Reservoir characterization using the integrated analysis of CSEM, seismic and well log data.

James Tomlinson, Lucy MacGregor & Paola Newton, RSI, 2600 S Gessner, Houston, Texas

Abstract

The objective of any geophysical study is firstly to produce a high quality image of the sub-surface to identify structural and stratigraphic prospect and secondly to understand the rock and fluid properties within those prospects. It is well known that no single geophysical method can provide a complete picture of the earth and its properties, and recently integrated interpretation and joint inversion of multiple data types have become much studied topics. In particular the combination of seismic, CSEM and well log data has the potential to improve the certainty with which reservoir lithology and fluid properties are constrained. By integrating these data types, and exploiting the strengths of each, ambiguities inherent in the interpretation of each when considered separately can be resolved. A typical integrated interpretation workflow is shown in Figure 1.

Method

The seismic method is in many situations the tool of choice: it is general and widely applicable, and can provide detailed images of sub-surface structure and stratigraphy from which complex geological models can be constructed. If seismic methods can provide the answer to the question of interest then this is undoubtedly the tool to use. However although seismic data are extremely sensitive to the changes in lithology occurring at the boundaries between geological units, they are less sensitive to fluid changes within these units even when these changes are substantial. This is because acoustic and elastic properties of the earth show only small changes when the fluid content or saturation is changed. These changes can in some circumstances be detected and used to provide information on fluid distribution. In other situations this is difficult or impossible to do with certainty, and complementary geophysical methods must be employed to meet the reservoir characterization goal.

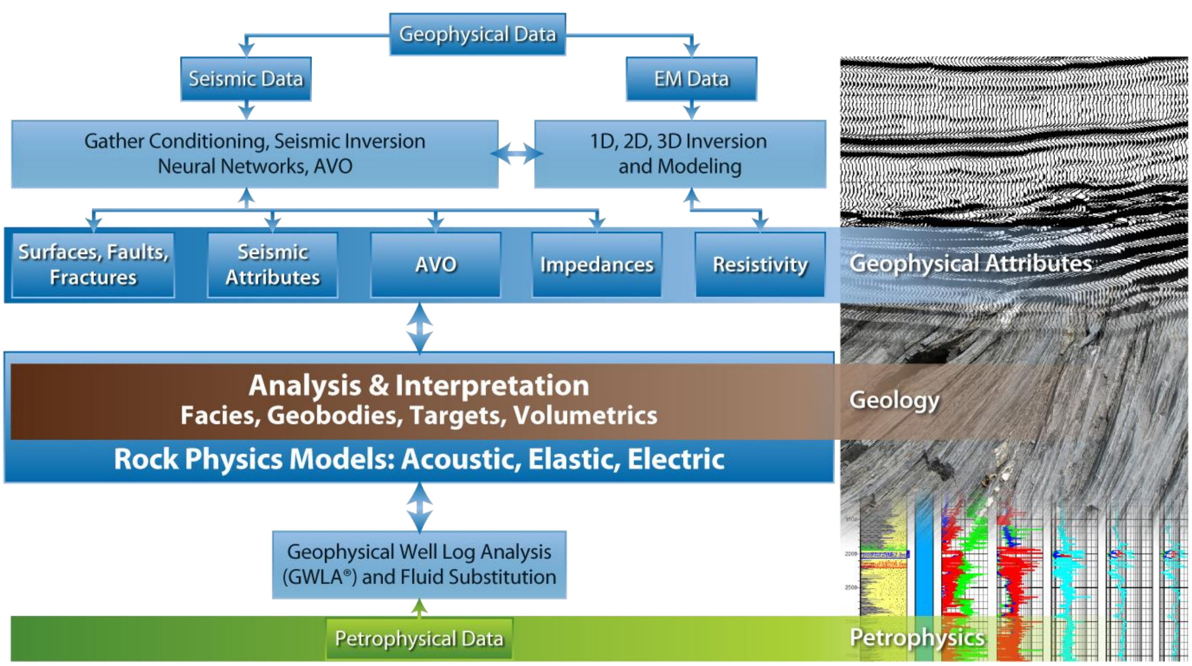

Figure 1: *An overview of the integrated interpretation workflow applied to seismic, well log and CSEM data. The goal of this process is to develop a geologically sound earth model consistent with all of the data types used in the analysis.*

In many situations electrical resistivity is driven by the properties and distribution of fluids in the earth. This change in resistivity caused by variations in fluid content and saturation can, in principle, be detected using CSEM tools. However when only CSEM data are considered, structural resolution is poor because of the diffusive nature of the EM fields, and the results can be ambiguous because the effect of an increase in pore fluid resistivity cannot be distinguished from the effect of a decrease in porosity. The presence of frustrating resistors in the section (for example tight carbonates, cemented sandstones or volcanics) can also complicate the interpretation.

