Automatic time picking and velocity determination on full waveform sonic well logs

Lejia Han, Joe Wong, John C. Bancroft, and Robert R. Stewart

ABSTRACT

Full waveform sonic logging is used to determine formation interval velocities within a well bore. In order to obtain P-wave velocities, we must perform time-picking on the first arrivals on the recorded sonic seismograms. A typical full waveform log from a well consists of thousands to tens of thousands of seismograms, and manual time-picking is not practical. We have developed and evaluated new methods of automatic picking of first arrivals by computer. We used MATLAB for coding the software for these methods. Techniques employed within the automatic time-picking algorithms include energy ratio calculation, noise reduction, deconvolution, wavelet approximation, and median filtering. The time picks resulting from these methods are much more accurate than those obtained from a commercial software package. Our automatic time picks compare very favorably with manual time picks, even over noisy data segments. We show P-wave velocity results from a full waveform log using a monopole source, and S-wave velocity results from a log using a dipole source.

INTRODUCTION

First-arrival picking on seismic survey data has been well-studied (Willis and Toksoz., 1983; Coppens, 1985; Boschetti et al., 1996). This fundamental task is ubiquitous in seismic processing, and in particular is necessary for determining the velocity values of the near-surface low-velocity zone needed to make static corrections. Similarly, first arrival times from full waveforms sonic well logs are used for interval velocity determination of formations encountered by the logging tool as it moves up or down the well. Picking first arrivals on full waveforms sonic well logs is a crucial part of well-log processing.

INSTRUMENTATION AND FIELD ACQUISITION

CREWES has the capability to acquire sonic seismograms using the logging system and the full waveform sonic logging tool shown on Figure 1. The tool consists of a single transmitter configured either as a monopole source (for P-wave acquisition) or a dipole source (for S-wave acquisition), and three receivers Rx1, Rx2 and Rx3 located .914 m, 1.22 m and 1.52 m above the transmitter.

The full waveform sonic tool with a monopole source was used to gather P-wave data in the U of C test well located near the Rothney Astrophysical Observatory. The starting acquisition depth is 3.9 m, the ending depth is 125 m, and seismograms were recorded at depth intervals of 0.1 m, for a total of 1212 recording depths. As the tool has three receivers, we actually acquire three seismograms at each recording depth, so that the complete dataset consists of 3636 seismograms. Each seismogram consists of 525 digital samples with a sampling rate of 4 microseconds. The digital dataset was recorded in a computer file for post-acquisition analysis.

MOTIVATION FOR THIS RESEARCH

The first 1000 microseconds for the Rx1, Rx2, and Rx3 seismograms have been plotted on Figure 2 using the commercial software package WELLCAD. This package has an option for picking first arrival times. On Figure 2, the time picks generated by the program are joined by the black lines; where no black lines appear indicates that the program was not successful in picking the arrival time due to insufficient energy in the first arrival. The erratic appearance of the black lines suggests that the automatic picking routine within WELLCAD does not perform reliably or satisfactorily.

Using CREWES software, the data has been plotted (with AGC and low-cut filtering) on Figure 3 in variable density colour-coded format. Visually, the first arrival breaks on Figure 3 are quite clear. We have obtained the first-arrival times through manual picking using the gathers of Figure 2 but on expanded displays. Manual picking is very time-consuming, and is not practical on a regular basis. However, in this case we performed manual picking in order to provide a standard against which the results of computerized automatic picking may be compared.

Devising automatic picking routines is challenging. They might produce unacceptable time picks, which is unusual with manual picking. However, with an appropriate method, automatic picking would be much faster, and could be more reliable than manual picking, particularly on noisy data.

In the following sections we will investigate several algorithms for use in automatic time-picking of first arrivals. The ideas include energy ratio calculation, noise reduction through semblance stacking, cross-correlation, deconvolution/wavelet approximation, and median filtering. We have implemented these ideas using MATLAB code.

ENERGY RATIO METHOD

The energy ratio technique has been explored extensively, and we have found that a modified form may be an improvement over the generic calculation.

With various ways of implementation, the stacking strategy greatly contributes to the noise reduction, which is essential to picking accuracy as well.

The basic energy ratio (also referred to by the term eRatio in this report) at each testing point is defined as the energy within the following window divided by the energy within the preceding window (see Figure 4).

$$\boldsymbol{er}(\boldsymbol{i}) = \sum_{j=i+1}^{i+winLen} \boldsymbol{grm}(\boldsymbol{j})^2 / \sum_{k=i-winLen}^{i-1} \boldsymbol{grm}(\boldsymbol{k}) \tag{1}$$

Where $grm(j)$ and $grm(k)$ represent the seismogram values at index j and index k respectively.

If the first-arrival energy is high compared to the noise preceding the first break, this ratio will be a maximum very near the first-break time. However, when noise strongly interferes with the first arrival, the eRatio method does not perform well.

Instead of the standard eRatio formula, we have tried and tested a modified version. The following modified formula provides a significant improvement in picking time accuracy, as shown in Figure 6.

$$\boldsymbol{mer}(\boldsymbol{i}) = \boldsymbol{er}(\boldsymbol{i})^{\boldsymbol{3}} * \boldsymbol{abs}\big(\boldsymbol{grm}(\boldsymbol{i})\big) \tag{2}$$

where $\boldsymbol{abs}\big(\boldsymbol{grm}(\boldsymbol{i})\big)$ is the absolute value of $\boldsymbol{grm}(\boldsymbol{i})$ **.**

The window length in above formula for accumulating energy has a significant effect on time picking. Through testing, we found that 32 time samples for each energy collection window give the best performance for the full waveform sonic data.

On full waveform sonic logs, tube waves (slow, high-amplitude events) exist and can dominate the seismic traces. Energy ratio calculations without accounting for the tube waves can fail to have maximum values at the first arrival. Prior to do the eRatio calculations, the seismic data should be windowed to eliminate tubes waves. A window which zeros out the seismic trace at the water wave arrival time is effective for doing this. The deleterious effects of strong late arrivals on time-picking of first arrivals using the eRatio method are shown on Figure 7. Automatic picking without windowing out tube waves often generate many abnormal time picks for the first arrivals.

