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Background Resistivity Prediction from Seismic Velocities

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SUMMARY

The interpretation of co-located CSEM and velocity data benefits significantly from integrated analysis and joint calibration due to the fact that, although each method responds to a distinct physical property, they both respond to the same rock and fluid volumes; useful correlations are therefore expected to exist. The literature describes empirical relationships between velocity and resistivity background depth trends. It has generally been noted that the primary petrophysical link between the two physical properties is porosity. Although this connection can be described using porosity-based rock physics models, we recognize that real log data often do not conform to strict theoretical assumptions; therefore, we adopt a data-driven approach to resistivity prediction that implicitly accounts for the underlying relationships without incorporating bias toward a particular rock physics model. Using this methodology, we predict background (non-hydrocarbon bearing) horizontal resistivity sections from interval seismic velocities for calibration of CSEM inversions. The background horizontal resistivity predictions generally have strong agreement with the CSEM inversion background resistivity.

Introduction

The interpretation of co-located CSEM and velocity data benefits significantly from integrated analysis and joint calibration due to the fact that, although each method responds to a distinct physical property, they both respond to the same rock and fluid volumes; useful correlations are therefore expected to exist (Baltar and Barker, 2015). Faust (1953) defined empirical relationships between velocity and resistivity background depth trends. This research was driven by the objective of predicting sonic log responses from resistivity logs in order to compare with pre-existing velocity maps. While Faust defines a direct depth dependence, it has generally been observed that the primary petrophysical link between the two physical properties is porosity. Although this connection can be described using porosity-based rock physics models such as Archie (1942) and Hermance (1979), we recognize that real log data often do not conform to strict theoretical assumptions; therefore, we adopt a data-driven approach to resistivity prediction that implicitly accounts for the underlying relationships without incorporating bias toward a particular rock physics model. Using this methodology, we predict background (non-hydrocarbon bearing) horizontal resistivity sections from interval seismic velocities for calibration of CSEM inversions. The background horizontal resistivity predictions generally have strong agreement with the CSEM inversion background resistivity. We defer the challenge of electrical anisotropy to a future publication.

Method

The horizontal resistivity prediction methodology is illustrated in Figure 1. The sonic-derived velocity and resistivity log data are cross-plotted over the entire log depth range, and the relationship analyzed. Over a significant geologic depth interval, there will always be a positive correlation between velocity and resistivity. The strength of this correlation depends on the underlying petrophysical and stress characteristics of the subsurface formations. Typically, there is a strong trend with surrounding scatter, as illustrated in Figure 1a. A smooth polynomial with optimal least squares fit is computed from the data (red line). As a further validation, the polynomial is then applied to the derived velocity log in depth, and the resulting resistivity prediction is compared to the measured resistivity log. The difference between the predicted and measured logs should be minimized. An assumption of the method is that the 1D velocity-resistivity relationship in the calibration log is a good approximation for the background velocity-resistivity relationship in the 2D/3D geophysical data. In cases where an analog well is used, it might be necessary to depth correct and rescale the log data to a representative trace from the geophysical

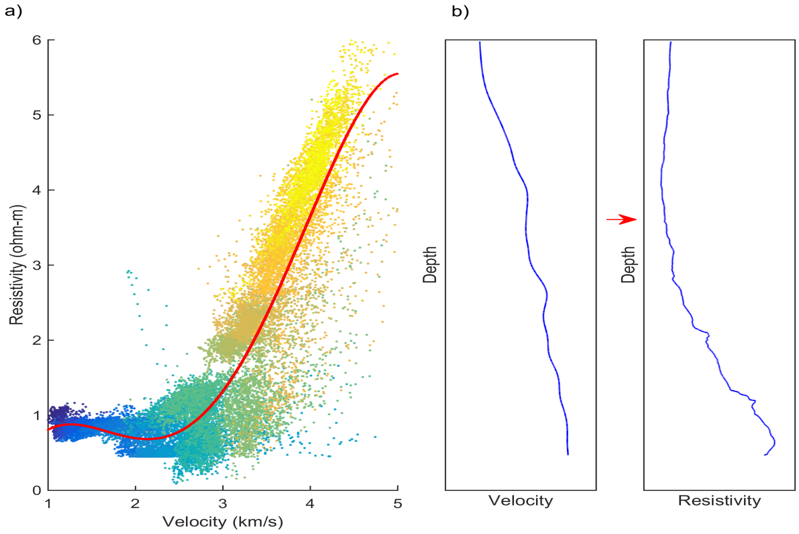

Figure 1 *(a) crossplot of Rh vs velocity with polynomial fit and (b) prediction of resistivity log from velocity.*

