Marine CSEM Sounding: Moving Beyond the Image

L. MacGregor\textsuperscript{1}, P. Harris\textsuperscript{2}

\textsuperscript{1}OHM LTD, \textsuperscript{2}ROCKSOLIDIMAGES

Summary
Up until now the CSEM method has been used primarily in an exploration context to derive the resistivity within formations, and to provide an indication of the likelihood that they are hydrocarbon bearing. Inversion and imaging approaches can be used to derive cross sections or volumes of resistivity, which can be analysed in conjunction with seismic or other geophysical data. Whilst information provided in this way is extremely valuable, it is possible to go further in the analysis of CSEM data, by using the measured values to examine the underlying rock and fluid properties. Combining this information with other information derived from surface seismic or well log measurements can reduce ambiguities inherent in the analysis of either data type alone.

Introduction
Marine electromagnetic methods are becoming widely recognized as valuable tools in the hydrocarbon industry. Controlled source electromagnetic (CSEM) sounding methods and their application to the mapping of hydrocarbon accumulations in particular have received attention recently, with many companies now acknowledging their place among the geophysical methods routinely applied in hydrocarbon exploration (e.g. Smka et al., 2006; Moser et al., 2006). The CSEM method, which traces its roots back over twenty years to early studies of the oceanic crust, uses a high powered electric dipole to transmit low frequency signals through the earth to an array of seafloor receivers. Analysis of the received signals allows the resistivity structure in the underlying earth to be determined.

Data Interpretation
Analysis and interpretation of the data acquired in CSEM surveys typically proceeds in stages, starting with initial reconnaissance modelling and analysis of simple normalized field anomalies. These methods can give a broad overview of the classes of structure consistent with the data, and highlight any large variations in resistivity over the survey area. However caution must be exercised in interpreting results such as these: since only a small subset of the data are used, it can be difficult to establish the depth of features causing the anomalies. Shallow resistive structure (for example that caused by shallow gas or hydrates) may be confused with resistive bodies at greater depth in the earth. Geophysical inversion (MacGregor, 1999) and imaging (Tompkins, 2004) provide a more comprehensive method of interpreting CSEM data. Results are improved further by incorporating results from other geophysical methods. For example, marine magnetotelluric data can be used to constrain background structure in a CSEM survey. By including MT data in the inversion and analysis process, potential ambiguities in the CSEM survey results can be resolved. This is illustrated in Figure 1, which shows results of a simplified synthetic inversion for a target overlying a more resistive basement. The CSEM data alone cannot resolve the target as a localized resistive body in the presence of the more resistive basement structure. By including the MT data in a joint inversion with the CSEM data, the resolution of the target layer is greatly improved.
Figure 1. Jointly inverting CSEM and MT data can remove ambiguities in the interpretation of a single data type. Left panel: 2D inversion of data generated from a simple structure containing a resistive target overlying a more resistive basement structure. Although the effect of the target can be seen in the result (as a slight decrease in depth to basement) it is not well resolved. Right panel: including MT data in the inversion improves the resolution of the result.

Integrated interpretation of CSEM and seismic data can provide further insights into the geological structure of the earth. Such interpretation can range from simple co-rendering of seismic and EM results, through constrained inversion in which structural information from seismic data is used as an a priori constraint in EM inversion. An example of the former is shown in Figure 2. Here the results of inversion of CSEM data collected in the North Falkland Basin are co-rendered with coincident seismic data. The resistive zone highlighted by the CSEM analysis correlates well with the seismically identified structural closure. Whereas a high resistivity zone coincident with an identified prospect cannot unambiguously demonstrate the presence of hydrocarbons (other geological materials such as tight carbonates, volcanics or coals can also exhibit increased resistivity), it does increase significantly the probability that the prospect is hydrocarbon bearing.

Figure 2. CSEM inversion result co-rendered with seismic data to highlight the correlation between seismic and electrical features.

Moving Beyond The Image

Inversion and imaging results such as those shown provide valuable insights that can significantly de-risk exploration prospects. However this can be viewed as a first step in the analysis process. A CSEM survey and the resulting data can do more than simply provide a picture of the resistivity structure of the earth. In performing a CSEM survey we are making a measurement of the resistivity of subsurface materials. In the same way that seismic measurements of elastic parameters can be used to derive rock property information (for example through amplitude versus offset (AVO) analysis and inversion), measurements of electrical properties can also be used to constrain both rock and fluid
parameters. The electrical and elastic properties of the earth are controlled by very different physical processes, so by careful combination of seismic and CSEM data, exploiting the strengths of each, we can derive information which is not available or is unreliable from either type of data alone, thus reducing ambiguity and risk. A number of approaches to the integration of these data types have been proposed (e.g. Greer, 2001; Gallardo and Meju, 2004; Harris and MacGregor, 2006; Hoverston et al., 2006). Fundamental to the combination of these disparate data types is the development of a consistent rock physics model linking both electromagnetic and elastic properties to the underlying rock and fluid properties. Such relationships may derived through theoretical and laboratory studies, and by using well-log information (if available) to calibrate measurements to the known properties of the subsurface.

**Conclusions**
Integration of electromagnetic and seismic data allows us to move beyond the creation of an image of the resistivity structure of the earth, to obtain valuable measurements of reservoir properties such as saturation and porosity. By doing this the range of situations in which CSEM methods are applicable increases, with obvious applications in reservoir appraisal, monitoring and management becoming possible.

**References**
Harris, P & MacGregor, L., 2006, determination of reservoir properties from the integration of CSEM, seismic and well log data, *First Break*, **24**, 53-59