On Figure 8, we show an example of first arrival time-picking on full waveform sonic traces over a selected depth interval using the modified eRatio method. When the input seismograms are windowed to eliminate interference from tube waves, the resulting time picks are very close to the first arrivals, except where the seismic traces are noisy.

We have also tried deconvolving the seismograms before applying the modified eRatio technique. However, no real improvement in the quality and accuracy of the time picks resulted from deconvolution when the input traces are noisy.

NOISE REDUCTION TECHNIQUES

As noise is common in our data and it seriously affects the accuracy of our time-picking method, we attempted to remove the noise as much of the noise as possible. We used two schemes: minimum variance summation over channels (channel summation), and trace average over depths (depth average). Both were successful in reducing noise before the first arrivals when used individually, and in combination.

Channel averaging using minimum variance

There are 3 channels of seismograms recorded at each depth, and we expect the first arrivals are delayed in a systematic way as the channel distance from source increases. Thus we can shift the Rx1, Rx2, and Rx3 seismograms systematically to find an average trace. In practice we keep the Rx3 trace unshifted, and shift the Rx2 and Rx1 traces forward by times of Δt and $2\Delta t$. The three traces are then windowed to reduce the tube wave influence, and summed to obtain an average trace. The total variance of the individual shifted traces with respect to the average trace is calculated and plotted as a function increasing time shift. The lowest variance occurs when all three shifted traces are as close in phase as possible. The average trace with gives the minimum variance is our target, and we call it the Rx3' trace and use it to replace the noisy Rx3 trace for time picking. The minimum variance process is similar to the standard semblance calculation (Sheriff, 1991). However, the semblance works best when many traces are used. For a limited set of three input traces, we believe that using minimum variance is a better choice.

The technique is demonstrated on Figure 9. Note that, in the average trace, that the noise in the time interval before the first arrival is much reduced. Figure 10 compares the velocity profile obtained by using the time picks from the noisy Rx3 seismograms, to the improved one obtained by using time picks from the noise-reduced Rx3' seismograms.

Depth averaging

Because the depth sampling interval is so small (0.1 m), we expect that adjacent seismograms in a depth gather for a given receiver would be similar but with noise. We take a reference trace at a given depth and keep it fixed in time. We take two other traces just above and below the reference trace, and find time shifts for the upper and lower traces that put all the first arrivals in phase. Then, adding all three together would increase the signal relative to the noise. This depth-averaged trace could be used to replace the reference trace for time-picking with the modified eRatio method. The required time shifts can be found by cross-correlation of the reference trace with the two auxiliary traces. On Figure 11, we see an example of how the depth-

RESULTS

Figure 12 shows the velocity profiles obtain by picking first arrival times from depth-averaged Rx1, Rx2, and Rx3' seismograms. A five-point median filter has been applied to remove outliers on the profiles. It appears that the velocities increase with the distance of the receiver. This is a systematic trend that we need to investigate. One possible reason for this is that the modified eRatio technique cycle skips, i.e., it tends to pick a high-amplitude peak or trough following the first break. This error has a relatively more serious effect on the calculated velocities the closest receiver, since the absolute first arrival times are smallest for the closest receiver.

Figure 13 compares the velocity profile in the Rothney Test Well calculated using automatic time-picks on depth-averaged, channel-averaged Rx3' seismograms with the velocity profile calculated form manual time-picks. There is good agreement, except for depths with noisy seismograms (see Figure 4). Clean direct P-wave arrivals are totally absent above 30 meters. At these shallow depths, the formations are likely not water-saturated, and the casing might be loose in the hole, conditions which cause poor coupling for the full waveform tool to the surrounding rock.

SUMMMARY AND DISCUSSION

The foundation of our first arrival time-picking method is the modified energy ratio attribute. The method works very well when signal-to-noise ratios are high. The seismograms need to be windowed to eliminate spurious energy ratio peaks caused by high-amplitude events following the first arrivals. Noise reduction by averaging seismograms over channels as well as over short depth intervals were used to enhance signal over noise, a step that is especially beneficial for data from the far receiver Rx3. Median filtering improves the accuracy of velocity determination as well, by eliminating outlier values in the time picks and velocities.

Our method of automatically generating time picks from full waveform sonic logs has performed much better than version of the commercial software package WELLCAD that CREWES has purchased. Using it, we obtained a velocity profile that is very similar to a velocity calculated from manually picked first arrival times. The biggest discrepancy occurs, not surprisingly, at those depths where the seismograms are very noisy. It should be noted that, in manual picking, when no clear first arrival can be seen, the tendency is interpolate between good arrivals. Such a tendency to interpolate can be built into an automatic picking routine.

ACKNOWLEDGEMENTS

We are grateful for support from the sponsors of CREWES Project and from NSERC in doing this research.

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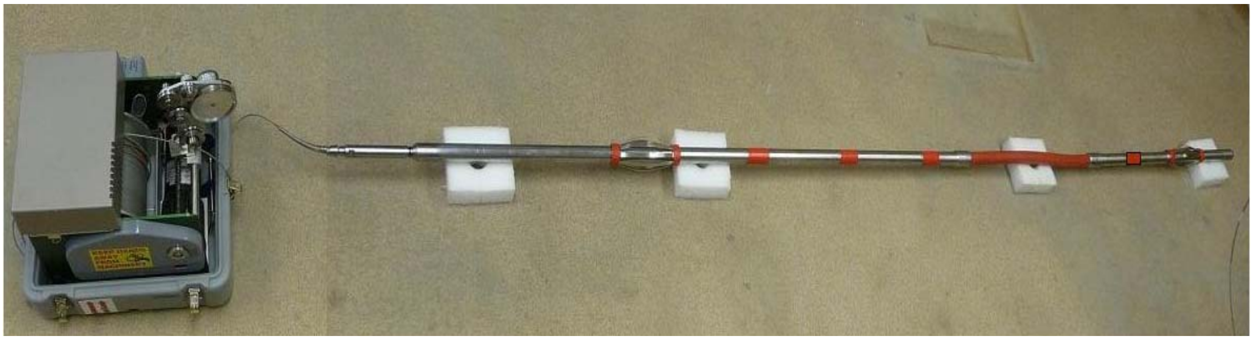

FIG. 1. The full waveform sonic logging tool. The long red section is the acoustic isolator. The transmitter is the small red band just to the right of the acoustic isolator. The three receivers are the three red bands just to the left of the acoustic isolator.

