Marine controlled-source electromagnetic methods in the hydrocarbon industry: A tutorial on method and practice

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Abstract

We provide a tutorial on the marine controlled-source electromagnetic (CSEM) method aimed at geoscientists and explorationists who are new to EM methods. This tutorial highlights some of the issues to be considered in planning and executing a CSEM survey, and interpreting the results. CSEM methods can add valuable information on the resistivity structure of the subsurface, which complements measurements obtained from seismic or other geophysical methods. We also discuss the development of the method and provide an overview of the CSEM acquisition approaches applied today. Understanding the sensitivity of the CSEM method to seafloor resistivity structures is key to ensuring a successful survey. We illustrate this with simple examples, demonstrating the effect of reservoir and overburden properties and the effect of electrical anisotropy. It is also important to understand how well a given resistivity structure can be recovered from realistic survey data. We apply an inversion approach to illustrate this for 2D resistivity structures. Finally, we discuss the importance of interpreting CSEM in an integrated framework alongside seismic and well log data.

Introduction

Multiphysics approaches to geophysical analysis, in which multiple geophysical measurements are integrated to provide a constrained earth model, are becoming more and more popular. Controlled-source electromagnetic (CSEM) survey methods provide a valuable complement to more conventional geophysical approaches. For example, whereas in many situations the seismic method provides high-resolution images of structure and stratigraphy, determining fluid properties using seismic data alone can be difficult or, in some cases, impossible. The sensitivity of resistivity to hydrocarbon saturation and fluid properties such as temperature and salinity is well known, and widely exploited in well log analysis and interpretation. The resistivity attribute derived from CSEM data, if properly interpreted, can provide information which when integrated with seismic data allows fluid properties to be determined with more certainty. However, caution must be exercised: Resistivity is by no means a unique indicator of fluid fill. Variations in porosity and lithology can also result in large resistivity variations, which must be distinguished from the fluid effects of interest.

The marine CSEM method

The marine CSEM method in its most commonly applied form uses a high-powered horizontal electric dipole (HED) source to transmit a low-frequency electromagnetic (EM) signal through the seafloor (Figure 1a). The source is towed at about 30 m above the seafloor to ensure good coupling of the signals with the earth, while avoiding the risk of entanglement with, or damage to seafloor infrastructure and obstructions. The transmitter itself comprises a 300 m neutrally buoyant streamer supporting two conducting electrodes forming the two ends of a grounded dipole. The transmitter current is usually in the range 1000–1500 A, although currents up to 7500 A are reported for the deck mounted, shallow towed source system described in Barker et al. (2012). This provides source dipole moments of around 250,000 Am in the lower harmonics. The source transmits a coded tristate waveform, designed to optimize the frequency content for sensitivity to the target of interest (Mittet and Schaug-Pettersen, 2008; Myer et al., 2011). Frequencies in the range 0.01–10 Hz are typically employed.

The receivers are deployed on the seafloor at the start of a survey and log autonomously. They detect and record up to three components of the electric and three components of the magnetic field, although it is usual to record just the horizontal electric and magnetic field components. At the end of the survey, the receivers are recovered to deck and the data downloaded for processing and interpretation. By studying the variation in the received fields as a function of source-receiver separation (range), geometry, and signal frequency, using a combination of forward modeling, inversion, and hypothesis testing approaches, the resistivity of the
seafloor can be determined at scales of a few tens of meters to depths of about 3 km below mudline, depending on the structure and resistivity of the overburden. A recent paper by Constable (2013) provides a review of this type of CSEM acquisition technology.

Alternative CSEM acquisition strategies have also been developed. Yuan and Edwards (2000) describe a system in which the source and receivers, linked in a linear array, are dragged across the seafloor. Source receiver separations between 85 and 493 m are employed. The resulting data, analyzed in the time domain, are used to quantify marine gas hydrate concentration in the upper approximately 250 m of the seafloor. Constable et al. (2012) describe a CSEM system that is also designed to map the shallow subseafloor. In this system, three-component electric field receivers, comprising inline, crossline, and vertical electric dipoles, are towed at offsets up to 1 km behind a horizontal electric dipole source (Figure 1b). Although the system can be towed close to the seafloor in deep water (in contrast to the surface-towed system of Mattsson et al. [2012] discussed below) the short offsets make it primarily applicable to the mapping of resistivity in the shallow subsurface, for example mapping gas hydrates or shallow hazards.

Mattsson et al. (2012) describe a towed system designed to look deeper into the seafloor (Figure 1c). The source and receiver are towed at depths of 10–100 m below the sea surface in water depths from 5 to 400 m. The source is again a horizontal electric dipole, towed at the front of the array, transmitting into a series of inline horizontal electric dipole receivers at offsets of 500–8000 m. The effects of motional noise are reduced using data from auxiliary motion sensors on the towed streamer. This acquisition method provides significant operational efficiencies over seafloor deployed systems; however, it comes at the expense of multiazimuth coverage in the resulting data set. However, good results have been achieved (e.g., Zhdanov et al., 2012; Bhuiyan et al., 2013).

Holten et al. (2009) describe a CSEM system in which the source and receivers are vertical electric dipoles (Figure 1d). The challenge with making this measurement is the small magnitude of the vertical electric field response in comparison to the horizontal electric field. As a result, only small tilt angles in the vertical source and receiver can be tolerated before the horizontal component dominates the response. However, resistive earth structure can be detected at significantly shorter offset than in the horizontal electric dipole case (Cuevas and Alumbaugh, 2011) with the result that the vertical dipole system has the potential to improve lateral resolution of subseafloor resistivity structure.

A brief history

Thorough reviews of the history of the CSEM method and its application to hydrocarbon exploration have been published by many authors (e.g., Chave et al., 1991; Edwards, 2005; Constable and Srnka, 2007; Constable, 2010), so only a short summary is provided here. The CSEM method was developed originally in the late 1970s as a tool to map the resistivity structure of the deep ocean floor, and applied successfully to this end in several surveys (Young and Cox, 1981; Constable and Cox, 1996). Throughout the 1980s and 1990s, the method evolved through surveys targeting mid-ocean ridge hydrothermal and magmatic systems (Evans et al., 1994; MacGregor et al., 1998, 2001). Even in these early studies, the importance of integrating seismic and CSEM was recognized. Seismic data were used to map the structure of the mid-ocean ridge system, with CSEM data providing complementary resistivity information used to constrain the fluid properties, primarily the saturation and/or temperature of melt or hydrothermal fluid, within the magmatic and hydrothermal systems under study (Sinha et al., 1998).

