Integrated analysis of well log, seismic and CSEM data for prospect appraisal: a case study from West Africa.

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Summary

Integrated analysis of well, seismic and controlled source electromagnetic (CSEM) data is key in order to provide valuable information on reservoir properties and content. The purpose of this study was to jointly analyze well data, seismic data and CSEM data to provide a clear appraisal of a prospect offshore West Africa. Firstly, CSEM data was modeled and inverted. Results were then integrated with the available seismic and well data in order to better understand the resistivity changes we were seeing in the CSEM inversion. In particular, the observation of a low resistivity zone coincident with the seismically mapped prospect is disappointing; however two plausible geological explanations were considered and led to the decision of dropping the block.

Introduction

Seismic methods are considered to be a very good tool to provide a detailed image of subsurface structure. However, in many situations, the seismic methods show their limits when it comes to fluid discrimination. In contrast, electrical resistivity is driven by properties and distribution of fluids. The resistivity of a hydrocarbon charged reservoir, for example, can be considerably more resistive than the surrounding earth resistivity. In theory, CSEM data is sensitive to changes in porosity and saturation. This makes the CSEM technique an excellent tool to complete the information provided by the seismic and well data and to aid in pre-drill appraisal. Here we illustrate the need for a carefully integrated analysis using a case study of pre-drill appraisal of a prospect offshore West Africa, where a CSEM dataset was acquired in 2009.

Background Information

Electrical anisotropy is common in seafloor sedimentary structures, and has been observed in a number of areas offshore West Africa. Resistivities measured in the vertical direction are commonly a factor of two and can in places be up to a factor of ten higher than the corresponding horizontal resistivities. Typical induction log data measures primarily the horizontal component of the resistivity, which may be significantly lower than the vertical component to which inline CSEM data are primarily sensitive. Care must be exercised to ensure that modeling the CSEM data takes this into account. During interpretation of CSEM data, anisotropic effects must be accounted for. Whereas an isotropic approximation can in many instances provide useful insights into the resistivity structure of the seafloor, CSEM results showing primarily vertical resistivity can often be difficult to integrate with well log information or with coincident MT data, both of which constrain the horizontal component of resistivity. The constraint on the depth of resistive features is also improved if anisotropy is correctly taken into account in the interpretation.

The survey area lies in 2000-2200m of water in and is covered with a 3D seismic survey providing high resolution structural information. Although there is no well in the immediate vicinity, wells from surrounding areas, penetrating the same stratigraphic intervals encountered in the prospect area, are available. These, along with experience of the regional geology, were used to construct a background model, and examine the sensitivity of both seismic and CSEM attributes to variations in rock and fluid properties likely to be encountered.

The survey was designed to provide high resolution 3D coverage. It is centered on the prospect area and consists of an array totaling sixty-one receivers. Comprehensive in-line and multi-azimuth data coverage is available, providing a better constraint of the electrical anisotropy in the section. The fundamental frequency of the source was 0.08Hz, with significant power in its harmonics to give a dataset with rich frequency coverage between the fundamental and 1.5Hz.

Figure 1: Map of the 3D CSEM survey area overlain on seafloor bathymetry. The Campanian (light blue) and Santonian (dark blue) prospects are outlined. Receiver locations are shown in yellow, and CSEM source tow lines in black.
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Inversion of CSEM data

The 1D modeling work that has been performed on the CSEM data using both inline and broadside data highlighted a high level of electrical anisotropy across the survey area, mainly in the overburden section. Therefore a 2.5D anisotropic inversion approach has been conducted to account for this anisotropy variation.

The unconstrained inversion approach seeks a 2D resistivity model that provides a good fit to the acquired data, and which is smooth in a first derivative sense (Constable et al. 1987). Resistivity reconstructions are therefore as close to a uniform half-space as can be supported by the data. Sharp resistivity contrasts would be expected to be smoothed, whereas the resistivity-thickness product accurately estimated. Although this unconstrained approach results in a low resolution image of the resistivity structure, it is a useful first step, allowing the sensitivity of the data to earth structure to be assessed before any a priori constraints are added. In this case study, the structure and depths to major stratigraphic boundaries are well constrained by coincident seismic data. Seismic structural constraints can be included in the CSEM inversion in order to improve the resolution of the result.

