## Reducing exploration risk with marine EM: Hydrate detection and base salt mapping

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Marine EM methods have been enthusiastically embraced by the petroleum industry as a means to assess in situ electrical resistivity of potential reservoirs prior to drilling. As industry becomes more conversant with this new methodology, we expect to see electrical methods used much more widely to reduce exploration risk. For example, one of the early applications of marine EM was the use of magnetotelluric (MT) data to map base of salt independently of seismic data. The addition of MT data provides a means to distinguish between competing base salt models, particularly in rooted or otherwise steeply dipping geometries, and to refine velocity models. We continue to develop this use of the MT method by improving instrumentation, processing, and data collection technologies. A more recent example is the use of controlled source EM (CSEM) for detection of shallow gas hydrate. Hydrate is a drilling hazard, can potentially destabilize seafloor adjacent to production infrastructure, and for some countries is seen as a potential energy source. Electrical resistivity mapping provides one of the few mechanisms to quantify the total hydrate volume in the section prior to drilling. We have carried out preliminary studies with encouraging results.

## Reducing Ambiguity in CSEM Inversion

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Geophysical inverse modelling is very rarely a well-posed modelling problem, and the CSEM interpretation problem is no exception. The ambiguity is manifested by the equivalence between models having the same resistivity thickness product. For example, with the most basic survey configuration a 300m thick section of carbonate rich material can produce an identical CSEM anomaly to a 10m thick, hydrocarbon saturated reservoir. This non-uniqueness associated even with a simple 1D layered earth results in the need for regularisation to be incorporated in any inverse modelling algorithm. Although regularisation is necessary to obtain a unique solution to the interpretation problem, it is difficult to determine the probability that any returned ‘optimal' model is correct. Regularisation artificially reduces the confidence intervals associated with each model parameter, leading to overconfidence in the inverse model. The effect on a drilling decision could be disastrous if the regularisation constraint favoured the more economically interesting model.

The ambiguity in the inverse CSEM problem has numerous sources, viz, the fact that there is noise in the data, the fields are not perfectly sampled, and the geometry of the survey apparatus varies during acquisition. The equivalence can be quantified (for simple problems) by measuring the volume of the region enclosing all the ‘acceptable' models according to a data misfit criteria. The influence of the different sources of error can be quantified, and the improvement in resolution obtained through alternative acquisition methods assessed.

## De-Risking Deepwater Sarawak with Controlled Source Electromagnetic Imaging

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Newfield and Petronas Carigali, in late 2005, acquired controlled source electromagnetic imaging (CSEMI) data over a series of rank, wildcat prospects in the Deepwater 2C block, offshore Sarawak, Malaysia. The CSEMI, in conjunction with 3D seismic and other remote sensing data was used as a risk reduction tool to high grade a prospect for drilling in late 2006.

The CSEMI survey acquired 390 Kms of data along 10 lines over eleven prospects and two dry holes. The prospects are Pliocene turbidites and large structures at the Mid Miocene unconformity (MMU). Water depths were generally greater than 1,000 meters with reservoir targets 1500 to 2500 meters below seabed. Sediments are primarily shales and sands, with resistivities in the 1.5 to 2.5 ohm range. Data was collected at approximately 1 Km intervals along the lines with a fundamental transmission frequency of 0.25 Hz.

A series of EM anomalies, 20 to 60% above the normalized field amplitude, were found over a number of the Pliocene turbidite prospects and large MMU structural prospects, although not all of the turbidite or MMU prospects showed EM anomalies. In addition no EM anomalies were found at the two dry holes. Unconstrained and constrained 2.5D inversion, co-rendered with the 3D seismic, confirmed that the EM anomalies coincided with identified prospects and were in good agreement where the EM lines crossed.

A positive test of the EM anomalies will considerably reduce future exploration risk in the block.

## Reservoir Resistivity Mapping using Nonlinear 3D Inversion of Marine CSEM Data

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Marine controlled-source electromagnetic (MCSEM) surveys are a promising method for Upstream hydrocarbon applications. Significant technical challenges exist in the realistic modeling and accurate inversion of such data. These challenges are due primarily to the computational costs for geologic problems of realistic scale, the relatively sparse coverage and useful bandwidth of the data, the usually subtle responses (i.e. weak scattered fields) of deep targets, and the strongly ill-posed nature of the electromagnetic inverse problem. However, recent inversion results from several locations in deepwater West Africa illustrate the progress that has been made in confronting these technical challenges. Results from nonlinear three-dimensional (3D) inversions show that the derived resistivity images can, under appropriate conditions, play a useful role in mapping reservoired hydrocarbons. Joint interpretation of the 3D resistivity images and reflection seismic data shows clear promise for more effective geophysical imaging of the subsurface and subsequent application to Upstream problems.

## Integrating Controlled-Sourced Electromagnetism (CSEM) as an Exploration Tool

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Controlled Source Electro-Magnetic imaging (CSEM) is a recently developed technology that maps subsurface resistivity variations (Eidesmo et al., 2002). It uses a horizontal electrical dipole (HED) which emits a low frequency (0.25Hz – 10 Hz) electromagnetic (EM) signal into the underlying seabed and into the subsurface. In the presence of an anomalous resistor the dispersion of the EM field is distorted, which may be considered analogous to seismic refraction. Energy is constantly refracted back to the seafloor and is detected by receivers placed on the sea floor. The detection of the ‘guided and refracted' energy is the basis of CSEM. Archie's law indicates that the method is more sensitive to high saturation hydrocarbon pore fill and due to the low frequency nature only relatively large accumulations of high saturation will be detectable.

With such low frequency sources the 3D interpretation of the data is complex, and requires robust and advanced 3D forward modelling of ultra-low frequency propagation of EM fields and close integration with other sub-surface data such as seismic to constrain the required 3D structural information and interpretation.

In this paper three examples are provided in different geological settings, illustrating the use of CSEM. Although the technology holds great potential, it is still rather primitive and is not a ‘silver-bullet' to exploration success. Further advances of the technology are arising from sophisticated 3D acquisition, imaging and inversion of all EM effects constrained by acoustic and potential field data, which Shell is currently testing in the Asia-Pacific region.

## Integrated Electromagnetic Methods for Exploration, Reservoir Characterisation and Monitoring

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During the last two decades Eni applied natural source electromagnetic methods oriented especially to onshore exploration. Several thousands of magnetotelluric soundings have been acquired on land in complex geological settings, where seismic methods alone revealed their limitation in providing satisfactory imaging. Also DC data have been collected in difficult exploration areas, aimed at improving the solution for static corrections of seismic data. Moreover during the last ten years also several Marine MT surveys have been performed. In the last few years more robust and systematic results have been collected by Eni, after a full understanding of the importance of quantitative integration of electromagnetic, seismic and gravity data. Many tests and applications of Controlled Source EM methods have been performed, using both time domain (on land) and frequency domain (offshore) approaches. The acquisition workflows have been designed in order to acquire electromagnetic data sets that can be successfully integrated with the seismic information. Innovative procedures of joint, cooperative and sharp/constrained inversion have been set in order to provide a fully integrated interpretation of electromagnetic, seismic and gravity data. In this paper the general integration approach used in Eni is presented and some significant case histories are discussed.