Industry interest in CSEM began in the mid-1980s with theoretical work on the use of CSEM to directly map the fluid content of reservoir structures (Srnka, 1986). Although the application looked promising in theory, the economics of the survey prevented its application in practice. Throughout the 1990s however, industry interest in CSEM continued, applied as a comple-
mentary method to the mapping of subbasalt sediments and structure (MacGregor and Sinha, 2000).

The first practical application of CSEM as a method of mapping resistivity within a hydrocarbon reservoir took place in late 2000 on a field offshore Angola. During the six week survey exercise, a full 3D CSEM survey (albeit on a relatively sparse grid) was acquired, processed, and interpreted. The results demonstrated in practice for the first time that the CSEM method could be used to map a hydrocarbon reservoir (Ellingsrud et al., 2002; Eidesmo et al., 2002).

The history of the CSEM industry, born of that first survey offshore Angola, has been somewhat checkered. Early successes were followed by a dramatic rise in the number and value of companies offering CSEM surveys, and bold statements as to the utility of CSEM across the exploration industry were made. However, in 2007, there was a dramatic crash in the CSEM market. Multiple reasons for this can be mooted. First, the strong marketing and bold statements made in the early years were coupled with disappointing results where customers failed to realize value from their CSEM data, or were provided misleading results. Second, despite the marketing hype, the CSEM method was still relatively immature, in terms of acquisition and particularly interpretation. The importance of careful integration with seismic and wells was not well understood, nor were the effects of electrical anisotropy. Third, overly optimistic estimation of market size led to overcapacity. Finally, it can be argued that aggressive patent battles stifled market growth, making potential users wary of adopting the technology.

However, resistivity remains a valuable attribute to include in an interpretation of rock and fluid properties, and CSEM, if acquired and interpreted carefully can provide a robust estimate of this property. The purpose of this paper is to provide an overview of considerations when planning a CSEM survey or interpreting the results, and to demonstrate some of the pitfalls and dangers in using the technology. It is an obvious statement to make, but CSEM is not seismic, so particular emphasis will be given throughout the paper to similarities and differences in the technologies and considerations when using them. An extensive bibliography is provided at the end of the paper for readers wishing to delve further into the details of the subjects discussed.

Sensitivity analysis

The first stage in any CSEM exercise is to conduct a thorough sensitivity analysis, and establish whether CSEM, either alone or in combination with seismic, can address the geophysical question of interest. Pre-survey modeling should also include inversion analysis of how accurately, and with what resolution, structures of interest can be recovered from the data. This “recoverability” question is discussed later, and must also consider what constraints must (or can) be applied to the inversion to optimize the results at the pre-survey modeling and post-survey interpretation stages.

In contrast to seismic sensitivity analysis that is often reservoir-focused, assessing sensitivity for CSEM surveys must consider not only the reservoir, but the complete structure, from seafloor to some distance beneath the reservoir. This is because a CSEM response cannot be said to be coming from, or caused by a single formation: It is the cumulative result of the resistivity within a volume of the earth. This necessitates construction of a comprehensive background resistivity model prior to any sensitivity analysis. This model should include any known resistors (for example, gas hydrates in the shallow structure, carbonates, volcanics), and resistive electrical basement, if present, which may affect the results even if it is some distance beneath the reservoir interval, and is often a source of uncertainty in the analysis. The background model must also account for anisotropy in the overburden section. This latter point is also often a source of uncertainty in the analysis. Electrical anisotropy is seldom logged in wells, and where it is, such measurements are often confined to the reservoir intervals. Only a few examples of electrical anisotropy measurements through the overburden exist (e.g., Loseth et al., 2013). In most cases, overburden anisotropy must be estimated, either from prior experience in the area, or from knowledge of anisotropy encountered in similar lithologies elsewhere. The uncertainty of such estimates can be high, and must be factored in to the sensitivity assessment.

To illustrate how sensitivity varies with the structure under study, consider the simple 1D, isotropic model shown in Figure 2a (the effect of anisotropy will be considered later in the paper). The most basic question to ask is whether a CSEM survey is likely to be sensitive to the reservoir of interest. It is also important to establish the optimum acquisition parameters, in terms of required source-receiver separation (range) and transmission frequencies.

The inline electric field is the component detected along a line passing through and parallel to the axis of the dipole, and is optimally sensitive to thin resistive layers (MacGregor and Sinha, 2000; Ellingsrud et al., 2002). The basic sensitivity question can be answered by contouring the percentage change in the measured inline electric field as a function of source receiver separation and source frequency (Figure 2b). The choice of frequency coverage to be used is a trade-off. At very high frequency, the effect of the target reservoir on the measured field is large; however, signals are attenuated rapidly and may not be detected above the noise level. At very low frequency, signal-to-noise ratio (S/N) is excellent, but the fields are unable to resolve small-scale structures. In practice, the usable frequency band is therefore relatively narrow. Although an optimum frequency for sensitivity to a given target may be chosen in this way, it is good practice to ensure that the transmission frequencies used cover a band around this frequency. As will be shown below, the choice of
frequency depends critically on the background structure, and therefore transmitting a range of frequencies ensures some contingency for uncertainty in this parameter, as well as improving the quality of interpretation results.

It could be argued that the solution to this problem would be to transmit a broadband signal and indeed such signals have been tested (Ziolkowski, 2007; Ziolkowski et al., 2011). However, the CSEM source has a finite energy budget. If this is spread across too many harmonics, the magnitude of each is diminished, and hence S/N may be compromised. It has been shown that because the variation in response with frequency is smooth and can be adequately represented by a few carefully selected frequencies, the most important factor in controlling sensitivity and resolution is the overall frequency bandwidth, whereas frequency sampling within the bandwidth is less critical (Key, 2009). Concentrating power within certain harmonics between an upper and lower limit has the dual effect of ensuring good frequency coverage, while maintaining good S/N.

The reservoir property to which the CSEM method is primarily sensitive is the transverse resistance, defined as the vertically integrated resistivity. For a simple 1D layer, this corresponds to the resistivity-thickness product (Constable, 2010; MacGregor, 2012). The effect of transverse resistance on sensitivity is shown in Figure 3. For ease of comparison between different models, percentage anomalies for a range of frequencies are shown at a source-receiver separation of 5.5 km, corresponding to an extraction along the horizontal yellow dashed line in Figure 2b. As one would expect, the higher the transverse resistance, the larger the effect of the reservoir on the measured fields. However, an important point to note here is that, although the magnitude of the anomaly changes with transverse resistance, the frequency at which that anomaly is observed does not alter significantly. Optimum transmission frequency is controlled primarily by the overburden structure, and much less by the properties of the reservoir to be detected.