Figure 2 shows the 2.5D anisotropic inversion result along CSEM survey lines 1 and 2. The inversion was prejudiced to an a priori resistivity of 10 Ωm, derived from analysis of the coincident magneto-telluric data, below the deepest stratigraphic boundary where CSEM sensitivity is poor, and a break in the smoothness constraint was allowed at this boundary. Apart from this the inversion was allowed to vary the resistivity freely. The starting model was a pseudo-section derived from the 1D modeling phase.

Figure 2: Vertical (top) and horizontal (bottom) resistivity sections along line 1, co-rendered with seismic data. Red colors correspond to areas of high resistivity. Major stratigraphic boundaries are also shown. Black ticks show the receiver locations at the seafloor and the crossing point of the two lines is marked by the vertical black dashed line. The approximate extent of the seismically mapped prospect is shown by the white arrow.

The horizontal resistivity section is relatively featureless, whereas there are pronounced lateral and vertical variations in the vertical resistivity sections. This suggests that the features observed in the vertical resistivity section originate from relatively thin structure in the seafloor, which are not well resolved by the data constraining the horizontal resistivity.

At relatively shallow depths (2.5-3km below sea surface) there is a zone of high resistivity, which varies laterally along the line. The prospect lies at 5-5.5km in the below sea surface in the Campanian-Santonian interval. At this level there are clear lateral variations in resistivity along the line. However the resistivity at prospect level appears to be low compared to the same depth interval outside the seismically mapped prospect extents. A similar effect was observed on the other lines in the survey.

To investigate these features further, the lateral variation in integrated vertical resistivity (corresponding to the transverse resistance across an interval of choice) derived from inversion of each line in the survey was co-rendered with a seismic depth slice (figure 3). The upper panel shows resistivity at shallow depths, highlighting the variation in the shallow structure and its correlation with seismic variations. The lower panel shows the equivalent integrated vertical resistivity across the prospect interval (Campanian-Santonian) mapped onto a seismic depth slice, taken at 5000m below sea surface. The approximate prospect outlines are shown in grey. The results confirm the observation from Line 1: the area of the prospect appears to be coincident with a region of low resistivity.

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Figure 3a: Lateral variations in vertically integrated resistivity at shallow depth mapped onto equivalent seismic depth slices. CSEM receiver lines are overlain (white lines). The lateral variations in resistivity appear well correlated with the variation in seismic character across the area.

Figure 3b: Lateral variations in vertically integrated resistivity at prospect depths, mapped onto equivalent seismic depth slices. CSEM receiver lines are overlain (white lines). At prospect depths, the lateral variations in resistivity observed conform the results from lines 1 (figure 2): The prospects, outlined in grey, appear coincident with a region of low resistivity (green/blue colors)

Integrated Interpretation

Shallow resistivity variations
A region of relatively high resistivity, which varies laterally across the survey area, is observed in the Tertiary section at about 500m-1km below mudline. Figure 3a shows that areas of high resistivity are present at the northern and southern end of the survey, with a lower resistivity region in between showing an EW trend. Correlation between the seismic and the shallow resistivity features can also be seen. There are a number of possible interpretations of these shallow resistive features. Gas hydrates for example are present in some areas in West Africa (e.g. Cunningham & Lindholm, 2000), and may produce shallow resistivity anomalies such as those observed (e.g. Weitmeyer et al. 2006). However in this case the seismic and well log data from the area suggest an alternative cause. Although there is no well within the survey area itself, a seismic tie line to the nearest well, approximately 70km to the East of the survey area penetrating the same shallow Tertiary section was analyzed. The resistivity log from this well shows similar high resistivity spikes in the Tertiary section. Detailed analysis of seismic data in the survey area shows morphological features that suggest biogenic carbonate deposits may be the cause of the high resistivity observed, and indeed carbonates are present in most of the wells in the region. Although these features are not of immediate exploration interest, the good correlation with seismic and well log information and a geological consistent explanation of their origin builds confidence in the interpretation of the remaining features.

