Evaluation of Borehole Effect of Mud Filtrate on Density Logging and a Brief Analysis of its Impact on Well-Seismic Tying

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Abstract

The application of seismic data in reservoir characterization, direct hydrocarbon indication and production monitoring rely on the accuracy of elastic logs (Vásquez et al., 2004), which can be damaged by the mud filtrate invasion associated to the borehole condition. Corrections on density log sometimes are neglected, however, meaningful improvements on the correlation of the well to seismic tie can be achieved by performing proper rectifications. For this reason, in this paper we present a analysis of the impacts of borehole enlargement on the well-to-seismic tie based on density modelling and on a analysis of the caliper log.

Introduction

The well logging consists of an imperative resource for the accurate characterization of any reservoir. The in-depth information provided by the wireline procedures, when tied properly to the data acquired by surface surveys, allows the interpreters to verify whether their geological conclusions about the seismic background are suitable to the observed lithology parameters (White and Hu, 1998). A central matter to the well profiles interpretation are the log corrections, which are necessary, assuming that there are many issues about the borehole conditions (Serra, 1994). A example of that is the interaction of the drilling fluid and the formations around the borehole which is a relevant factor for the in-depth acquisitions, especially concerning to the density log, whose precision is directly related to the well-tie response.

The size of the borehole is one of the most obvious factors of environmental effect on the well measurements, whose corrections must be applied to preserve the meaning of the log values (Ellis and Singer, 2007). In the case of unconsolidated shale formations for example, the occurrence of hole enlargement is not unusual, because their typical expressive clay content favors formation collapsing during the drilling process. In general, this borehole effect implies on log distortions, including density irregular measures that result from the formation original components combined to the mud filtrate (Liu and Zhao, 2015). The strong impact of these imprecise logs on the well-tie calculus is one of the reasons to verify possible bed collapses near the wellbore wall, which may be observed on the caliper log.

The main goal of computing the borehole effect on density log is to increase the correlation of the synthetic trace calculated by the well information with the real seismic trace in order to improve the geophysical interpretation. In order to perform the necessary corrections to the log data and ensure a soft response on the well-tie, a key approach is to model the density according to the mud fraction interference on the geology originally contained on the wellbore cavities, which is the purpose of this paper.

Theoretical Elements

In this section, we present the theoretical framework used to establish the analysis of density logging under wellbore enlargement conditions and the correction of its impact on the well-to-seismic-tie results.

Evaluation of Density Distribution around the Borehole

In theory, the stability of the wellbore is supposed to be controlled during the drilling process as the geomechanical conditions were properly evaluated. The prediction of the pore pressure and elastic parameters estimation, for example, are key elements to safe well planning (Gholami et al., 2015). However, non-predicted occurrences of formation collapsing might change the density distribution around the borehole, causing a common logging distortion that can be solved by correcting the data segments that have anomalous caliper values. Respecting these assumptions, the apparent geometric factor theory - first introduced by (Doll, 1949) - is a conventional and consistent method for the proposed logging quality control.

The expected geometry of the borehole is a cylinder of radius size similar to the drill bit, with a smooth inner surface. Irregularities along the borehole due to unconsolidated formations affect the signals recorded by the logging tool, which in this situation are more related with the driling mud than to the formation. Furthermore, when the difference between the caliper logging value and the bit diameter is meaningful, it is presumed that the density values may decrease due to the mud influence, as shown in Figure 1. When borehole enlarges it is correct to assume that the media around the borehole is now composed of mud and formation rock. The density measurement is obtained from a weighted average of mud and formation densities (2) as a consequence of the apparent geometric factor that satisfy the condition (1).