A frequency of 0.3 Hz provides a good trade-off between S/N and anomaly size in this example. Figure 3b shows the variation in the anomaly associated with the target reservoir at this frequency, as a function of source-receiver separation and reservoir transverse resistance. As the transverse resistance increases, so does the measured inline electric field anomaly. Taking a conservative limit on the level of 1D normalized anomaly required for a response to be detected in real data of 20% (other authors have suggested 15%, e.g., Hesthammer et al., 2010), the minimum transverse resistance required for the CSEM survey to be sensitive to the reservoir corresponds to the point at which the 20% contour crosses the noise floor, set to $10^{-15}$ V/Am$^2$ in this case and marked by a white diamond in Figure 3b. This corresponds to a transverse resistance of 720 $\Omega$m$^2$, or a bulk average of 14 $\Omega$m resistivity if the reservoir interval is 50 m thick.

It is clearly important to understand the sensitivity of a CSEM survey to the reservoir properties of interest.
However, it is equally important to understand the background resistivity structure. This is illustrated in Figure 4, which again shows percentage anomalies for a range of frequencies at a source-receiver separation of 5.5 km, corresponding to an extraction along the horizontal yellow dashed line in Figure 2b, to allow comparison between different models. In this case, the background resistivity structure of the baseline model shown in Figure 2a has been altered.

As the background structure becomes less resistive, the size of the anomaly associated with the reservoir increases because the contrast between reservoir and background is greater; however, its effect shifts to lower frequency. This is because attenuation of the signals in the more conductive overburden increases, with the result that only low-frequency signals penetrate as far as the reservoir. As the background resistivity increases, the size of the anomaly decreases as the

Figure 3. (a) Percentage anomaly in the inline electric field extracted at a source-receiver range of 5.5 km, corresponding to the horizontal yellow dashed line in Figure 2b. The line is dashed when the signal strength falls below a noise floor of $10^{-15}$ V/Am$^2$. Although the magnitude of the anomaly increases with increasing transverse resistance, the frequency at which the anomaly is observed is unaltered. (b) Effect of transverse resistance on the measured inline electric field anomaly. Dashed white lines show the 20% and 50% anomaly contour. The solid white line shows a representative noise floor of $10^{-15}$ V/Am$^2$. The minimum reservoir transverse resistance to which 0.3 Hz CSEM data will be sensitive is 720 $\Omega$ m$^2$ in this example, corresponding to the point at which the 20% anomaly contour falls beneath the noise floor and is marked by the white diamond.

Figure 4. Effect of background resistivity on the sensitivity of a CSEM survey. (a) The background structure of the baseline model in Figure 2a has been made more conductive and more resistive by factors of two and three. (b) The result is a large change in the sensitivity of a CSEM survey. The percentage anomaly is extracted at a source receiver separation of 5.5 km for ease of comparison between models.
contrast associated with the reservoir is smaller. In the example shown, the more resistive overburden results in an anomaly that is unlikely to be detected.

Of course, in practice, variations in background resistivity structure are likely to be more complex than the simple bulk shifts assumed here; however, this example does illustrate that variations in background have the potential to affect not only the transmission frequency chosen, but the overall feasibility of the survey. Knowledge of the background structure is as important as knowledge of the potential reservoir properties: The background should be considered as much of a target as the reservoir interval of interest.

In areas devoid of well log information, construction of a background resistivity trend is difficult, and therefore uncertainties in assessing survey feasibility and establishing effective survey design parameters are large. In areas where standard well log-derived resistivity information is available, this may be used to construct a suitable background model. However, the uncertainty in this background model remains large. The reason for this is electrical anisotropy. In general, standard induction log measurements in vertical well bores measure the horizontal component of the resistivity (e.g., Luling, 2013). The vertical component of resistivity, to which the inline electric field is primarily sensitive (Ramananjaona et al., 2011), is often many times higher. Factors of two to three are common, and factors as high as ten have been reported in some cases (Klein et al., 1997; Ellis et al., 2010; MacGregor et al., 2012; Colombo et al., 2013; Gabrielsen et al., 2013).

Anisotropy of this magnitude can significantly affect the response of a CSEM survey and its sensitivity to a reservoir target. Figure 5 shows a sensitivity plot of the same form as Figure 2; however, in this example, the ratio of anisotropy in the overburden has been increased to a factor of two. The reservoir is assumed to be isotropic because, although the anisotropy within reservoir intervals can be large, the sensitivity of the CSEM method to anisotropy within the reservoir itself is small (Brown et al., 2012). The response is dominated by the anisotropy in the background structure. Comparing Figure 5 to Figure 2, it is clear that the anisotropy in the overburden changes the sensitivity of a CSEM survey to the reservoir significantly. The overall magnitude of the anomaly has decreased and is now observed at longer ranges than when an isotropic overburden is considered.

Correctly estimating or predicting anisotropy in the background structure is therefore important. It is also extremely difficult. Electrical anisotropy values measured in three-component well logs, and CSEM surveys from around the globe show that this parameter is extremely variable, within a given section, and between areas. Even when three-component logs are available, they may fail to resolve the bulk anisotropy that affects CSEM data (Gist et al., 2013). The controls on electrical anisotropy are not well-understood, and therefore building robust models is a challenging task. Several authors (Ellis et al., 2010; Bachrach, 2011) have suggested rock physics modeling approaches to address this; however, these require calibration and are (at the moment) unlikely to be general enough to address all geologic situations. Work continues to address this need.

Figure 5. (a) Simple canonical for which the horizontal resistivity is the same as that of Figure 2, but the vertical resistivity in the overburden is a factor of two higher. The reservoir target is assumed isotropic. The model is overlain by a water layer of thickness 1500 m and resistivity 0.3 $\Omega$m. (b) Sensitivity of a CSEM survey to the presence of the target reservoir, expressed as the percentage change in the inline electric field as a function of source-receiver separation and signal frequency. The solid white line shows the $10^{-15}$ V/Am² electric field strength contour, corresponding to a typical noise floor for this water depth. The dashed white lines show the 20% and 50% percentage anomaly contours. Comparing this to Figure 2, it is clear that the effect of the anisotropy is large.
In the meantime, background models must be constructed using best estimates of anisotropy derived from previous CSEM experience in a given area, three-component well logs where available, and experience in similar geologic domains. Recent work on the use of isotropic seismic-resistivity transforms derived from well log data to build background models based on seismic velocity is also promising (Wertmuller et al., 2013). Background resistivity trends can also be derived from magnetotelluric (MT) data, which uses naturally generated electromagnetic fields (Constable et al., 1998; Hoverston et al., 1998; Ellingsrud et al., 2002). However, such data provides a measure primarily of horizontal resistivity, and at a resolution scale lower than that of CSEM. Where significant uncertainty remains, contingency should be built into survey planning exercises to ensure that the resulting data will provide the required sensitivity across a range of background resistivity and anisotropy values.

