The role of EM rock physics and seismic data in integrated 3D CSEM data analysis

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Summary

An extensive 3D CSEM dataset was acquired early 2008 over the North Sea Troll West oil and gas field, primarily addressing the CSEM tool's ability to identify relatively thin hydrocarbon zones. The survey's purpose was to address the value of dense versus sparse receiver grids, the value of 3D versus 2D acquisition and the value of a 3D approach in processing and interpretation. The latter topic focused on the value of 3D versus 1D and 2.5D inversion, and how additional geological and geophysical information contribute to the inversion process to produce a 3D resistivity cube. These topics were addressed by acquiring data by a variety of receiver grid configurations. Due to rich variety in geophysical and well datasets over this field, an integrated approach in analyzing the CSEM data is well suited here. This study is currently in progress, addressing in particular the role of geological processes, rock physics and seismic data.

In this abstract we report initial findings using conventional NMVO responses and discuss the role of rock physics and seismic interval velocities in CSEM feasibility studies and inversion schemes. We address in particular the value of this additional information when building models designed for CSEM feasibility studies and initial models and constraints for CSEM inversion.

Introduction

Reported case studies have demonstrated the risk reduction potential of marine CSEM (Controlled Source Electro Magnetic) technology in hydrocarbon exploration. CSEM techniques are typically applied in both early phase (like a scanning tool for "sweet spots") and in later phase prospect ranking. The latter topic is preferably approached by 3D survey configurations, similar to seismic surveying. CSEM was introduced to the exploration community as a DHI (Direct Hydrocarbon Indicator) tool early in its development phase. It was enthusiastically received and immediately applied to directly address prospectivity. After pilot and first pre-drill applications with associated successes and failures, it appears that exploration teams are in a period of reflection and consolidation regarding the CSEM technology.

It appears to be a consensus among exploration teams that there are natural limitations in the CSEM technique to be applied as a stand-alone DHI tool. Likely elements of the next step in exploration application can therefore be a fit-for-purpose designed acquisition configuration, followed by processing and interpretation processes honoring complementary geophysical information and the geological deposition and compaction processes through rock physics principles. Practical CSEM workflows should be based on this integrated approach, applied in feasibility studies, survey design and actual data interpretation.

One important step in improving processing and interpretation of CSEM data is to include the effect of the geological processes on electromagnetic properties. This can be done by using rock models linking electromagnetic properties (like resistivity) to rock properties (like porosity and clay volume) and in-situ conditions (like temperature and stress). Seismic data will be included as it carries key information about structure (geometry) and medium properties. Using electromagnetic and seismic rock models, both seismic and CSEM data are linked to the geology by such an integrated approach. This can again be utilized in feasibility studies and actual interpretation of datasets.

As a preparation for development of the above discussed (next generation) CSEM technique, StatoilHydro and EMGS in early 2008, through the framework of an R&D Agreement, decided to acquire a 3D CSEM dataset over the Troll oil and gas reservoir to address a suite of elements in acquisition and interpretation.

Receiver grid layout and processing of NMVO responses

One specific problem addressed by the Troll survey layout was the role of angular ("azimuth" or off-line) information in generating conventional normalized magnitude versus offset (NMVO) responses. Thus, receivers both on and off the source towline recorded data to enable processing of magnitude and phase from individual receivers inline with the source as well as receivers on neighbor lines ("azimuth" information). This approach was used in analyzing both a dense and sparse receiver grid. The actual receiver grid layouts and shot lines are shown in Figure 1.

Normalized responses were produced at all common source-receiver midpoints including azimuthal information (neighbor lines), by normalizing recorded magnitude to a receiver located outside the hydrocarbon reservoir units. From these data, magnitude and phase response maps were produced, both for the coarse and dense grid types. The coarse or scanning grid data simulate the survey layout typically used in an early exploration phase, while the dense grid is typically used for prospect characterization. Figure 1 shows the normalized magnitudes at excitation frequency of 0.25 Hz using the measured field magnitude at an offset of 6.5 km. A smoothing operator was applied to produce these images.

The thin oil and gas zone in the western part (typical 40 m thick) is detected, as can be seen in Figure 1. The corresponding normalized magnitude anomaly is represented a little differently in the coarse and dense grids, but both demonstrate the ability to image the oil zone. The importance of 3D information in detecting the oil zone is effectively demonstrated, because the sail lines are located at the western and eastern edges of the oil zone. Analyzing these two lines individually results in a very uncertain interpretation of the magnitudes. The much thicker gas zone is easy to detect, as it shows normalized magnitudes of about two to three times stronger than in the oil zone.

