Aligning microseismic reflections for imaging

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ABSTRACT

Microseismic data are not created ready for imaging. They can be extremely noisy and it is not a straightforward task identifying reflections. In a previous work, we were able to use multiplets or events of the same waveform to identify some reflections. However, realizing that reflections were weaker on the stack than they are on the individual seismograms, we inferred we had a misalignment issue between the different seismograms. In this work, we use fractional shifts and receiver-by-receiver shifting to align seismograms more effectively. We also investigate some aspects of multiplets and how they are related to each other in space and time, as well test the use of cross correlations of P-direct arrivals with whole seismograms to identify the unfound P-reflections.

INTRODUCTION

The ultimate goal of our research is to use reflections of hydraulically induced microseisms in the Bonner sand of the Bossier play to image the subsurface. In our previous work (Farghal and Levin, 2012), we successfully utilized a method adapted from earthquake seismology to find events originating from closely related sources which produced almost identical seismograms. This method involved cross-correlation of a particular event waveform (called a master) consisting of a P and S direct arrival with the whole dataset to find replicas of this waveform (the collection of which is known as a *multiplet*). Upon identification of similar waveforms (sources), we aligned and stacked their seismograms together to decrease the data size and increase the S/N ratio. Since we were only able to identify S reflections, we were also hoping that by stacking similar seismograms we will boost companion P reflections as well. However, for reasons discussed later in this report, this first attempt was not fruitful.

In SEP–147, we noticed that reflections are weaker on the stack than they are on the individual seismograms. We proposed that this was due to misalignment of the reflections after we aligned the direct arrivals. We attributed this to misalignment of the reflections that may differ by a small amount due to small source location differences in cases of similar rather than identical/coincidental sources. We have since realized that the fracturing and pressure changes could have affected propagation velocities even if the source locations happen to be the same.

In this report, we will show how we successfully address the misalignment problems and enhance the stacked amplitude of reflections. Moreover, we attempt to find P-reflections by cross-correlating P direct arrivals with the whole seismogram in which it lies. The faintest P reflection may well be useful when we come to the migration stage.

Finally, in preparation for imaging, we apply the previously mentioned concepts (of cross-correlations, alignment and stacking) to the whole Bonner dataset.

WARPING OR RECEIVER-BY-RECEIVER VARIABLE SHIFTING

In a previous report, we used the general locations of “stacked” cross-correlation peaks of the microseismic events to find a bulk shift to apply to the whole seismogram (Farghal and Levin, 2012). In Figure 1, we show the stack of two aligned seismograms. Extracting the reflection wavelet on the 30th channel, we can see that the highest positive magnitude is around 0.03, as shown in Figure 3 (a).