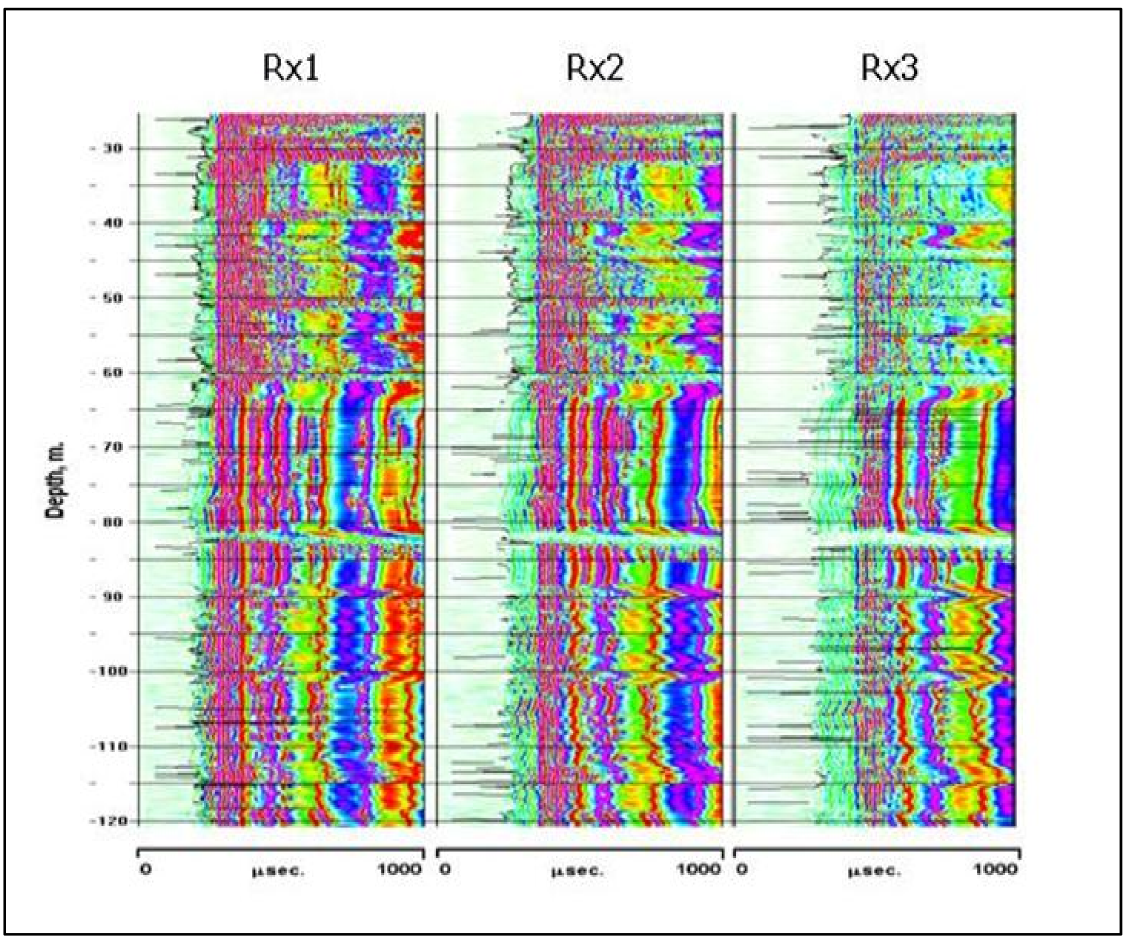

FIG. 2. The field seismograms as plotted by WELLCAD. The black lines join the WELLCAD time first arrival picks for Rx1, Rx2, and Rx3. These time picks are erratic and unreliable.

