depths at that time were around 300 m, and that, coupled with a lack of computational capability, limited digital acquisition capacities, and the growing emphasis on 3D marine seismic technology meant that this work was far ahead of its time in terms of commercial viability.

By the late 1990s, exploration was being routinely carried out in water 1000 m deep, and ExxonMobil resumed EM investigations, and Statoil began examining, marine CSEM as a tool for hydrocarbon exploration. In November 1999, Steven Constable was invited to review Statoil's internal research project which consisted of a variety of numerical and analog modeling (featuring an innovative use of a water-bed mattress). The conclusion was that

> if the target is not too small compared with its depth of burial, and the water depth is sufficient to suppress the air wave, then the controlled source signature of the oil-filled layer is detectable, yielding controlled source amplitudes that are a factor of 2 to 10 different than models without the oil layer. The signals are above the noise threshold, and the experimental parameters (frequency, range, antenna length, and power) are practicable.

This result was sufficient for Statoil to proceed with field trials in offshore Angola in late 2000. Around the same time (research was under way in mid 1998), ExxonMobil was carrying out investigations into the use of 3D EM methods for marine CSEM survey design, acquisition, data processing, inversion, and interpretation. ExxonMobil's field programs started in late 2001 with field trials off Scotland followed by West African tests (examples are shown subsequently).

It is important to note that exploration's move to deeper water had already driven interest in marine MT as an exploration tool, which had led to the development of commercially viable CSEM/MT receiver instrumentation. Although early attempts to use the MT method in the marine environment (Hoehn and Warner, 1983) foundered for reasons similar to the early CSEM attempts (shallow water, lack of digital equipment, etc.), by the early 1990s, electromagnetic techniques were being considered as an aid to mapping the base of salt in the Gulf of Mexico (Hoversten and Unsworth, 1994). In April 1994, a prototype MT receiver based on the Scripps CSEM receiver was deployed off southern California, and the results were sufficiently encouraging to attract support from industry to develop the instrumentation (Constable et al., 1998) and method (Hoversten et al., 1998). This early work consisted of a collaboration between Mike Hoversten and Frank Morrison of the University of California, Berkeley, Arnold Orange of AOA Geophysics, and Scripps. Field trials over the Gulf of Mexico Gemini prospect between 1996 and 2003 resulted in systematic refinement of the instrumentation and methodology (Hoversten et al., 2000; Key et al., 2006). Commercial surveys were carried out by AOA using Scripps equipment in carbonate terranes of the Mediterranean (1995 and 1996 for Agip), subsalt prospects in the Gulf of Mexico (1998 for Agip and BP), and subbasalt prospects in the North Atlantic (2001 for Agip and Statoil). Martin Sinha's LITHOS consortium at the University of Cambridge examined the use of CSEM for subbasalt prospecting (MacGregor and Sinha, 2000), which also helped to raise the profile of marine EM methods within industry.

THE MARINE CSEM METHOD

The theory and practice of the marine CSEM method are fairly well documented. In addition to the references cited in the introduction, we refer the reader to Edwards (2005) and Constable and Weiss (2006). Here we will just summarize the key elements. The frequency-domain dipole-dipole electric configuration shown in Figure 1 is the method of choice for various reasons:

1) An alternative to the frequency-domain approach is the time-domain method, which is well suited to land exploration where the geologic formations are on the conductive side of the air/earth system; after transmitter turn off, the direct wave in the atmosphere dissipates at the speed of light to leave eddy currents propagating more slowly in the ground. On the deep seafloor, the seabed is generally more resistive than seawater, and so information about the geology is embedded in the early time response, whereas the (uninteresting) seawater response dominates late time. In the frequency domain, however, the longer skin depths associated with seafloor rocks mean that at a sufficient source-receiver distance, the field is dominated by energy propagating through the geologic formations. Energy propagating through the seawater has essentially been absorbed and is absent from the signals. Furthermore, by concentrating all the transmitter power into one frequency, larger signal-to-noise ratios can be achieved at larger source-receiver offsets.

