Missing Well Log Estimation by Multiple Well-log Correlation

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Summary

We propose a method to estimate missing logs by correlating a reference log from surrounding well logs. The approach correlates similarities in the character of the reference log to account for stratagraphic variations to estimate the log of interest. Using several wells from the Teapot Dome dataset, the results of applying this method to estimate full sonic logs are superior to those from conventional log estimation methods.

Introduction

Finding seismic to well ties typically involves estimating a reflectivity series and time depth relationship (TDR) using the available sonic and density logs (White and Simm, 2003). In plays where numerous wells are drilled, sonic and density logs may be absent or have missing section because of cost considerations or borehole problems. The missing logs or log sections make it challenging to integrate all of the available well data with seismic.

Simple interpolation of missing log section could estimate the reflectivity series and TDR; however, such interpolation does not account for variations in lithology. Several data-driven methods can be used to estimate missing logs for seismic well ties. Gardner's equation provides a reasonable emperical relationship between sonic and density for a large number of brine-saturated rock types (Gardner et al., 1974). Additionally, the Faust method (Faust, 1953) and Smith method (Smith, 2007) can provide interval-specific emperical relationships between resistivity and sonic logs. Each of these methods can produce a useful predicted log; however, specific well logs need to be collected at every well location in order to carry out the estimation.

An alternative approach is based on the assumption that rock properties do not vary significantly in lateral space, so a density or sonic log from a nearby well can be used at the well of interest to carry out the synthetic well tie. This method does not take into consideration structural complexities or stratagraphic variations in lithology. To account for the stratagraphic variations, the wells must be correlated to a common relative geologic time. Wheeler and Hale (2014) and Wu et al. (2017) use dynamic time warping (DTW) (Berndt and Clifford, 1994; Hale, 2013) to correlate multiple well logs. Shi et al. (2017) use local similarity (LSIM) (Fomel, 2007a) to optimally sort and flatten multiple well logs. Once the well logs are flattened, missing well log section can be estimated from the available data.

We propose a method to estimate missing logs by correlating a reference log in nearby wells. We correlate a reference gamma log from each well using LSIM and employ the estimated shifts to align all available logs in the dataset. The aligned logs are then used in a least-squares minimization problem to estimate the missing well log. We provide an example from the benchmark Teapot Dome dataset where a complete sonic log is estimated and compared with both the actual sonic log and the result of a conventional method for estimating missing sonic logs.

Theory

We focus on using other well logs of the same type and logs within the same well in our estimation of a missing log. Ideally, we include all of the well log information in the prediction of our missing log. In a mathematical vector notation,

$$\begin{bmatrix} \boldsymbol{W_1} \\ \boldsymbol{W_2} \\ \vdots \\ \boldsymbol{W_N} \end{bmatrix} \tilde{l} = \begin{bmatrix} \boldsymbol{W_1}\hat{l_1} \\ \boldsymbol{W_2}\hat{l_2} \\ \vdots \\ \boldsymbol{W_N}\hat{l_N} \end{bmatrix} \tag{1}$$

where our estimated log, $\tilde{l}$, is a function of all available well logs and empirical predictions. If we simplify the prediction to one unknown log and one known log, Equation 1 collapses to the following linear relationship:

$$W_k(z)\tilde{l}(z) \approx W_k(z) l_k(z + z_k(z)) \tag{2}$$

where $W_k(z)$ weights the specific value used to estimate the missing log value, $l(\tilde{z})$, from an available well log or emperical relationship, $l_k(z + z_k(z))$. To estimate a missing log at each depth sample, we must first remove structural and stratagraphic variations between the well logs by correlating the well logs to common geologic time using time shifts, $z_k(z)$, estimated from LSIM.

Multiple well-log correlation aligns reference log data along common geologic time, and the correlation coefficient can be used to quantify the quality of the match (Hampson-Russell, 1999). The correlation coeffecient provides one number to compare the entire length of two signals. This measure is inconvenient as we are interested in comparing two similar signals with local variations. Instead, the

LSIM method begins with the square of the correlation coefficient (c) which can be split into a product of two factors (Fomel, 2007a):

$$c^2 = p * q \tag{3}$$

where p and q are least-squared inverses. This problem is posed as a regularized inversion where the regularization operator is defined using shaping regularization (Fomel, 2007b) and designed to enforce smoothness. The result provides a measure of local similarity between two signals at every point along each signal where high similarity is related to high correlation. By smoothly selecting high similarity values, we estimate the shifts, $z_k(z)$, that correlate the signals along the entire length of each signal. In Figures 1(a) and 1(b), LSIM is used to estimate the shifts and align a reference gamma logs from two wells along constant geologic time, and the shifts used to align the reference gamma logs for each well are used to align available sonic logs in Figures 1(c) and 1(d).