Well-log data provide a range of measurements, including both resistivity and acoustic/elastic properties, as well as a range of further properties. A petrophysicist analyzing this well log data will take all of these measurements and integrate them together to provide an interpretation of the lithology and fluid properties. The resistivity measurement in particular provides key information on the fluid content at the wellbore. However such information cannot provide any constraint on the variation of properties away from the well, across a reservoir.

Although integrated interpretation brings many benefits, there are a number of challenges to be overcome before such approaches can be robustly applied. Firstly measurements made using very different physical processes (electric and elastic in the case of CSEM and seismic) must be combined and linked to the underlying rock and fluid properties in a consistent fashion. This requires a rock physics framework to be either numerically derived or empirically calibrated at well locations. In both cases such models are subject to uncertainty, which in turn leads to uncertainty in the resulting interpretation.

Secondly seismic, CSEM and well log techniques sample the earth at very different scales, varying from a few cm in the case of well logs, to hundreds of metres for CSEM. These different scales must be reconciled in an integrated interpretation or joint inversion approach.

Finally in order for an integrated interpretation approach to be successful, both seismic and CSEM methods must be sensitive to the interval of interest and changes in properties within it. Although this is perhaps an obvious statement, it is however a key consideration in determining where such approaches can be applied. For example a reservoir that can be imaged and constrained seismically may lie at too great a depth below mudline, or be embedded in too complex or resistive a background structure for CSEM methods to be effective. Similarly low saturation gas clouds above a reservoir may render seismic method ineffective, whilst having little or no effect on the CSEM response or interpretation.

The solutions to these challenges are case dependent and must be considered with care. For any given geophysical question, the most robust answer will be obtained by using the tool, or combination of tools best suited to the task, and determining this combination is the first step in any analysis. The resulting choice of data must then be integrated within a rock physics framework, to provide a shared earth model that is geologically reasonable, and consistent with each of the geophysical data types available.

Integration Workflow Case Studies

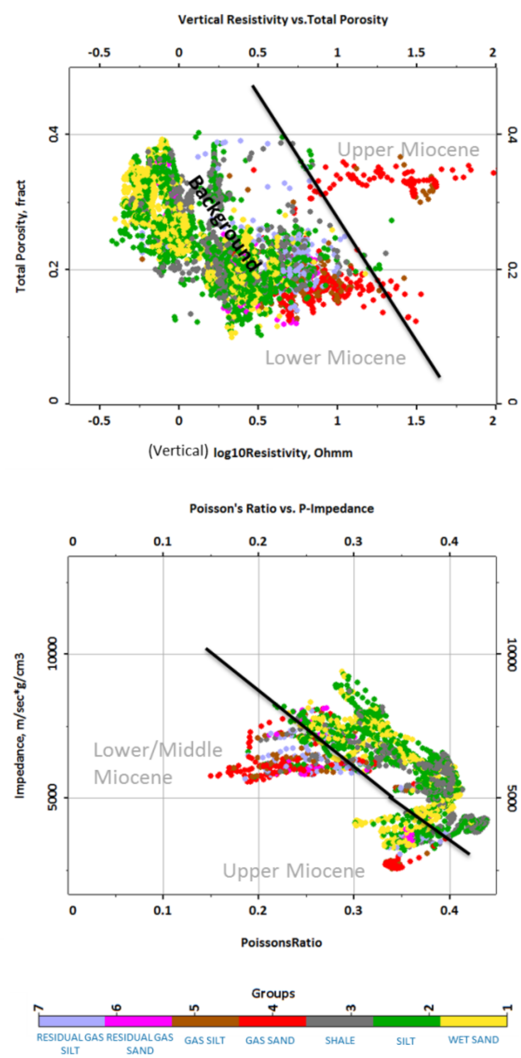

Figure 2: *Log_{10} of vertical resistivity versus total porosity and Poisson's ratio (PR) versus acoustic impedance (AI), color coded by litho-classes. Upper Miocene gas sand stands out from non-reservoir sediments in resistivity domain (upper plot) but not in PR-AI. Middle and Miocene reservoirs generally remain within background in these spaces.*

Case Study 1: Rock physics driven sensitivity analysis in the elastic and electric domains

Before an integrated interpretation study is undertaken it is very useful to understand the sensitivity of the geophysical data to be integrated, to the geological targets of the study. This allows the optimum combination of geophysical data types to be determined. Ideally this type of study should be conducted pre-survey in order to define the acquisition parameters that will provide data with sensitivity to the geological target of interest.