   The reader should bear in mind, however, that these are operational considerations, and that the physics of both the time-domain and frequency-domain methods are the same. In principle, a sufficiently broadband frequency-domain survey would be equivalent to a time-domain survey. In practice, a square wave, or other binary switched waveform, is easier to generate than a pure sinusoid for a frequency-domain survey. A square wave has the additional advantage that the fundamental harmonic has an amplitude of $4/\pi$ times the zero to peak current.
2) Electric fields are well suited to operation in seawater. Transmitter currents of 1000 A or more can be passed through seawater with simple electrode systems and reasonable power consumption (of order 100 kW), and transmitter antennas several hundred meters long can easily be towed along their length through the seawater. Receiver noise is very low because cultural and MT noise is highly (if not totally) attenuated in the CSEM frequency band. Magnetic field receivers are employed, but motion of the sensors as water currents move the receiver instrument limits the noise floor. (On land, magnetic sensors are buried to avoid this problem, but they can still be subjected to noise associated with ground motion from trees, microseisms, traffic, etc.)
3) A horizontal electric dipole excites both vertical and horizontal current flow in the seabed, maximizing resolution for a variety of structures. A vertical magnetic dipole, for example, would excite mainly horizontal current flow (Chave et al., 1991). Horizontal magnetic dipoles also excite both vertical and horizontal currents, but are less favored than electric dipoles for operational reasons.

With reference to Figure 1, the CSEM transmitter excites energy throughout the seafloor-seawater-atmosphere system. However, because the fields decay both geometrically and (most importantly) exponentially with a characteristic *e*-folding distance (length over which fields decay by 1_e, or 37%, in amplitude) given by skin depth

($z = \sqrt{2\rho/\omega\mu_0}$, where ρ is resistivity, μ_0 is the magnetic permeability of free space, and $\omega = 2\pi f$ is angular frequency), the tendency is that for a given source-receiver range (r), propagation through one part of the system will dominate the received fields. This effect is illustrated in Figure 2, where we present the amplitude and phase curves versus source-receiver offset for the canonical oilfield model (a 100-Ωm reservoir 100-m thick, buried at a depth of 1000 m, in a host sediment of 1 Ωm in 1000-m water depth). To highlight all the dominant propagation paths in one figure, we have taken a transmission frequency of 10 Hz, which yields signals too small to measure, and made the calculations through the use of the 1D code of Flosadottir and Constable (1996). The two lines represent the radial electric fields, in which the receiver is positioned along the axis of the transmitter and measures a linearly polarized field oriented along this axis; and the azimuthal electric fields, in which the receiver is positioned broadside to the transmitter and measures a linearly polarized field oriented parallel to the transmitter.

The skin depth in water at 10 Hz is 87 m, so close to the transmitter that we see the $1/r^3$ amplitude falloff from a static dipole and nearly constant phase. At ranges between a few hundred meters and 2 km, skin depth in the seafloor sediment (158 m) is larger than in seawater, and we see exponential attenuation dominated by the seafloor resistivity. Up to this point, the mathematics of propagation is reasonably approximated by the double half-space (i.e., infinite water depth and no reservoir layer) solution of Chave et al. (1991), valid for very resistive seafloor:

$$E_\rho = \frac{A\rho_o}{2\pi r^3}\cos\phi[(\gamma_o r + 1)e^{-\gamma_o r} + (\gamma_r^2 r^2 + \gamma_r r + 1)e^{-\gamma_r r}],$$

$$E_\phi = \frac{A\rho_o}{2\pi r^3}\sin\phi[(\gamma_o r + 1)e^{-\gamma_o r} + 2(\gamma_r r + 1)e^{-\gamma_r r}],$$

$$\gamma_o = \sqrt{i\omega\mu_o/\rho_o},$$

$$\gamma_r = \sqrt{i\omega\mu_o/\rho_r}$$

(ρ_o and ρ_r are seawater [ocean] and seafloor [rock] resistivities, respectively. Here, E_ρ is the radial electric field, E_ϕ is the azimuthal electric field, r is source-receiver offset, and A is the source dipole moment (transmitter current × antenna length). The dipole azimuth is ϕ, which would be 0° for the purely radial mode shown in Figure 2 and 90° for the purely azimuthal mode. The γ terms are complex wavenumbers related to reciprocal skin depth. The r^3 dipole dependence is evident in these equations, along with terms associated with exponential attenuation through the water (first term, in γ_o) and through the seafloor rocks (the second term, in γ_r). It is clear from these equations that for any azimuth ϕ other than integer multiples of 90°, both modes will be present, and because the phases typically are slightly different (see Figure 2b), a polarization ellipse will be formed (i.e., the instantaneous horizontal electric-field vector will sweep out an ellipse during every cycle of the transmitter).