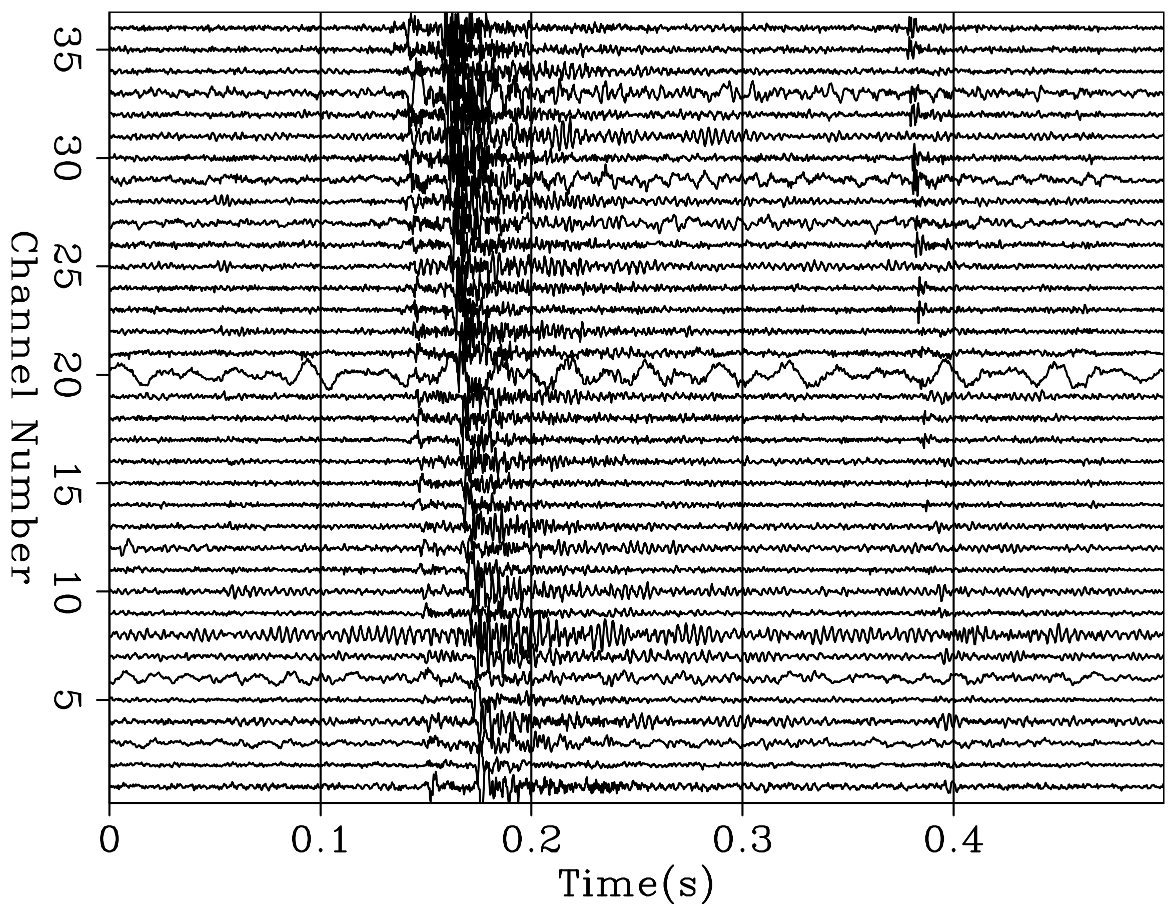

Figure 1: Stack of two seismograms aligned by bulk shifting. [**ER**]

We will now introduce receiver-by-receiver variable shifting, a limited form of warping, to align seismogram reflections within a multiplet. Figure 2 shows the

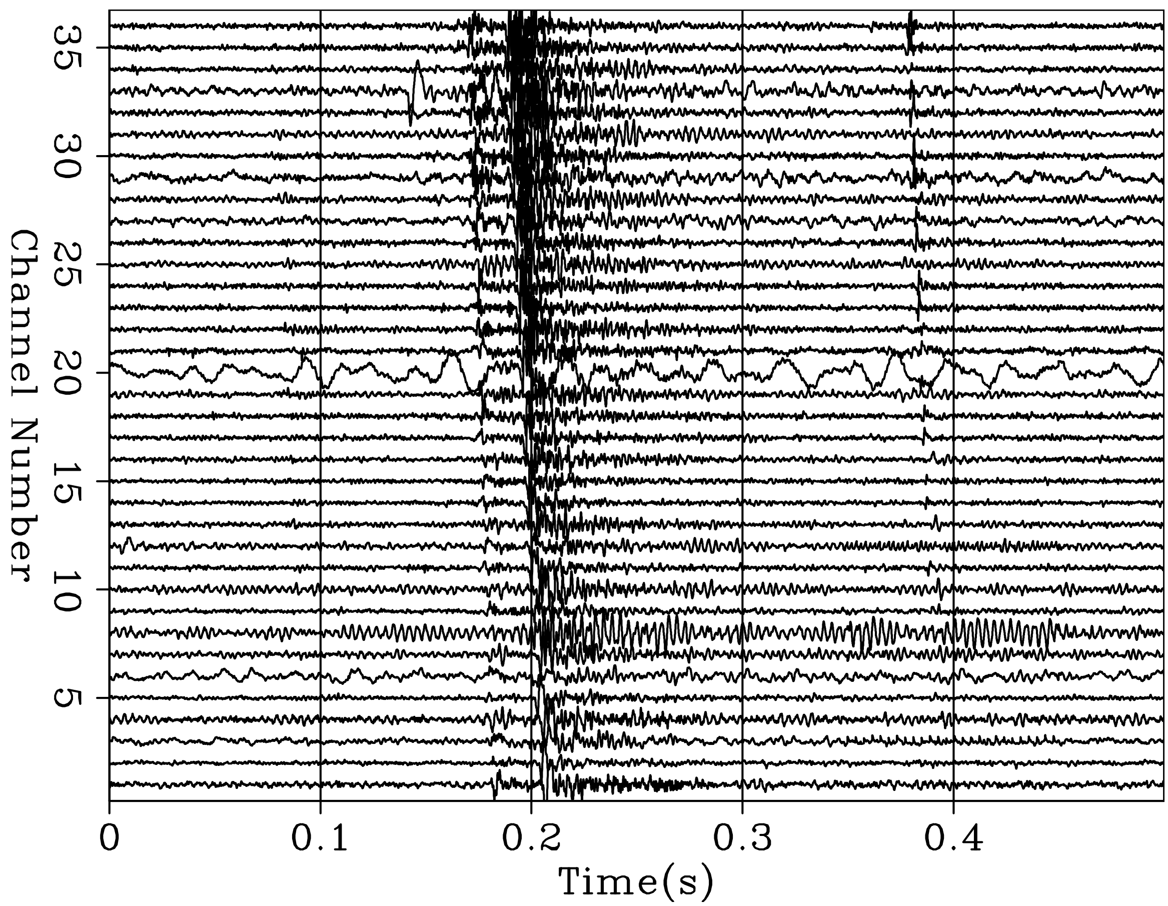

Figure 2: Stack of two seismograms aligned by warping. [**ER**]