Constraining electrical anisotropy using CSEM data

It has been demonstrated that the presence of electrical anisotropy in the earth can have a significant impact on the choice of acquisition parameters. It also affects the interpretation of CSEM survey data once acquired, and the constraint of anisotropy in the overburden section is a key component of any such analysis. Ramananjaona et al. (2011) have demonstrated that, for simple structures in deep water, the inline component of the electric field is primarily sensitive to the vertical component of resistivity. In contrast, the broadside component, detected along a line passing through and perpendicular to the source dipole axis, is primarily sensitive to the horizontal resistivity. This leads to the observation that multiazimuth data coverage is required to properly constrain anisotropy (e.g., Newman et al., 2010). However, the situation is considerably more complex in shallow water, and in more complex structures.

Figure 6 shows the electric field response of an anisotropic halfspace with a vertical resistivity of 2 Ωm and a horizontal resistivity of 1 Ωm in polar diagrams plotted at a source-receiver separation of 6 km, for water depths of 1500 and 100 m. The frequency is 0.2 Hz. For the deep water case, along the axis of the dipole in the inline direction, the measured response is close to that of a 2 Ωm isotropic halfspace suggesting as expected that the inline response is primarily sensitive to the vertical resistivity. In contrast, across the axis of the dipole in the broadside direction, the response is much closer to that of a 1 Ωm isotropic halfspace, suggesting that this geometry is more sensitive to the horizontal resistivity. At azimuths between these end members, the response is sensitive to horizontal and vertical components. This deep water response has been used to constrain anisotropic structures using field data (e.g., Newman et al., 2010).

The behavior in shallow water is different (Figure 6b). The broadside response is still close to that of a 1 Ωm halfspace; however, in the inline direction, the response now differs from the 1 and 2 Ωm isotropic cases, suggesting that, in shallower water, the response has sensitivity to the horizontal and vertical component.

Figure 6. Polar diagrams illustrating the effect of anisotropy on the measured response as a function of azimuth. The inline direction corresponds to an azimuth of 0° along the axis of the source dipole (represented by the double-headed arrow). The broadside geometry corresponds to an azimuth of 90°. The frequency is 0.2 Hz and the source-receiver separation is 6 km. (a) Water depth is 1500 m. (b) Water depth is 100 m.
The response is governed by the complex interaction of signals interacting with the seafloor below, and the resistive air layer above (Andreis and MacGregor, 2008). The situation is further complicated if the earth has a more complex structure. Although multiazimuth data are therefore useful, they do not provide simple, independent constraints on the horizontal and vertical resistivity except in the simplest deep water environments.

Given the sensitivity of the inline electric field component to horizontal and vertical resistivity, inline data can be used alone to determine anisotropy. Sensitivity to anisotropy as a function of frequency is shown in Figure 7, where the quantity contoured is an anisotropic response similarity defined as

\[
\text{Anisotropic similarity} = \frac{E^{21} - E^{22}}{E^{11} - E^{22}},
\]

where \(E^{21}\) is the inline electric field response of the anisotropic halfspace with vertical resistivity 2 \(\Omega m\) and horizontal resistivity 1 \(\Omega m\), \(E^{11}\) is the response of a 1 \(\Omega m\) isotropic halfspace, and \(E^{22}\) is the response of a 2 \(\Omega m\) isotropic halfspace. This metric tends to 1 if the response of the anisotropic model tends toward the response of the isotropic halfspace equivalent to the vertical resistivity, and tends to zero in the opposite case, where the response tends to that of the isotropic halfspace equivalent to the horizontal resistivity. It therefore provides a useful guide to the relative sensitivity to horizontal and vertical resistivity across a given parameter range.

Figure 7 again highlights the large difference between deep and shallow water cases. In deep water, at longer offsets and higher frequencies, the results suggest primary sensitivity to the vertical resistivity, whereas at the same offsets in shallow water, the response is primarily sensitive to the horizontal resistivity, a result of signals interacting with the resistive air (Andreis and MacGregor, 2008). At shorter ranges and lower frequencies, the response is clearly sensitive to horizontal and vertical resistivity in both cases. Thus, although real situations are considerably more complex than the example shown here, given a realistic multifrequency, multioffset inline data set, it is possible to constrain anisotropic resistivity, and indeed several case studies bear this out (MacGregor et al., 2012; Mattsson et al., 2013).

Resolution and recoverability

Although it is important to establish the sensitivity of CSEM data to a target of interest prior to a survey, and choose the optimum acquisition parameters, it is also important to understand how well the structure of interest can be recovered from a finite noisy CSEM data set, with what resolution and under what circumstances given the inversion tools available. This “recoverability” question is addressed by Key (2009) and MacGregor (2012) for the case of a 1D structures. Here, simple isotropic 2D structures are considered. The goal of this section is not to present a complex inversion study, but rather highlight some of the positives and negatives of, and controls on, resolution and recoverability.

In the first example (Figure 8), three resistive features of varying size are embedded at a depth of 1 km below the seafloor in a 1D background structure in which the resistivity gradually increases with depth. The water depth is 900 m and the structure is invariant perpendicular to the plane of the page. Receivers are deployed at the seafloor at intervals of between 400 m and 4 km. The source positions are 10 m above the seafloor with a spacing of 200 m in all cases. A sensitivity plot (see Figure 2 for details) for this structure (Figure 8b) demonstrates that there is extremely good sensitivity across a wide range of frequencies and source-receiver separations to the embedded resistive targets in this case, at least if they are considered to be 1D.

Although in practice multiple frequencies are acquired and interpreted using either an amplitude/phase, or real/imaginary representation of the measured fields, in the interests of illustration, amplitude data at a single frequency of 0.75 Hz is chosen for the analysis below. Synthetic data were generated for each receiver and contaminated with 2% Gaussian noise, assuming an external noise floor of \(10^{-15}\) V/Am².

The inversions use the Occam approach of Constable et al. (1987) to derive models that are smooth in the first-derivative sense, and are thus as close to a uniform halfspace as is compatible with the data. All inversion results shown have converged to a constant root-mean-square (rms) misfit level just above the fit of the true model to the synthetic data to avoid overfitting the data. Although the inversions may not be precisely optimum for each model and data set, this approach ensures an internally consistent set of results that may be directly compared.