Essential elements in integrated analysis of CSEM data

A central element in any forward modeling and inversion of CSEM data is the structural (geometrical) model. The conventional way to build such models is to import a set of horizons as defined on seismic data interpretation systems. These are based on contrasts in seismic properties between sediment sequences, and may not be associated with contrasts of the same strength in resistivity properties. The "layers" (sequence), limited between successive horizons, are then assigned a resistivity value, normally based on well log data (deep resistivity log) which has penetrated the relevant sequence. Possible lateral variations are normally not honored in such studies, but they can easily be estimated from using advanced CSEM schemes by repeated CSEM 1D inversion on individual receivers.

The overburden (sediment sequences above the target zone) and "underburden" (below target zone) must both address possible lateral and depth variations in resistivity. These variations, creating contrasts in resistivity, can be estimated from interpreted horizons and expected spatial trends due to rock type variation, depositional and burial control. A control point will be a well log dataset, if it exists and located within or close to the CSEM receiver grid. A more direct way which does not require the existence of a well, is to let the seismic data guide the resistivity estimation. This can be done because the effects of deposition and compaction processes on seismic and electromagnetic properties are often similar. Differences in controls, due to different source generated excitation of the rocks will however occur and must be addressed separately.

We used here seismic interval velocity as input to predict resistivity, normally the horizontal component, as the log datasets we applied were acquired in vertical wells. We report here the specific workflow designed for use in shale sequences. The seismic interval velocities were produced from stacking velocity field. Seismic derived horizons were used to overlay structural information to the interval velocities.

A total of 7 wells are included in this pilot study on how rock physics and seismic data sets may contribute in the analysis of 3D CSEM data sets. Lack of a well log derived shale indicator (no volume of clay interpretation) was repaired by defining shale sequences using a rock model relating density and P-wave velocity.

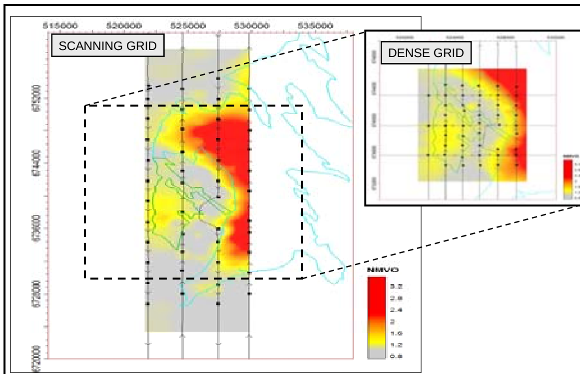

Figure 1: *Receiver positions (black squares) and shot lines (gray) in scanning (left) and dense (upper right) grids. Normalized smoothed magnitudes (NMVO) are shown in color according to legend. The excitation frequency is 0.25 Hz, and data at an offset is 6.5 km were used. The reference receiver is the lowermost located one in the second line from left side. The western oil and gas zone is outlined in green (left) and the much larger eastern gas zone in blue.*

This approach was applied using seismic interval velocities to establish an initial resistivity model and constraints for inversion and forward modeling schemes. Our first 3D inverted resistivity model has been obtained without using initial resistivity model and constraints. It will serve as a reference model for following inversion processes which will include this additional information. The actual value of this additional information in producing resistivity values from the CSEM dataset will then be addressed.

A typical well log resistivity depth profile is seen in Figure 2. A rock model transforming the well log P-wave velocity to a horizontal resistivity in shale sequences performs well, except in two intervals, where we observe differences between measured and predicted resistivity (upper left panel in Figure 2). The upper interval is (through the density-velocity rock model) interpreted as a shale, but the predicted resistivity is far too small (about 1 compared to the measured about 2-3 Ohmm). This interval is represented by so-called glacio-marine sediment, and is associated with very heterogeneous grain/particle sizes, and hence shows poor continuity of conductive clay platelets. A separate rock model is therefore made for this shallow rock type. In this way, the role of geological information is evident in building effective rock models.

section, and it is placed at a depth corresponding to the top reservoir horizon.