$$G_b + G_{mud} = 1 \tag{1}$$

$$\rho_a = G_b \rho_b + G_{mud} \rho_{mud} \tag{2}$$

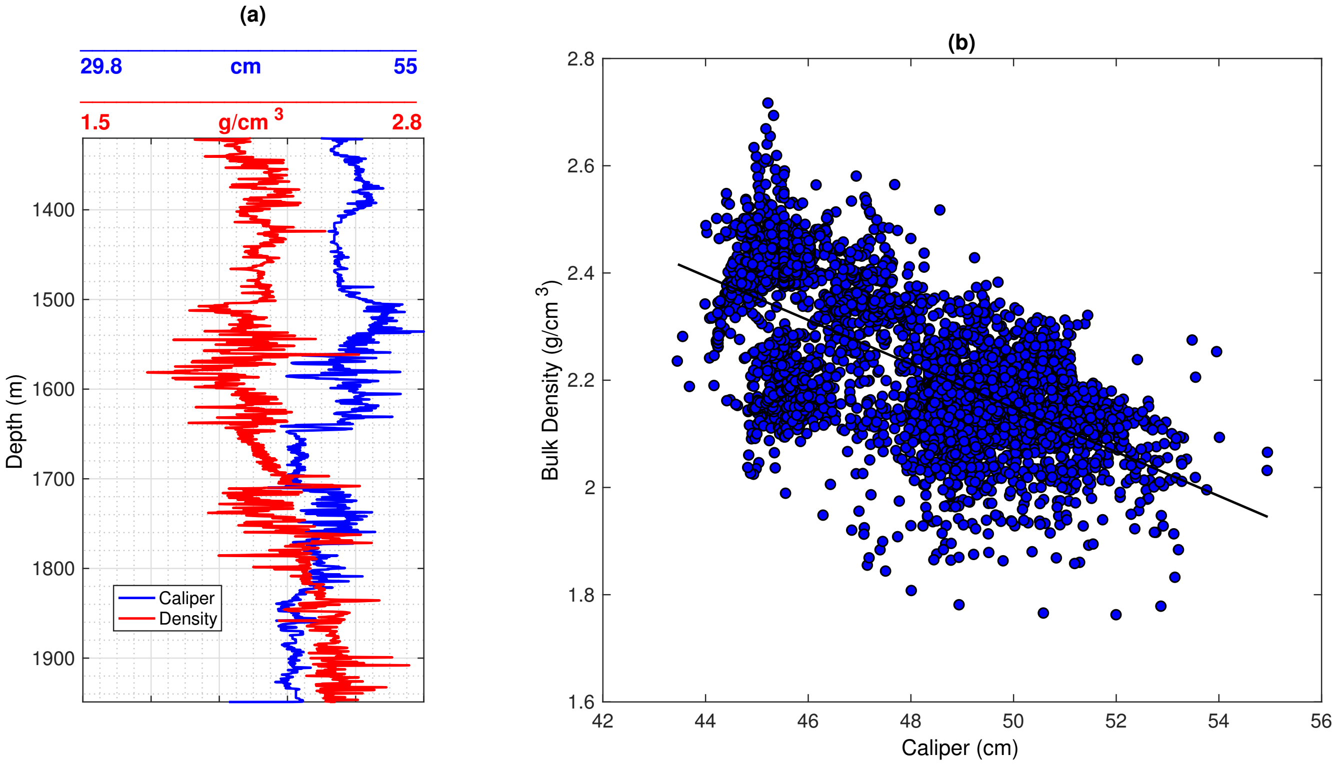

Figure 1: (a) A density and a caliper log over the same section of a well data. (b) Correlation between the logs to the left (dispersion in blue and linear trend line in black).

where G_b is the coefficient for the formation rock, $0 \leq G_b \leq 1$; G_{mud} is the coefficient for the mud, $0 \leq G_{mud} \leq 1$; ρ_a is the apparent density (g/cm^3); ρ_b is bulk density (g/cm^3); and ρ_{mud} is mud density (g/cm^3). Based on these equations, it is possible to analyze the mud influence on the mass concentration indicated by the tool recordings. If there is significant borehole diameter expansion, exceeding the detection limits of density log, all values are represented by mud density, according to the equations (1) e (2), $G_{mud} = 1$, $G_b = 0$, $\rho_a = \rho_{mud}$; in contrast, if the logging tool keeps contact with a regular wellbore wall, then $G_{mud} = 0$, $G_b = 1$, $\rho_a = \rho_b$. Therefore, in terms of error estimation due to borehole expansion, G_{mud} and ρ_{mud} are fundamental parameters that needed to be investigated.

To determine the true values of density that represent the subsurface formations, we derive from the equations (1) e (2) the following expression:

$$\rho_b = \frac{\rho_a - G_{mud}\rho_{mud}}{1 - G_{mud}} \tag{3}$$

which indicates the correct value of bulk density, in terms of apparent density, mud density and apparent geometry factor of mud. The method we assumed to analyze how the borehole effect is propagated to well-tie results is to explore a semi-quantitative application of G_{mud} and ρ_{mud}, using equation (3) to investigate the proper values of formation density (ρ_b) that should increase the correlation between the well logs and the seismic data.

