Session 3A1b
Seabottom Electromagnetic Imaging and Detection Technologies

Modeling and Inversion of Marine CSEM Data

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The principle of the marine controlled-source electro-magnetic (CSEM) technique used for remote detection of hydrocarbons (HC), is described by Ellingsrud et al., (2002). A horizontal electrical dipole (HED) emits an ultra-low frequency (0.1–5 Hz) electromagnetic (EM) wavefield into the underlying seabed and downwards into the subsurface. EM energy is rapidly attenuated in the conductive seafloor sediments. In high resistive layers such as HC-filled sandstones and at a critical angle of incidence the energy is guided along the layers and attenuated less. The detection of this guided and refracted energy is the basis of marine CSEM in HC exploration.

Before interpretation of the CSEM data is possible, extensive data processing is required. Important processing steps include: (1) window-based Fourier transform from time to frequency, (2) separation of down-going and up-going (scattered) fields, (3) depth migration, and (4) full inversion, estimating subsurface conductivity. Here we will focus on the last two processing steps; depth migration and inversion, and the use of forward wavefield simulations as part of the necessary workflow.

Zhdanov et al., (1996) introduced frequency-wavenumber (fk) and finite-difference depth migration methods for CSEM data, based on familiar ideas from seismic imaging (Claerbout, 1985). There are, however, important differences in migration of CSEM data, compared to seismic data: First, the attenuation of EM-fields in a conducting subsurface is very strong, and ultra-low CSEM data suffer significantly from dispersion. Second, the conductivity contrast at the sea floor is usually significant. Third, the horizontal and vertical conductivity can differ significantly, which leads to strong anisotropy.

The migration methods mentioned above does not handle EM-wavefield amplitudes correctly. In fact their seismic counterparts, were never assumed, nor designed, to do so. Hence, the result of depth migration is only a structural image of conductivity contrasts. To compute estimates of the subsurface conductivity, full inversion must be used. In steepest-decent and conjugate-gradient inversion schemes (Newman et al., 1997), the gradient in the first iteration provides a structural image of the subsurface. In seismic imaging the gradient calculation is referred to as reverse-time migration (Mittet et al., 2005).

A subsurface conductivity anomaly is not a unique hydro-carbon indicator. It may be due to other resistive bodies or layers in the subsurface, such as salt and igneous intrusions (sills) or regional trends (e.g., basin thickening). In the interpretation of marine CSEM data for HC exploration, these anti-models must be considered. In a typical workflow, numerical forward modelling is used to simulate and evaluate all realistic scenarios. The EM results are used, together with other information, e.g., seismic data, to risk exploration prospects before drilling decisions are made. In the presentation we will show examples from marine CSEM field data, and discuss some of Statoils experience using this technology.

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Experience with the Three-dimensional Imaging of Marine Controlled Source Electromagnetic Data for Hydrocarbon Exploration

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Experience with the three-dimensional inversion of frequency domain, controlled, multi-source, electromagnetic data collected in the deep water marine environment suggests that the derived resistivity images can, under appropriate conditions, play a useful role in commercial hydrocarbon saturation predictions. Significant technical challenges exist in the simulation and inversion of these data.

The Marine Controlled Source Electromagnetic (MCSEM) surveys conducted by ExxonMobil beginning in 2002 provide data for which electromagnetic imaging offers a significant potential due to the relatively high spatial density of the electric field recordings, the low level of anticipated noises and the excellent electrical coupling provided by the marine environment. Unfortunately, significant technical issues are presented by the large subsurface volume probed by low frequency electromagnetic recordings, the large dynamic range of the recorded data, the large number of source positions, and the three-dimensional nature of the anticipated targets. Inversion results at locations offshore of West Africa illustrate the progress made in confronting these technical difficulties and progress toward the goal of establishing a new class of hydrocarbon exploration tools.

Electromagnetic soundings in conductive sediments are heavily constrained by the skin-depth phenomena to a very narrow range of frequencies which must both successfully penetrate to maximum target depth and also resolve significant conductivity variations between the sea bottom and the target zone. The implied frequency range for targets of practical interest varies from approximately $1/16\,\mathrm{Hz}$ to $2\,\mathrm{Hz}$ and the skin depth from $2\,\mathrm{km}$ to no less than $0.2\,\mathrm{km}$. On these scales reservoir targets are unquestionably three dimensional objects for which two dimensional approximations are either inappropriate or unnecessarily restrictive. Sediments and seawater are assumed to exhibit conductivity values ranging from about $6\,\mathrm{s/m}$ to values in the range of $0.01\,\mathrm{s/m}$ in well saturated hydrocarbon reservoirs. Only three general techniques for simulation and, therefore, inversion of Maxwell's equations (in the frequency domain) are available for three-dimensional models: integral equations (IE), finite difference (FD), and finite element (FE). Weak scattering approximations, particularly of the distorted wave type, may have some domain of application (yet to be shown) due to the limited range of subsurface conductivity values anticipated. However, these methods may face difficulties associated with the large size of the domain of unknown subsurface resistivities sought by the inversion process. The availability of a massively parallel FD approach dictated its selection for this undertaking versus a more sophisticated FE approach restricted in scope to a single processor platform. Inversion results reported in this presentation use both amplitude and phase information derived from the ocean bottom electric field recordings.

