Overcoming scale incompatibility in petrophysical joint inversion of surface seismic and CSEM data.

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Summary

In this paper we propose a new workflow to perform Petrophysical Joint Inversion (PJI) of surface to surface seismic and Controlled Source ElectroMagnetic (CSEM) data, to recover reservoir properties (clay volume, porosity and saturation). Seismic and CSEM measurements provide independent physical measurements of subsurface that complement each other. In the case of well-logs, the basis of the PJI training dataset, taking advantage of such complementarity is straightforward. Indeed, elastic and electric measurements of earth properties sense the same earth volume at much the same scale. When applying the training dataset to the surface data derived geophysical attributes, the order of magnitude gap in between the scale at which those elastic and electric attributes represent the earth undermines dramatically PJI validity. Various CSEM inversion constraining methods (regularization breaks, prejudicing, use of an a priori model etc) help to reconcile seismic and CSEM resolution, but they are usually proven to be insufficient or inaccurate. In addition to these methods, we suggest adding a further downscaling step, so the recovered electric attribute resolution can be adequate with respect to the seismic one, hence fit for purpose. Such downscaling is designed to be consistent in electrical attribute space via transverse resistance within a rock-physics framework. The workflow will be demonstrated on a case study.

Introduction

Elastic attributes seismically derived, can be linked to porosity, lithology and under certain conditions and limitations, to fluid saturation prediction. Electric attributes derived from CSEM, can be linked to fluid saturation, especially if porosity and lithology can be constrained by the former. On this basis, the integration of prestack seismic inversion attributes with CSEM attributes constitutes one of the most modern and robust methodologies to estimate reservoir properties (Du and MacGregor, 2010; Chen and Hoversten, 2012). Such integration can take many forms. One of them consists of a statistical Bayesian approach PJI (Grana and Della Rossa, 2010). The workflow is sketched in Figure 1. First of all, a training dataset is required to acquire probability density functions (PDFs). Differently from Grana and Della Rossa (2010) where Gaussian distributions are used, in the proposed approach, the PDFs are non-parametric and are calculated using the kernel density approach. The training

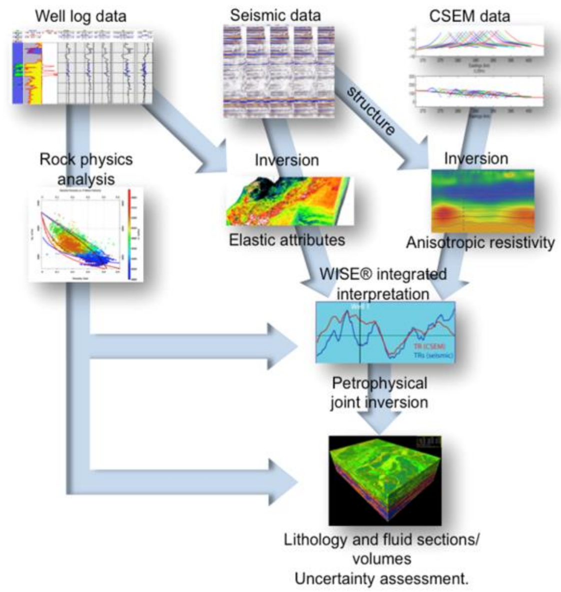

Figure 1: Full PJI workflow, including the electric attribute downscaling (WISE® integrated interpretation).

data could come from log measurements, or from rock physics modeled data, which includes both the petrophysical properties (Clay Volume, Porosity, Saturation) and elastic/electric attributes. At this stage, electric and elastic attributes resolution are trivially consistent. To derive the petrophysical properties away from the training data, section/volume of the same elastic/electric attributes, called geophysical sample data, are required. They are derived from standalone seismic/CSEM inversion. Given the PDFs, appropriate prior probabilities and the distribution of the geophysical sample data, the posterior probabilities can be calculated according to Bayes' theorem. At each section/volume location, the recovered petrophysical properties with consistent elastic/electric attributes in between training and geophysical sample data, are the ones with the highest posterior probabilities.

Even though the seismic and CSEM inversion are standalone, it is critical that they are structurally consistent and in agreement with the well log data. Such endeavor helps improving the CSEM resolution by constrained inversions means. However, this is usually still insufficient to reconcile seismic and CSEM resolution scales, making the matching process of the elastic/electric attributes in between training and geophysical sample data impossible.

This is illustrated on Figure 2, where elastic (acoustic impedance IP and Poisson ratio PR) and electric (vertical resistivity) attribute resolution can be compared. The reservoir is located in between the Sto and Base Sto horizons and is hydrocarbon charged around the Wisting Central Well. The constrained CSEM inversion does recover an anomalous resistivity high, but this is spread between the Sto and Snadd horizons rather than being confined to the reservoir layer, due to the lower resolution of the CSEM method.