In this case we consider well, seismic and CSEM data post drilling. The well encountered hydrocarbon saturated sands in three Miocene reservoirs. The Upper Miocene reservoir exhibited a strong resistivity response in the CSEM inversion, however the Middle and Lower Miocene reservoirs did not. The objective of this study was to understand the observed CSEM responses and define an integrated workflow to characterise the three reservoir intervals.

The first stage is to understand the impact of elastic and electric reservoir properties using the discovery well as the calibration. Theoretical rock physics models were used to predict elastic curves (Bulk Density, Vp, and VS) at in situ conditions, and then main reservoir rocks were perturbed in terms of water saturation by applying Gassmann theory in the elastic domain, and modified Simandoux's relationship in the electrical domain. Seismic sensitivity was evaluated using synthetic seismograms and CSEM sensitivity was evaluated by calculating the synthetic electric field amplitudes.

In this study, three main steps were followed:

Step 1: Geophysical Well-Log Analysis (GWLA) and Rock Physics Diagnostics (RPD) – This was required to build a good and consistent well-log data set for the rock physics modeling. In this step, we estimated volumetric fractions of solid and fluid constituents.

Step 2: Rock physics modeling and fluid substitution was conducted for different fluid saturation scenarios. Gassman's fluid substitution is used for the elastic data and Simandoux's equation is used for resistivity data (figure 2).

Step 3: Geophysical modeling and sensitivity analysis: The objective is to assess the effect of changes in the fluid content on the reservoir on the measured seismic and CSEM responses. Synthetic Seismic and AVO modeling is used to calculate the effect of variations in reservoir properties and physical conditions on synthetic seismograms. Similarly, 1D CSEM modeling based on upscaled resistivities from the GWLA and rock physics analysis was used to investigate the sensitivity of measured CSEM data to changes in the reservoir charge (figure 3).

Case Study 1: Results

Modelling and sensitivity analysis revealed that hydrocarbon charged Upper Miocene rocks can be differentiated from wet clay rich intervals in Poisson's ratio and resistivity domains, whereas Middle and Lower Miocene responses may not clearly distinguished in the elastic or electrical domains. The use of seismic alone for interpreting the Upper Miocene may result in misleading results due to false positive anomalies caused by residual gas in the sands.

In the Middle and Lower Miocene both seismic and CSEM data may further assist in delineating if the reservoir changes its laminated nature away from the calibration well location. In this case careful application of constrained inversion techniques and integration with seismic reservoir properties, a more thorough understanding of the reservoir distribution and fluid charge may be achieved.

