The art of well tying with new MATLAB tools

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ABSTRACT

To tie seismic data to well logs, four steps are required. The first step involves editing the sonic and density well logs, including de-spiking the logs, truncating any anomalous values and smoothing the logs to prevent stratigraphic attenuation. Since the velocities that seismic data experience are different then the velocities sonic tools measure a calibration step is needed. The most common way to do this is to use checkshot data, however when this data is not available the calibration can be computed from an attenuation (Q) estimate or by matching seismic events to event son the synthetic. The third step includes the calculation of the time-depth relationship using the calibrated sonic and the calculation of reflection coefficients from the sonic and density. In the last step the wavelet is estimated from the seismic data and phase rotations are applied to get good correlation between the seismic and the synthetic. A series of MATLAB tools have been developed to make the well-tying process easier and good synthetics obtainable in a short amount of time and are available in the CREWES Toolbox.

INTRODUCTION

When computing a well tie there are four main steps in the process modified from White and Simm (2003):

- Edit the sonic and density logs.
- Calibrate the sonic log to check shot or VSP (Vertical Seismic Profile) times.
- Create the synthetic reflection coefficients using the calibrated logs in two way time
- Determine the best match location and estimate wavelet at the location

Sonic and density logs can both contain anomalies that need to be removed such as high amplitudes due to cycle skipping and poor tool-borehole contact. These spurious events may need to be clipped or the logs smoothed. Smoothing the logs may also be done to account for the stratigraphically induced velocity dispersion caused by the difference between seismic and sonic frequencies (White and Simm, 2003).

The second step is the most important as this effects the timing of the synthetic. A mismatch in time is significantly more detrimental than a mismatch in amplitudes (White, 1997). Ideally this involves calibrating the integrated sonic times with measured check shot or VSP times, but other methods as described the next section can also be used. To create a time-depth relationship the integrated sonic times and the check shot or VSP times are compared at equal depths. These depth points are also known as knee points and should correspond to a reflector to reduce artificial coefficients being introduced in the corrected sonic log. The difference between the integrated sonic log and the check shot or VSP times is known as the drift curve. Ideally this curve should be smooth and have small time changes with depth.

This calibration step is necessary as the velocity that seismic waves experience is not the same as the velocity that sonic logging tools estimate. This is because of the basic theory of wave propagation in an attenuating medium which predicts that velocity must depend upon frequency. Seismic velocity and logging velocity are related by

$$V(f) \approx V_o\left(1 + \frac{1}{\pi Q} ln\left|\frac{f}{f_o}\right|\right), \qquad 1$$

where V is velocity, Q is attenuation, f is the frequency of the current wavefield, f_o is the dominant frequency of the reference wavefield and V_o is the velocity measured by the reference wavefield (eg. Margrave,2010). What this equation shows is the seismic data (frequencies of 0 Hz to 70 Hz) will measure a slower velocity than the sonic tool (frequencies ~10^4 Hz).

Well log measurements are measured in depth and need to be converted to time to match the well synthetic with the seismic data. This is done by integrating the calibrated sonic values to create the time-depth relationship. The reflection coefficients are also calculated using the calibrated sonic and combined with the density to calculate the impedance (impedance=density x10^6/sonic). The following expression shows the relationship between reflectivity (r) and impedance (I) for each sample (k)

$$r(t) = \begin{cases} r_k = \frac{I_k - I_{k-1}}{I_k + I_{k-1}}, t = t_k, k \in [1,2, \ldots \infty] \\ 0, \text{ otherwise} \end{cases}. \qquad 2$$

Once the synthetic seismogram has been created from the calibrated sonic, the final wavelet can be estimated. Since the phase of reflectivity is very complicated it is best that the final wavelet is estimated after all corrections so that the phase can be estimated properly. When estimating a wavelet it is important that no assumptions are applied to the wavelet such as is appearance or timing (White and Simm, 2003), including the phase. For wavelet estimation there are several ways of estimating the amplitude spectra such as modeling it with a spline, a polynomial or computing a more statistical amplitude spectrum such as the method defined in White (1980).

The wavelet phase can also be estimated, but it is more difficult to get a good model as it is very sensitive to effects such as noise. Therefore it is common practice to assume a phase model. For this discussion we will assume that the data has been deconvolved. This implies that only residual wavelet phase remains and the common industrial model for that is that it is constant (independent of frequency). If the wavelet model is assumed to be minimum phase the phase spectra must be formed from a minimum phase operator. If phase is assumed to be constant than a zero phase wavelet can be rotated to accommodate the phase.