A prominent feature of the resistivity background is a continuous and shallow high resistivity zone above about

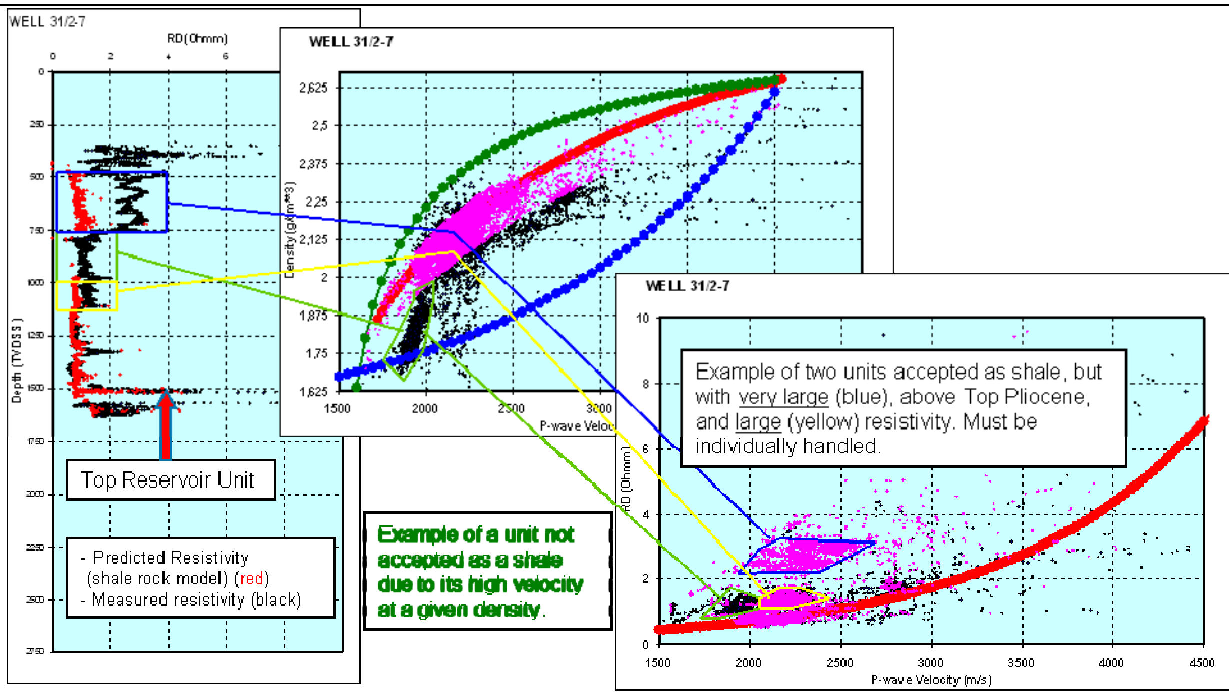

Figure 2: *Resistivity well log panel (left), shale indicator panel (middle) and related well log values of resistivity and P-wave velocity in shales (violet) and other rock types (black) (right) in Troll well 31/2-7. The left panel relates measured (black) and rock model predicted (red) resistivity and depth. The middle panel relates measured density (vertical axis) and P-wave velocity in shales (violet) and other rock types (black). Anomalous resistivity values (with reference to rock model (red line)) are represented by blue, green and yellow intervals. The green and blue curves in the shale indicator panel are Reuss and Voigt realizations for shale, while the red curve represents a preferred rock model. The red curve in the lower right panel represents a preferred rock model enabling prediction of resistivity from P-wave velocity in shales.*

Reference 3D resistivity cube

A 3D CSEM inversion tool developed by EMGS was applied using data including azimuthal information in the dense grid type. The initial resistivity model was based on 1D inversion of the reference receiver used to produce the normalized magnitude plots seen in Figure 1. No constraints were applied in order to establish this “reference” case for addressing the value of rock physics and seismic data. A vertical section of the resulting resistivity section along one south-north line over the thinner oil dominated reservoir zone is shown in Figure 3. This reservoir zone is a prominent feature in this resistivity

800 m depth. This feature is in accordance with the well log data (Figure 2) and is caused by the glacio-marine sediment package discussed previously. The actual resistivity values appear to be higher (about 6-7 Ohmm) than predicted ones using the seismic interval velocities (about 2-2.5 Ohmm). This can be due to calibration problems but also to presence of anisotropic properties in this layer which the rock physics transformation does not account for. Note also the consistent increase in predicted horizontal resistivity and inverted resistivity at about 2500 m.