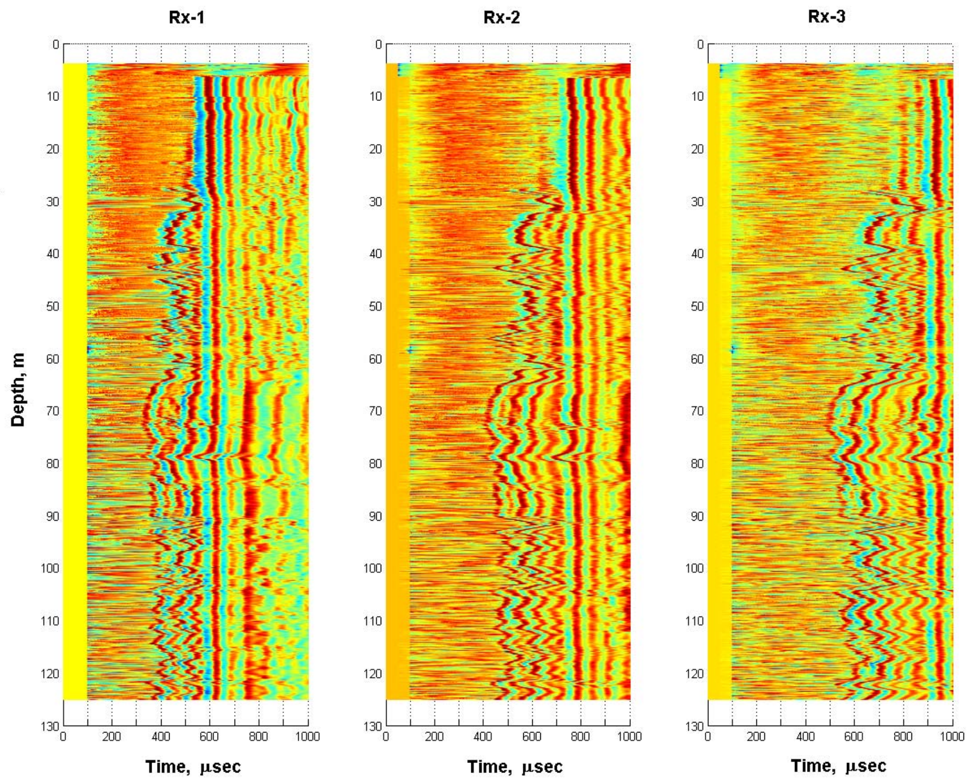

FIG. 3. Full waveform seismograms for receivers Rx1, Rx2, and Rx3, re-plotted with filtering and AGC by CREWES software.

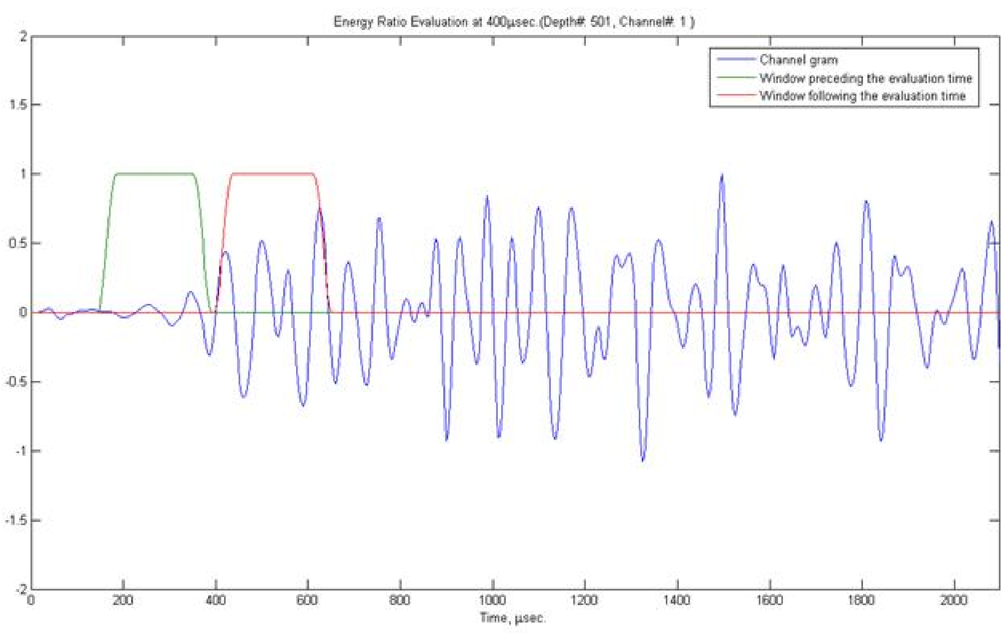

FIG. 4. The energy ratio is defined at each digital time sample as the energy within the following window (in red) divided by the energy within the preceding window (in green). The length of each energy window shown here is 32 time samples.

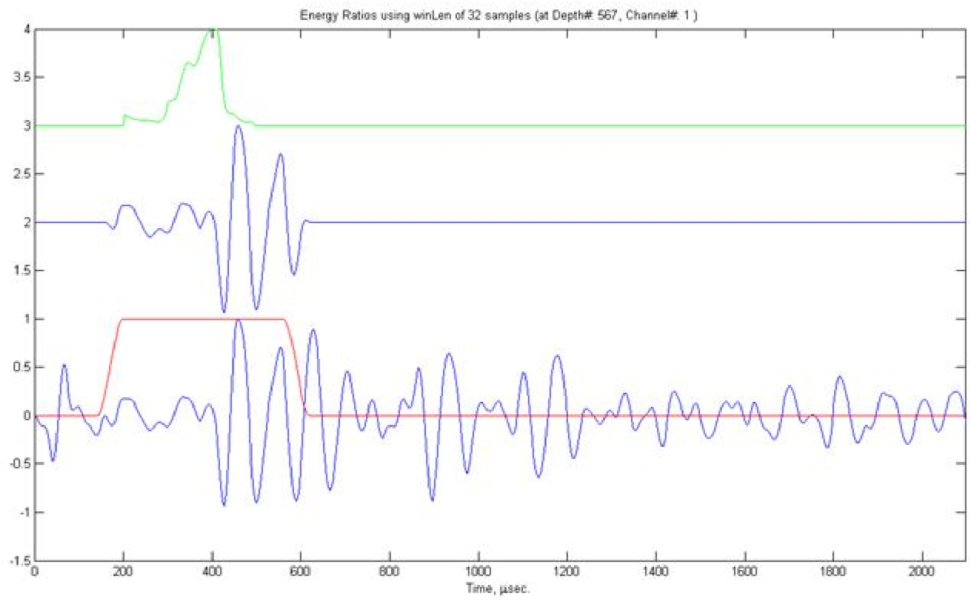

FIG. 5. Energy ratio for a windowed seismogram. Bottom blue trace is the original seismogram; red trace is the window to focus the analysis on the first arrival. Middle blue trace is the windowed seismogram. Top green trace is the energy ratio trace for the windowed seismogram.

