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

***Matthew B. Carr*[1], *Miguel Ascanio*[1], *Maggie Smith*[1], *and Joel Walls*[1]**

1. *Rock Solid Images, 2600 S. Gessner Suite 650, Houston, TX 770063*

ABSTRACT

Water Based or Oil Based Mud filtrate invasion can occur in many types of permeable brine or hydrocarbon bearing formations. It often causes erroneous values for the shallow looking devices, such as density and sonic tools. Uncorrected, it can cause substantial errors in well ties to seismic. Walls and Carr (2001), and later Vasquez, et al. (2004) presented methodologies to correct for Water Based Mud (*WBM*) filtrate invasion; herein a similar methodology has been extended to Oil Based Mud (*OBM*) filtrate invasion. The problem can be easily detected with multiple depth resistivity logs and then can be corrected using careful application of Biot-Gassmann fluid substitution. The results are shown to give a better seismic tie, and provide insight to the link between petrophysical properties and the seismic domain.

DISCUSSION

Open hole log measurements often are affected by conditions inside or near the wellbore (See Figure 1). The shallow looking devices, such as density and sonic tools, can be affected by the drilling mud; as such the logging companies have created detailed correction charts for each of their tools. 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. However, the possibility of mud filtrate in the pores that are seen by the density, compressional velocity, and shear velocity curves has not been completely addressed by the "normal" environmental corrections.

Ideally the mudcake quickly shuts off invasion of filtrate into porous rock, but not always. The problem for synthetic seismic generation occurs when the near wellbore density and sonic 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). Walls and Carr (2001) expanded the discussion to include density and S wave affects and how to correct each. Here in the *WBM* filtrate correction has been expanded to *OBM*.

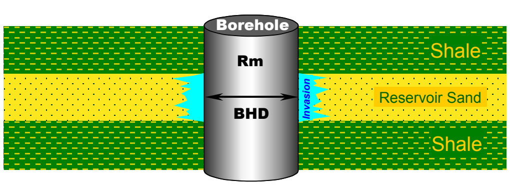

Figure 1: Schematic of borehole and invaded region.

Oil Based Mud Correction

The workflow designed to correct *OBM* filtrate invasion is that of careful use of fluid substitution similar to the workflow presented by Wall and Carr (2001). The invasion profile for *OBM* could be split into two main groups depending on original formation fluid saturation conditions. Figure 2 shows different invasion profiles for a water zone and a hydrocarbon zone at irreducible water saturation.

In the zones where water is the movable fluid, *OBM* filtrate will replace water, and the invaded zone saturation (***S_{xo}***) will be lower than the virgin zone saturation (***S_w***), but may be still be higher than the irreducible water saturation (***S_{wirr}***, see Figure 2a). In hydrocarbon zones at irreducible water saturation, oil is displaced by oil and generally ***S_w=S_{xo}=S_{wirr}*** (see Figure 2c). However, in some cases, one may paradoxically still observe ***R_{xo}>R_t*** and ***S_w>S_{xo}*** (see Figure 2d). This normally occurs when surfactant invades the formation, changing the wettability of the sand grains (La Vigne, 1997).

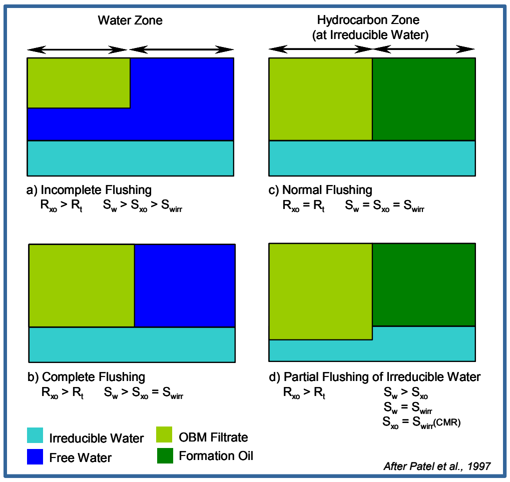

Figure 2. Different Oil Based Mud invasion profiles for a water zone and a hydrocarbon zone at irreducible water saturation.

Correction Recipe

Oil Based Mud Filtrate correction, is more difficult than the *WBM* correction due to the fact that the actual invasion profile cannot be completely known. As a result the correction recipe requires several iterative steps. The context of the likely flushing type outlined in Figure 2 is key in the interpretation and resulting correction for *OBM*. The well logs should be analyzed, based on rock physics, that focuses on the entire well bore, thus creating the most robust set of curves for acoustic modeling and ultimately correlation to the seismic data. The steps are given:

- Generate Relative Abundance for each Mineral.
- Identify Invaded Zones with Multiple Depth of Investigation Resistivity Curves
- Calculate Total Wet Porosity from, Density (*DENPORW)*
  Effective Wet Porosity (shale corrected density porosity; *PHIEW)*
- Compute Water Saturation *(SW),* Oil and Gas saturation *(SO* and *SG,* respectively)
  Using the Archie (1947) Equation (or Variation of Archie)
- Calculate Fluid Parameters (VP, Bulk and Shear Modulii) of Formation Brine, In Situ Hydrocarbon, and Oil Based Mud
- Calibrate Total Porosity to Core Values (If Present)
- Identify Invasion Mechanism (See Figure 2), Based on R_t, R_{xo}, S_w, and S_{xo}
- Calculate and Interpret $S_{wirr,}$ Using Equation 1 (Brickell 2004):

$$S_{wirrt} = 0.08 + \frac{\log\left(\frac{\varphi_t}{10000}\left(10^{0.9987-1.91Vsh}\frac{\varphi_t}{1-\varphi_t}\frac{1}{0.0314}\right)^2\right)}{-5.77} \qquad (1)$$

Where S_{wirr} is the irreducible total water saturation, *VSH* is the log derived Volume Shale, and φ_t is total porosity.

- Calculate the Saturation of *OBM* filtrate for Wet and Hydrocarbon Zones (S_{OBM} = S_{XOO})
- Extract the Saturation of Mud Filtrate (*SMF*) From the Invaded Bulk Density Relation, for Both Original Wet and Hydrocarbon Sand Units

- Calculate the Fluid Relation S_{XW}, S_{XOG}, where S_{XW} is the Water Saturation in the Invaded zone, S_{XOG} is the Formation Oil Remaining After Invasion
- Then Normalize the Flushed Zone Fluids Such that S_{XW}+S_{XOO}+S_{XOG} Equal to 1
- Compute Based on Biot-Gassmann (1951), the Bulk Density, V_P and V_S Curves for the Virgin S_W in the Zone of Interest.
- Finally, Create and Compare Synthetic Seismograms for uncorrected measured Values and the Mud Invasion Corrected Values

Gulf of Mexico Example

Two wells in Green Canyon Blocks 236 and 237 were examined, where Oil Based Mud invasion was seen (GC 236 #2 and GC 237 #2 wells). The situations of "Incomplete Flushing", "Normal Flushing", and "Partial Flushing" were encountered (See Figure 2). In the GC 236 #2 well we see "Incomplete Flushing" (See Figure 2a). "Incomplete Flushing" is defined as where $\boldsymbol{R_{xo}}$ is greater than $\boldsymbol{R_t}$, and $\boldsymbol{S_w}$ is greater than $\boldsymbol{S_{xo}}$ which is greater than $\boldsymbol{S_{wirr}}$. The 100% Brine saturated sand (17852'-17884' Measured Depth) yields uncorrected density, V_P, and Poisson's Ratio that are lower than the corrected (Figure 3).

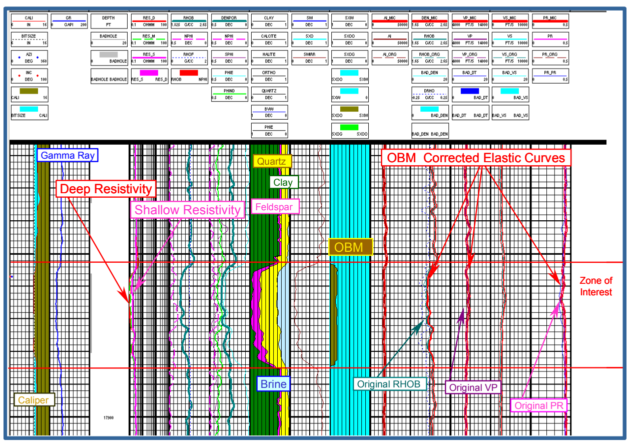

Figure 3. Log plot of GC 236 #2 well showing the location of the Incomplete Flushing of the **OBM** *filtrate invasion profile in the 100% Brine saturated sand (17,852'-17,884' MD). See the relation RES_S > RES_D. The results of the Mud Invasion correction for Bulk Density, Compressional Velocity and Poisson's Ratio (red curves) are also displayed.*

In the GC 236 #2 well "Normal and Partial Flushing" was also observed (See Figure 2c and 2d). "Normal Flushing" is defined in a hydrocarbon-saturated formation (generally oil) where R_{xo} is equal to R_t, and S_w, S_{xo}, and S_{wirr} are all equal. The oil saturated sand (21,704' - 21,724' Measured Depth) yields uncorrected density, V_P, and Poisson's Ratio that are higher than the corrected (Figure 4).