models, as will be exemplified in the next section. The log-derived cross-property relationship has better spatial and depth coordinate registration than do the velocity and CSEM data, and therefore yields a more precise definition of this relationship. Once the relationship is defined and validated on the log data, it is applied to the traces of the resampled velocity model. The resampling is performed by defining the spatial and depth sampling of each of the two grids, and interpolating the original velocity grid onto the CSEM grid. The velocity model then exists in the same "sampling space" as the CSEM grid so that the datasets can be related quantitatively. Next, the polynomial relationship is applied to each of the velocity traces as in Figure 1b, thereby generating the resistivity prediction. The prediction is not generally valid in the water column, so a measured water resistivity profile is substituted for the water samples. Also, a threshold is applied to basement resistivity because the polynomial relationship can become unstable for extreme values that are not captured within the well data range.

Examples

A regional CSEM survey was conducted in a frontier basin of offshore Uruguay with no well control. While we observe better calibration when local wells are available to be used as a resistivity tie to the CSEM inversion and define the velocity-resistivity relationship, we use well data from offshore Brazil Pelotas basin that is considered geologically analogous to portions of the survey area. Velocity data were also available for calibration with CSEM data, enabling joint analysis and calibration of bulk rock properties.

Since changes in velocity are related to reflectivity (Aki and Richards, 1980), the velocity derivative attribute can be used as the basis for well tie analysis (Figure 2) in order to calibrate the well depth. The quality of the well tie is also an indicator of the appropriateness of the well as a geologic analogue. First, the velocity log is upscaled. The velocity derivatives are then computed for the selected interval velocity model background trace and the upscaled log. Next, a bulk shift is performed in order to find the best match between the survey background velocity model trace and the upscaled well log response. We do not perform stretching and squeezing in the calibration. Figure 2 shows the velocity derivative well tie. For a 400 meter well depth shift, a good fit is achieved between the survey velocity model and velocity log, so this shift is applied to the well for further analysis of the velocity-resistivity characteristics. Interestingly, strong correlations between the curves can be observed despite the fact that the data are from different basins. Simple data-driven resistivity prediction is accomplished by computing polynomial coefficients that relate the velocity log to the measured resistivity log. These coefficients can then be applied to the velocity log for validation and then to the velocity model itself to generate a 3D model. Figure 3 illustrates the result of resistivity prediction applied to the analogue well shifted according to the tie shown in Figure 2. Due to differences in the depth-property trends between the analogue well and the 3D data, the logs are first rescaled using appropriate linear and logarithmic transforms to synchronize the trends:

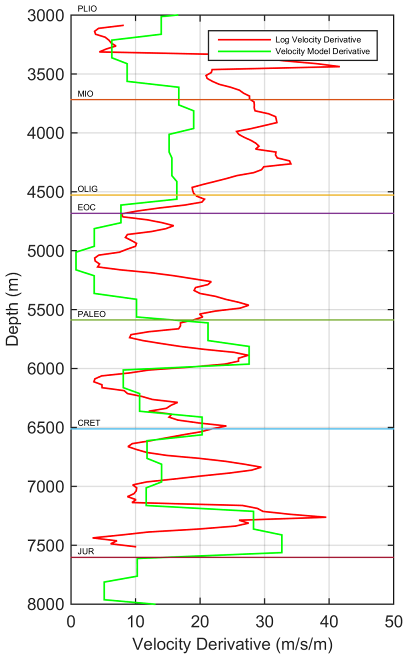

Figure 2 *Velocity derivative tie for calibration well with tops.*

$$V_r = V - .6 \tag{1}$$

$$R_r = ln(R+1)/ln(1.75), \text{where} \tag{2}$$

$V =$ original velocity (km/s)