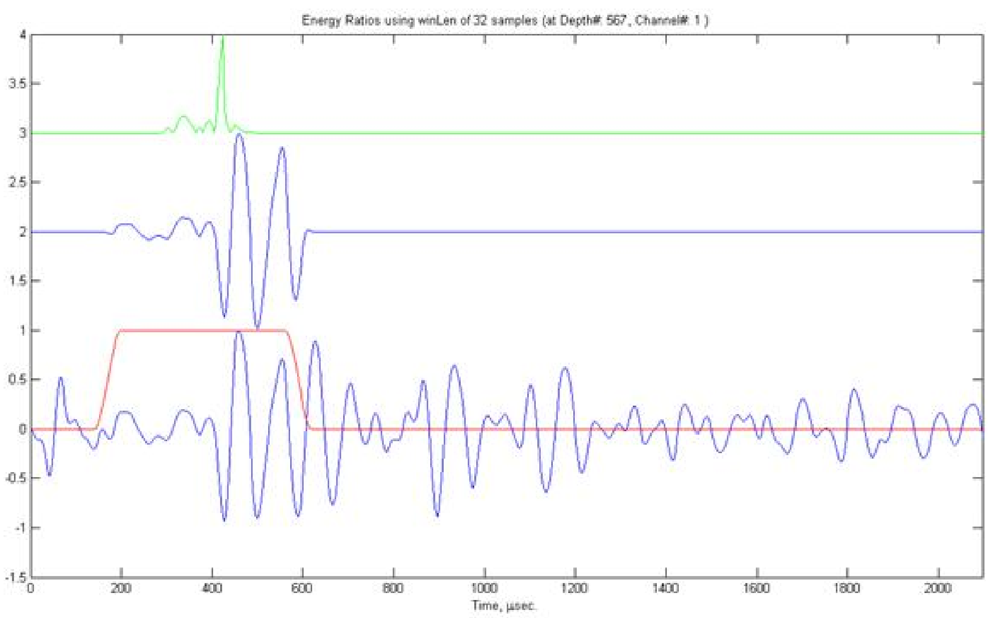

FIG. 6. Modified energy ratio for a windowed seismogram. Every trace here is identical to the traces on Figure 5, except the green trace. Top green trace is the modified energy ratio trace for the windowed seismogram. Compared to the energy ratio trace on Figure 4, the modified energy ratio is much sharper.

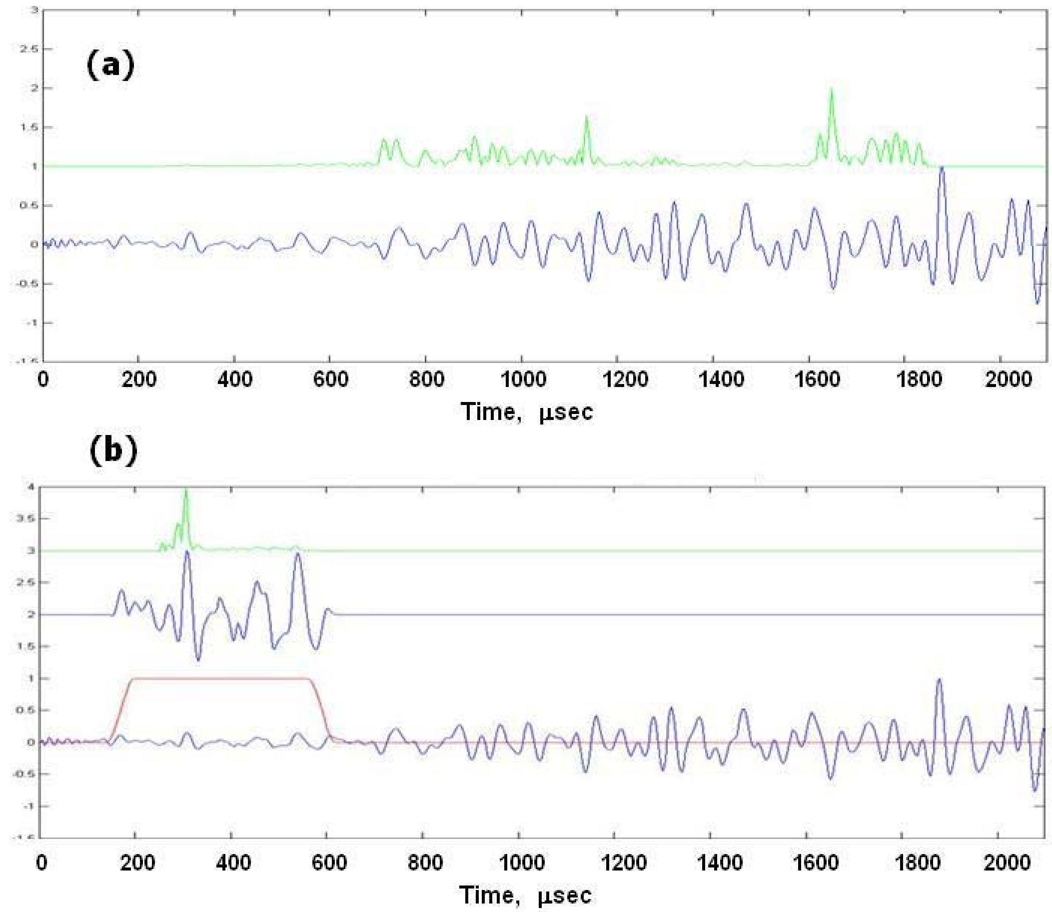

FIG. 7. (a) Modified energy ratio shown in green calculated over entire length of a seismogram shown in blue. The energy ratio maximum occurs at 1640 µsec, far from the first arrival. (b) The window in red is applied to the input seismogram. Middle trace in blue is the amplified windowed seismogram. Top trace in green shows the modified eRatio for the windowed seismogram. The maximum occurs at about 310 µsec, very close to the first arrival time.

