The impact of density log correction on the well-to-seismic-tie: application on real seismic/well log data.

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Abstract

The accuracy of elastic logs is of paramount importance in the reservoir characterization. During the acquisition of the well log measurements it is necessary to guarantee that the logging tool is stable during the drilling process in order to do not compromise the information about the physical properties in the vicinity of the well. The caliper log might be a indicator of the quality of other logs whose data may be degraded by holes that are out of gauge. Bad well log data, specially density and velocity profiles, might affect the quality and accuracy of the well-to-seismic tie. In this paper we present a analysis of the impacts of borehole enlargement on the well-to-seismic tie based on density log corrections. Our approach uses the Doll's geometric factor to correct the density log for bad hole conditions using the caliper readings. For both deterministic wavelet estimation and statistical wavelet estimation, our results on the real dataset from the Viking Graben field - North Sea show a meaningful improvement on the correlation of the well-to-seismic tie when comparing to the case where no corrections on the density log are made.

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). 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). This interaction of the drilling fluid and the formations around the borehole is a relevant factor to be concerned for the in-depth acquisitions, especially concerning to the density log, whose precision is directly related to the well-to-seismic-tie response, a central matter of this research. An expanded borehole or an irregular borehole wall may affect the density log curve so markedly that the curve drops precipitously, and the measured density value is much lower than the true density value Yong and Zhang (2007).

Macedo et al. (2017) analyzed the influence of the stability of the diameter of the borehole during acquisition on the well-to-seismic-tie and show that anomalies on the caliper logs can directly affect the quality of the tie and consequently, the estimated wavelet. Within this scenario, this work aims to show the well-to-seismic-tie response when the proper corrections on the density log for the borehole enlargment are made. The corrections are based on Doll's geometric factor. We use the same methodology for the well-to-seismic-tie, the same estimatives of the wavelet, and the same real data set as Macedo et al. (2017). For both deterministic wavelet estimation and statistical wavelet estimation, our results on the real dataset from the Viking Graben field - North Sea show a meaningful improvement on the correlation of the well-to-seismic tie when comparing to the case where no corrections on the density log are made.

Methodology

To perform the well-to-seismic-tie, it is necessary to calculate the synthetic seismic; therefore, it is necessary to calculate the reflectivity series generated by changes of impedance $I = \rho V_p$ within the earth and then convolve it with a wavelet. The reflectivity is created directly from the sonic log and bulk density curves, according to the equation 1

$$R_c(i) = \frac{\rho_{bi+1} v_{i+1} - \rho_{bi} v_i}{\rho_{bi+1} v_{i+1} + \rho_{bi} v_i}, \tag{1}$$

where i represents the index of a sample in depth, R_c is the reflectivity, v is the P-wave velocity and ρ_b is the corrected bulk density according to the equation 5.

Since the sample rate of the well logs (in depth) are larger than the sample rate of the seismic trace (in time), the next step is to resample the reflectivity, so it can be fit on the time axis from the time-depth relationship. With the reflectivity on time axis, it can be convolved with a seismic wavelet to create a synthetic seismogram, according to the equation of the convolutional model 2, where $s(t)$ is the synthetic seismic trace, $w(t)$ is the seismic wavelet and $r(t)$ is the resampled reflectivity in the time domain.

$$s(t) = w(t) * r(t). \tag{2}$$

The seismic wavelets in this work were estimated by two different approaches: a deterministic estimation of the wavelet, which uses both real seismic trace and well log data, and a statistical estimation of the wavelet, which uses only the real seismic trace. The first approach was based on the building of a filter and the second one was based on the predictive deconvolution. We follow the exactly methodology made by Macedo et al. (2017) to estimate both wavelets.

Once the synthetic trace is calculated, it will be further compared to the real seismic data. As a consequence of the density correction, the correlation should increase in this well-to-seismic tie when comparing to the one without the density correction, provided that the other parameters related with the well tie such as wavelet estimation and time-depth relationship are fixed.

In order to correct the density log for the borehole enlargment through the caliper log readings we use the Doll's geometric factor described on the equation 5. Doll (1949) developed the apparent geometric factor theory for the induction logging. For this log, the theory states that the voltage at the receiver is the sum of the contribution of a large number of infinitesimal rings of Focault current. The geometric factor of each coaxial cilindrycal area would represent the fraction of contribution of this singular area to the entire signal, assuming a uniform condutivity within each zone.

When borehole enlarges it is correct to assume that the media around the borehole is now composed of mud and formation rock. As well as proposed by Doll (1949) for the induction logging, the density measurement can also be obtained from a weighted average of mud and formation densities 4 as a consequence of the apparent geometric factor that satisfy the condition 3

$$G_b + G_{mud} = 1, \tag{3}$$

$$\rho_a = G_b \rho_b + G_{mud} \rho_{mud}, \tag{4}$$

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). 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 (3) and (4), $G_{mud} = 1$, $G_b = 0$, $\rho_a = \rho_{mud}$; in contrast, if the logging tool keeps contact with a regular wellbore wall, then $G_{mud} = 0$, $G_b = 1$, $\rho_a = \rho_b$.