Quite often during a well tying process a good fit of the synthetic to the seismic data cannot be made. Most users are tempted to stretch or squeeze the synthetic to match the seismic data, this might not be the best course of action when time variant phase rotations may be the culprit of the mismatch. Time variant phase rotations can occur after deconvolution as the wavelet used in the deconvolution is optimized for a specific interval thus leaving a residual wavelet in the rest of the signal. If this is the case and the phase is assumed to be time variant, then constant phase rotations can be calculated in Gaussian windows and then applied to the synthetic or the seismic data.

MATLAB TOOLS AVAILABLE

Editing Logs

There are several tools available in the CREWES toolbox that can be used to edit logs. If there are undefined values in the logs then the function removenull can be used, where the null values are either replaced by nan (the MATLAB null value) or interpolated using linear or cubic interpolation methods. For clipping log values the function cliplogs can be used; the clipped values can either be replaced with a constant, by a nan, or interpolation methods as described in removenull. If the log needs to be smoothed, bcarsmooth is a function that will convolve the log with a boxcar of specified length. Filtf can also be used to smooth the logs by filtering out the high frequency content of the logs.

To use the MATLAB tools the sonic log needs to start at the surface. To do this an overburden is added to both the sonic and density logs. The logoverburden function can be used to add an overburden with a constant value specified by the user as well as a linear trend starting with an initial value and increasing to the average of the first 10 samples of the log. The other choices include the average log value or two marine setting options where two

Calibrating Logs

Traditionally the sonic log is calibrated to checkshot or VSP data. This can be accomplished using the cscali function. It requires the checkshot or VSP data to be in depth time pairs. The time depth relationship is calculated and a residual slowness is calculated between the checkshot data and the sonic log. The residual slowness is then added to the sonic log resulting in the calibrated sonic log output.

In Academia it is not common to have checkshot or VSP data for a well. In this case there are two alternate methods that can calibrate the sonic log to the seismic data. The first function drift_corr calibrates the sonic log by estimating the difference in velocity between the seismic frequencies using an attenuation (Q) model. The second method allows the user to match seismic and well synthetic events and line them up by adding a residual slowness to the sonic log. Stretchwell is a function that does this but can produce errors if there are any embedded phase rotations between the seismic data and the estimated wavelet. Envelopematch is a better method as it attempts to match events that occur in the envelope of the seismic and synthetic seismogram. The Hilbert envelope is calculated by

$$HE = \sqrt[2]{tr^2 + tr_q^2}, \qquad 3$$

where tr is either the seismic trace or the synthetic and tr_q is the quadrature or the 90 degree phase rotated trace. It is better to match envelope peaks and zero-crossings as Hilbert envelopes are insensitive to any constant phase rotation.

Calculating Reflection Coefficients

Seismo is a function that will calculate the reflection coefficients in time. This function uses the calibrated sonic log to calculate the time depth relationship and the density log and the calibrated sonic log to calculate the reflection coefficients. The time depth relationship can be obtained independently using the sonic2tz function.

Wavelet Estimation

There are several functions in the CREWES MATLAB toolbox that can create a predefined wavelet such as Ormsby, minimum phase, Ricker and Klauder wavelets. The functions that will create these wavelets can be found in Table 1. Constphase and phsrot are two functions that can be used to rotate the phase of these wavelets to match the seismic data. For a wavelet that can estimate the spectrum of the seismic waveletestimator should be used. This function allows the user to select the time window the wavelet will be estimated in as well as the function that will be fit to the frequency spectrum graphically. This function can also create a minimum phase wavelet or zero phase wavelet and can predict a constant phase rotation that can be applied.

If time variant phase rotations are need the functions tvconstphase and tvphsrot can be applied to the synthetic or if the seismic is to be used for inversion the seismic can be phase rotated. If the seismic is being phase rotated and multiple well ties have been performed, tvlsphsrot can be used where it will create the least squares solution to calculate the optimal phase rotations for the seismic section.

Plotting

There are several functions in the CREWES MATLAB toolbox that can be used for plotting. Wtva will plot single traces as a wiggle trace with variable area. If a seismic section needs to be plotted as wiggle trace with variable area choose plotseis. If a variable density display of the seismic data is desired use plotimage which has several display options available.

Table 1 : Functions used for computing well ties

Function Name	Description
cliplogs	Clips logs that have values outside the range that a user specifies
removenull	Removes null values and interpolates between them
bcarsmooth	Smoothes the log with a boxcar operator
filtf	Filters high frequencies of the log thus smoothing it
logoverburden	Adds an overburden to the logs
cscali	Applies corrections to a sonic log from time-depth pairs from checkshots or VSP data
drift_corr	Applies corrections to a sonic log and synthetic from a Q model
Stretchwell	Allows the user to match events on the synthetic and seismic calibrating the sonic log in the process
envelopematch	Allows the user to match envelope peaks and zero-crossings on synthetic seismogram and seismic data calibrating the sonic log in the process
seismo	Calculates a synthetic seismogram in time from sonic and density logs
sonic2tz	Calculates the time-depth relationship for sonic logs
waveletestimator	Estimates a wavelet from seismic data by fitting a polygon to the amplitude spectra.
wavemin	Creates a minimum phase wavelet that simulates a noise free impulse source
ricker	Creates a Ricker wavelet
ormsby	Creates an Ormsby wavelet
wavevib	Generates a Vibroseis waveform (Klauder wavelet)
convz	Convolves the reflectivity series with a zero phase wavelet
convm	Convolves the reflectivity series with a minimum phase wavelet