We define the weight, $W_k(z)$ in Equation 2, is a function of the distance between the unknown and the available well logs and the caliper value at that depth. The caliper measures the size of the borehole at all depths, and we assume that deviations from the anticipated borehole size while drilling is a proxy for an inaccurate measurement.

$$W_k(z) = \phi(|x - x_k|) * C_k(z + z_k(z)) \tag{4}$$

where $\phi(|x - x_k|)$ is a radial basis function in terms of the well location with missing logs (x) and well with available logs (x_k) and C_k is inversely proporational to the deviation between the expected and actual caliper value at each depth.

Radial basis function (RBF) is used to weight each input log value based on the distance from the missing log location (Powell, 1987). There are several different choices for radial basis functions, we implemented inverse mulitquadratic radial function

$$\phi(r_k) = \frac{1}{\sqrt{1 + (\epsilon r_k)^2}} \tag{5}$$

which weighs locations further from the well less as compared to points near the well, ϵ is a small constant.

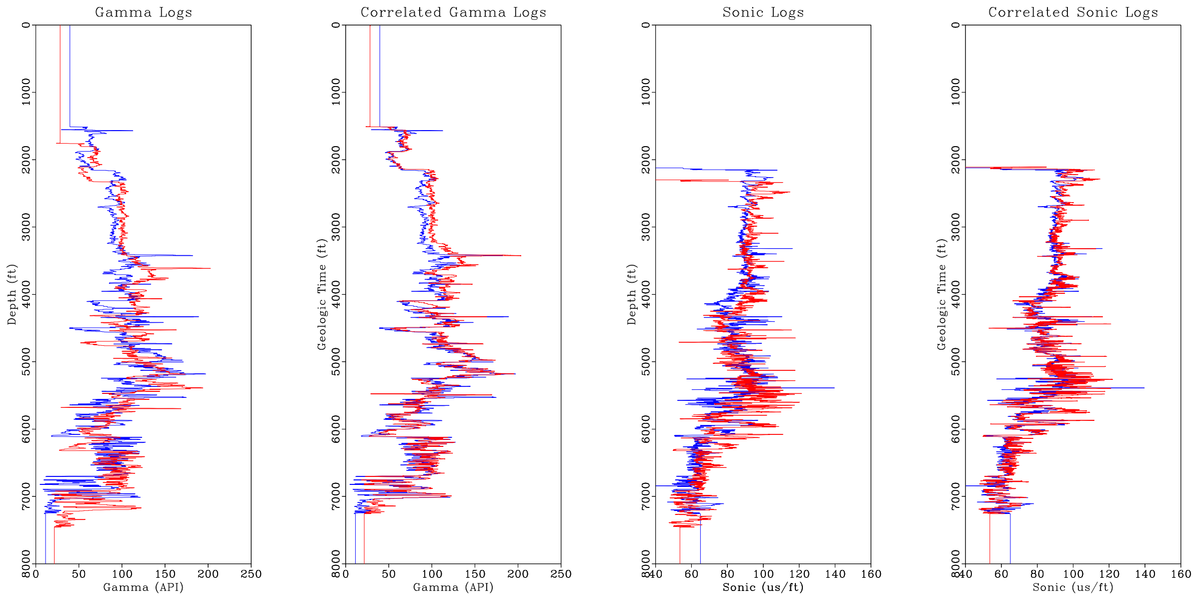
Returning to our original linear relationship, Equation 1, the estimated log, $\tilde{l}$, is a function of all available well logs, empirical predictions and weighted by each well's distance and caliper log. By solving the least-squares solution to Equation 1 at each depth, the prediction of a new well log at the location of interest is a weighted average.

$$\tilde{l(z)} = \frac{\sum_{k=1}^{N} W_k^2(z) l_k(z + z_k(z))}{\sum_{k=1}^{N} W_k^2(z)} \tag{6}$$