To resolve this difference, two approaches can be considered. A higher CSEM resolution technique, beyond classic constraining, can be developed. For instance, the CSEM localized model-based inversion of Zerilli et al (2011), subsequently applied to PJI (Miotti et al, 2017). Alternatively, the conventional constrained inversion result, can be downscaled (WISE® integrated interpretation, on Figure 1) in a CSEM consistent fashion via transverse resistance within a rock-physics framework. The second method consists of focusing vertically any excess of resistivity identified as background, into the zone identified as hydrocarbon charged. It has the advantage of not having to reperform a costly and rather uncertain high resolution CSEM inversion and guarantees the desired resolution consistent with the chosen interpretation scenario.

After a brief description of the data, we will review PJI results when solely applied to the elastic attributes. It is a pre-requisite before the CSEM inversion result can be downscaled. After detailing the downscaling process, the final PJI of elastic and downscaled electric attributes will be shown.

Data

The dataset used comes from the Wisting area of the Barents Sea, and covers a significant oil discovery in the Hoop Fault Complex on the Bjarmeland Platform, Norway. Figure 2 to the left, shows the detailed view of the studied area. PGS provided 2D GeoStreamer® seismic and towed streamer CSEM data. There are also two calibration wells (Central: 7324/8-1 and Alternative: 7324/7-1S). The green outlines show the location of the proven reservoirs in the area (data courtesy NPD). Figure 2 to the top right, shows the seismic derived elastic properties (Impedance and Poisson's ratio) on seismic line 5001, together with the wells (Central and Alternative) projected onto this 2D line. Figure 2 to the bottom right, highlights the CSEM-derived vertical resistivity in the same window of analysis used for the seismic inversion. Details of the workflows followed by, in the respective seismic and CSEM inversion to recover these elastic and electric attributes, is detailed by Alvarez et al. (2017).

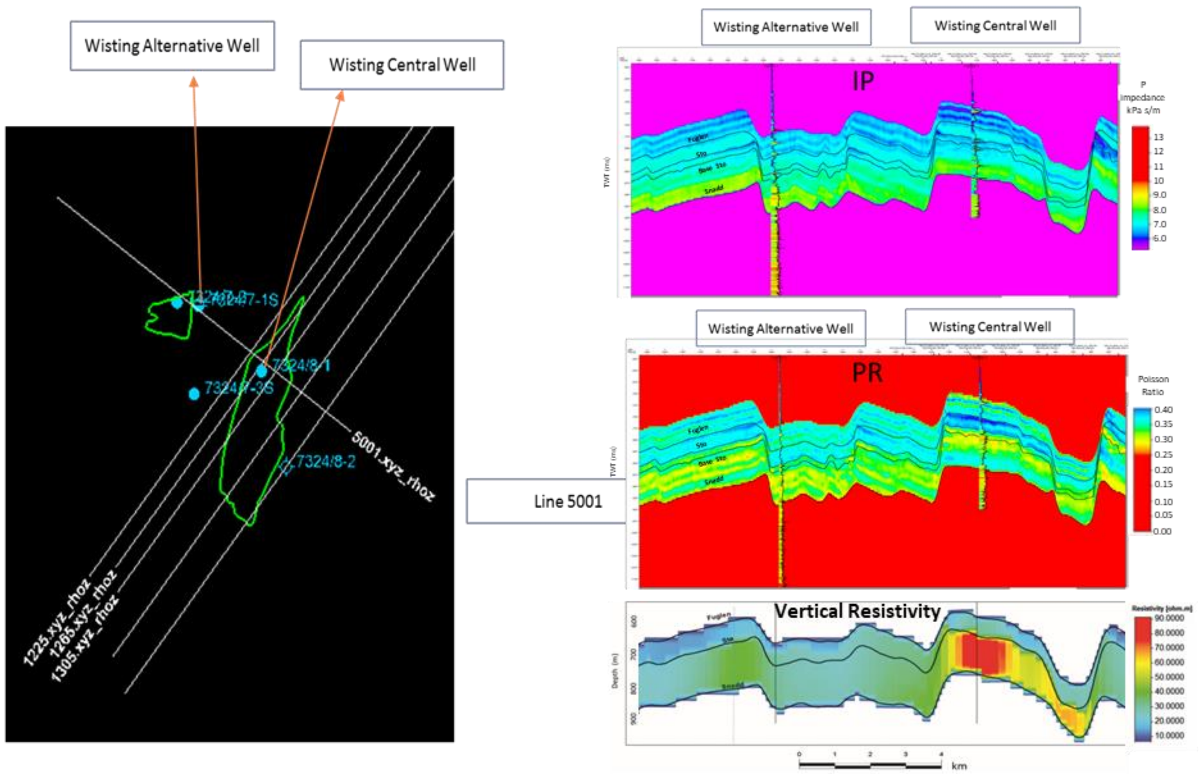

Figure 2: Detailed view of the studied area to the left (Wisting area in the Barents Sea). Seismically derived elastic properties (acoustic impedance and Poisson's ratio, top right) and CSEM derived electric property (vertical resistivity, bottom right), both cropped at the zone of interest.