Function Name	Description
constphase	Calculates the constant phase rotation needed
phsrot	Applies a constant phase rotation calculated with constphase
tvconstphase	Calculates time variant phase rotations in Gaussian windows
tvphsrot	Applies time variant constant phase rotations calculated with tvconstphase
tvlsphsrot	Applies time variant constant phase rotations calculated from the least squares solution when using multiple seismograms.
balans	Balances power of the signal to the power of the reference signal
tvbalans	Balances the power of the signal to a reference signal in time variant Gaussian windows
wtva	A wiggle trace and variable area display of a seismic trace
plotseis	A wiggle trace and variable area display of a seismic section
plotimage	A variable density display of a seismic section

EXAMPLE FROM HUSSAR

This example uses the Hussar Kirchhoff migrated stacked seismic section and well 14-27. Well 14-27 has both a density and a sonic log that will be used. The first thing that needs to be done to the well logs is to plot them and determine any areas that will need to be clipped due to bad hole conditions or unphysical readings. Next the null value set in the LAS file (-999.25) needs to be replaced by either the MATLAB null value or an interpolation method. To determine the size of the holes in the logs the MATLAB null value was chosen. Since the holes are very small, an interpolation method is acceptable. If the holes are large splicing a portion of another sonic log from a different well or using Gardner estimation may be a better choice than the interpolation. Next the sonic log needs to be clipped as it has negative sonic values, any value less than 150 μs/m were replaced by pchip interpolation. Some values in the upper section of the density log are also unrealistic as we would expect values of at least 1500 kg/m^3 for this area. Values less than 1600 kg/m^3 were also replaced with pchip interpolation between 200 meters and 800 meters as around 1400 meters there is coal where lower densities would be expected.

Next an overburden was applied. For both the sonic and density a linear overburden was chosen as this is land data. The starting value for the sonic log was 600 μs/m and then linearly increased until it matched the values at the top of the log. The starting value for the density log was 1500 kg/m^3 and increased linearly until the top of the log. A boxcar of length 10 was applied to both signals. The editing process of the density log can be seen in FIG 1 where the editing for the sonic process can be seen in FIG 2.