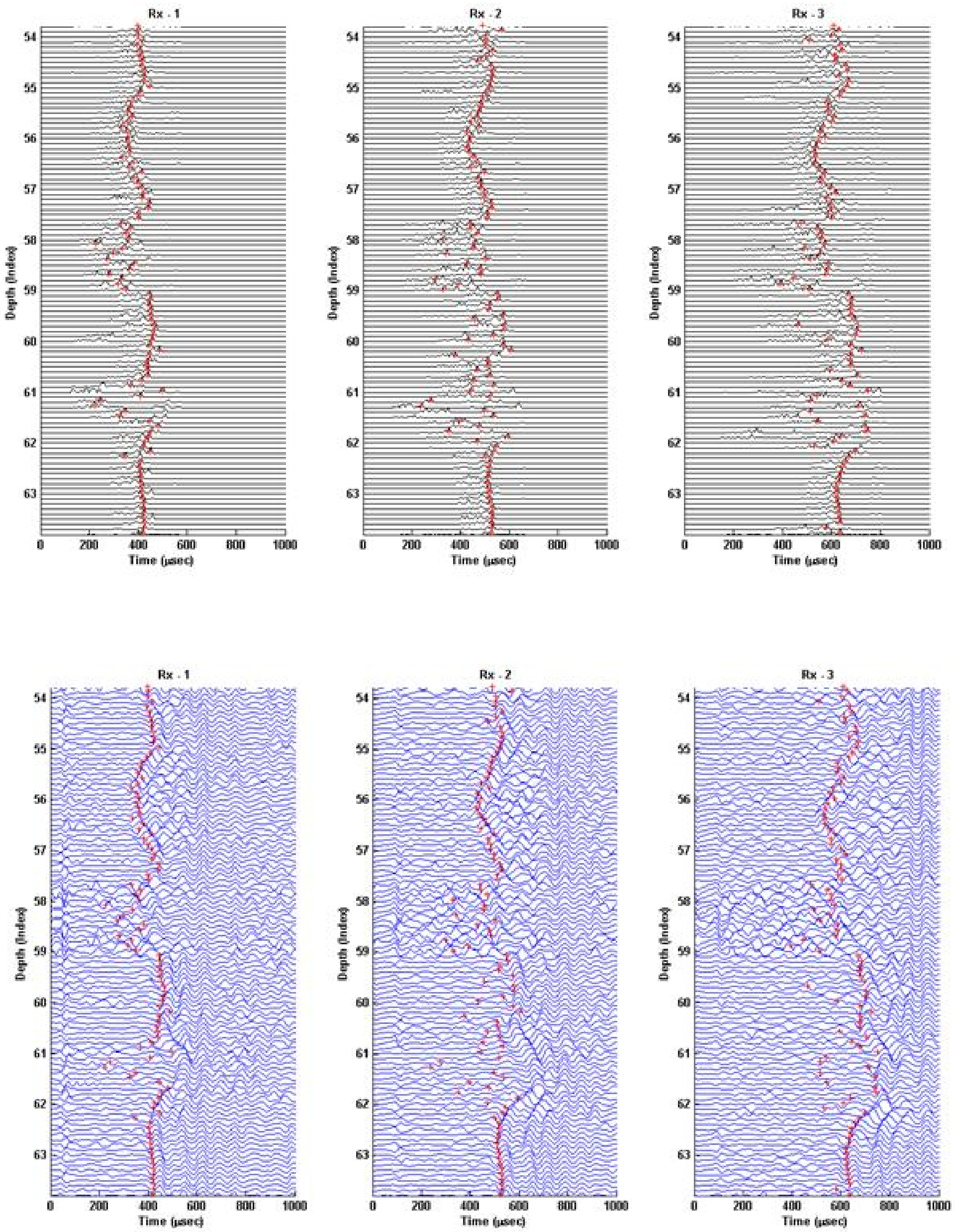

FIG. 8. First arrival time-picking using the modified eRatio method on sonic seismograms for depths 53.8m to 63.8m. Top: the time picks (red crosses) are plotted at the maxima of eRatio traces. Bottom: Picked times are plotted on the input seismograms. The time picks are quite accurate, except where the seismograms have low signal-to-noise ratios.