Referring again to Figure 2, at ranges between 2 and 10 km, we see increased electric-field amplitudes (relative to those that would be measured in the absence of a resistive layer), associated with a larger skin depth (1600 m) in the more resistive reservoir layer. There is a corresponding increase in apparent phase velocity. Finally, at ranges greater than 10 km, propagation through the atmosphere dominates the receiver fields and the amplitude returns to a l/r^3 dipole attenuation, along with a phase that becomes constant (i.e., the apparent phase velocity is now comparable to the speed of light).

Much has been made of the different behavior of the azimuthal and radial modes in the presence of a thin resistor (e.g., Eidesmo et al., 2002; Constable and Weiss, 2006), whereby the azimuthal mode has a smaller reservoir response than the radial mode. This different behavior occurs only at relatively low frequencies in which the CSEM fields are dominated by the galvanic response of the reservoir (a charge buildup on the upper and lower surfaces of the resistive layer) generated by the vertical electric fields of the radial mode (which are largely absent in the azimuthal mode). In Figure 2, the frequency is high enough that inductive effects in the reservoir layer produce a significant response in the azimuthal mode. The static vertical offset between the radial and azimuthal modes is presumably associated with the galvanic contribution of the reservoir to the radial mode fields.

Equipment

Transmitted electric fields are directly proportional to the source dipole moment A, in turn given by the dipole length times the emission current. Data for interpretation are normalized by the dipole moment, so the system noise floor gets lower as A gets larger, allowing larger source-receiver offsets to be recorded and deeper structure to be detected. Dipole lengths are typically 100–300 m; making them significantly longer than that would make towing transmitter antennas close to the seafloor a technologically challenging proposition. The current practice is to transmit a high-voltage AC (typically 400 Hz) current down a towing cable to a transmitter unit close to the seafloor. Although purely AC transformed sources are in use, most systems transform the high voltage to low voltage/high current, rectify this low-voltage AC, and switch the resulting quasi-DC into a square wave or other binary/ternary signal (e.g., Sinha et al., 1990; Constable and Cox, 1996). To estimate what magnitude transmission currents can be achieved, we work back from the antenna electrodes. The resistance to seawater is purely a function of seawater resistivity ρ and geometry. For a long cylindrical electrode, the resistance per electrode is given by

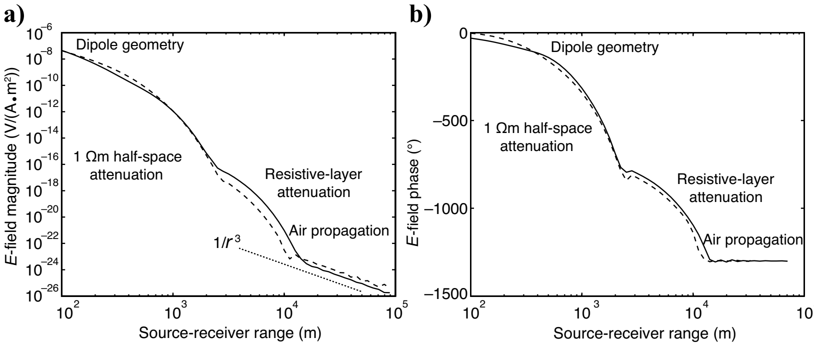

Figure 2. Radial (solid lines) and azimuthal (dashed lines) amplitude and phase responses over the canonical model for a frequency of 10 Hz and a transmitter altitude of 30 m.

$$R = \frac{\rho_o}{2\pi L}\left[\ln\left(\frac{2L}{a}\right) - 1\right]$$

(equation 3.09 of Sunde, 1949), where L is electrode length and a is diameter. For reasonable values of L and a, 0.1 Ω is easy to achieve; less than 0.01 Ω is more difficult but possible. To utilize electrodes that have lower resistance, antenna resistance must be kept comparably low, and so wire diameters are of order 2 cm. Thus, it might be possible to construct an antenna with a total resistance of about 0.01 Ω, but much smaller would be very difficult. More likely, total antenna resistance will be between 0.1 and 1 Ω. Therefore, with a total power of 10 kW delivered to the antenna, output currents of up to 1000 A are possible. With 100 kW delivered to the antenna, currents could be as large as 3000 A for the lowest-impedance antenna.