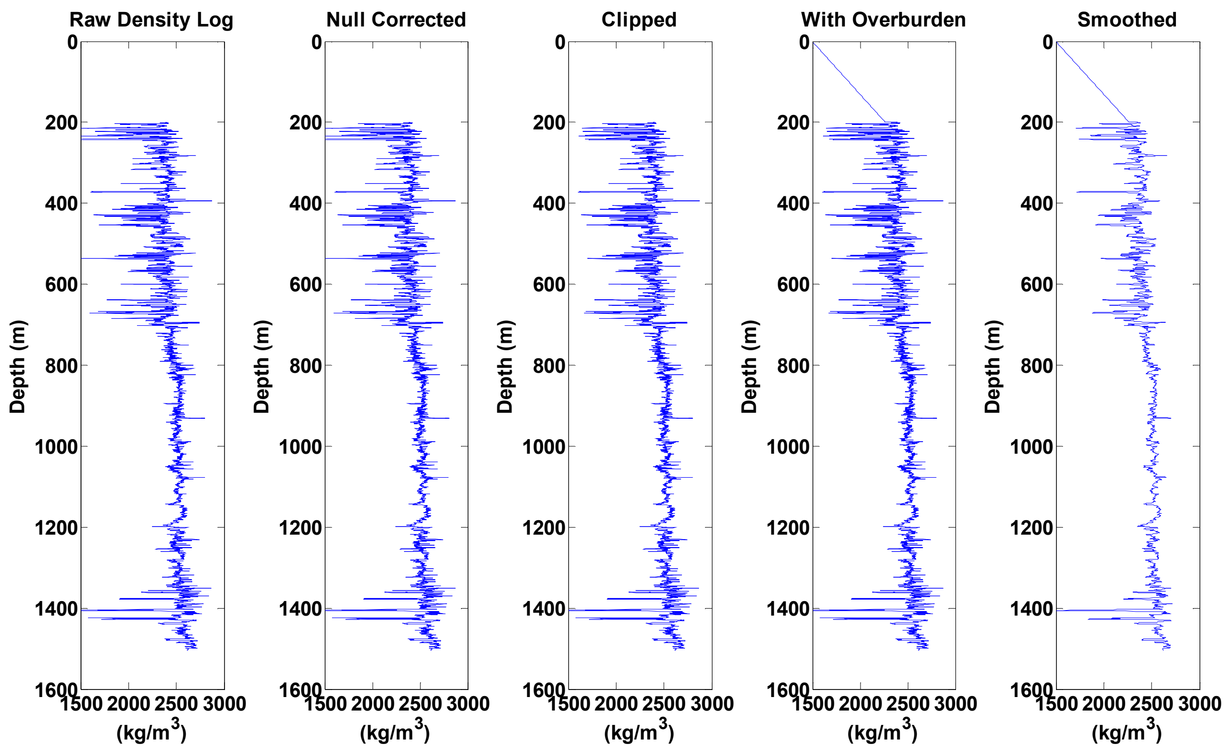

FIG 1: The editing process for the density log for well 14-27.

Now that both the density log and the sonic log have been edited and an overburden applied the sonic log can now be calibrated. The synthetic will be matched to the nearest trace at a common depth point number 681. Since no checkshots are available for this well other methods need to be used. For this example both the envelopematch method and the attenuation method (drift_corr) are be compared. The envelopematch method requires a wavelet to be able to calibrate the sonic log. A first pass of the wavelet using the waveletestimator is approximated (FIG 3), but it is recommended to recalculate the wavelet after the sonic log is calibrated. At this first look at the synthetic compared with the seismic, it is evident that the seismic data needs to have some gain applied. One method that can work well is to do a time variant balancing between the power of the synthetic and the power of the seismic in Gaussian windows. This was done using 100ms windows with a 10 ms increment. It is important that the window is large enough so that reflections are not created.

Once the seismic is balanced it can be used in the calibration of the sonic log using envelopematch. This utility allows the user to match envelope events. The user specifies a time pick where the two envelopes match then selects an event that needs to be lined up on both. Once the three picks are made the sonic is adjusted and the procedure repeats until all events line up satisfactorily, FIG 4. Besides the overburden adjustment it is recommended that the synthetic is always stretched down to match the seismic.