To determine the true values of density that represent the subsurface formations, we derive from the equations 3 and 4 the following expression:

$$\rho_b = \frac{\rho_a - G_{mud}\rho_{mud}}{1 - G_{mud}}, \tag{5}$$

which indicates the corrected value of bulk density, in terms of apparent density, mud density and apparent geometry factor of mud.

In order to correct the density log for the borehole enlargment through the caliper log readings we use the Doll's geometric factor described on the equation 5. During the completion of a well the mud density is a known value that is used on equation 5, but the apparent geometric factor of the mud is not known. In this work we first establish a possible value for the mud density of $1.10 g/cm^3$.

We performed the correction on the density log at each point in depth by creating a linear relationship between the minimum and maximum values of the caliper log with the minimum and maximum values of the apparent geometric factor of the mud G_{mud}. Through the equation 4 it is possible to note that when the apparent geometric factor is zero, the corrected bulk density is equal to the measured bulk density. It means that in this situation there are no enlargment or shrink of the borehole, therefore, the minimum value of G_{mud}, which is zero, is related with the minimum value of the caliper log, that occurs when it is stable. The choise of the maximum value of G_{mud}, that will be related with the maximum value of the caliper log, need to take into account prior information. It happens because although mathematically the use of $G_{mud} = 1$ means that the tool measures only the density of the mud (equation 4), it is necessary to produce corrected bulk density logs that are geologically consistent. By geologically consistent we mean that the corrected bulk density log values must agree with the possible geology of the area and with the density values that we commonly find for the rocks on the earth.

In order to create a log of G_{mud} values in depth to proceed with the correction of the bulk density log at each point in depth, a linear relationship between the caliper log and the G_{mud} values was established according to the equations described below and the graphic from the figure 1a. The figure 1b shows the linear trend between the caliper log values and the density log values from the real data set from the Viking Graben field.

The figure 1 shows that as the diameter of the borehole increases, the density log value decreases; on the contrary, density log values increase as borehole diameters approach normal levels. It means that on the portions of the density log that occurs the enlargment of the borehole, the density log values are underestimated. Hence, the correction for the geometry of the wellbore should increase the values of the density log on those portions. The higher the enlargement of the borehole, the higher the value of G_{mud} that needs to be used to proper correct the density log.

To correct the density log for the geometry of the borehole, we calculate the slope of the line of the figure 1a:

$$m = \frac{Cal_{max} - Cal_{min}}{G_{max} - G_{min}}, \tag{6}$$

where Cal_{max} and Cal_{min} represents the maximum and

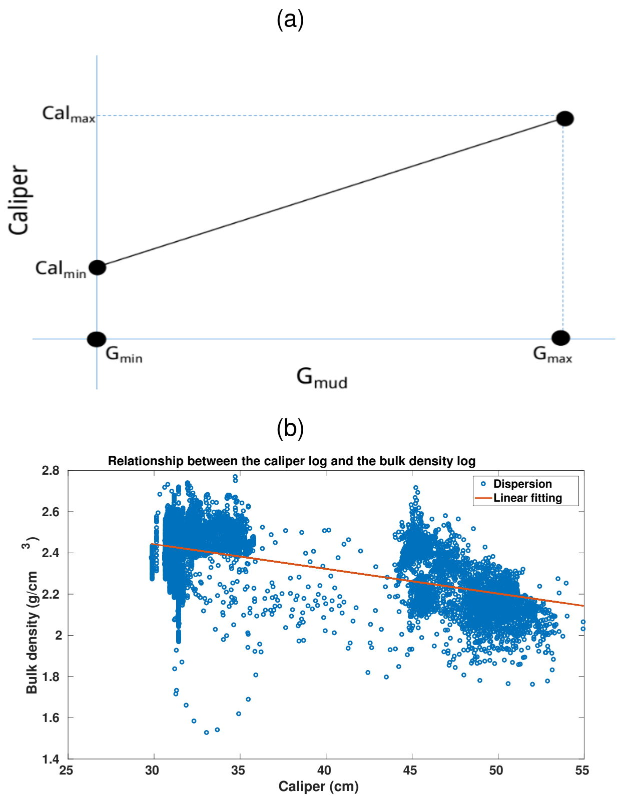


Figura 1: a) The linear relationship between the apparent geometric factor G_{mud} and the caliper log, according to its maximum and minimum values. b) The linear trend between the caliper log values and the density log values from the real data set from the Viking Graben field.

minimum value of the caliper log, and G_{max} and G_{min} represents the maximum and minimum value of the apparent geometric factor of the mud G_{mud}, with the minimum value being zero and the maximum value depending upon the geology and the logging tool. For the Viking Graben data set, the real data we used in this paper, we used $G_{max} = 0.4$. The reasons for that will be described later.