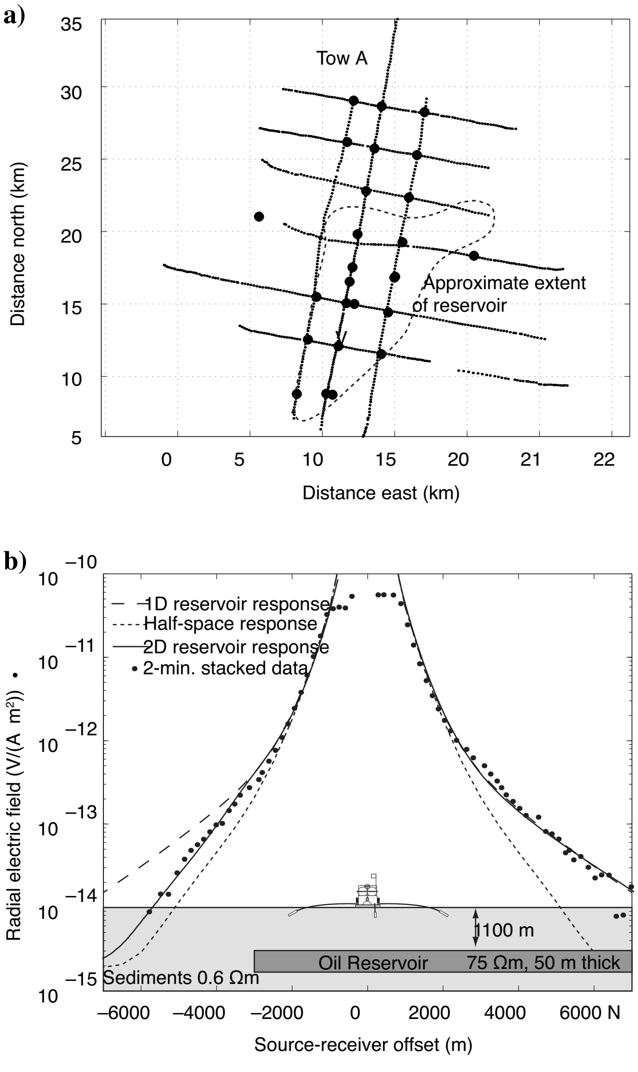

Figure 3. (a) Survey layout and (b) radial-mode horizontal electric-field data collected during tow A on receiver V during the first proof-of-concept marine CSEM survey over the Girassol hydrocarbon reservoir, offshore Angola (Ellingsrud et al., 2002). Water depth was 1200 m, and the transmission frequency was 0.25 Hz. The 2D response of the reservoir was calculated by using the code of Li and Key (2007). The data follow the modeled response to a remarkable degree because a 2D model is a reasonable approximation to the geology along this survey line.

Bear in mind that 100 kW corresponds to 1000 V and 100 A at the bottom end of a deep-tow cable, it appears that it will be hard to achieve significantly more than the 1000 A transmission currents now being advertised by industry, with corresponding dipole moments up to 300 kA.m.

Switching such large currents entails dealing with stored energy in the transmitter antenna. The approximate self-inductance of a long wire in microhenries (μH) is given by Rosa (1908) as

$$Z = 0.2L\left[\ln\left(\frac{4L}{a}\right) - 0.75\right].$$

A typical antenna would have an inductance of order 500 μH. Early attempts by Charles Cox to build a transmitter failed because he ignored the effect of inductance, and the back EMF during switching destroyed the equipment. Recognizing that voltage and current were out-of-phase in the antenna, he solved this problem by detecting zero-current crossings in the rectifier bridge and switching at those times. In the current SIO transmitter, a capacitor bank absorbs the energy associated with the back EMF during switching.