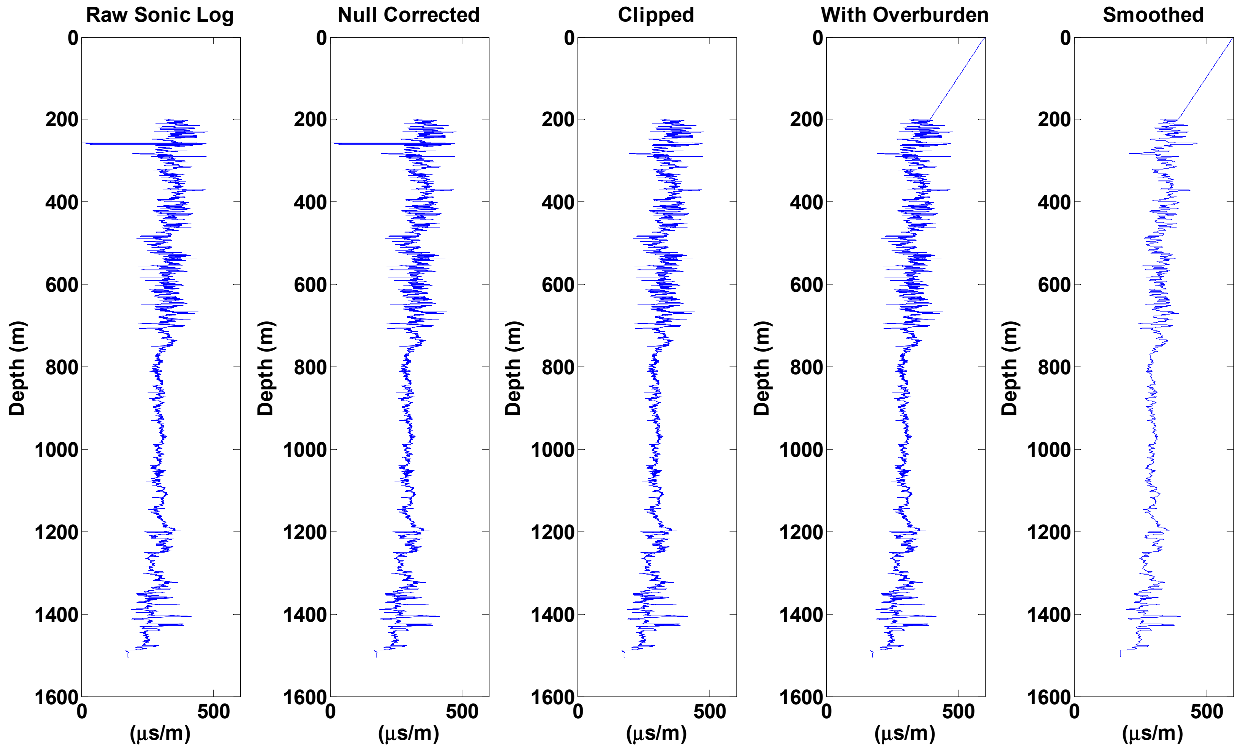

FIG 2: The editing process for the sonic log for well 14-27

Drift_corr attempts to solve the disparity between the velocities observed by seismic waves and the velocities measured with sonic tools. This disparity is caused by Q and can be related using equation 1. To determine which Q would be optimal in the Hussar field several Q's were tested between 10 and 100. The synthetic seismograms calculated from the calibrated sonic were then cross-correlated with the balanced trace. To eliminate any phase rotations that could be present in the data the cross-correlation of the envelopes of the synthetic and seismic were also calculated. FIG 5 shows this correlation where the optimal Q for the envelope cross-correlation was 37, which will be used as the calibration attenuation value. To verify that the results from the envelopematch and drift_corr calibration methods were comparable the time depth curves were computed for both and the result was very close, FIG 6. The synthetic result for the non-calibrated sonic, the envelopematch calibration and the drift_corr calibration can be seen in FIG 7.

From the synthetics that were created it can be seen that there may be time variant phase rotations in the data. Near the top of the well-tie the match is fairly good but as the time increases the phase changes. At this point the wavelet needs to be estimated again and then time variant phase rotations need to be applied to get the optimal well tie. FIG 8 shows the synthetics with the new wavelet applied and the result after the time variant phase rotations were applied using 100 ms windows with 10 ms increments.

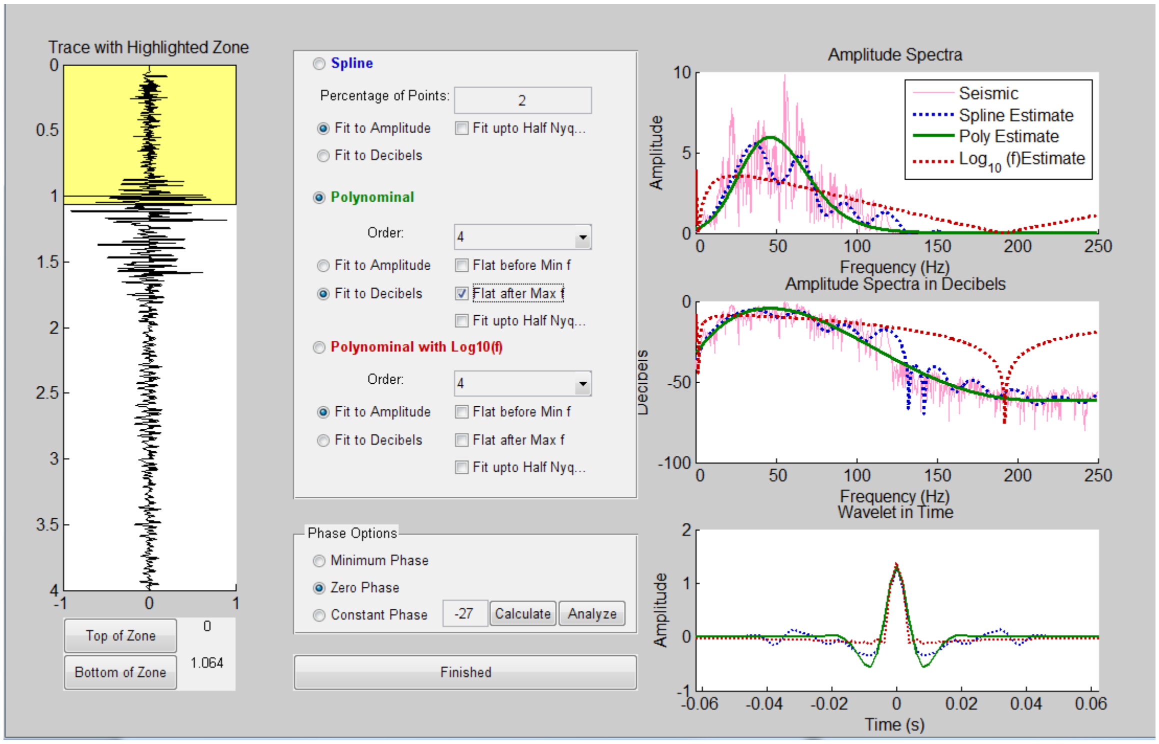

FIG 3: First pass at wavelet before sonic calibration using the waveletestimator.