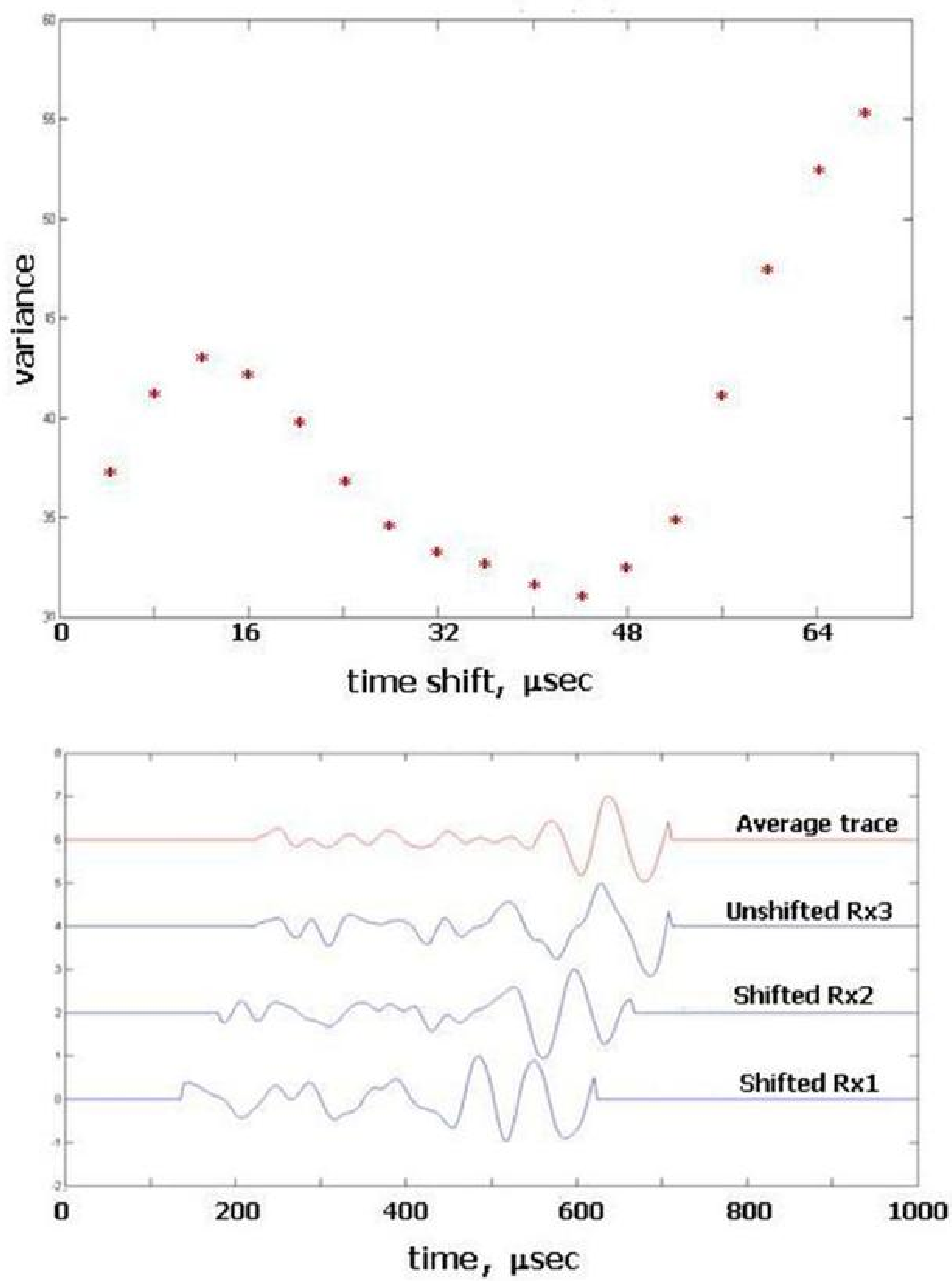

FIG. 9. Noise reduction for using minimum variance summation. The average trace results from the sum of the Rx1, Rx2, and Rx3 at a given depth. Before summing, Rx1 is shifted to the right a positive amount 2Δt, Rx2 trace is shifted to the right by a time Δt, and Rx3 is unshifted. The three traces are then windowed. The windowed traces are normalized by its maximum value, and then averaged. The total variance between the average trace and the three input traces are calculated and plotted as a function of the shift Δt. The average trace showing the minimum variance is chosen as the noise reduced trace Rx3' to replace Rx3 for time-picking.

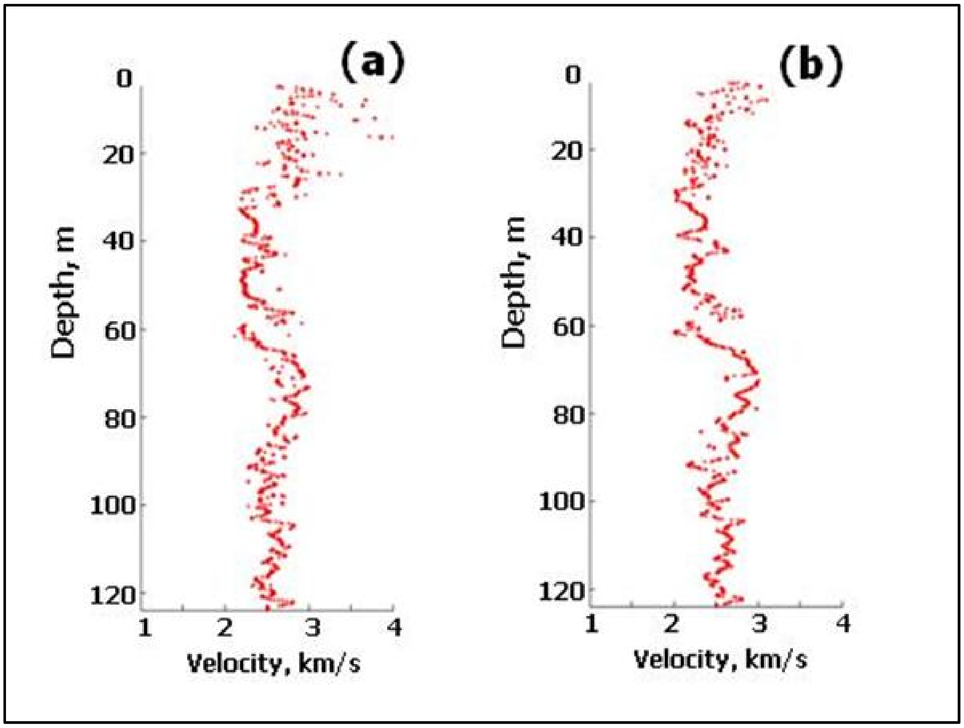

FIG. 10. (a) Velocities based on first arrival picks form original Rx3 seismograms. (b) Velocities based on first arrival picks from minimum variance averaged Rx3' seismograms.