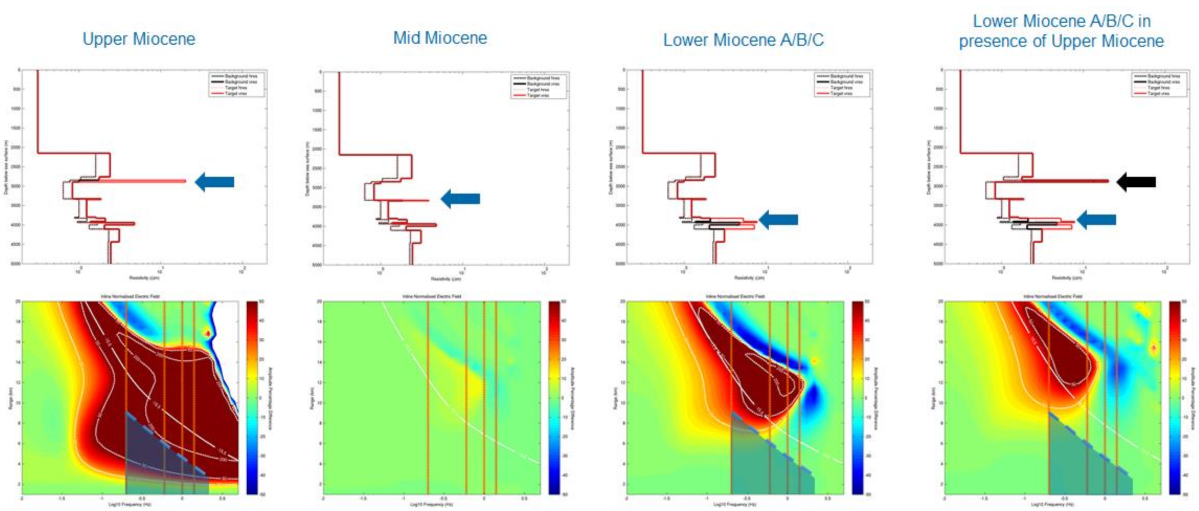

Figure 3: *Normalized results for 1D CSEM sensitivity analysis shows good sensitivity to the Upper Miocene target (left). Sensitivity to the Middle Miocene target (second from left) is poor. Sensitivity to the stacked Lower Miocene targets (third from left) is limited to long offsets of the two lowest acquisition frequencies. In the presence of the Upper Miocene target, sensitivity to the stacked Lower Miocene targets is further decreased (right plots). Areas shaded blue correspond to survey data included in initial higher-dimensional analysis; longer offset data may be incorporated to increase the sensitivity of the survey dataset to the Lower Miocene targets.*

Case Study 2: Integrated interpretation of seismic and CSEM inversion results.

The results of the second case study show the results of an integrated interpretation from an area with multiple wells, including a significant oil discovery, a post stack 3D seismic volume and a 3D CSEM dataset.

A sensitivity analysis was conducted and this revealed that whereas the post-stack seismic data could be used to delineate sands in the area, it had as expected little sensitivity to the fluids within these sands. CSEM in contrast showed good sensitivity to changes in hydrocarbon saturation, however resistivity if taken by itself could not distinguish between fluid and lithological effects.

Based on the sensitivity analysis the following integration workflow was defined:

1. Constrained CSEM inversion
2. Post stack seismic inversion
3. Quantitative calibration of the CSEM and seismic inversions at the discovery location. The calibration workflow is shown in Figure 4.
4. Integrated geological interpretation of the CSEM and seismic inversion volumes away from the well calibration to determine whether high resistivity zones identified in the CSEM results were the result of hydrocarbon charge or lithological effects.

Case Study 2: Results

The results of case study 2 show that although the sensitivity of the CSEM data to the target reservoir was limited (due to depth of burial and shallow water depths) careful constrained inversion produces a result that when quantitatively compared with the post stack seismic data calibrates with the reservoir identified in the well logs.

Aided by the confidence provided by the calibration to the well evaluations of two further prospects were evaluated. The first showed similar characteristics to the calibration discovery, whereas the second produced seismic and CSEM responses that suggested the resistivity "anomaly" was in fact related to lower porosity sands rather than hydrocarbon bearing reservoir sands.

Conclusions

Both case studies show that using rock physics to carefully define a target based multi-physics integration workflow allows explorationists to understand the value of the data they plan to acquire, and ultimately the chance of success that the resulting integrated interpretation will have.

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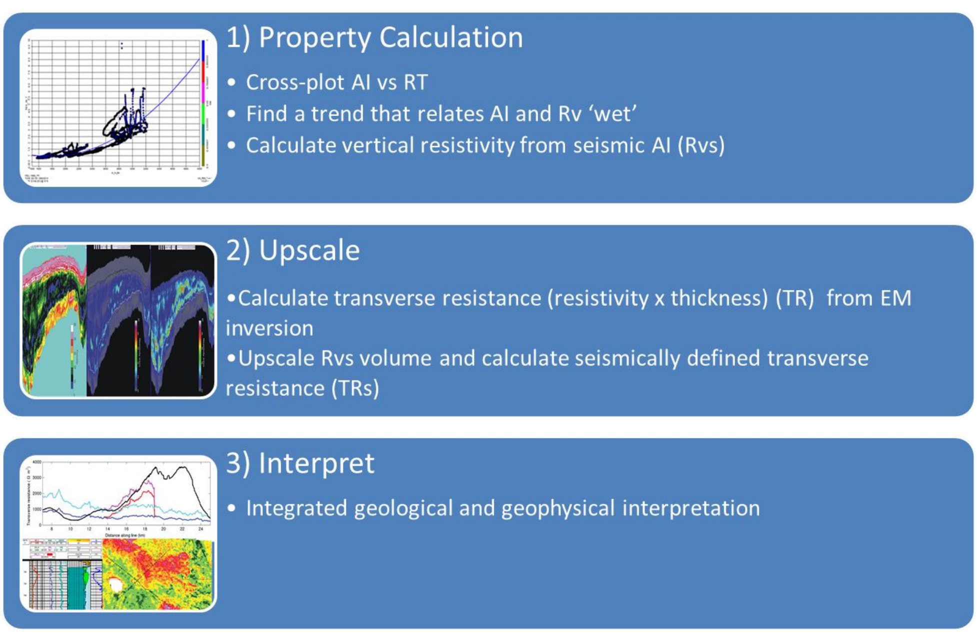

Figure 4: *Integrated interpretation workflow applied to the CSEM and post stack seismic inversion data.*