Effects of Fluid Saturation on Seismic AVA and CSEM Response in the Norwegian Sea

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Introduction

One of the hottest trends in geophysical exploration today is the integration of 3D seismic and controlled source electromagnetic (CSEM) surveys. The combination of these data sets offers explorationists a powerful tool for risk reduction. Seismic data provides the detailed depth and structure information, while CSEM provides electrical resistivity for fluid discrimination. The combination of the two can greatly improve our ability to invert for porosity, lithology, and hydrocarbon saturation. However, the key to inversion is forward modeling. In this paper we will show how well logs and rock physics can be used to provide the input for modeling both seismic amplitude versus offset (AVO) and CSEM radial amplitude versus source-receiver spacing.

Model Results

The work reported here is the first stage of a seismic and CSEM integration study and serves as a feasibility check on our ability to discriminate gas-filled from wet sands. The log data that is used in the modeling is from the Norwegian Sea 6707-10-1 well (Luva discovery). This well is located in the Nyk High, Vøring Basin, off the northwest coast of Norway in about 1300 meters of water. The well has about 140 meters of gas filled sand at about 3000 meters total depth. Figure 1 shows the smoothed well log data and the modeled gas sand zone.

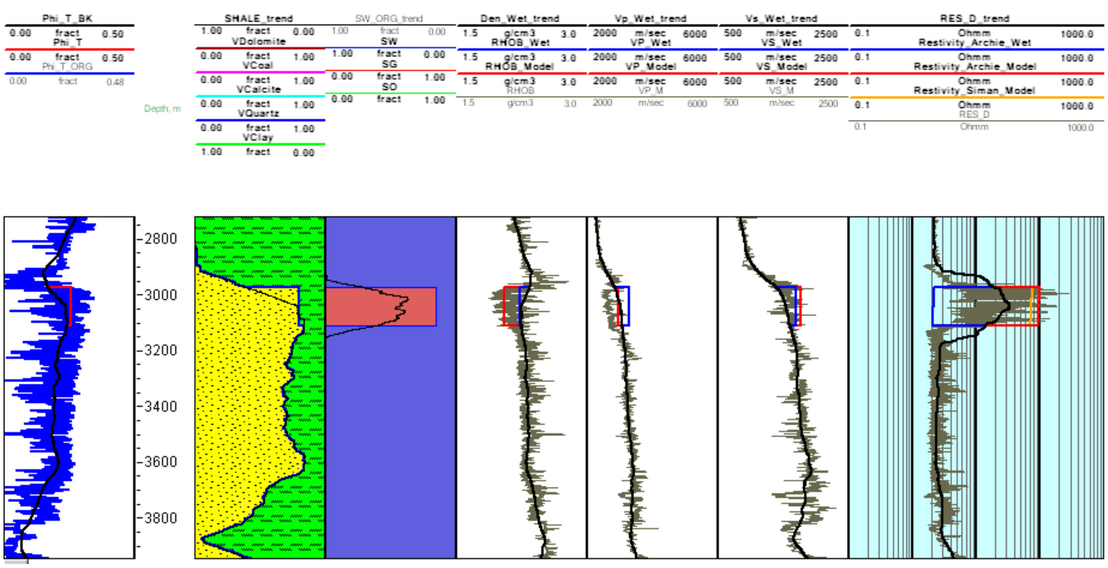

Figure 1: Fine scale (grey) and smoothed (black) well log curves (6707-10-1 well) and modeled gas sand at about 3000 meters depth.

The first step in modeling is Rock Physics Diagnostics (RPD). In RPD we compare various elastic and electrical rock physics models to the well data to asses overall log quality and to determine which effective medium models provides the best match to the data of interest, in this case a depth range from about 2800 to 3800 meters total depth. The next step is to compute the seismic AVA and 1D CSEM responses at in-situ and 100% water saturated conditions. If these models show substantial differences between gas and wet cases, then we have an important indication that hydrocarbon detection is feasible. The average in-situ gas saturation in the pay sand is about 85%, so our initial model will represent the 85% Sg case. As shown in Figure 2, there is a substantial difference between the wet and 85% gas synthetic gathers. In the wet case, the top of the sand has positive amplitude (high impedance) but in the gas case, we see negative amplitude (low impedance) assuming the USA polarity standard. We used Biot-Gassmann to compute the seismic velocity changes. Electrical resistivity changes were computed for clean sand and shaly sand cases using Archie and Simandoux, models respectively (Mavko, et al, 2003). Seismic gathers were computed using a 30 Hz Ricker wavelet and the CSEM frequency was 1 Hz.