In a more complex geology setting, such information about background resistivity can be essential for inversion initial models. As explained above, combined seismic and well log information from the areas could then be utilized to describe resistivity trends in an inversion initial model. Other ways to integrate such structural information is to formulate model constraints for the inversion algorithm, and as input for a geological interpretation study of inversion results.

Conclusion

An integrated workflow for 3D CSEM inversion and feasibility studies are discussed. A reference 3D resistivity cube was produced and will serve as a reference for further inversion processes, where the role of rock physics and seismic data will be addressed by using this additional information in building initial models and constraints.

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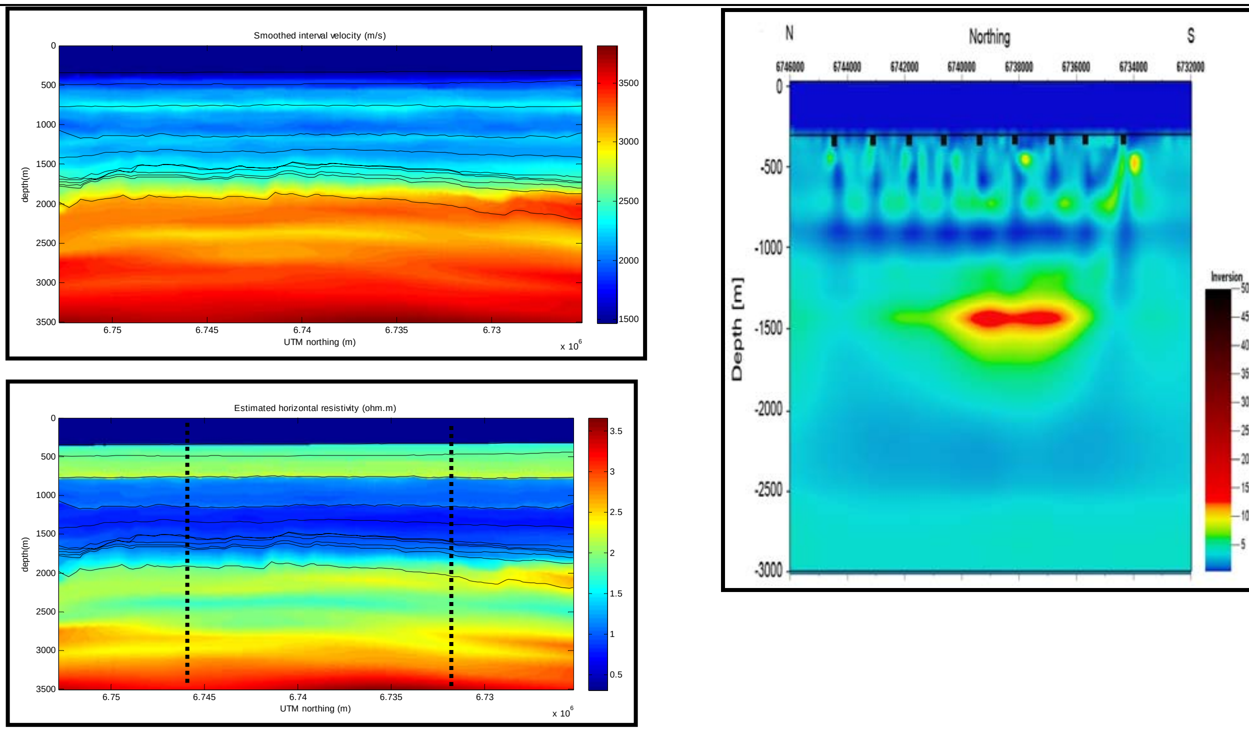

Figure 3: *Seismic interval velocity (upper left) and predicted horizontal resistivity (lower left) of the background shale sequences with key horizons (black) at a north-south CSEM line. The inverted resistivity values at this line are shown in the display at upper right. Note the deeper depth range (down to 3500 m) in the velocity and predicted resistivity displays compared to the inverted resistivity display (3000m). The inverted resistivity line span the lateral range as indicated by the dotted black vertical lines in the estimated resistivity display at lower left. Note that legends for the estimated horizontal and inverted resistivity are not equal.*

The inverted reference resistivity model is consistent with depth variations estimated using rock physics transformations of seismic interval velocities. In the next step we will build an improved initial model and define a set of constraints to be applied in the inversion process.

EDITED REFERENCES

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REFERENCES

None