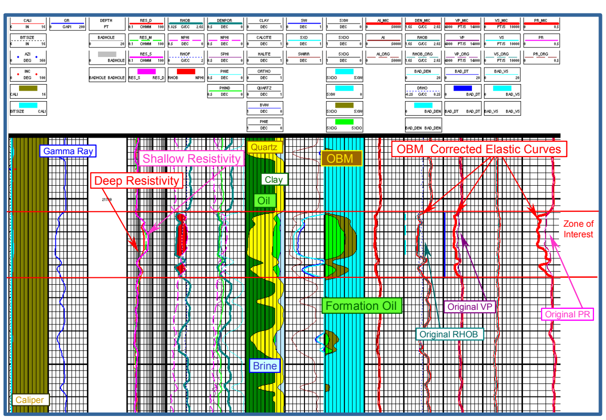

Figure 4. Log plot of GC_236_2 well showing the location **OBM** *invasion profile (Normal and Partial Flushing) in the oil sand units (2,1704'-21,724' MD). See the relation RES_S > RES_D. Bulk density and velocity were corrected by OBM invasion algorithm.*

Finally, the log plot shown in Figure 5 would be *OBM* filtrate invasion again as "Normal" and "Partial Flushing" (See Figure 2c and 2d). "Partial Flushing" is defined in a hydrocarbon saturated formation (generally oil), where $\boldsymbol{R_{xo}}$ is greater than $\boldsymbol{R_t}$, and $\boldsymbol{S_w}$ is greater than $\boldsymbol{S_{xo}}$, and was seen in GC 237 #2 well in the sand zone at 16,666' to 16,711' Measured Depth. Note the changes from measured to corrected are very small in this case. The example shown in Figure 5 illustrates the case where *OBM* invasion has displaced formation water and probably some hydrocarbon. The saturation profile (8th track from the left) of the log plot reveals the presence of movable water ($\boldsymbol{S_w}$>$\boldsymbol{S_{xo}}$). The saturation after the invasion will depend on the initial hydrocarbon content and on the contrast between the mobility of the filtrate and that of the hydrocarbon.

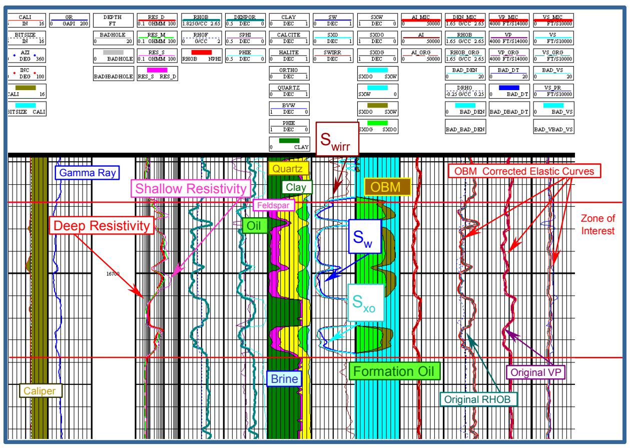

Figure 5. Log plot of GC 237 #2 well showing the effect of **OBM** *invasion profile in Oil sand (16,666'-16,711'). The process is known as Partial Flushing of Irreducible Water (Rxo>Rt, S_w>S_{xo}, Sxo=S_{wirr}, see Figure 2d).*

The ***OBM*** correction workflow was applied to two example wells in the Blocks 236 and 237 of Green Canyon. Synthetic seismograms were made for each well. The GC 236 #2 well showed a significant correction effect on the Compressional velocity for an oil saturated sand unit (Zones from: 14,720' –14,768', and 21,704'-21,724' MD). The seismic to well tie was performed using the original curves and the ***OBM*** Invasion corrected values. The results were an improved seismic to well tie with the ***OBM*** Invasion Corrected values for both Wet and Oil saturated zones (see Figure 6).

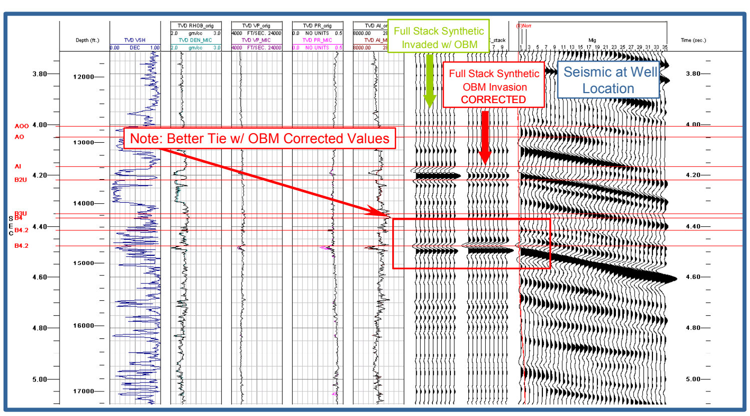

Figure 6. In situ full stack synthetic seismograms and the Seismic trace for the GC 236 #2 well using Original curves (RHOB, VP, VS, AI, PR) and OBM Invaded corrected curves (DEN_MIC, VP_MIC, VS_MIC, AI_MI, PR_MIC). Note the improved seismic to well tie for the oil zone enclosed inside the red rectangle.

CONCLUSION

Mud filtrate invasion (Oil or Water Based) can occur in many types of permeable hydrocarbon bearing formations. It often causes erroneous sonic and density logs. 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 (1956 and 1951) fluid substitution. The correction recipe yields values that produced significantly better synthetic ties. The use of the rock physics principles resulted in the correct context of the rock properties data when compared to the seismic data. The insight gained results in a reduction of risk in exploration and production.

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