Figure 7. Anisotropic similarity metric (see text for discussion) for 1500 m of water (a) and 100 m of water (b). In each case, the response of an anisotropic halfspace with vertical resistivity 2 \(\Omega m\) and horizontal resistivity 1 \(\Omega m\) is compared to the responses of a 1 \(\Omega m\) and a 2 \(\Omega m\) isotropic halfspace.
Figure 9 shows the results of unconstrained inversion of the synthetic data for receiver spacings of 400 m to 4 km. In this example, only inline data are included in the data set: we assume a single tow line in the plane of the page, along the line of receivers. For the 400 m receiver spacing, all three resistive features are resolved as discrete bodies. When the receiver spacing is 1–2 km, the larger two features are clearly resolved, but the central, smaller body becomes less clear, and starts to merge with the deeper structure. At 4 km receiver spacing, none of the three resistive features are separated from the more resistive structure at depth.

To investigate the results further, Figure 10 shows three pseudowells, extracted at across axis positions of −3, 1, and 3 km through the true model and the four

![Figure 8](image-url)  
*Figure 8.* (a) Simple 2D model (invariant perpendicular to the page) consisting of three resistive bodies embedded in a 1D background. The model is overlain by a water layer of thickness 900 m. Receivers (white triangles) are spaced at between 400 m and 4 km separation at the seafloor. The source spacing is a constant 200 m. (b) One-dimensional sensitivity plot for the model shown assuming the resistive bodies at 1 km depth are infinite in extent. There is good sensitivity to the resistive targets. A frequency of 0.75 Hz (vertical dashed yellow line) is used in the analysis.

![Figure 9](image-url)  
*Figure 9.* Unconstrained inversion of inline amplitude data generated from the model shown in Figure 8, and contaminated with 2% Gaussian noise. The outline structure of the true model is shown by the white dashed lines, and results from receiver spacings of 400 m, 1 km, 2 km, and 4 km are shown.
inversion results shown in Figure 9. The pseudowell extracted at 1 km across axis does not intersect any of the resistive features and so represents a background trend. Results from inversion of the data with 400 m, 1 km, and 2 km receiver spacings accurately recover a smoothed version of this background trend, with little difference in the results between cases. For the 4 km result, the background resistivity is significantly overestimated, the result of merging the effect of the resistive bodies into the background structure.

Looking at the pseudowells at −3 km and 3 km across axis, that in both cases intersect one of the resistive features, the three smallest receiver spacings (400 m, 1 km, and 2 km) recover the resistive bodies in each case as a localized increase in resistivity, albeit vertically smeared across a relatively large interval. For a receiver spacing of 4 km, it is clear that in a vertical sense at least the resistive features have not been resolved, but are merged into the background structure.

The pseudowells shown in Figure 10 highlight the poor vertical resolution of the CSEM method: Features tend to be smeared over a relatively large vertical interval and have lower resistivity than in the true model. However, although the absolute resistivity is not well-resolved, the transverse resistance is usually better constrained by the inversion process (Constable, 2010; MacGregor, 2012). Figure 11 shows the transverse resistance calculated across an interval from 200 m above the resistive features, to 200 m below them (800–1400 m below seafloor). The results for the two smaller receiver spacings reproduce the transverse resistance in the two wider bodies relatively well. The results for the 2- and 4-km receiver spacing underestimate the transverse resistance in these bodies. In all cases, the transverse resistance in the central narrower body is underestimated. An important point to note in Figure 11 is that, even when the receiver spacing is 4 km and there is little vertical resolution, the transverse resistance shows that the effect of the localized resistors is seen laterally. It is generally the case that the lateral resolution of the CSEM method is considerably better than the vertical resolution.

The results in Figures 9–11 suggest that resolution is compromised at receiver spacings greater than 2 km when only inline data are considered. The resolution of the relatively shallow resistive features considered here improves as the receiver spacing decreases below this. Of course, a finer spacing also leads to significant data redundancy, that in itself can lead to improved data through the application of stacking or synthetic aperture approaches to improve S/N and sensitivity (Fan et al., 2012; Mattsson et al., 2013).

Figure 12 shows the effect of including inline and off-line data in the inversion. Receivers are spaced at 4-km intervals across the structure; however, in this case, the source is towed over the line of receivers to give inline data, and in two parallel tows, offset by 4 and 8 km from the line of receivers (Figure 12a). The addition of the multiazimuth data for this sparse receiver array improves the result significantly, allowing the resistive bodies to be resolved as isolated resistive features, and giving a result that is comparable to the equivalent results for finer receiver spacings when only inline data are considered. This is because inclusion of multiazimuth data can resolve ambiguities between the response of localized resistive features and more
gradual increases in resistivity with depth inherent in sparse inline data taken alone (Ellingsrud et al., 2002). This result should not be taken to imply that, in all situations, a sparse 3D survey layout is as good or better than a finer inline only layout: The issue of the best survey layout is more complex in 3D structures, compared to the 2D case considered here, and must be assessed on a case-by-case basis with presurvey modeling. However, it does serve to illustrate the effect of including multiazimuth data in an interpretation process.

Figure 13 shows a slightly more complex model in which the resistive body of interest lies at approximately 2 km below the seafloor, and 1.5 km above a resistive basement fault block. The body is overlain by a more resistive layer in the shallow background structure, representing (for example) shallow biogenic carbonates or hydrates. In this case, synthetic amplitude and phase data at three frequencies, 0.08 Hz, 0.24 Hz, and 0.56 Hz are inverted. Once again, the data are contaminated with Gaussian noise and are inverted to an rms misfit level just above that expected for the true model. Despite the overlying resistive layer and the deeper basement structure, in this case, the presence of the localized resistive body is recovered by the inversion: It lies far enough from each to be resolved as a discrete resistive body. The depth of the recovered body is slightly shallower than in reality, a consequence of the poor vertical resolution of the CSEM method, made worse by the depth of the target below mudline in this example (Key, 2009; MacGregor, 2012).

Figure 14 illustrates the problem of resolving localized resistive features that are adjacent to more massive resistive features. The model in Figure 14 is the same as that in Figure 13; however, now the localized resistive target is slightly deeper in the section, lying less than 500 m from the resistive basement fault block. In this case, the inversion is unable to resolve the localized resistor, which is instead merged into the deeper
basement structure. This does not mean the effect of the localized target is not felt. The transverse resistance in the basement is higher than the true model, the consequence of the merged target structure, and if the basement resistivity were extremely well constrained, one might be able to infer the presence of the localized resistor. Information on deeper basement resistivity can be obtained in some circumstances using magnetotelluric (MT) data (e.g., Constable et al., 1998; Hoverston et al., 1998), and can be interpreted separately or jointly inverted with the CSEM data. However, even with such MT-derived constraints, interpretation of the results in terms of a resistive prospect may be challenging.