Modeling the Well-tie Response to Density Non-Compensated Logs

The evaluation of mud distribution is a well-established procedure for generating compensated logs and improve the wireline acquisition quality by suppressing the borehole effects (Poletto and Miranda, 2004). In terms of density, non-compensated logs implies on unbalanced synthetic traces and, therefore, well-tie underestimation. This fact is a strong motivation to quantify the response of the connection of well log data and seismic data. Moreover, there are good practices to avoid a poor well tie but very few alternatives to refine it after its development, as White and Simm (2003) argued. Improvements in the log conditioning and calibration consists in a more productive line of action.

Before proceeding to the response analysis itself, brief comments about the well-to-seismic-tie calculus are necessary to understand the seismic trace calculus. Bianco (2014) describes concisely the basic steps for the tying process, in the following order: log previous processing; time-depth relationship computing; determination of reflection coefficient in time; and the wavelet estimation. The first step involves our scenario about density measurements and it is important to perform simulations of hole enlargement, which basically needs to feature the elastic parameters of a stratified media, then continue the tie calculus.

On the next stages, the elastic parameters enable us to describe the earth based on the convolutional model (5), which is the key to compare the real seismic trace to the one derived from the well logs. Assuming normal-incidence, the p-wave reflection coefficient at a sample i

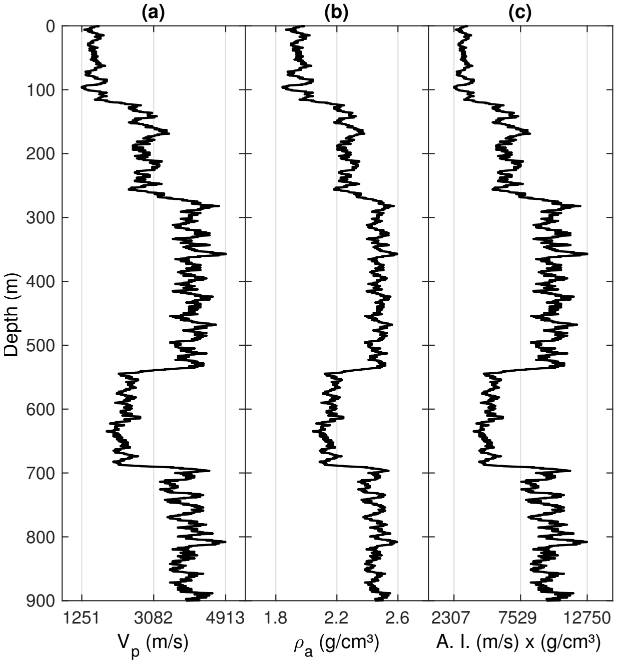

Figure 2: Hypothetical media represented by the elastic parameters: (a) compressional velocity, (b) apparent density and (c) acoustic impedance.

is given by:

$$R_i = \frac{Z_{i+1} - Z_i}{Z_{i+1} + Z_i} \quad (4)$$

where Z is the acoustic impedance, which is equal to the product of p-wave velocity and density. The time-depth relationship is used to resample the reflectivity series, from depth to time domain, and finally convolve that with an estimated wavelet $w(t)$ to obtain the synthetic seismic trace $s(t)$, which has a white noise component $\eta(t)$:

$$s(t) = R(t) * w(t) + \eta(t) \quad (5)$$

The final step consists of calculating the correlation between the real data and the synthetic result. This workflow was applied on a synthetic model as well as on a real dataset, which are presented on the next sections.

Application on a Synthetic Data

In order to verify how the well to seismic tie is affected by the mud content we applied the apparent geometric factors on a layered model described by the logs contained in Figure 2. We model five layers and the fourth (540 to 690 m) was used to simulate the mud filtrate effect on density measures. Then, we compared the synthetic trace obtained in the clean case to the ones affected by the drilling fluid. We assumed a casual pulse as our wavelet, with a peak frequency of 20 Hz, sampled at a rate of 4 ms in a time series with of 3 s. Thus, using the acoustic impedance of our hyphotetical model and the equation (4), the reflectivity series was calculated and resampled according to the depth-time proportion. Figure 3 shows the wavelet, the reflectivity on time-domain and also an white noise profile which was added to the convolution of the two first parameters in order to obtain the seismic trace (equation (5), which was used as our real trace.