PJI of the elastic attributes

Acknowledging that the CSEM-derived electric attribute is not fit for purpose, PJI is first run on the elastic attributes in isolation. Technically, this operation should be called PI (Petrophysical Inversion). Before applying the trained PDFs to the geophysical sample data, the inversion workflow is tuned and validated at log scale for each of the two wells (Figure 2: Wisting Alternative and Central). To do so, the trained PDFs are applied to the training data in a circular fashion.

Figure 3 shows PJI recovered total porosity (to the top), volume of clay (to the middle) and water saturation (to the bottom) when inverting the geophysical sample data (acoustic impedance and Poisson's ratio displayed on Figure 2). Through comparison with the results in the well, we see that good inversion results are obtained near the Wisting Central well. However, in the area near Wisting Alternative well, we do not have a good agreement with the well log interpretation. The inversion algorithm misclassifies the clean sands with the shale. The water saturation is also noisy, especially in the shallow section of the Wisting Central well, since elastic attributes have only a low sensitivity to the fluid.

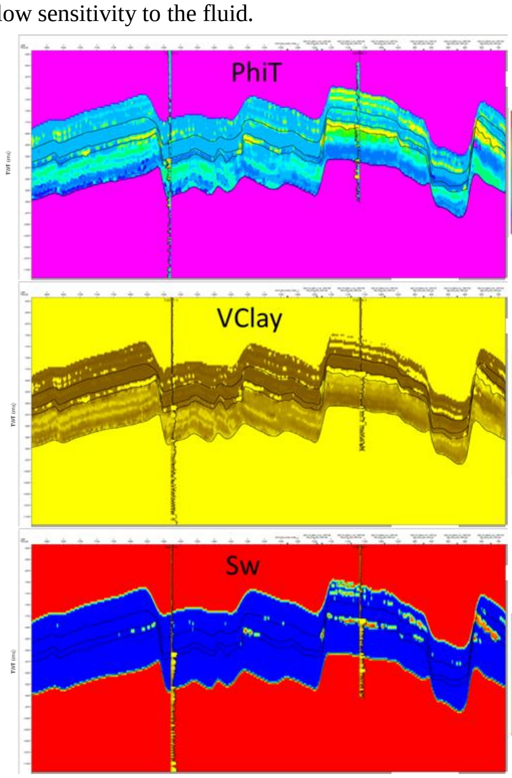

Figure 3: PJI outputs (total porosity to the top, clay volume to the middle and water saturation to the bottom), inverting acoustic impedance and Poisson's ratio displayed on Figure 2. Displays are in time domain and well log measurements for both Wisting alternative and Central are overlaid.

Downscaling of the CSEM-derived electric attribute.

A critical aspect of this method is to isolate the background from the potential pay zone (Figure 4, second panel from the top). To do so, a Probabilistic Facies Classification (PFC) workflow can be applied (Mukerji et al., 2001; Ellis et al., 2013). This uses Bayes' theorem applied to the classification of discrete properties (facies) rather than continuous ones. It is worth mentioning that for our downscaling purpose only elastic attributes can be used. Then the Simandoux rock-physics model (Simandoux ,1963) is calibrated at both wells, to give the tortuosity exponent (a) equal to 1, the cementation exponent (m) to 1.8, the saturation exponent (n) to 1.7, the shale resistivity to 6Ωm and finally the water resistivity to 0.18 Ωm. To derive background resistivities in the zone of interest, the previously recovered porosity, clay volume and water saturation are inputted in the above calibrated Simandoux rock-physics model. CSEM being primarily sensitive to transverse resistance (vertically integrated resistivity), any excess of resistivity recovered by the CSEM inversion with respect to the above calculated background resistivity, is focused in the pay zone so the transverse resistance is unchanged within some level of smoothing. Figure 4 top panel, shows the transverse resistance along the zone of interest from both the original recovered electric attribute (bottom panel) and the downscaled one (third panel). Any serious transverse resistance mismatch, where no potential pay zone is expected, highlights pitfalls in the workflow. Either the rock-physics calibration is inappropriate in those zones and maybe a more complicated facies dependent

