The Use of Fluid Substitution Modeling for Correction of Mud Filtrate Invasion in Sandstone Reservoirs

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Summary

Mud filtrate invasion can occur in many types of permeable hydrocarbon bearing formations. It often causes sonic logs to be too fast and density logs to be too high because these logs are sampling mostly water saturated rock. Uncorrected, it can cause substantial errors in well ties to seismic. The problem can be easily detected with multiple depth resistivity logs and then can be corrected using careful application of Biot-Gassmann fluid substitution.

Introduction

Well log data are commonly used to create synthetic seismograms that are then compared to real seismic data. The results are used to "tie" wells to seismic and hopefully gain an understanding of what properties of the formation are responsible for the observed seismic traces. The underlying assumption is that the sonic P wave velocity (V_P), S wave velocity (V_S) and density measured by the logging tools, give a true picture of the reservoir properties as sampled by the seismic wavefield. Unfortunately this is not always the case. Open hole log measurements often are affected by conditions inside or near the wellbore that are created during and after passage of the drill bit through the rock formation. Some logging tools are affected by the drilling mud between the tool and the formation. The logging companies have created detailed correction charts for each of their tools to accommodate the presence of the mud in the wellbore. These "environmental" corrections are based on a combination of mud weight, resistivity, wellbore diameter, tool response, etc. Generally the log curves delivered to the client have been corrected for environmental effects.

Another class of problems are caused by the brine that is used to make water-based drilling mud. This brine can penetrate into permeable formations, displacing some of the original fluids. As it penetrates the formation, the mud solids are left behind on the wellbore wall as "mud cake" and only the mud filtrate (typically a brine with Na and K) penetrates into the formation. This mud filtrate invasion affects shallow investigation tools such as sonic and density more than deeper investigation tools such as deep induction resistivity (ILD). Ideally the mud cake quickly shuts off invasion of filtrate into porous rock, but not always. The problem for synthetic seismic generation occurs when the near wellbore sonic and density logs are perturbed by the change in fluid properties. Normal environmental corrections do not address this situation. A discussion of the affects of filtrate invasion on the sonic P wave log is given by Alberty, 1994. Here in we will expand the discussion to include density and S wave affects and how to correct them.

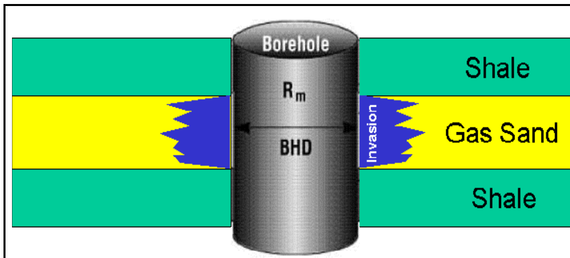

Figure 1: Schematic of borehole and invaded region

Method

The first step to resolving a mud filtrate invasion problem is to determine where the problem occurs and to what extent. First, it can be assumed that invasion occurs primarily in permeable zones with hydrocarbon. The best way to quantify the extent (if any) of mud filtrate invasion is with multiple depth reading resistivity devices (i.e. array induction tool). These are often labelled with numbers indicating the depth of penetration into the formation, such as AT10, AT30, AT60, and AT90, where the increasing number is for increasing depth into the formation (in inches). Conventional monopole sonic and density tools have depths of investigation of less than 10 inches. Therefore, it is safe to assume that the resistivity log AT10 is measuring the same shallow zone around the wellbore as the sonic and density tools. Lets further assume that invasion does not penetrate beyond 60 inches, so the AT60 log is sampling virgin formation (the same as a passing seismic wave).

