Joint analysis of marine active and passive source EM data for sub-salt or sub-basalt imaging.

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Abstract

Marine electromagnetic (EM) exploration methods, which allow the electrical resistivity of the seafloor to be determined remotely, have been developed in the academic sector over the last twenty years and are now being applied widely within the hydrocarbon industry. One area where such techniques can make a significant contribution is in regions where sediments of interest are obscured by (for example) salt, carbonate or basalt. Such high velocity layers can make the detection and characterisation of sediments lying beneath using conventional seismic technique difficult. However the electrical resistivity of basalt, carbonate or salt is typically in the range 100-1000 $\Omega$m, whereas the resistivity of the surrounding sedimentary sequences is typically 1-10 $\Omega$m. This marked contrast in resistivity is an ideal target for electromagnetic prospecting techniques. In this paper the combination of active source EM and passive source (magentotelluric) methods, each sensitive to different parts of a given resistivity structure, is discussed.

Introduction

Several marine electromagnetic techniques have been developed in recent years to address the problem of mapping offshore electrical resistivity structure, two of which will be considered here. The first is marine active source electromagnetic sounding in the frequency domain, which has been successfully applied to the study of oceanic lithosphere (e.g. Young & Cox, 1981; Constable & Cox, 1996). Several combined electromagnetic/seismic studies of active mid-ocean ridges have been performed (e.g. Evans et al., 1994; MacGregor, Constable & Sinha, 1998; MacGregor, Constable & Sinha 2001), yielding valuable information on fluid properties and distribution. More recently the method has been used to provide a direct indication of the presence of hydrocarbon bearing layers in the sub-seafloor (Eidesmo et al. 2002; Ellingsrud et al. 2002). The active source EM method uses a horizontal electric dipole source to transmit a low frequency (from a few tenths to a few tens of Hz) electromagnetic signal to an array of receivers that detect and record the electric field at the seafloor. By studying the variation in amplitude and phase of the received signal as the source is towed through the receiver array, the resistivity structure of the sub-surface can be determined at scales of a few tens of metres to depths to several kilometers. Since the source is 3-dimensional, the response of a given structure depends critically on the source receiver geometry. Careful experimental design to maximise the range of geometries in a survey is therefore necessary to maximise the sensitivity of the resulting data to structures of interest (MacGregor & Sinha, 2000).

The magnetotelluric (MT) method uses measurements of naturally occurring electromagnetic fields to determine the resistivity of the sub-surface. The depth to which the incident EM fields penetrate depends on the frequency of the field and the resistivity of the medium. Thus, by studying the variation in response as a function of frequency, the variation in resistivity as a function of depth may be determined. Charge build up at resistivity boundaries allows lateral changes in structure to be

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mapped. Traditionally the marine MT method has been used for mapping large-scale (tens to hundreds of km) resistivity variations, since the conductive seawater screened all but the lowest frequency source fields. However recent advances in instrumentation have increased the usable frequency band so that crustal scale variations can now be mapped (Constable et al. 1998). The method has been successfully applied to the study of salt structures in the Gulf of Mexico (Hoverston et al. 2000), and more recently to sub-basalt structures in the North Atlantic (Lewis et al. 2002).

The effect of fine layering in the high resistivity layer

The resolution capabilities of active source EM data, MT data and the two combined can be investigated by calculating the response of models which represent the problem of interest, perturbing these responses with Gaussian noise, and then re-inverting the resulting synthetic data to establish how much of the original structure can be recovered. As an example the case of a structure in which sedimentary layers are obscured by basalt flows will be considered, although the results could equally well apply to sub-salt or sub-carbonate structures.

The 1-dimensional trial model (figure 1) consists of a thin conductive surficial layer with a resistivity of 0.6 $\Omega$ m representing water saturated sediments, overlying a much more resistive region representing a sequence of basalt flows. Resistivity logs from boreholes in basalt flows exhibit rapid short wavelength variations in resistivity with depth, which have the potential to influence the results of EM sounding surveys. To model this variation the basalt sequence was represented as a stack of layers with thicknesses between 0.5m and 20m with a mean value of 8m, giving an overall basalt thickness of 1.5km. The thickness distribution was taken from Smallwood et al. (1998), based on the mapped thicknesses of basalt flows on Iceland. Resistivities within each layer of the basalt flow model were assigned according to the layer thickness, with the thinnest layers assigned the lowest resistivities. This gave a distribution of resistivities between 6 $\Omega$ m and 300 $\Omega$ m with a mean value of 150 $\Omega$ m. Beneath the basalt flows is a more conductive layer with a resistivity of 4 $\Omega$ m representing older sedimentary sequences, and the model is terminated by a uniform 1000 $\Omega$ m halfspace representing a pre-rift or crystalline basement. The entire model is overlain by a seawater layer.