CSEM data analysis and inversion

The simple examples above serve to illustrate some of the considerations in understanding the ability of CSEM data to resolve subseafloor resistivity structure. Modern CSEM data sets acquired in the field in general contain a rich coverage of frequencies, source-receiver separations and (for surveys using seafloor deployed receivers) source receiver geometries. These data can be used to constrain resistivity and anisotropy in the background structure, and the resistivity and lateral geometry of more localized resistors. Interpretation approaches in general proceed in stages starting with simple 1D approaches, moving through 2D analysis, and culminating in 3D analysis and inversion if this is required.

In the first stage, 1D forward modeling and inversion approaches are applied. These assume that the earth is a 1D stack of layers, which can be either anisotropic or isotropic. The source fields are still those of a point dipole (and are therefore 3D), and so the data analyzed can include inline and multiazimuth fields, i.e., 3D data can be analyzed using a 1D approach for constraint of bulk resistivity structure across an area, and to examine the presence and strength of anisotropy in the section. The assumption that the source can be modeled as a point dipole is valid when the source receiver separation is more than approximately four source dipole lengths (Chave and Cox, 1982). At shorter offsets, the effect of a finite dipole can easily be calculated by integrating the effect of point dipoles.

One-dimensional forward models or inversions derived locally at receiver locations can be stitched together to derive resistivity pseudo sections or volumes (Chave and Cox, 1982; Andreis and MacGregor, 2008). This process is similar to that used in seismic inversion where locally 1D models are used in the inversion and stitched together (with some cross trace regularization) to give an impedance section or volume. There is a major difference between the seismic and EM cases, however: In seismic, this approach is a fairly good approximation. In marine CSEM, it is in general not, and resistivity sections/volumes derived in this way should be used only for looking at bulk trends and lateral variations in resistivity and anisotropy, and developing starting models for higher dimensional interpretation approaches.

Two-dimensional inversion approaches assume that the earth is invariant along one horizontal direction, usually taken to be perpendicular to the survey line (Unsworth et al., 1993; MacGregor, 1999; Key and Ovall, 2011). The source fields are again 3D, and so as in 1D approaches inline and multiazimuth data can be included in the analysis, although it is conventional to include only inline (transmission line-parallel) data. The results are vertical sections through the resistivity structure of the seafloor which can be stitched together to provide a resistivity volume if appropriate. In many situations, a 2D inversion approach, carefully constrained with seismic structural information, can provide the information required to meet survey goals without recourse to full 3D inversion. If full 3D inversion is required, the 2D stage is critical in ensuring a robust starting model is constructed, so that 3D run times can be reduced as far as possible. Such 2D approaches also have the advantage of being reasonably computationally efficient, allowing multiple inversion scenarios, parameterisations, and constraints to be applied to ensure that the result is robust. Hypothesis testing

Figure 14. (a) Synthetic model as in Figure 13; however, with the localized 25 Ωm target now less than 500 m from the resistive basement fault block. Amplitude and phase data at 0.08 Hz, 0.24 Hz, and 0.56 Hz were generated and contaminated with Gaussian noise. Receiver positions are shown by white triangles. (b) Inversion of the synthetic data. In this case, the localized target cannot be resolved independently from the deeper basement structure.
using synthetic forward modeling and inversion based on geologic models of the area under study can also be used to further understand the inversion results.

Three-dimensional forward modeling and inversion approaches (e.g., Maao, 2007; Commer and Newman, 2008) provide the best approximation to the true resistivity structure because the earth and the source fields are assumed to be 3D. However, 3D inversion is a time-consuming process with run times on the order of weeks to reach a converged solution. For this reason, the construction of robust starting models using 1D and 2D approaches, and the constraint of the inversion itself with well log, seismic, or geologic information is critical to ensure the 3D inversion process is as efficient as possible. The result is an isotropic or anisotropic resistivity volume.

As in the survey design process, technical considerations and constraints imposed by budget and timing must be taken into account when considering the best approach to data analysis. It is not necessarily the case that in all situations a 3D inversion approach will be more effective at answering a given geophysical question than a carefully executed 1D or 2D inversion analysis: Workflows must be tailored for the problem at hand.

The result of the analysis is an understanding of the distribution of resistivity in the earth. However, this is seldom the ultimate goal of a study: These variations in resistivity must be interpreted in terms of the underlying rock and fluid properties controlling them, and this requires careful integration of the results with seismic and well log data.

### Integrated interpretation of CSEM data

When CSEM data are considered in isolation, structural resolution is poor and the results can be ambiguous because the effect of an increase in pore fluid resistivity cannot be distinguished from the effect of a decrease in porosity. The presence of resistors in the section; for example, cemented sandstones, tight carbonates, volcanics, or salt will also complicate the interpretation. Integration of CSEM-derived resistivity measurements with complementary seismic based measurements, under a rock physics framework can allow some of the ambiguities inherent in each method to be resolved.

The term “integrated interpretation” can cover a wide variety of different approaches and workflows and is used in the literature to mean many different things; however, generally these fall into four broad classes:

1. Recognizing the poor structural resolution of CSEM data, seismic data is often used to condition the inversion of CSEM data by providing structural constraints. Starting models can be constructed using seismic stratigraphy as a guide, and seismic horizons included as smoothness breaks at known boundaries in the structure; for example, top salt or basalt, top reservoir or top basement. Such strategies improve the resolution of the CSEM result (MacGregor and Sinha, 2000; Hansen and Mittet, 2009; Lovatini et al., 2009).

2. Following inversion of the CSEM data, corendering approaches are perhaps the simplest category of integration approaches (e.g., Lovatini et al., 2009; MacGregor et al., 2012; Alcocer et al., 2013). Resistivity sections or volumes derived from inversion of CSEM data are corendered with seismic data or attributes, and the correlation (or lack of it) between the two is used to draw inferences on the geology under study. This can be a very powerful first look tool; however, it fails to address the lower vertical resolution of the CSEM method compared to the seismic. Resistive bodies may be mapped at the wrong depth by unconstrained inversion approaches, and if corendered and interpreted alongside seismic without care could lead to erroneous geologic conclusions. Nor does it address the question of the underlying cause of the resistivity variations observed. A zone of high resistivity could as easily be caused by a lithological variation as by a change in hydrocarbon charge. Correlation between structural closures and zones of high resistivity can perhaps provide confidence in an interpretation of hydrocarbon; however, the underlying question remains: What is the cause of the resistivity variation?