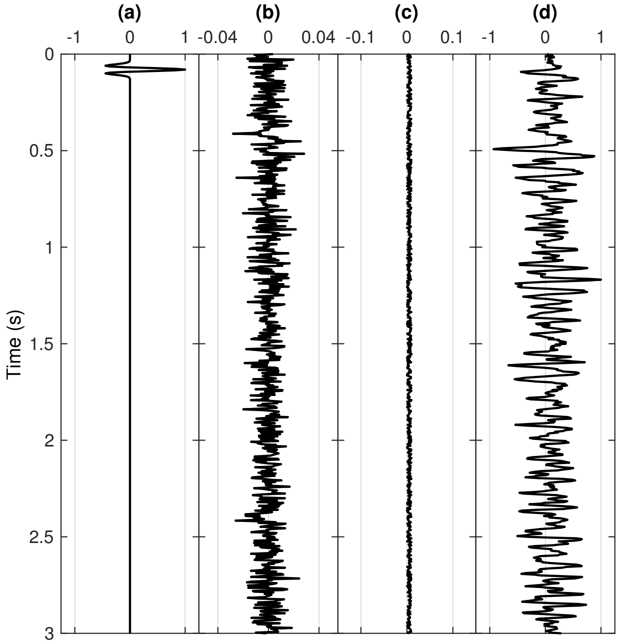

Figure 3: Convolutional model of the Earth for the proposed media: (a) seismic wavelet; (b) reflectivity series; (c) white noise; and (d) synthetic seismic trace.

At this point it is important to emphasize the assumption that the mixture of drilling fluid and the media near the wellbore satisfies the adopted mathematical model, which explains feasible distortions on density values recorded by the logging tool, that can be corrected if G_{mud} and ρ_{mud} are known. In terms of the density of the fluid, we considered a window of 1.05 to 1.25 (g/cm^3) for our hypothetic drilling. Therefore, we calculated different density logs with different values of fluid density for the fourth layer and then computed several different synthetic seismic traces using the same process already described. Figure 4 shows two of these seismic traces, corresponding to the extreme physical scenarios: no drilling fluid interaction with the fourth layer (blue curve) and mud filled formation over the limit of density logging (red curve). This theoretical analysis is made by the observation of the correlation behavior of the synthetic seismic traces modeled with different density logs and the real seismic trace. The higher the mud content on the simulated density curve, the lower the correlation between the synthetic and real traces, which is critical to

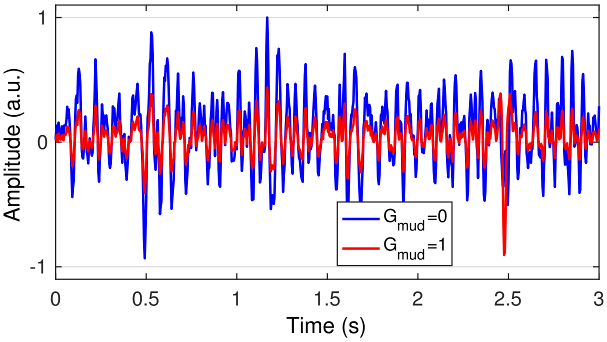

Figure 4: Comparison between two synthetic traces.

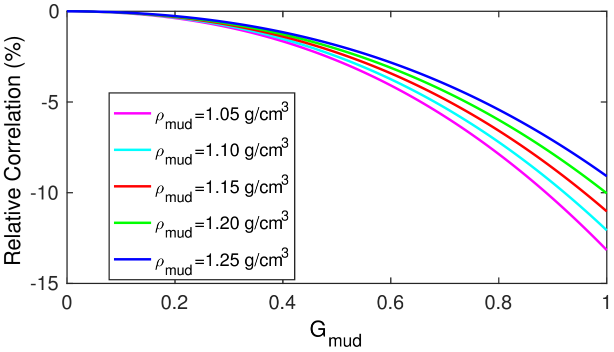

Figure 5: Relative correlation computed for different values of mud density and mud apparent geometric factor.

the well-to-seismic-tie results. In Figure 5 can be noticed that the correlation between the real and the synthetic trace tends to strongly decrease as the mud filtrate contaminates the formation and even lower correlation is reached for lighter drilling fluids. For real cases, non-compensated logs can lead to a bad well-tie response, which was tested by performing density corrections on a real well log data described on the next section.