Estimating a complete sonic log

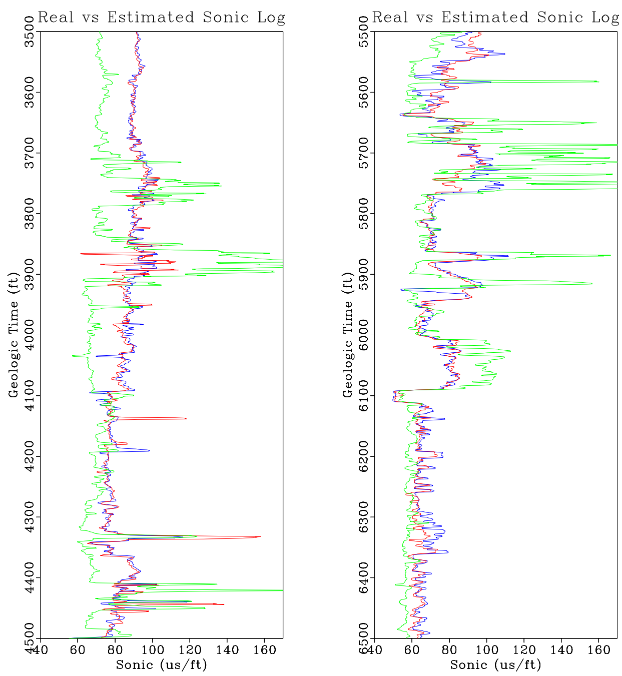
For our example, we select five of the most complete wells that have gamma ray, density, sonic and caliper measurements available from the Teapot Dome 3-D data volume made available by the U.S. Department of Energy and RMOTC to test the proposed approach. In the case of estimating a sonic log, the Smith (Smith, 2007) and Reverse Gardner (Gardner et al., 1974) equations are widely used empirical relationships. We compare the prediction from the Reverse Gardner equation against the results of estimating a sonic log using the proposed method.

Using the available gamma logs as the reference well logs, the well logs are aligned using LSIM as shown in Figures 1(b), and these shifts are used to align the remaining logs at each well. With both the aligned sonic logs and the emperical estimations from Smith and Reverse Gardner equations, we solve the least-squares problem, Equation 1, for the missing sonic log.



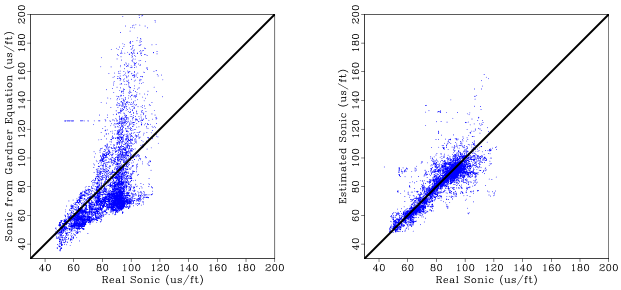
(a) (b) (c) (d)

Figure 1: Original gamma ray logs from well 1 (blue) and 2 (red) in depth (a). Aligned gamma ray logs from well 1 (blue) and 2 (red) in constant geologic time using LSIM (b). Original sonic logs from well 1 (blue) and 2 (red) in depth (c). Shifts estimated by aligning gamma ray logs in (a) and (b) are applied to align sonic logs (d). The character of the logs are aligned even though specific values are not identical.



(a) (b)

Figure 2: Real sonic log (blue) versus estimated sonic log (red) and Reverse Gardner's Equation (green) at two different 1000ft intervals along the log.



(a) (b)

Figure 3: Real sonic log cross-plotted against the sonic log estimated from the Reverse Gardner estimation (a). Real sonic log cross-plotted against estimated sonic log (b).

The estimated sonic log matches well with the actual sonic log along the intervals shown in Figure 2 as compared to the conventional method of using Reverse Gardner's Equation. Another way of comparing these results is to cross-plot the original versus estimated sonic log data. In Figure 3, it is easy to visualize the improvement the proposed approach has over a conventional method for estimating a missing sonic log. Numerically, between 2200ft and 7200ft, the Reverse Gardner's Estimation compared to the original sonic log results in a correlation coeffecient of 60%; the proposed approach achieves a correlation coeffecient of 83% when compared against the original sonic log. Judging from these results, we conclude that the proposed method generates a reasonable approximation to the actual sonic log.

Conclusions

We present an approach for estimating missing logs by multiple well log correlation. These results are verified by comparing against the actual sonic log. Our experiments demonstrate that the proposed approach can provide significant improvement over a conventional method for estimating missing log section. In this paper, we focus on estimating missing sonic logs; however, this approach can be also extended to estimating entire sonic and density logs at all well locations, which would allow the interpreter to tie any log to available seismic data.

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