The active source EM response at frequencies of 0.25 Hz, 0.75Hz, 8Hz and 24 Hz was calculated. Responses with a magnitude of less than $10^{-14.5}$ V/Am$^2$ were rejected since under typical survey conditions such data would be below the seaﬂoor noise floor. The remaining responses were contaminated with 10% Gaussian noise to mimic survey data. The resulting synthetic data cover ranges of 500m to 14km and a range of geometries necessary to optimize the sensitivity of the data to sub-basalt resistivity structure (MacGregor & Sinha, 2000). Similarly, the MT response, consisting of apparent resistivity and phase at frequencies of 1Hz to 0.000125 Hz, was generated, and again contaminated with 10% Gaussian noise to give a synthetic MT dataset similar to those collected in practice (e.g. Lewis et al., 2002).

Figure 1 shows the result of inverting the synthetic active source EM and MT data both separately and jointly, using a regularized inversion approach to return models smooth in the first derivative sense. When the MT data are inverted alone, the resulting model has a resistivity within the basalt layer that is significantly lower than in the original model (a modelled maximum of 30$\Omega$m, compared to the 150
Ωm mean resistivity within the basalt in the true model). This is because MT sounding relies on (predominantly) horizontal currents, which flow in the conductive parts of a structure. MT data are therefore notoriously insensitive to the presence of resistive layers, especially those that are thin compared to their depth of burial. For the basalt flow model considered here the presence of more conductive layers within the basalt further degrades the ability of the MT data to resolve the basalt layer (see for example Pandey, 2002).

In contrast a dipole source of the sort used in active source EM sounding excites both horizontal and vertical current flow. Vertical currents in particular are significantly perturbed by the presence of resistive layers. Figure 1 demonstrates that the active source data are much more sensitive to the presence and thickness of the basalt layer, and are much less affected by the presence of the thin inter-bedded conductive layers. However the crystalline basement, which is recovered to some extent by the MT data, is not well resolved using the active source EM data.

Inverting both data types jointly gives the model shown by the solid black line in figure 1. The active source data constrain the presence, resistivity and thickness of the basalt layer, whilst the MT data constrain the deeper sedimentary structure and crystalline basement. The result is a model that more closely resembles the true structure than the results of inverting either data type alone.

**Sensitivity to 2-dimensional structures**

The results obtained for 1-dimensional resistivity structures can be extended into 2-dimensions. Figure 2a shows a 2-dimensional model (with structure invariant in and out of the plane of the page) again representing a basalt flow overlying an older sedimentary sequence. For simplicity the basalt is assumed to have a uniform resistivity of 200 Ωm in this case. Synthetic active source EM and MT data from an array of receivers (R1 to R5 in figure 2) were generated. The active source data consist of electric field strengths at each receiver for 5 structure parallel source tows at 1Hz. The MT data consist of the TE and TM mode apparent resistivity and phase at frequencies of 0.2Hz to 0.001Hz for each receiver location. Both active source and MT data were contaminated with 5% Gaussian noise to mimic survey data under good conditions. As in the 1-dimensional case these data were then inverted both separately and jointly using a regularized 2-dimensional inversion to find models smooth in the first derivative sense. Since the top of the basalt can in general be readily determined using seismic data and this basalt/sediment boundary corresponds to a known discontinuity in resistivity, a break in the regularization condition was allowed at this point.

The model resulting from inversion of the synthetic MT data is shown in figure 2b. Many of the features of the starting model are recovered, in particular the presence of the sub-basalt sediments, and the deeper basement layer. The resistivity within the sub-basalt sediments is recovered well, however the basalt flow is not well resolved, particularly at the left hand side of the model, where it is thin. The model resulting from inversion of the active source EM data alone is shown in figure. It is clear that the sub-basalt sediments can be detected and the dipping base-basalt boundary is well resolved. However the
resistivity within the sub-basalt sediments is under-estimated, and the increase in resistivity at the sediment-basement boundary is not well resolved.

It is clear that the controlled and natural source data are sensitive to different parts of the resistivity structure. Active source EM data are sensitive to shallow resistive structure, but lack sensitivity to the deeper crystalline basement. Magnetotelluric data are insensitive to thin resistors, however they can constrain the resistivity of the sub-basalt sediments, and the basement beneath. In this respect the two electromagnetic sounding techniques provide complementary information about the sub-surface resistivity structure. The model resulting from joint inversion of the active source and MT data is shown in figure 2d. By combining the controlled and natural source data the geometry of the sub-basalt sediments is much better resolved than using either dataset alone. In particular both the base-basalt/sediment interface, and the sediment/basement interface is clearly defined.

Conclusions

Active and passive source EM methods provide complementary information about the earth, and combined can lead to enhanced resolution of resistivity structures. The MT data can be collected using the same instruments as are deployed for an active source experiment, and can be collected at little extra expense once an active source array has been deployed. In technically demanding environments a range of geophysical techniques are generally employed, however within these marine electromagnetic sounding can make a major contribution.

References


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