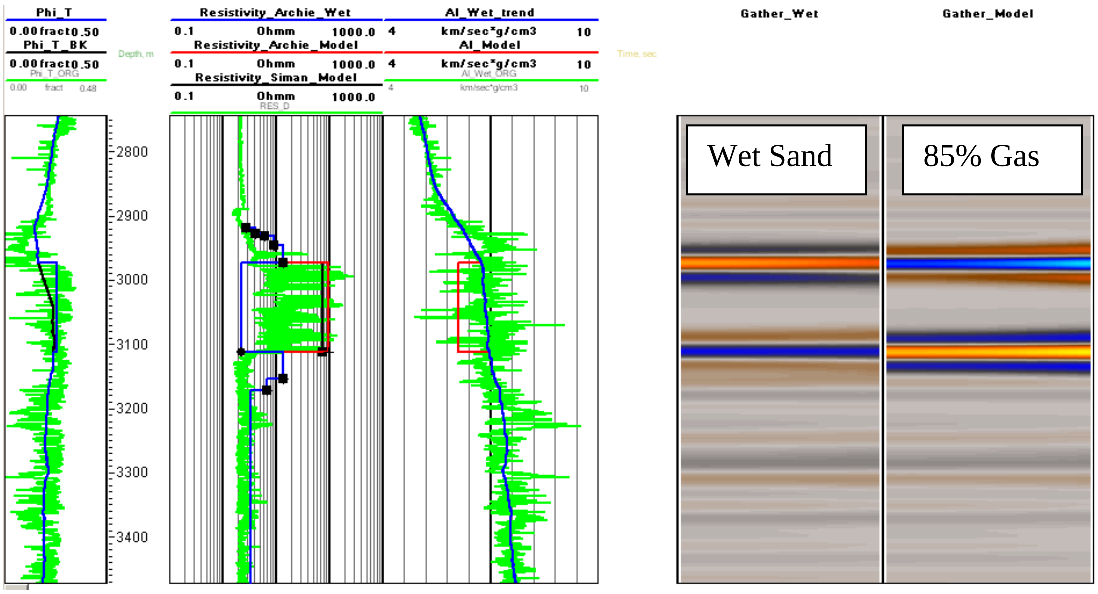

Figure 2: Synthetic seismic gathers show strong amplitude difference between wet case (left) and 85% gas case (right). Orange colors in the gather indicate positive amplitude (low AI over high AI), blue color indicates negative amplitude (high AI over low AI).

The relative effects of high gas saturation (85%) are shown in Figure 3 for both the seismic AVA method and the controlled source electromagnetic method. Note that for seismic response we see a change in reflectivity polarity when water is replaced by gas in the reservoir. The CSEM plot shows substantially higher amplitude for the gas case at about 10,000 meters total offset. This is about the limit of the measurement capability as the signal drops below the 10^{-15} V/(A*m^2) noise floor at around 10,000 meters offset.

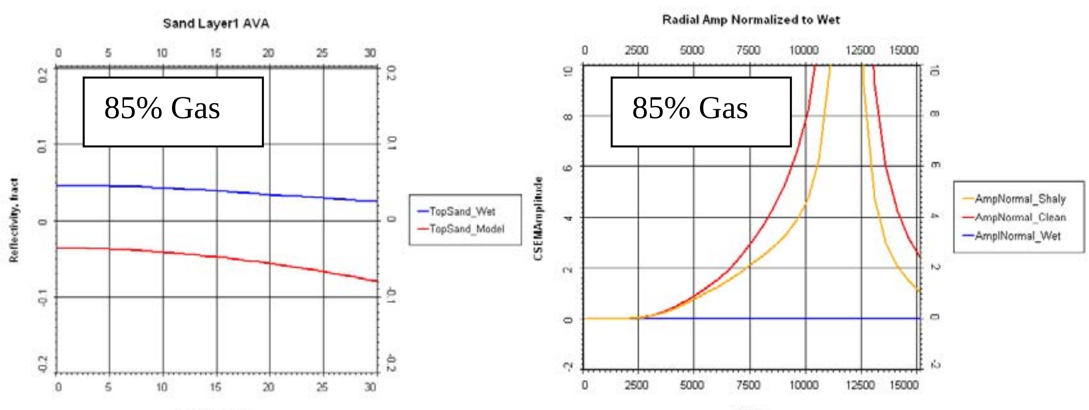

Figure 3: (left) Reflectivity versus angle of incidence for wet (blue line) and 85% gas case (red line); (right) Normalized radial CSEM amplitude versus source-receiver distance for wet (base case) and 85% gas case. Note that

the difference between the wet and gas case CSEM amplitude ranges from a factor of 5 for shaly sand (orange line) to a factor of 8 for clean sand (red line) at the maximum spacing of 10,000 meters.

The next set of models shows the effect on seismic AVA and CSEM response for the case where gas saturation in the sand is measurable, but not commercially viable. Figure 4 shows the synthetic seismic gathers for the wet case and the 30% gas case. The non-commercial 30% gas case on the right is almost identical to the 85% gas case gather in Figure 2. Note also that the seismic AVA crossplot on the left side of Figure 5 shows that the effect of 30% gas is about the same as the effect of 85% gas, shown in Figure 3. However, the CSEM data (right side of Figure 5) for 30% gas exhibits a very substantial difference from the 85% gas case in Figure 3.