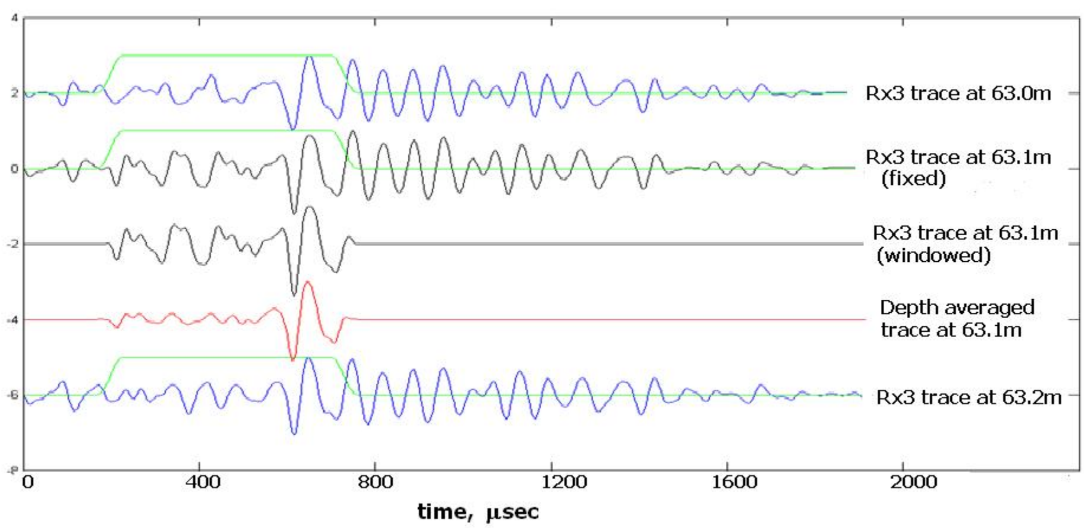

FIG. 11. Depth averaging for noise reduction using one reference (fixed) trace and two other adjacent traces. The depth-averaged trace (in red) has less noise preceding the first arrival than the reference trace. Averaged traces from using 5, 7, 9, and 11 adjacent traces have similar SNR.

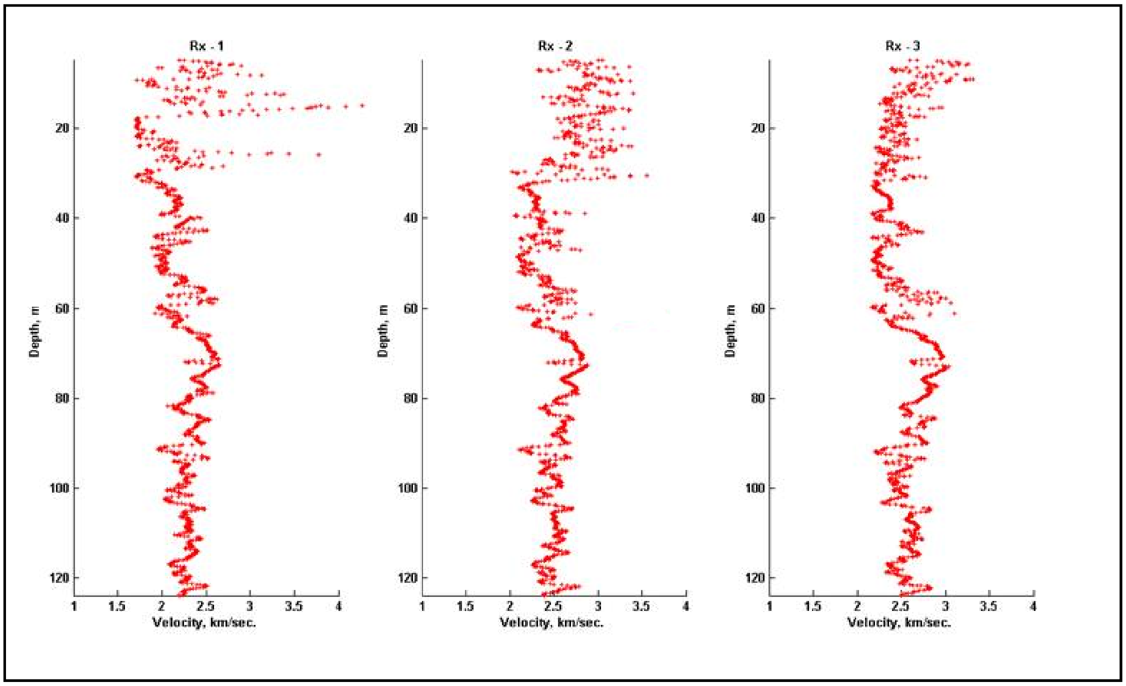

FIG. 12. Velocity profiles based on first arrival times picked using the modified eRatio method on depth-averaged seismograms Rx1, Rx2, and Rx3'. A five-point median filter has been applied to minimize the number of outlier values.

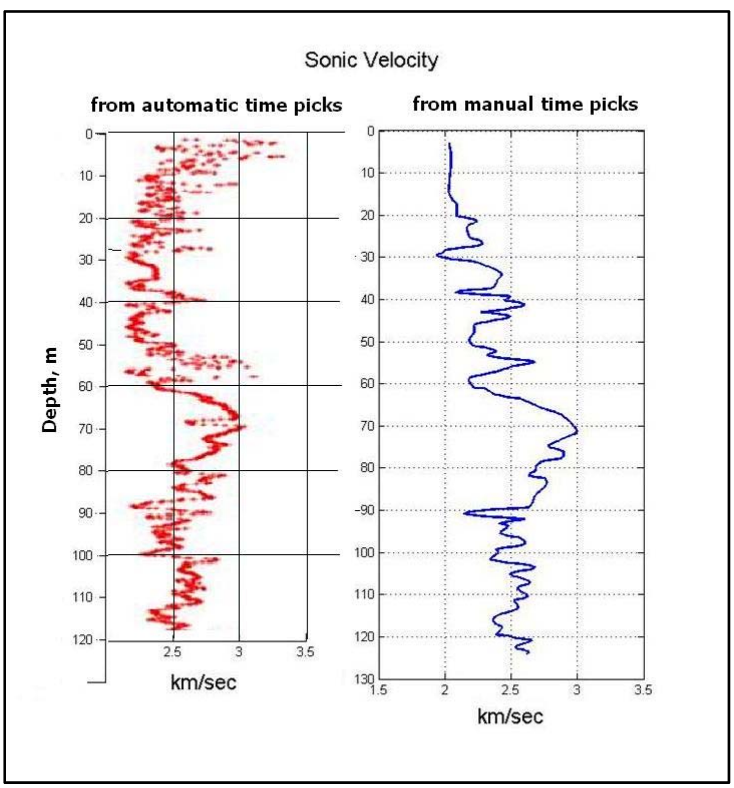

FIG. 13. Comparison of velocity profiles based on automatic and manual time picks.