Most current seafloor receiver instruments appear to be built around the principles outlined in Webb et al. (1985) and Constable et al. (1998). Although modern instruments are likely to use 24-bit analog-to-digital conversion instead of 16 bits, and solid-state data storage instead of disk drives or tape recorders, the 1-Hz noise floor of 0.1 to 1 nV/$\sqrt{\mathrm{Hz}}$ is similar. Constable and Weiss (2006) discussed the contributions to the total system noise. With reference to Figure 2, the noise floor of current equipment is around 10^{-15} V/(A.m^2) and is unlikely to be better than 10^{-16} V/(A.m^2) (i.e., such equipment would not be able to detect the reservoir layer in the example shown in Figure 2).

EXAMPLES

The rapid commercialization of marine CSEM and the high cost of surveys has resulted in few, if any, data sets available for academic studies at this time, and most of the best-quality data are proprietary. However, we are able to present examples from the first two research cruises carried out by Statoil and ExxonMobil.

In Figure 3a we show the survey layout from the first use of marine CSEM for hydrocarbon mapping carried out by Statoil, with support from Southampton University and Scripps (Ellingsrud et al., 2002). The location is the Girassol reservoir, offshore Angola in about 1000 m of seawater — a known oil reservoir of considerable extent. The receivers (larger dots in Figure 3a) comprised a mixed fleet of LEMURs from Southampton University (Sinha et al., 1990), ELFs from Scripps (Webb et al., 1985), and the Scripps broadband MT/CSEM instrument of Constable et al. (1998). The transmitter was the DASI instrument of Southampton, operating at a dipole moment of 16 kA.m at frequencies of 0.25 and 1 Hz.

This experiment was a success in that the data are clearly sensitive to the reservoir; this result alone provided the support Statoil and other companies needed to move ahead with the technique. However, the mixed fleet of receivers, along with the poor performance of the bolt-on super-short base line (SSBL) navigation system and the modest-sized transmitter, resulted in a data set of highly variable quality. Furthermore, the sites in the northern part of the array, which were designed to provide off-target control, were heavily influenced by a salt body in that location. In Figure 3b we present data from one of the more modern Scripps instruments (Bandicoot), which was positioned close enough to the edge of the reservoir to show an on-target and off-target response. The amplitudes are somewhat scattered, probably as a result of transmitter instability and navigational errors, but the noise floor for this instrument of around 10^{-14} V/A.m^2 is comparable to modern surveys. The data saturate at about 5×10^{-11} V/A.m^2 because of the high gain settings of the low-noise amplifier used in these instruments. Although saturation does not compromise the detection of the reservoir response, which does not appear until larger source-receiver ranges have been achieved, more modern surveys employ receivers with lower gains.

In order to compress the exponential falloff of electric-field amplitude with source-receiver separation, as well as highlight the larger amplitudes associated with target structure, it has become practice to normalize the electric-field amplitudes by a half-space response, as was done by Eidesmo et al. (2002), or to normalize data by the response recorded by an instrument assumed to be off-target (e.g., Johansen et al., 2005) (a technique that has some similarity to the shale baseline method in well-logging). As can be seen from 2D modeling, simple normalization of the data by the half-space response, as was done by Ellingsrud et al. (2002), overestimates the extent of the reservoir because the elevated electric-field response persists indefinitely off the edge of the target.

ExxonMobil researchers were independently planning their own field trials during the Statoil experiment and surveyed three prospects offshore West Africa in early 2002 (Srnka et al., 2006). These surveys were carried out in a manner very similar to the Statoil study; they used the British research vessel RRS *Charles Darwin* and the Southampton DASI transmitter. The receiver fleet, however, was now a uniform fleet of 30 modern instruments provided by Scripps, three of which were full MT/CSEM receivers, and more effort was put into the navigation of the transmitter and receivers.

In Figure 4 we present an example from a known discovery, with data acquired in January 2002, during the three offshore West Africa surveys. Saturated middle to lower Miocene oil sands are present 1400 to 2500 m below the seafloor. A total of 29 receiver positions and 210 line-kilometers of data were collected in water 1000 m deep. The radial towing pattern maximizes the amount of inline data collected and has advantages for data summation and 3D inversion (Srnka and Carazzone, 2003). The transmitter, again the DASI system provided by Southampton, was towed 50 m above the seafloor at a speed of about 1.5 knots. The maximum dipole moment was 15 kA.m.