Application of inversion technology to MCSEM datasets from offshore of West Africa over both hydrocarbon reservoir and non-reservoir locations shows that hydrocarbon data signatures, particularly for the electric field component parallel to the applied transmitter current, can be effectively imaged into three dimensional resistive bodies which are often broadly consistent with existing seismic structures. Carefully processed MCSEM data has repeated been found to fit likely three dimensional models to a very high percentage of electric field energy, frequently exceeding 95%. Inverted resistivity images displayed against the more conventional dense seismic depth images illustrate the potential for the new MCSEM tool in hydrocarbon exploration.

New Advances in 3D Imaging of Sea-bottom EM Data for Offshore Petroleum Exploration

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During recent years a significant progress has been made in developing new mathematical methods and computer codes for interpretation of the sea-bottom electromagnetic (EM) data for offshore petroleum exploration. In this paper I present an overview of effective imaging techniques, which include the fast sea-bottom EM imaging based on the principles of electromagnetic migration, different types of integral representations for EM responses in the receivers, and regularized inversion. Electromagnetic migration, similar to seismic migration, is based on a special form of downward continuation of the observed field, which can be computed as a solution of the boundary value problem for the adjoint Maxwell's equations, in which the boundary values of the migration field on the earth's surface are determined by the observed EM data. It is shown that EM migration can be treated as an approximate solution of the corresponding EM inverse problem.

Another approach is based on iterative quasi-linear (QL) inversion with the accuracy control using rigorous integral equation (IE) method. In the framework of this approach the background conductivity may be formed by a layered formation, or may be described by arbitrary conductivity distribution. This allows us to incorporate known information about the geoelectrical structures in the inversion and keep it unchanged during the inverse process.

The new imaging methods are tested on the typical models of the sea-bottom EM surveys for offshore petroleum exploration, including magnetotelluric (MT) surveys and Seabed Logging (SBL) synthetic data.

Three Dimensional Electromagnetic Modeling and Inverison of Seabottom Electromagnetic Data

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Modeling and inversion of low frequency (10 to 0.1 Hz) seafloor electromagnetic data present significant technical challenges because of the enormous quantity of data that is acquired during a field experiment. The problem is further compounded because transmitter-receiver offsets easily exceed ten's of kilometers and the large subsurface volumes that are sensed beneath the sea floor are inherently three-dimensional (3D) in the context of hydrocarbon exploration. Thus modeling and inverting such data is no simple task. There are several methodologies available to treat the problem and here we focus on finite-difference FD methods. Because FD solutions to the 3D time harmonic Maxwell's equations in the quasi-static limit can be solved relatively rapidly on distributive computing platforms, these methods have the flexibility to treat the large scale nature of the problem. Nevertheless much work remains in accelerating 3D FD solutions to the forward and inverse modeling problems. Here we are investigating a variety of approaches. For the forward problem we present some preliminary results of solution acceleration using multigrid (MG) as a preconditioner for Krylov subspace iteration methods that are used to solve sparse, large-scale, linear systems that arise from the finite difference approximation of 3D Maxwell equations. With the inverse problem we present some results for preconditioning the inverse iteration based on approximate adjoint methods for nonlinear conjugate gradient and Gauss-Newton optimization strategies. Because 100's to 1000's of solutions to the forward modeling problem are required with either optimization strategy, MG methods also offer the potential for significant speedup in the context of inverse modeling.

A Critical View about Marine Controlled Source EM Data Interpretation

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The Sea Bed Logging (SBL) or Marine Controlled Source Electromagnetic (MCSEM) method is aimed at detecting and characterising resistive layers, possibly corresponding with hydrocarbon bearing reservoirs.

The basic principle driving the interpretation of the Marine CSEM data is that electric field magnitude and phase vs. offsets (recorded by a series of receivers deployed at sea floor) will show different trends as a function of the resistivity distribution and depending on water depth.

An interpretation approach that is commonly used in the hydrocarbon industry is based on the assumption that, if a proper reference receiver is selected (for instance in correspondence of an area where hydrocarbon absence has been proven), the normalised magnitudes and phases vs. offset (i. e., the observed data vs. the reference data) can represent an indication of resistive layers, possibly associated with presence of hydrocarbons.

In that framework normalized magnitudes significantly higher than 1 at intermediate to far offsets can be interpreted in terms of subsurface resistivity anomalies. Using a similar approach, also the normalised phases are assumed to be indicators of resistivity anomalies.

It is not difficult to show that, especially in shallow water environment (300–400 m), the above assumptions can be misleading.

If a "perfect" up-down wave separation is performed many of the ambiguities can be avoided. The problem is that a perfect elimination of the airwave effect cannot be guaranteed in any case. The risk is the production of artefacts and misleading interpretation.

An additional open question is about the choice of the reference receiver. Other misunderstandings can be originated by effects due to the presence of resistive layers above and below the target, by the variations of water depth along the acquisition profiles, by the presence of noise and so on.

In this work we clarify better the above concepts using simple synthetic tests and real data. Our goal is to show how the interpretation techniques based on normalised plots should be integrated with a an approach massively based on inversion of MCSEM data.

This is fundamental for an appropriate interpretation, especially if constrained by seismic data, in order to limit the ill-conditioned and ill-posed nature of the inverse electromagnetic problem.