3. Integrated interpretation approaches start to address this question, by using rock physics relationships to interpret the observed variations in seismic and CSEM-derived attributes in terms of the underlying rock and fluid properties. Seismic data are inverted first to provide acoustic and/or elastic impedance, and derived properties such as Poisson’s ratio. Similarly CSEM data are inverted to provide a measure of resistivity and resistivity anisotropy. These are then coupled though rock physics relations, either theoretical, or empirically derived and calibrated from well log information, and jointly interpreted to understand variations in rock and fluid properties (e.g., Harris et al., 2009; MacGregor, 2012; Morten et al., 2012).

4. Finally, joint inversion approaches seek to do both steps at once by inverting directly for a model that satisfies seismic and CSEM data sets simultaneously. Various approaches to joint inversion have been investigated in the past. These fall broadly into two categories (de Stefano et al., 2011; Moorkamp et al., 2011). In the first category, are methods where the coupling between electric and elastic properties is primarily structural, constraining variations in resistivity to be spatially coincident with variations in elastic properties. Approaches where the different physical properties are coupled through cross-gradient functions (e.g., Haber and Oldenburg, 1997; Gallardo and Meju, 2004) fall into this category. Such methods are extremely powerful in cases where the variations in properties are known to be coincident, or where a direct relationship
between electric and elastic properties is uncertain or hard to obtain. A second approach is to relate the elastic and electric properties of the earth directly using either deterministic (e.g., Hou et al., 2006; Hoversten et al., 2006; Gao et al., 2012) or statistical (e.g., Chen and Hoversten, 2012) rock physics relationships. In this case, such rock physics relationships are used to relate elastic and electric properties to a set of reservoir properties, such as porosity, fluid saturation, or shale volume. Although this approach has a good physical grounding, the nonlinear nature of these relationships, uncertainties in them, and the possibility that the relationship varies (for example with lithology variations) over the inversion domain, has the potential to introduce additional nonuniqueness into the inversion.

Any workflow for the integration or joint inversion of different data types has to deal with a number of issues. Firstly, measurements made using very different physical processes (electric and elastic in the case of CSEM and seismic) must be combined and linked to the underlying rock and fluid properties in a consistent fashion. This requires a rock physics framework to be either numerically derived or empirically calibrated at well locations. In both cases, such models are subject to uncertainty, which in turn leads to uncertainty in the resulting interpretation.

Secondly, seismic, CSEM, and well log techniques sample the earth at very different scales, varying from a few centimeters in the case of well logs, to hundreds of meters for CSEM. For example, using seismic methods, the details of layering within a reservoir interval may be resolved, whereas CSEM methods are likely only to be sensitive to the bulk properties of the reservoir interval and not to the details of the fluid distribution within it. These different scales must be reconciled in an integrated interpretation or joint inversion approach.

Finally, in order for an integration approach to be successful, seismic and CSEM methods must be sensitive to the interval of interest and changes in properties within it. Although this is perhaps an obvious statement, it is nonetheless a key consideration in determining where such approaches can be applied. For example, a reservoir that can be imaged and constrained seismically may lie at too great a depth below mudline, or be embedded in too complex or resistive a background structure for CSEM methods to be effective. Similarly, low-saturation gas clouds above a reservoir may render seismic method ineffective, while having little or no effect on the CSEM response or interpretation.

Seismic and CSEM sensitivity to rock and fluid properties

Detailed interpretation of CSEM-derived resistivity in terms of the underlying rock and fluid properties is fraught with ambiguity if considered in isolation. This is illustrated in Figure 15, which shows the variation in P-wave velocity, S-wave velocity, and resistivity with porosity and gas saturation of a clean sandstone reservoir. Archie’s law (Archie, 1942) is used to calculate the variation in resistivity

$$\rho_b = a \phi^{-m} S_w^{-n} \rho_w,$$

where $\rho_b$ is the bulk resistivity of the reservoir, $\phi$ is the porosity, $S_w$ is the water saturation, and $\rho_w$ is the interstitial water resistivity. The empirical parameters $a$, $m$, and $n$, respectively the tortuosity factor, cementation exponent, and saturation exponent, are set to 1, 2, and 2, respectively, in this example. The soft sand model of Dvorkin and Nur (1996) combined with Gassman’s equation (Gassman, 1951; Mavko et al., 2009) are used to calculate the variation in seismic velocity.

Looking first at the resistivity, it is clear that there is a trade-off between porosity and saturation in the reservoir: A given value of resistivity may be explained by either a higher porosity sandstone saturated with resistive hydrocarbon fluids, or by a much lower porosity sandstone saturated with brine. These alternatives cannot be distinguished using resistivity alone. Velocity and density, in this example, are primarily controlled by the porosity of the reservoir. Significant variations with saturation are confined to low gas saturations (the area of high $S_w$).

Figure 15. Variation in P-wave velocity (a), S-wave velocity (b), and resistivity (c) for a simple clean sand reservoir in which the saturation of gas is varied.
Figure 16 illustrates the effect that this sensitivity can have on CSEM and seismic responses. The left-hand panel of Figure 16 shows the clean sand reservoir discussed above embedded at 1570 m below seafloor in a background structure in which resistivity increases gradually with depth. The center panel of Figure 16 shows the corresponding CSEM response at three frequencies, calculated for an 80% gas saturated reservoir and a water wet reservoir. As expected, the presence of gas in the reservoir causes an increase in field strength and an advance of the phase of the response. The response for a reservoir saturated with 20% gas overlies that of the water wet case: In terms of CSEM response, a water wet reservoir cannot be distinguished from one containing a low saturation of gas.

For comparison, the right-hand panel of Figure 16 shows the amplitude versus angle (AVA) response for the same reservoir scenarios, calculated using a two-term Shuey approximation to the Zoeppritz equations (Shuey, 1985). In contrast to the CSEM response, there is now a large difference between water wet and 20% gas saturated cases. However, when the seismic response is considered the difference between 20% and 80% gas saturations is small, with both exhibiting a class III AVO anomaly. The seismic response highlights the presence of some gas, but the saturation cannot be constrained well.

When interpreting geophysical data, such uncertainties have a large impact. Consider seismic and CSEM data sets acquired over the reservoir above, charged with an 80% gas saturation. The job of the geophysicist is to constrain as accurately as possible the properties and fluid content of that reservoir. In the simple case where only the reservoir properties are to be examined (in a real example, the reservoir and overburden would have to be constrained), the interpretation problem can be illustrated by calculating the rms misfit between the acquired data and the geophysical responses of models with varying porosity and fluid saturation. These misfit surfaces are plotted in Figure 17 for the case of seismic data alone, CSEM data alone, and a joint data set consisting of seismic and CSEM data.