Figure 5 shows a section of the 3D resistivity model developed by iterative forward calculations guided by 3D seismic data, well-log data from wells A and B, and the CSEM data collected on all instruments at all frequencies transmitted by all tow lines. The reservoir units are the four deep, highly resistive (50–70 Ωm), dipping units. Figure 4b shows source-normalized, inline, horizontal electric-field amplitudes acquired on receiver 21 during survey tow line 2, for a frequency of 0.25 Hz (the source fundamental). The responses of the 3D forward model with all oil-filled reservoirs (solid line) and all brine-filled reservoirs (broken line) are also shown, calculated by using a variant of the 3D finite-difference frequency-domain code of Newman and Alumbaugh (1995). It is clear that a charged-reservoir model fits the data much better than a no reservoir model.

Figure 6 shows a second 2002 survey also collected offshore West Africa prior to drilling an exploration prospect in a salt-withdrawal minibasin. The survey parameters were similar to the previous example, except that fewer receivers (23) and transmitter tows (182 line-km) were used, and the water depth was deeper (1900 m). Prospective lower Miocene and Oligocene sands are located 1200 to

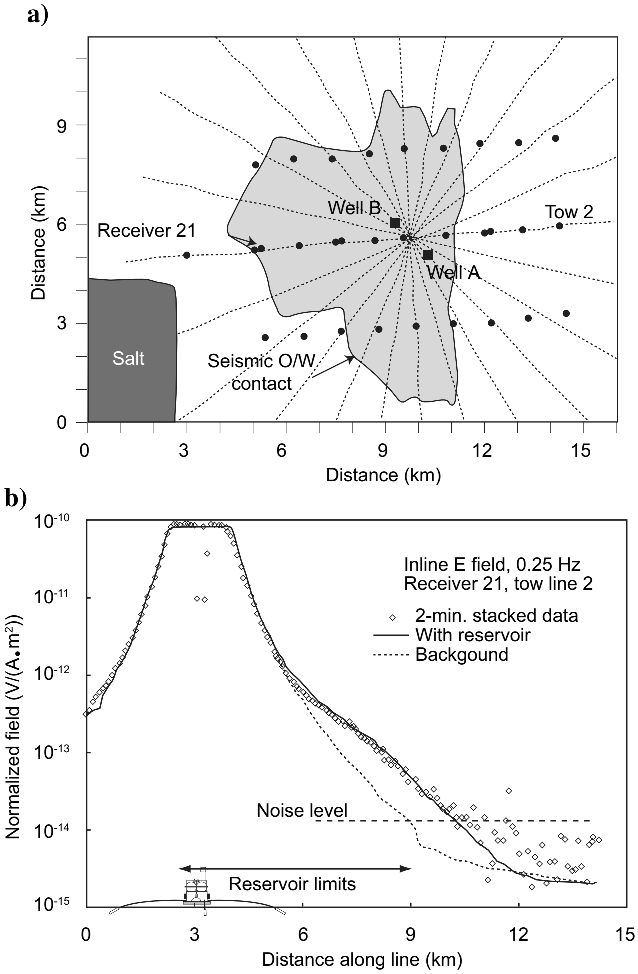

Figure 4. Marine CSEM data example over a discovered field. (a) Survey layout. (b) Data from receiver 21 for tow line 2 along with 3D forward-model responses for the charged-reservoir (Figure 5) and uncharged-reservoir models. The transmission frequency was 0.25 Hz, and the source dipole moment was 15 kA.m.

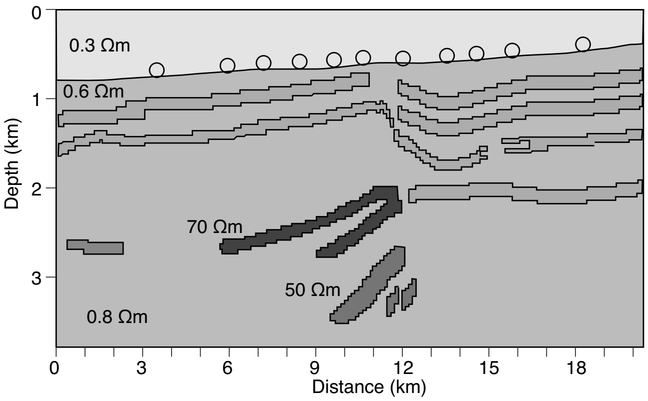

Figure 5. Section through 3D resistivity model taken along tow line 2 shown in Figure 4. Background resistivity is gradational from 0.6 Ωm at the seafloor to 0.8 Ωm at depth. The resistive layers in the overburden sediments are 2–4 Ωm. Receiver positions are shown as open circles at the seafloor.