The intercept of the line is:

$$b = Cal_{min} - mG_{min}. \tag{7}$$

Accordingly, the G_{mud} log is created through the equation:

$$G_{mud} = \frac{Cal - Cal_{min}}{m} + G_{min}, \tag{8}$$

where Cal represents each value of the caliper log in depth and G_{mud} is each value of G_{mud} created along the depth axis. By applying the relation 8 in the equation 5, we generate the relation that we used to correct the bulk density value for each point in depth 9.

$$\rho_b = \frac{\rho_a - [(Cal - Cal_{min})/m + G_{min}]\,\rho_{mud}}{1 - [(Cal - Cal_{min})/m + G_{min}]}. \tag{9}$$

In the situation where there are no enlargment of the borehole (when the caliper log is stable), $m = 0$ and the equation 9 turns into:

$$\rho_b = \frac{\rho_a - G_{min}\,\rho_{mud}}{[1 - G_{min}]}. \tag{10}$$

Also in this situation, the minimum value of the apparent geometric factor of the mud is $G_{min} = 0$. Hence, when the caliper log is stable and the diameter of the borehole mantains its bit size during the drilling, there is no need to correct the measured bulk density since $\rho_b = \rho_a$.

The procedure to perform the correction on the density log and proceed with the well-to-seismic tie are described in the following steps:

1. Edit the sonic and density logs to do not deal with noisy spikes
2. Establish a possible value of ρ_{mud}
3. Establish the value of G_{max} and set $G_{min} = 0$
4. Create the G_{mud} log in depth according to the equation 8
5. Perform the correction on the measured density log using the G_{mud} log and the equation 9
6. Calculate the reflectivity series with the corrected density log using the equation 1
7. Estimate the seismic wavelets through the deterministic and statistical approaches described in Macedo et al. (2017)
8. Convolve the reflectivity series with the estimated wavelets to calculate the synthetic seismic trace

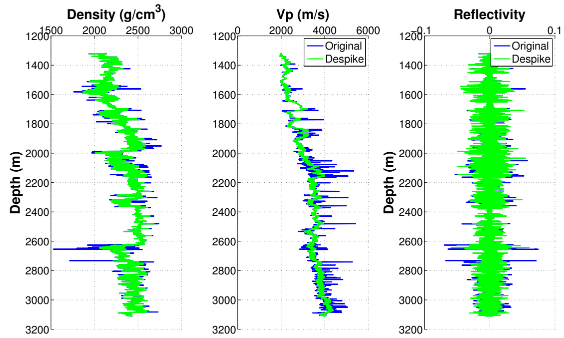


Figura 2: Logs of the studied well from the Viking Graben field after the despiking process for further use on the well-to-seismic tie: (a) Bulk density; (b) P-wave velocity; and (c) Reflectivity.

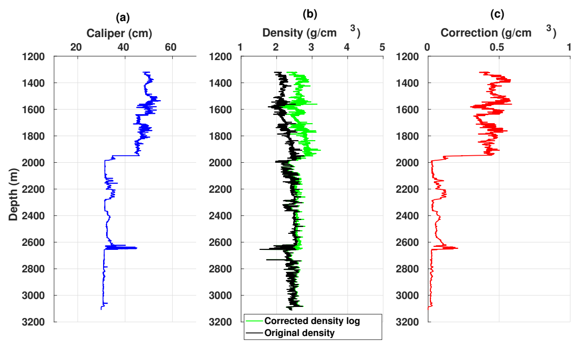


Figura 3: Logs of the studied well from the Viking Graben field used to calculate the correction on the density log for the borehole enlargement. a) Caliper log indicating how the diameter of the borehole varies in depth b) Original and corrected bulk density logs c) The correction applied to the density log.

9. Compare the synthetic seismic trace with the real seismic trace through the cross-correlation
10. Compare the correlation of the well-to-seismic tie without correction on the density log with the correlation of the well-to-seismic tie with the correction on the density log