$V_r =$ rescaled velocity (km/s)

$$R = \text{ original resistivity (ohm-m)}$$

$$R_r = \text{ rescaled velocity (ohm-m)}$$

Because the velocity trend is approximately linear in the depth range of the survey (this does not generally hold over the full depth range of the earth's crust), the bulk linear velocity log shift shown in Equation 1 suffices to approximate the trend of the velocity model background trace. This corrected version of the velocity log can then be used in the calibration of the resistivity prediction rather than the original depth-shifted log. Unlike the velocity field, resistivity generally shows logarithmic variation over depth. Therefore, the resistivity log is rescaled using the logarithmic transformation given by Equation (2). In order to enforce positivity, a constant of 1 is added to the resistivity trend followed by a logarithmic change of base. We believe that rescaling operations can potentially provide important clues about the relationships of the bulk earth properties in disparate geological environments and basins since the trends can be related by simple transformations. However, further investigation using different velocity and resistivity logs and models is required in order to assess the broad relationships that do or do not exist across basins. Figure 1a shows the cross-plotted corrected well log data, and Figure 3 illustrates the results of the resistivity prediction using those data. The corrected velocity and Rh logs (black) are upscaled (green). In Figure 3a, the upscaled velocity log (green) shows an approximate fit with the survey velocity model trace (blue). Geological discrepancies in all zones will limit the quality of the local match; we focus on the overall trend that is important for low frequency velocity and resistivity models. In Figure 3b, the upscaled resistivity log (green) has a satisfactory match to the unconstrained CSEM inversion (cyan) down to Eocene and an excellent match below. The resistivity prediction from the survey velocity model (blue) has a good fit.

We apply the polynomial prediction coefficients to the survey velocity model along one line of CSEM resistivity data, with results displayed in Figure 4. Figure 4a shows the Rh component of an unconstrained CSEM inversion; Figure 4b shows the well-calibrated Rh prediction from the velocity model; and Figure 4c shows the absolute difference between the unconstrained CSEM inversion and predicted resistivity models. The two models have similar trends, although differences exist due to the geographical origins of the data. Basement effects can be observed in the lower left area of Figure 4c.

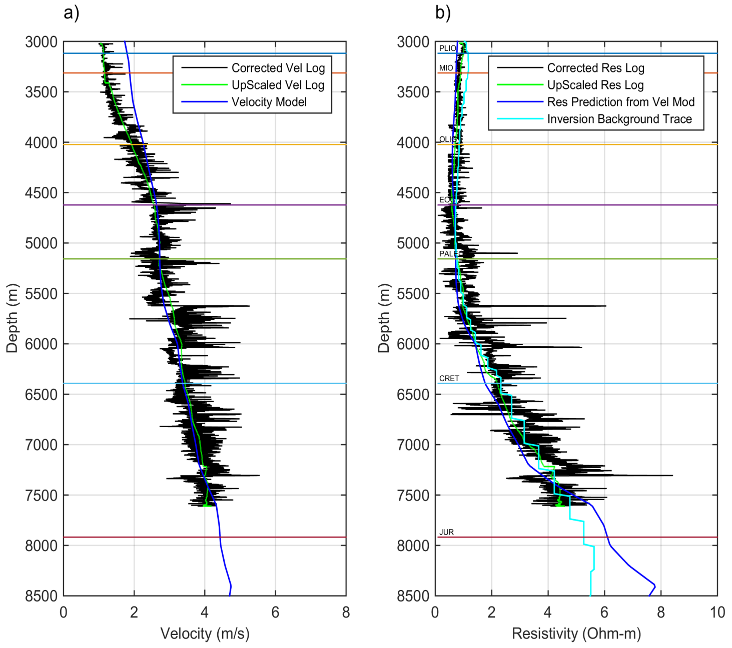

Figure 3: *Well resistivity prediction calibration a) velocity and b) resistivity curves.*

Conclusions

Our results indicate that geophysically-derived background velocity and resistivity data can be related in a manner similar to log data. We have observed on other (unpublished) datasets that better calibration is feasible when well log data are available inside the survey area bounds. However, despite the fact that the data are from distinct basins of the South American Atlantic coast, we are encouraged by the results and recommend further interpretation and geologic calibration between the survey area and the distal well. While the work described in this paper was focused on the horizontal resistivity component, the method can be extended to vertical resistivity in order to study the anisotropic background. We believe that such analysis will further geological understanding in both exploration and production settings.