1500 m below the seafloor; their seismic reflection signature showed indications of hydrocarbons. In contrast to the example shown in Figures 4 and 5, the inline horizontal electric-field data fit the 3D forward-model response for a brine-filled reservoir (Figure 6b). The predicted response for models of hydrocarbon-filled reservoirs is significantly larger than the observed data. The CSEM prediction was thus for a dry hole, which was confirmed upon drilling. This result was a success for the marine CSEM method, although less of a success from an exploration perspective. Drilling showed that the sands were partially gas saturated, which contributed to a seismic direct hydrocarbon indicator (DHI) interpretation.

Between 2002 and the end of 2004, thirty-four additional surveys were carried out by ExxonMobil in a variety of geologic environments offshore West Africa, South America, and North America in water depths between 100 and 3200 m. To evaluate the extent to which marine CSEM could be applied to exploration problems, surveys were conducted with calibration from well control, over exploration prospects, and in development and production settings. It was demonstrated that marine CSEM data could be successfully acquired simultaneously with seismic surveys, drilling operations, and hydrocarbon production. From the start, ExxonMobil developed a strong 3D modeling and inversion capability, and prospect evaluation relied heavily on 3D model-based interpretation utilizing seismic depth control and geologic constraints. These results have confirmed that the method is useful for distinguishing hydrocarbon reservoirs from wet sands, subject to the current limitations of the method. These limitations include signal-to-noise ratio, target size, and geologic structure (e.g., targets below salt are largely invisible to the method as currently practiced). However, it has been shown that integrated interpretation of marine CSEM data using iterative 3D forward modeling can be effective even in complex geologic settings (Green et al., 2005) and that 3D inversion can illuminate subtle resistivity effects that would otherwise be difficult to interpret manually (Carazzone et al., 2005).

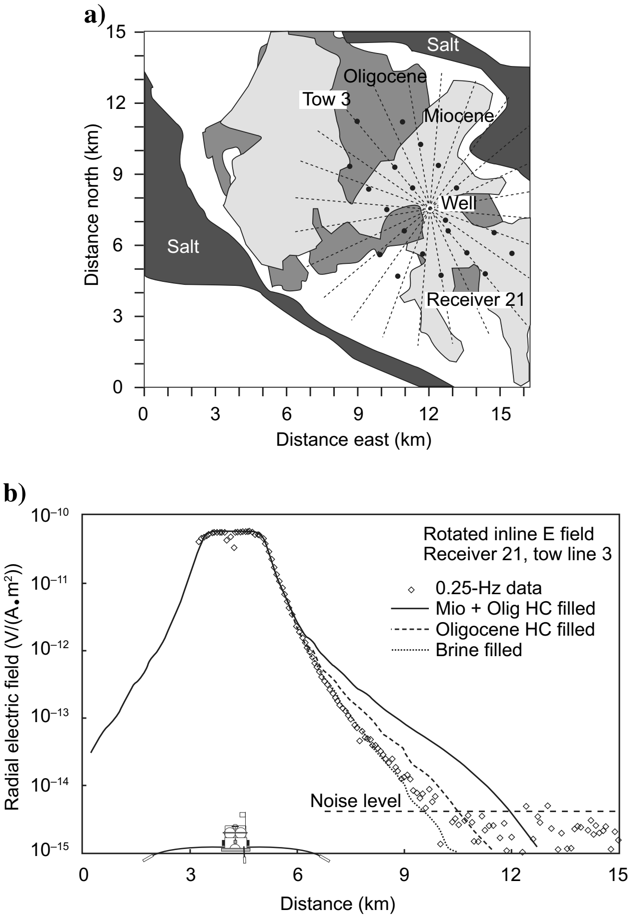

Figure 6. Marine CSEM data collected over an active exploration prospect. Predrill CSEM data suggested that the potential reservoir was brine-filled, which was confirmed by drilling. The transmission frequency was 0.25 Hz and the source dipole moment 15 kA.m.