Results on Viking Graben dataset

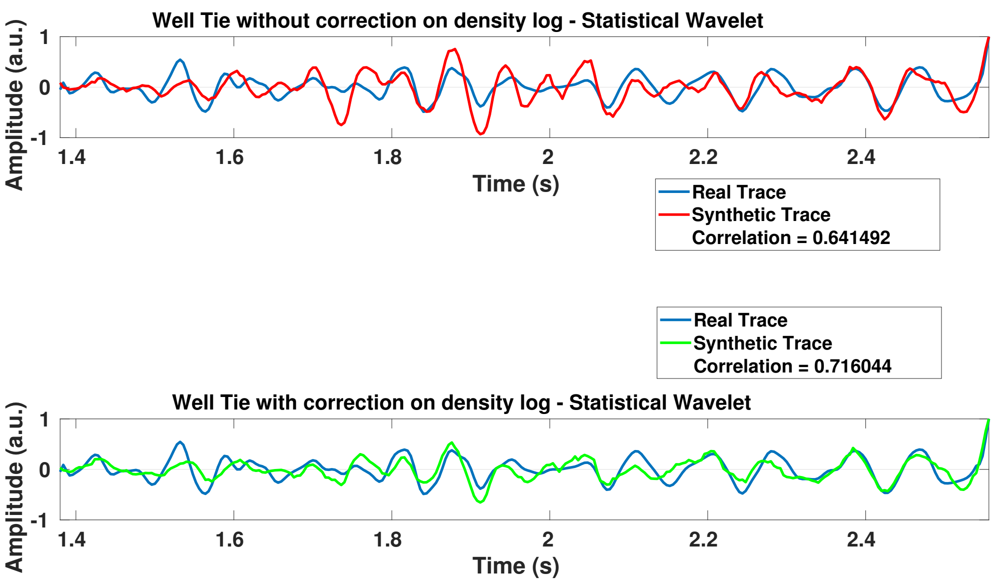
The dataset that we used to apply the proposed study was acquired at the northern Viking Graben, located on the North Sea basin. In Figure 2 there are log segments from the well named well A located in a line where there is also a seismic section avaliable. Macedo et al. (2017) performed well-tie procedures 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, which raises the chances of density logging contamination by mud filtrate.

To obtain the corrected density log of the figure 3 we use the value of $G_{max} = 0.35$ since it produced a reasonable correction on the density log with values around $0.5 g/cm^3$. Figure 4 shows the impact on the well-to-seismic-tie of the correction on the density log.

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. Our methodology of correction using the Doll's geometric factor for the density log produced a increase on the correlation of the well-to-seismic-tie on the real dataset from the Viking Graben field. When using the statistical wavelet estimation, the correlation increased from 0.64 to 0.71 with the correction on the density log, and from 0.71 to 0.75 when using the deterministic wavelet estimation. Those results shows that the enhance of quality on the well-to-seismic-tie for interpretation purposes goes beyond the choice of a good wavelet.

(a)



(b)

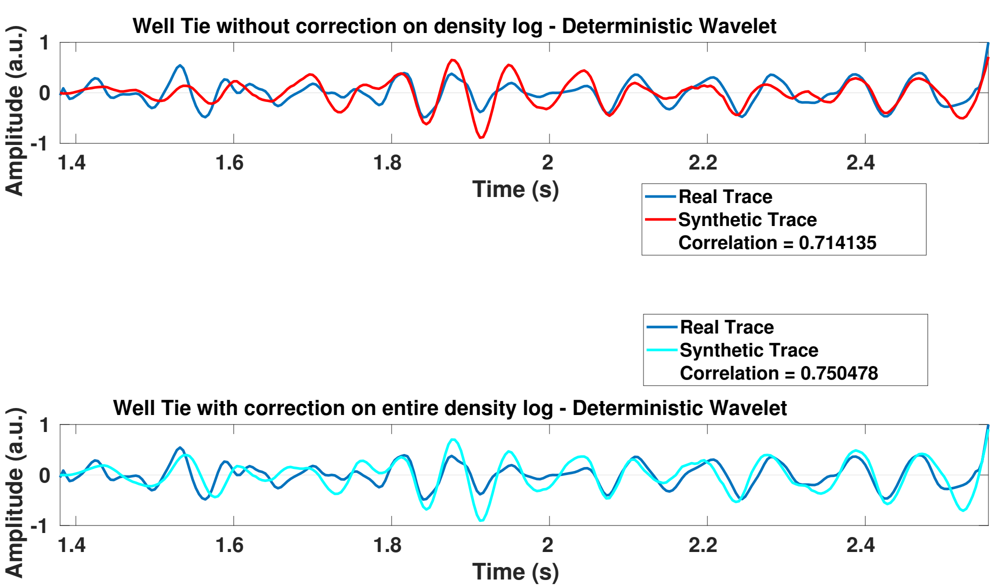


Figura 4: a) Comparison of the well-to-seismic-tie with and without the correction on density log using a statistical wavelet estimation b) Comparison of the well-to-seismic-tie with and without the correction on density log using a deterministic wavelet estimation. For both cases, there is a improvement on the quality of the well-to-seismic-tie after the correction, with a correlation increasing from 0.64 to 0.71 for the statistical case, and from 0.71 to 0.75 for the deterministic case.

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