Based on these models, we conclude that pre-stack seismic gathers alone cannot discriminate low gas saturation from high gas saturation in this case. However, if CSEM data is available at this location, then we have a very sensitive indication of the commercial versus non-commercial gas concentration.

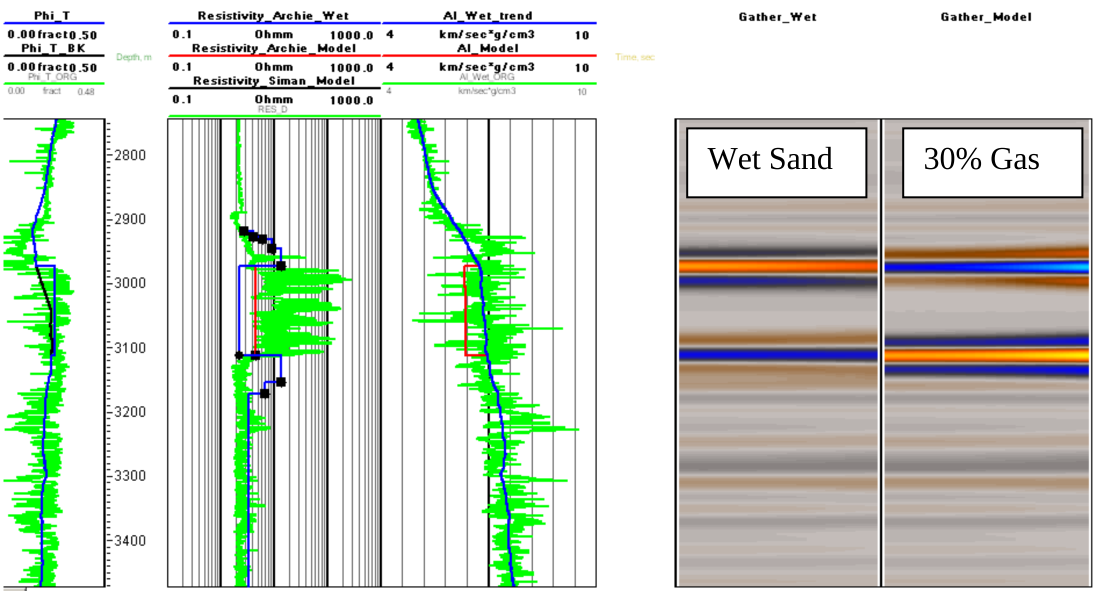

Figure 4: Synthetic seismic gathers show strong amplitude difference between wet case (left) and the non-commercial 30% gas case (right).

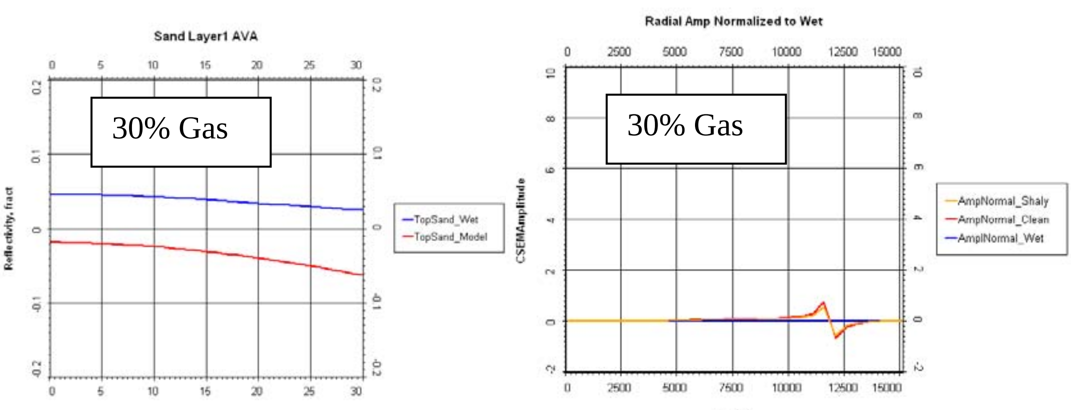

Figure 5: (left) reflectivity versus angle of incidence for wet (blue line) and 85% gas case (red line); (right) natural log of normalized radial CSEM amplitude versus source-receiver distance for wet and 30% gas case.

Summary

In the Luva well from the Vøring Basin, offshore Norway, we have used established rock physics principles to model the relative effects of high gas saturation and low gas saturation on both seismic AVA and CSEM amplitude. The results are striking. While high gas saturation is clearly discriminated from 100% water saturation by both seismic and CSEM methods, the non-commercial low gas saturation case (30% gas) can only be diagnosed by CSEM. Seismic AVA modeling shows that the non-commercial 30% gas case and the commercial 85% gas case are virtually identical. But when CSEM response is considered, there is a large difference between the 85% gas and 30% gas saturation response. This difference is large whether one assumes that the sand is clean or shaly. This result demonstrates that an integrated CSEM-seismic approach can be very effective in this Norwegian Sea gas field.

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References

Mavko, Gary, Tapan Mukerji, Jack Dvorkin; The Rock Physics Handbook, Cambridge University Press, 2003.