DISCUSSION AND A LOOK FORWARD

Marine CSEM may well become the most important geophysical technique to emerge since the advent of 3D reflection seismology 25 years ago. Calibrations of the method over known reservoirs, using well-data comparisons and realistic 3D model simulations, demonstrate that the fundamental methodology is sound. The high quality of marine CSEM data is a result of the low noise environment at the deep seafloor, the high sensitivity and low system noise of seafloor receivers, and the large source strengths now being used. The utility of the data for hydrocarbon applications stems from the good coupling of the transmitted fields to geologic structures and the absence of a strongly attenuated direct-source signal through the seawater at large source-receiver separations. As might be expected, interpretation is improved significantly when CSEM data are integrated with other geoscientific information such as seismic reflection data, well logs, and geologic syntheses. Although the nonuniqueness of geophysical inversion and modeling, coupled with the fact that many geologic formations exhibit enhanced resistivity (evaporites, volcanics, coals, carbonates, and freshwater sands, to name a few), presents potential pitfalls to using the method, the fact that CSEM provides information that is independent from seismic data and intimately connected to the nature of the fluid component means that the method can make significant contributions to exploration and, possibly, to field development and production. Although the spatial resolution of EM methods is lower than for seismic methods, there is an intrinsic sensitivity to the depth of the target, and the resolution is significantly better than for potential-field methods.

The early commercial development of marine CSEM leaned heavily on the academic community for software, instrumentation, and methodology and has progressed very rapidly as a result. The balance of activity has now moved heavily toward industry; thus one expects that further progress will come from the commercial sector, as has clearly happened in the areas of 3D modeling and inversion (Green et al., 2005; Carazzone et al., 2005). Another area of improvement is the collection of useful phase (cf. amplitude) data. The phase stability of acquisition systems used in early academic and industrial surveys was problematic, primarily because of source and receiver timing issues, so the use of potentially valuable information in the frequency-dependent phase response has been limited. This situation applies to the data examples shown in Figures 3, 4, and 6. These problems have been addressed in more recent instrument systems, and now accurate absolute phase is recorded. Data quality as characterized by signal-to-noise floor has improved by a little more than an order of magnitude, from the worst of the academic data (a little more than 10^{-14} V/(A.m^2)) to the best of the current commercial data (a little less than 10^{-15} V/(A.m^2)), mainly through increases in source dipole moment. On the other hand, the only significant modification to the original marine CSEM method as proposed 25 years ago is the collection of vertical electric-field data (Srnka and Carazzone, 2003). The most likely near-term innovations are the collection of a much broader frequency spectrum of data, deploying more numerous receiver instruments, and continuous collection of data in a reconnaissance survey mode. The success of deepwater CSEM has created a demand for shallow-water applications and a solution to the airwave problem, which may well come about through the use of time-domain methods or at least a broadening of the frequency spectrum.

Current efforts have focused on screening previously identified prospects. As the methods are adopted by industry, and the equipment becomes more commercially available, one can envisage a variety of other applications. Time-lapse methods for reservoir monitoring during production (so-called 4D-EM) are obvious applications of the technology that might incorporate borehole transmitters or receivers and certainly improve the repeat-survey method by installating fixed infrastructure. Use of higher frequencies and shorter offsets will allow resistivity structure in the shallow section to be studied, useful for avoiding drilling hazards such as gas hydrates (e.g., Yuan and Edwards, 2000; Schwalenberg et al., 2005; Weitemeyer et al., 2006). The seismic method has dominated exploration so effectively that it is possible that the discovery of reservoirs is biased toward those with a seismic signature. As we gain confidence and expertise in marine CSEM methods, we may be able to explore for hydrocarbons that are visible only through their resistivity signature. Indeed, the optimists among us may imagine that marine CSEM will play a critical role in providing the necessary supply of hydrocarbons for the world's growing economy and thus help ease the eventual transition to other energy sources.

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