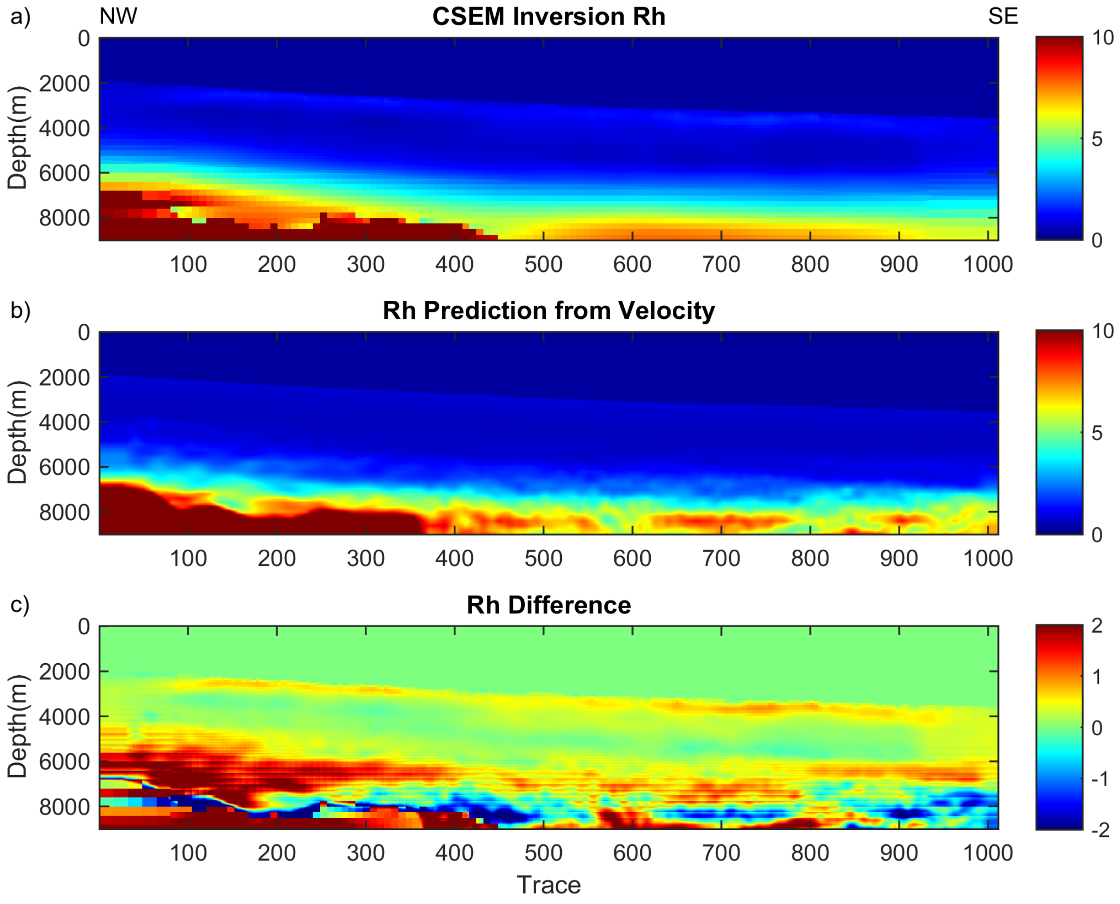

Figure 4 *Resistivity prediction from the velocity model along a line of CSEM data. The (a) prior CSEM inversion Rh using a half-space start model, (b) velocity-derived resistivity, and (c) difference.*

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