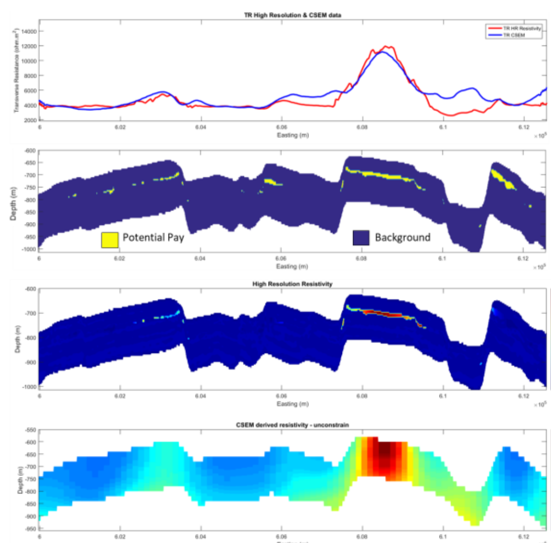

Figure 4: From top to bottom: transverse resistance along the zone of interest from both the original recovered resistive model (blue). Litho fluid facies model, differencing pay from background. Downscaled resistive model. Original vertical resistivity recovered by the standalone CSEM inversion.

calibration could be envisioned. Or the PJI recovered porosity, clay volume and water saturation (Figure 3) are inadequate. Overall the match is acceptable.

Full PJI of the elastic and electric attributes

Note that, because of the inclusion of the electric attribute, this inversion (Figure 5) was performed in the depth domain, while the previous one (Figure 3) was performed in the time domain. We find good inversion results near the Wisting Central well. The water saturation is accurate in both the Wisting Central and Alternative wells, and the noisy water saturation is removed in the shallow section of the Central well. However, we still cannot get the correct lithology and porosity in the area near the Wisting Alternative well, since it does not agree with the well log interpretation. The inversion algorithm still confuses the clean sands with the shale, because in the training data the porous sand and tight shale have the same, or similar elastic/electric response.

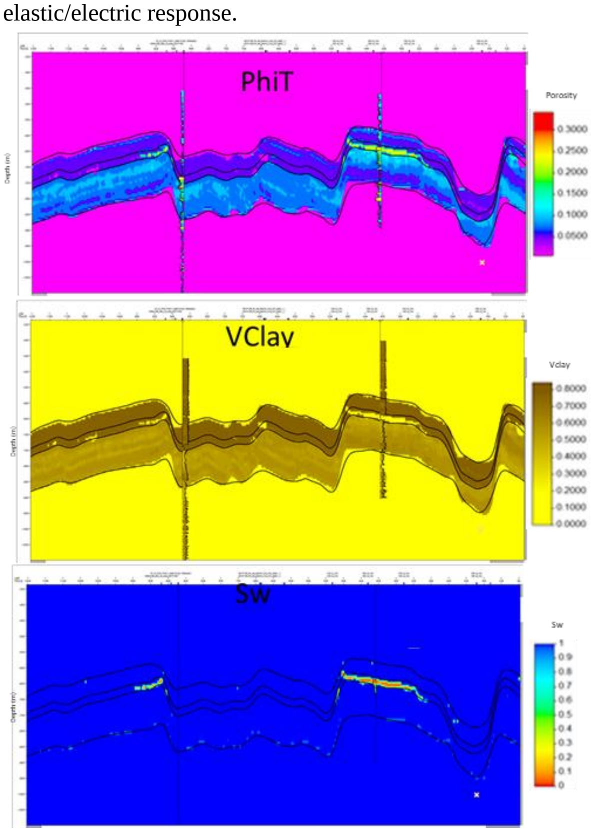

Figure 5: PJI outputs (total porosity to the top, clay volume to the middle and water saturation to the bottom), inverting acoustic impedance and Poisson's ratio displayed on Figure 2 and the downscaled vertical resistivity on Figure 4 third panel. Displays are in time domain and well log measurements for both Wisting alternative and Central are overlaid.

Conclusion

This case study shows successful joint inversion of the elastic and electric attributes to recover rock property models, within a Bayesian rock-physics framework. The addition of the electric attribute improves the results by reducing the water saturation ambiguity inherent to the elastic domain. Although not covered in this abstract, Bayesian inversion produces a suite of probability distributions for each recovered property. It can be shown that including the electric attribute, increases those probabilities, improving in turn the results confidence level. To properly perform PJI, the electric attributes CSEM-derived must be, as much as possible, at the elastic attribute resolution. To do so, we choose a downscaling methodology requiring no additional CSEM inversion, thanks to calibrated rock-physics and transverse resistance principle.

The joint inversion workflow can still confuse some clean sand with the shale, for the given dataset. A formation dependent joint inversion might solve the problem. The downscaling process to derive high resolution electric attribute, depends on the recovered reservoir properties when only the elastic attributes are inverted. Those reservoir properties are then refined by including the previous high-resolution model in the analysis. This circular argument, might suggest an iterative process, where the downscaling is performed again, using the updated reservoir properties.

Acknowledgement

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