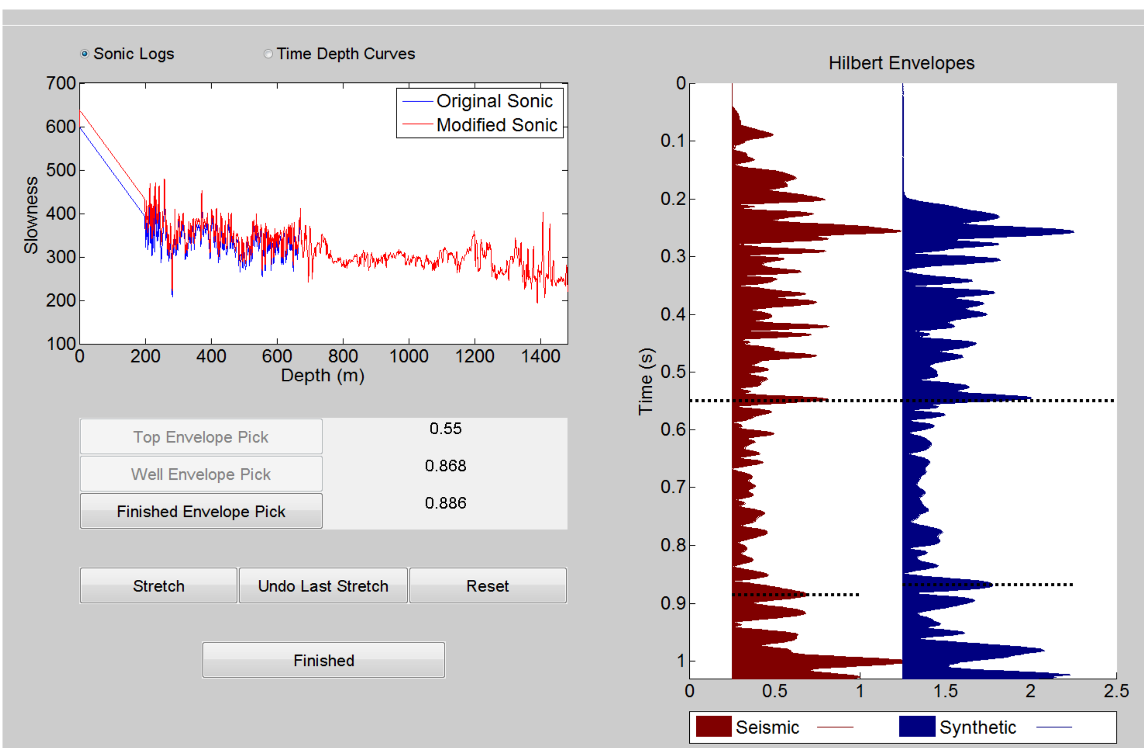

FIG 4: Envelopematch interface calibrating the sonic log by matching key envelope events.

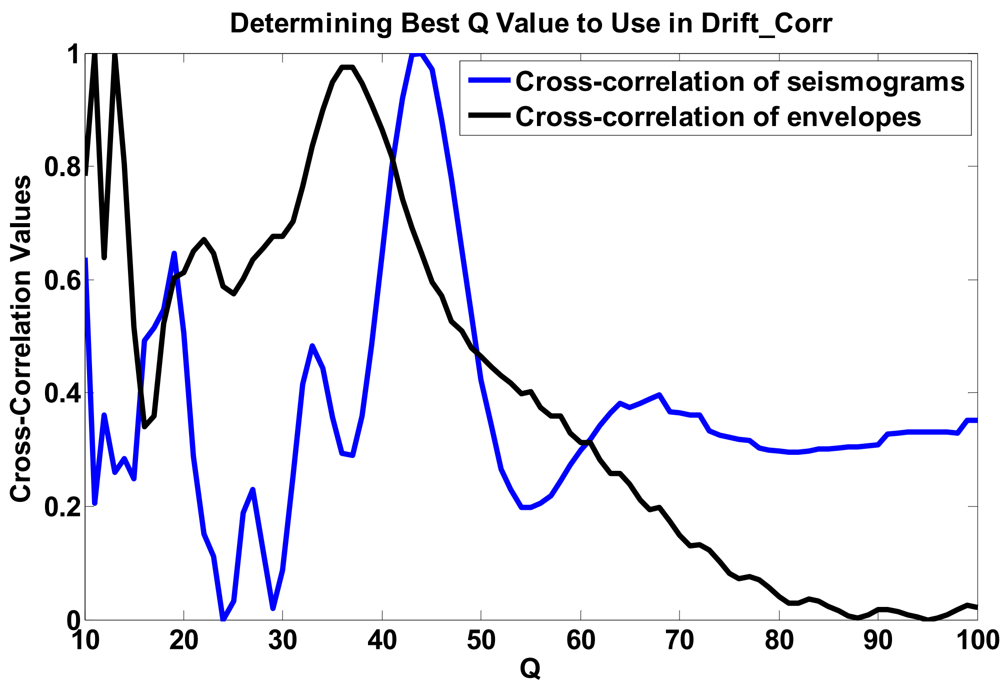

FIG 5: Cross-correlation of synthetic created using drift_corr and the balanced trace. The blue curve is the result from the cross-correlation of the seismogram and seismic and the black curve is the cross-correlation of their envelopes.