Real Data Example

The dataset that we used to apply the proposed study was acquired at the northern Viking Graben, located on the North Sea basin. In Figure 1 there are log segments from a Well located in a line where there is also a seismic section avaliable. Macedo et al. (2017) performed well-tie procedures using these logs and the same seismic section, verifying that the best match to the well data is the CMP 809, which we also used as the real trace. There is a caliper anomaly on the shallow section of the drilled borehole (Figure 6), what raises the chances of density logging contamination by mud filtrate. The dertemination of G_{mud} along the depth interval of 1320m to 1984m would solve this potential problem Equation (3) was used to map the relative correlation for the same set of mud parameters used on the synthetic example. In this case we compared the correlation computed using the synthetic trace derived from the original log to the ones obtained using the compensated logs. As expected, the relative correlation increases as the modelled correction of mud volume on the formation around the borehole is higher, as shown in Figure 7. The mean density value adopted for the drilling fluid is 1.15 g/cm^3, which is very low compared to the rock formation range and, in physical terms, a compromised well log would be limited to values close to the mud density. The corrections we tested tending to 100% of mud contamination ($G_{mud} = 1$) have less physical meaning because the calculated bulk density would be out of the known range of rocks.

Conclusions

Although there are several well established ways to seek good quality of a well-to-seismic tie, our natural disposal as geoscientists is to combine useful methods with perception. The analysis presented consists of a simple mathematical modelling that fulfills the goal of enhancing the tie correlation by taking into account that uncertainties on density measures can be related to mud invasion. Among some invasion correction methods, Vásquez et al. (2004) mentioned the caliper role as an indicator of bad borehole conditions and, thus, part of the quality control of density logging. The featured applications in this work confirmed that anomalous caliper segments suggest contamination on density logs, which may be properly evaluated in order to avoid misinterpretations on well tie results.

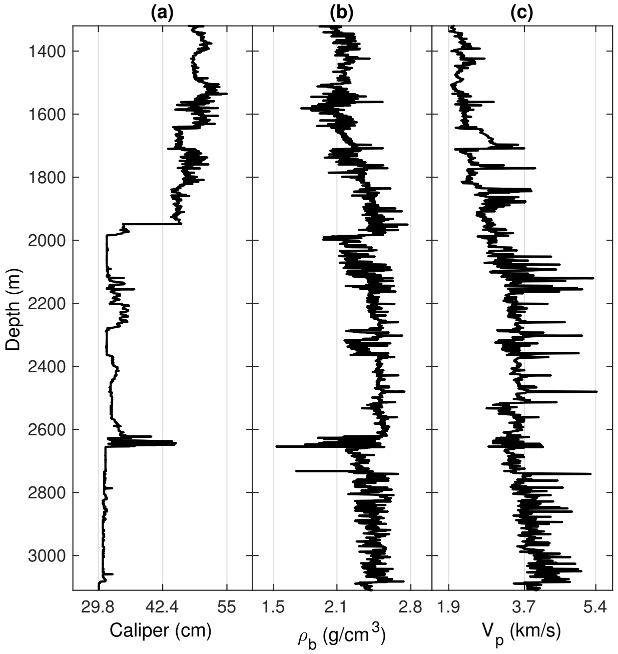

Figure 6: Logs of the studied Well: (a) caliper; (b) bulk density; and (c) p-wave velocity.

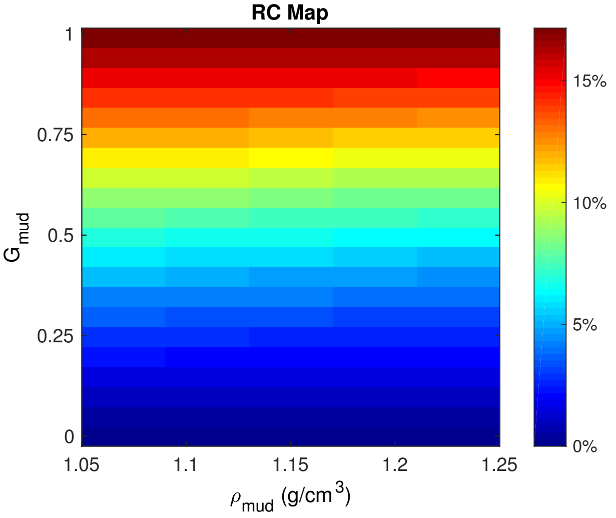

Figure 7: Mapping of percentual relative correlation (RC) between the well-tie before and after the mud correction on the segment of anomalous caliper.

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