Resistivity variations at prospect depth
The observation of a low resistivity zone coincident with the seismically mapped prospect is disappointing, however a plausible geological explanation must be sought before it can be considered conclusive. Two hypotheses were considered:

Hypothesis 1: Tight carbonates of variable thickness
A regional resistive carbonate layer is present at or around the prospect depth, which thins over the prospect. As the layer thins the integrated resistance, to which the CSEM data are sensitive, reduces resulting in the observed low resistivity zone. This would be consistent with the observation from wells in the region that carbonates are present across most of the section at various locations.

Hypothesis 2: Laterally varying resistivity within the prospect interval
The resistivity of the prospect interval varies laterally and is lower over the prospect than outside it. Support for this hypothesis comes from analysis of over forty wells in the region, penetrating Campanian-Santonian reservoir sands. Cross plots of the properties from a nearby well with significant hydrocarbon saturation is shown in figure 4, color coded by water saturation. The data are characterized by a horizontal trend corresponding to the background shales and silty sands. Their resistivity is almost constant at around 1Ωm, consistent with the CSEM inversion results in the overburden. The hydrocarbon saturated sands are represented by the red color on the left plot. They are, as expected, more resistive than brine-saturated sands and background shales/silty sands. However clean brine saturated sands show a significantly lower resistivity than the hydrocarbon saturated and shaly sands. This type of response is typical for the region, and a pattern that can be related to what is observed in the target region on CSEM analysis results. The low resistivity region within the prospect area could be explained by the presence of high quality reservoir sands within the prospect, which are saturated with brine.
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Figure 4: Resistivity vs. Acoustic Impedance (AI) cross-plots from a representative well in the region. Clean reservoir sands show a consistently lower resistivity than either hydrocarbon sands or the surrounding clay rich intervals.

To test this last hypothesis further, anisotropic resistivity models along line 1 were constructed. From these, synthetic CSEM data were generated and contaminated with noise levels consistent with those observed in the survey data. Only the vertical model is shown in figure 5.

The vertical earth model obtained after performing the synthetic inversion (figure 5) is very similar to the inversion result of the survey data (figure 2 upper plot). The observed resistivity variation could be caused by either a regional resistive carbonate layer that thins over the prospect, or by good quality reservoir sands within the prospect that are saturated with brine, giving rise to a lateral variation in resistivity. CSEM data are primarily sensitive to the transverse resistance (vertically integrated resistivity) and therefore a change in thickness of a layer of constant resistivity will have much the same effect on the data as a lateral change in resistivity of a constant thickness layer. Seismic data analysis could be used to distinguish these possibilities: a good quality reservoir sand of high porosity would be expected to have low impedance compared to the surrounding strata, whereas a high resistivity tight carbonate would be expected to be a high impedance feature. However given that neither hypothesis supported the presence of hydrocarbons in this case, no further work was undertaken, and the block was relinquished without drilling.

Conclusion

An integrated analysis of well, seismic and CSEM data is essential in order to guide the interpretation process and provide valuable information in pre-drill prospect appraisal. In this case study from offshore West Africa, the subsurface is characterized by a very high electrical anisotropy; therefore a 2.5D anisotropic inversion of the CSEM data was conducted and the results showed an area of low resistivity coincident with the prospect outlines. A careful analysis of nearby wells showed that clean brine-saturated sands have a considerably lower resistivity than the hydrocarbon-saturated sands, and most importantly than the clay rich sands. This observation, combined with a thorough comaprison with the seismic depth slices at prospect depth led to the conclusion that good quality sands saturated with brine are predominant in the prospect area.

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