![Figure 16](image)

**Figure 16.** (a) Simple resistivity model containing a clean sand reservoir of porosity 28% at a depth of 1570 m below mudline. (b) CSEM receiver gather calculated from the model on the left at three frequencies, and for two reservoir scenarios: water wet and 80% gas saturation. Note that the 20% gas saturation case overlies the water wet curve. (c) Seismic AVA response for this reservoir.

![Figure 17](image)

**Figure 17.** Root-mean-square misfit between geophysical data calculated from a 28% porosity, 80% gas saturated reservoir, and the responses from models with a range of porosity and saturation values. In each case, the white star shows the misfit of the true model. (a) Seismic AVO data taken alone. (b) CSEM data taken alone. (c) Joint CSEM-VO data misfit surface. Note the same color scale is used in all plots.
Consider first the misfit surface when only seismic AVO data are considered (Figure 17a). The true model lies at a misfit minimum; however, this minimum is elongated along the saturation axis, demonstrating that, although the porosity is well-constrained, the gas saturation could take almost any value between 100% and approximately 20% and still be consistent with the data. This leaves a large uncertainty in saturation from any seismic analysis.

Figure 17b shows the corresponding misfit surface when only CSEM data are considered. Again, the true model lies within the zone of minimum misfit as it should; however, the same misfit would be obtained if the porosity were much lower, and the water saturation higher. The minimum misfit area is elongated along a line of constant transverse resistance. Using CSEM data alone, there is a tradeoff between porosity and saturation.

Figure 17c shows the combined misfit surface when seismic AVO and CSEM data are considered. In this case, the seismic constraint on the porosity resolves the saturation-porosity trade-off inherent in interpretation of the CSEM data: The minimum in misfit is now much better localized around the true model. Although this is a simple illustration, using perfect synthetic data, it demonstrates the advantages of combining multiple data types so that the strengths of each are utilized.

Turning first to P-wave velocity-resistivity space (Figure 18a), it is clear that there is little variation in P-wave velocity with changes in the fluid properties or saturation. This is to be expected when only acoustic parameters are considered. However, there is a large difference in resistivity between the water saturated and fizz gas cases, and the more resistive 80% gas or 80% oil case. Although a measurement of resistivity could not distinguish between gas and oil, it could be used to discriminate commercial from noncommercial hydrocarbon saturations, adding significantly to the information available from P-wave velocity alone. However, care must be exercised in the interpretation. In this example, a sequence of coals lying just beneath the reservoir complicates the result. These coal measures have a resistivity that overlaps with the resistivity of the 80% gas or oil cases, and their P-wave velocity is only marginally lower than the reservoir case. In the P-wave-resistivity domain, these coals add significant ambiguity to the interpretation.

If prestack seismic data are available for the analysis, elastic attributes may be added to the interpretation. This is illustrated in Figure 18b, which shows the same data in the acoustic impedance (AI)-Poisson’s ratio domain.
ratio (PR) domain. There is significantly more sensitivity to the properties of the reservoir fluid content in this domain, although the ambiguity between noncommercial and commercial hydrocarbon saturation remains. However, the subreservoir coal measures in this domain are clearly separated from the fluid cases having significantly higher PR. Resistivity and elastic parameters are therefore required in this example to provide a robust interpretation: the resistivity to assist in distinguishing noncommercial from commercial hydrocarbon saturations, and the elastic to characterize the coal measures and ensure that high resistivities associated with these are not misinterpreted.

Discussion

The CSEM method has strengths and weaknesses like all geophysical approaches. The strength of the method is that it can provide valuable information on the resistivity of the subsurface. This resistivity attribute is complementary to more traditional attributes derived from seismic data, and when interpreted carefully in a seismic framework is particularly helpful in determining saturation within reservoir intervals.

However, the method also has weaknesses. The structural resolution achievable with CSEM data taken alone is poor, because CSEM makes a bulk measurement of a volume of the earth, using physics governed by the diffusion equation, rather than the wave equation as in the case of seismic data. Resolution in a vertical sense in particular is challenging: Often, the uncertainty in vertical positioning of features can be several hundred meters. Seismic data, however, provides extremely good structural and stratigraphic constraint, and so these weaknesses in the CSEM method can be mitigated through careful interpretation and integration with such seismic derived information.

As with any geophysically derived attribute, the resistivity attribute obtained from CSEM analysis must also be interpreted carefully. This is best achieved when well log calibration is available so that the cause of variations in resistivity, and indeed variations in seismic attributes or responses, can be understood in terms of the underlying rock and fluid properties.

This combination of strengths and limitations should perhaps guide the CSEM method to areas in oil field lifecycle where it can bring the most value to an analysis. In rank exploration, in the absence of well log data and with little or no seismic data, the CSEM interpretation problem is poorly posed. An unconstrained inversion of CSEM data will have poor resolution in terms of structure, and even if resistivity variations are observed, there is no way to know the underlying cause: Is it a lithology or fluid effect? Similarly, the absence of high-resistivity features in an area may be the result of poorly targeted acquisition parameters resulting from a lack of understanding of the background geology, or a lower-than-expected hydrocarbon charged reservoir resistivity, and therefore cannot by itself be taken to rule out the presence of commercial hydrocarbons. Therefore, although it is of course possible to apply CSEM methods in frontier areas (e.g., Lovatini et al., 2009; Fanavoll, 2012), the interpretation risks resulting from the lack of constraint and calibration can be extremely high.

In more targeted exploration or prospect-ranking exercises where seismic and (perhaps) well log data are available, along with detailed interpretations of structure and stratigraphy, the CSEM interpretation process becomes better constrained, and the answer achieved is likely to be more certain. Reservoir appraisal is better still, where seismic and well log data are available, and the reservoir properties are known at the well location. Here, the question for the CSEM (and seismic) analysis to answer is how these properties vary away from the calibration points.

Ultimately, CSEM methods may find a use in reservoir monitoring where understanding changes in the fluids within a reservoir over time is the goal. There have been numerous studies of this application undertaken (e.g., Orange et al., 2009; Andreis and MacGregor, 2011); however, the method has yet to be tried in the field on an offshore reservoir.

Conclusions

This paper has sought to provide an overview of CSEM methods, the challenges and pitfalls that must be overcome when applying them, and considerations for designing a successful survey campaign. It is clear that resistivity, which can be derived from CSEM measurements, can provide useful additional information on subseafloor lithology and fluid properties in exploration, appraisal, and perhaps ultimately reservoir monitoring. Whatever the application, the best results are achieved when CSEM is analyzed and interpreted in an integrated framework in conjunction with well log, seismic, and other available data types.

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References


Biographies and photographs of other authors are not available.