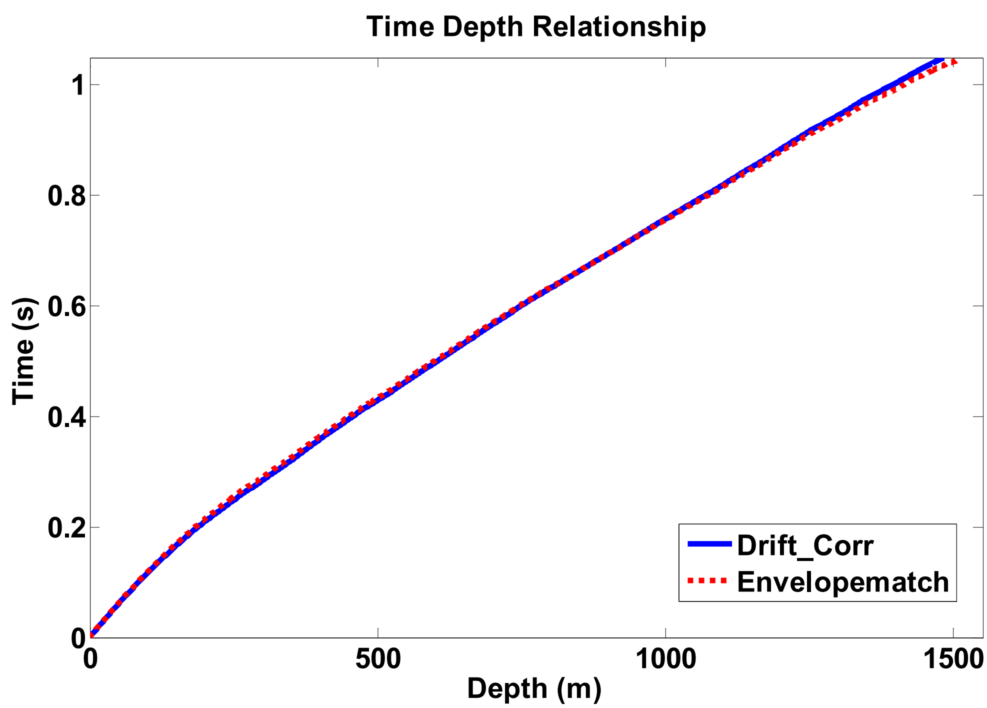

FIG 6: Time-depth relationship for the envelopematch calibrated sonic (red) and the drift_corr calibrated sonic (blue).