The next step is to compute water saturation from the shallow (AT10) and deep (AT60) resistivity curves, separately. To compute water saturation (Sw) from deep resistivity data (Rt), it is necessary to have a reasonable water resistivity value (Rw). Rw in the virgin formation can be obtained from resistivity measurements in water saturated sands (often called apparent water resistivity, Rwa). Also necessary is the mud filtrate resistivity (Rm), usually obtained from the log header. Note that the actual brine in the pores near the wellbore will be a mixture of mud filtrate and original pore water. Using measured values of AT60 for the deep conditions (Rt) and the AT10 curve for the shallow (Rxo), then Sw shallow and deep can be computed from the usual Archie or dual-water algorithms.

Once the Sw curves for shallow and deep have been obtained then the problem is reduced to one of fluid substitution. The objective is to compute V_P, V_S, and density at true reservoir conditions beyond the invaded zone. The properties of the water, oil, and gas at true reservoir conditions can be computed from empirical relations such as Batzle-Wang. Computing new V_P and V_S curves is based on Biot-Gassmann theory. New density values are computed based on simple mass balance considerations. Of course accurate knowledge of the solid mineral density and pore fluid density is crucial. These should be computed depth-by-depth to account for variations in mineralogy and water saturation. Below are two examples of mud invasion corrections.

Example 1: South American Reservoir

In this reservoir gas, oil, and water contacts were present at some well locations. The wells had modern log suites with array induction and dipole shear wave curves. In Well *SA1* it was observed that predicted V_S did not match measured values. Upon closer inspection, we observed that this was mainly in the gas bearing interval. In other wells in this area we were able to predict V_S accurately in gas, oil, and wet zones using the Greenberg-Castagna method. We examined all of the Well *SA1* log curves and analyses carefully for evidence of errors or bad data but found none. In this well there was no shallow resistivity data, however when the measured deep water saturation was replaced by Sw in the 95% to 100% range, the predicted and measured V_S values were in close agreement. This was considered to be substantive, but not conclusive, evidence of mud filtrate invasion in the gas-bearing zone.

We then performed a mud filtrate invasion correction that consists of the following computations:

- Porosity, Volume Shale, Deep Sw
- Pressure, Temperature
- Brine Moduli, Density; Deep
- Brine Moduli, Density; Shallow
- Oil and Gas Moduli, Density
- Solid mineral Moduli, Density
- Average Fluid Mixture Moduli, Density; Deep
- Average Fluid Mixture Moduli, Density; Shallow
- Biot-Gassmann Fluid Substitution (from 100% Sw to Deep Sw)

This entire process was implemented as a "workflow" in PetroSolutions software. The original and corrected V_P, V_S and density curves are shown in Figure 2.

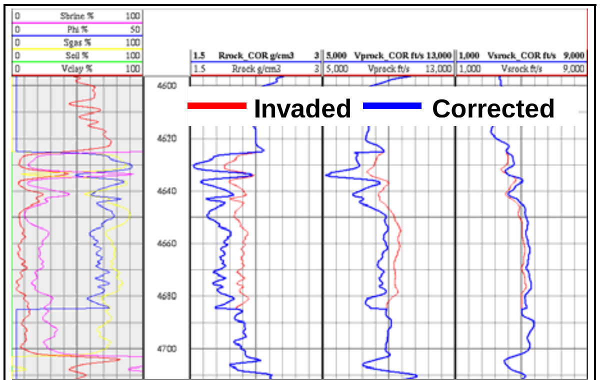

Figure 2: Well SA1: V_P, V_S, and Density before and after correction

Synthetic seismograms were made from the original and mud filtrate invasion corrected log curves. These are shown in Figure 3. The resulting synthetic seismic provided a better tie to the actual stacked traces than before correction. The center group of traces are from the post stack seismic data and the left and right traces are from stacked offset synthetics.