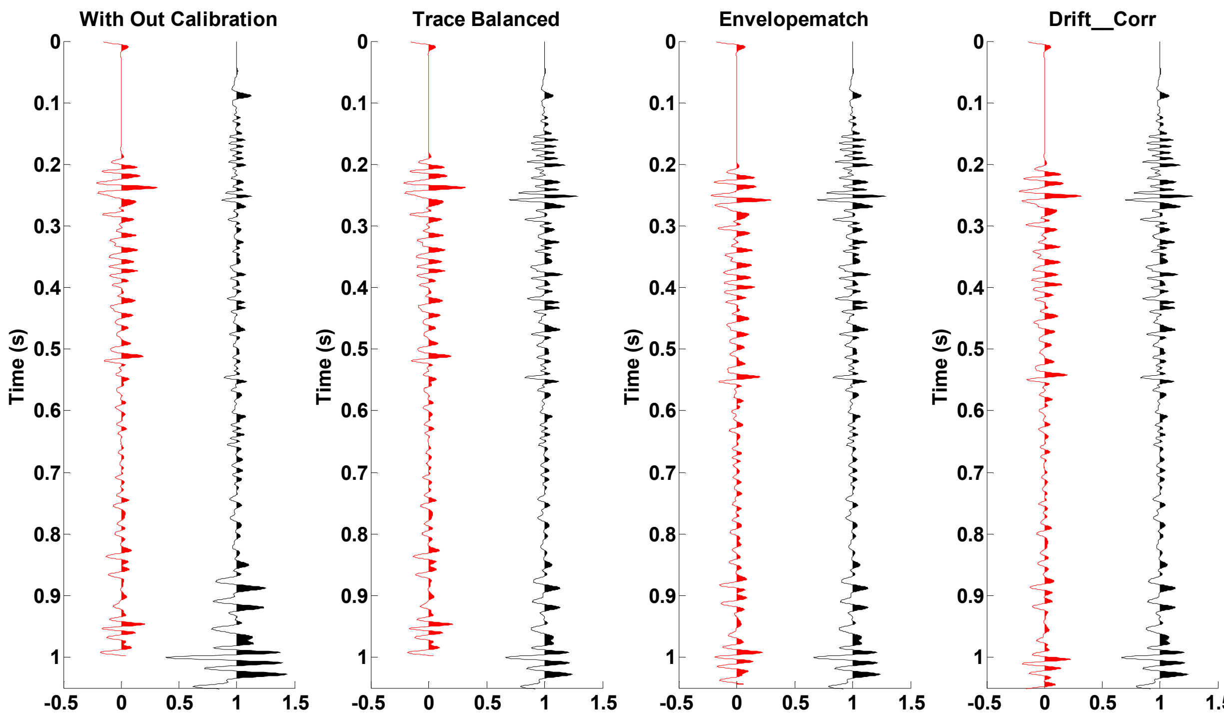

FIG 7: The synthetic (red) and the trace before sonic calibration, after trace balancing and after the envelopematch sonic calibration and the drift_corr sonic calibration.

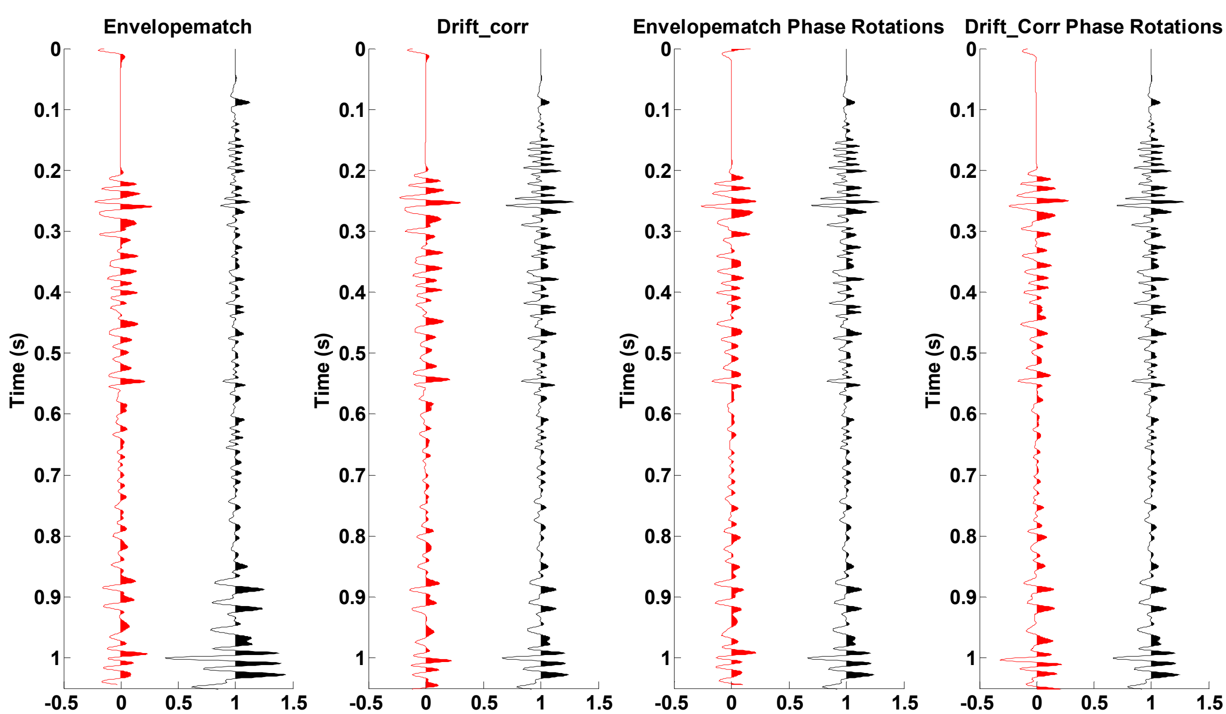

FIG 8: Synthetics after envelopematch and drift_corr sonic calibration using new wavelet and time variant phase rotations applied.

CONCLUSIONS

This paper highlights some of the tools available for well tying in the CREWES MATLAB Toolbox. The goal was to provide tools that were easier to use and required less knowledge about programing in MATLAB. This project did produce a selection of tools that can be used to create very good well ties even when no checkshot or VSP data is available. Both the envelopematch and drift_corr methods create reliable sonic calibrations and are relatively simple to use.

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