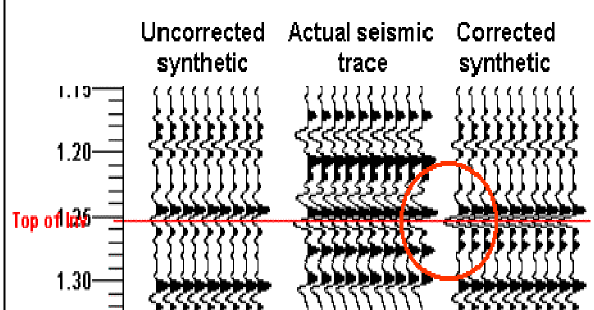

Figure 3: Mud filtrate invasion correction improves tie to seismic in gas bearing sand from South America.

Even though pre-stack seismic data was not used in this project we observed that the AVO response between

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corrected and uncorrected cases was quite different. This has implications for other areas where AVO is used. The effect of mud filtrate invasion can cause significant Poisson's ratio changes thereby giving an erroneous AVO response from synthetics.

Example 2: North Sea Reservoir

In this case, one of the wells did not give a satisfactory tie to the seismic data. Deep and shallow resistivity curves showed that the oil zone was invaded and was effectively water saturated in the region sampled by the density and sonic logs. This well (NS5) had dipole sonic data (V_S). A mud invasion correction workflow similar to that used in Example 1 was applied. The V_P, V_S, and density curves before and after correction are shown in Figure 4.

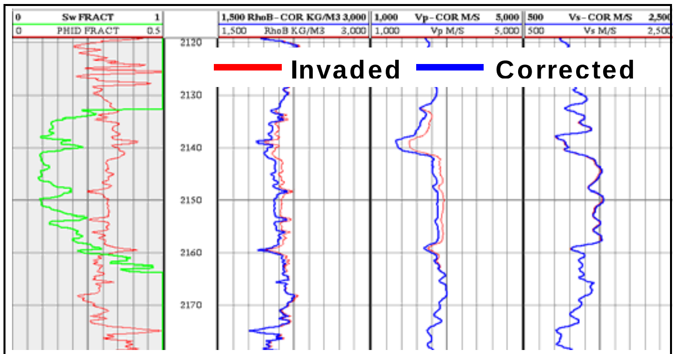

Figure 4: Well NS5 V_P, V_S, and density before and after correction

Figure 5 shows the synthetic seismic traces before and after mud filtrate invasion correction was applied to well log. As in the previous case, the corrected synthetic seismic provided a better tie the actual stacked traces than the original sonic and density curves.

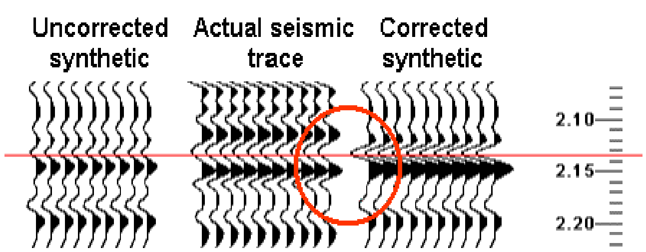

Figure 5: Mud filtrate invasion correction improves tie to seismic in gas bearing sand from North Sea.

Cases where no Shear Velocity (V_S) data is available

In wells that have no dipole shear wave log the problem of mud invasion is a bit more complicated to resolve. First, a shear wave velocity curve must be predicted from the V_P curve, which may have been contaminated by the mud filtrate. Therefore, application of V_S prediction methods that typically work in hydrocarbon bearing formations will give incorrect results. Thus, the correct procedure is to compute the invaded zone saturation and fluid properties then use this data as input to the V_S prediction algorithm. The result will be a computation of V_S that correctly corresponds to the V_P curve from which it came. Then the remaining mud invasion correction computations can be done in the same way as with a measured V_S curve.

Conclusions

Mud filtrate invasion can occur in many types of permeable hydrocarbon bearing formations. It often causes sonic logs to be too fast and density logs to be too high because these logs are sampling mostly water saturated rock. Uncorrected, it can cause substantial errors in well ties to seismic. The problem can be easily detected with multiple depth resistivity logs and then can be corrected using careful application of Biot-Gassmann fluid substitution.

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