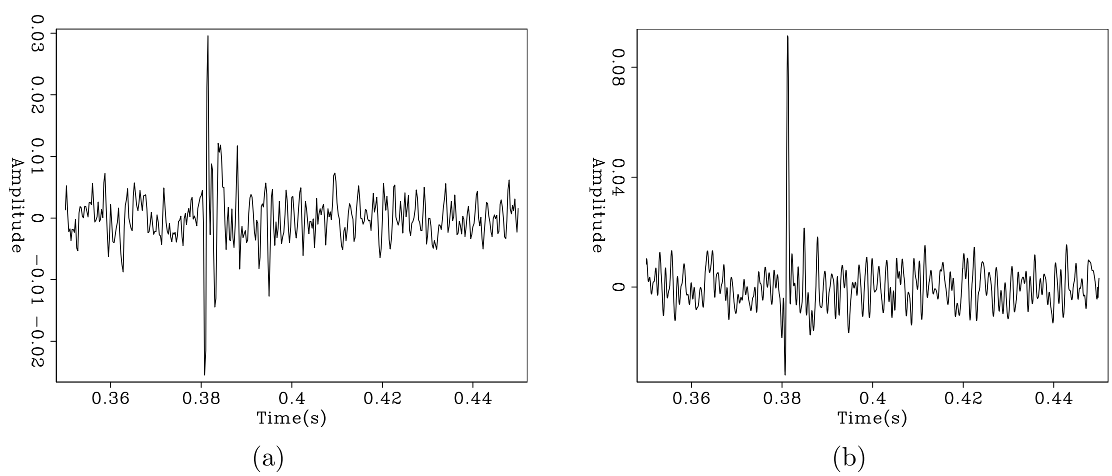

Figure 3: a) Selected reflection (30th channel) in a stack of 2 seismograms aligned by bulk shifting. b) Close up on the reflection (30th channel) in a stack of 2 seismograms aligned by receiver-by-receiver shifting (warping). Observe the increased peak amplitude after warping. [**ER**]

stack of two aligned seismograms using this warping rather than bulk shifting. Figure 3(b) shows a closeup on the 30th channel reflection wavelet, with almost three-fold improvement in peak magnitude, confirming our better alignment of the individual seismogram reflections.

IN SEARCH OF P-REFLECTIONS

The reader will, of course, have observed that we have only shown a shear reflection in the above. Looking at the direct arrivals, we can see that the direct P waves are weaker than the direct S waves, so it should not be surprising that the reflected P waves may be quite weak.

We used our running window cross-correlation program to cross-correlate direct P arrivals with whole seismograms with the hope of finding P-reflections. Results of such an approach can be seen on Figure 4(b). We can see in this figure that on the original seismogram, the P reflection seen at around 2.2s was not apparent and was actually brought up by the cross-correlation of the direct P with the whole seismogram. It turns out that the stronger the P arrival we use in cross correlations, the more likely we are to find an arrival that can be a P-reflection.

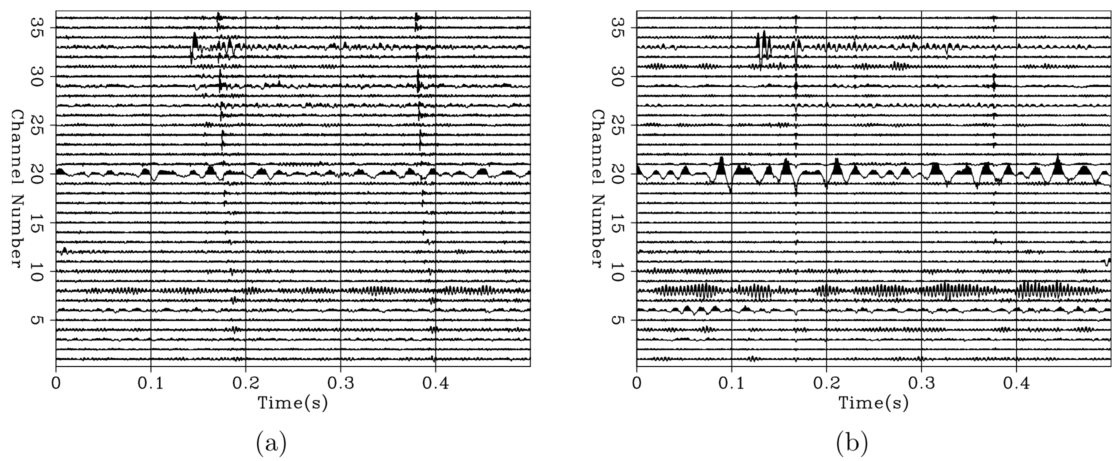

Figure 4: a) seismogram with P-reflection not strong enough to be seen b) cross-correlation result with direct P-wave, with a possible reflection appearing at about 0.23s. [**ER**]

AN OBSERVATION ON “POPULAR” WAVEFORMS

Most microseismic sources in the Bonner sand are along the hydraulic fracture (Sharma et al., 2008). Many of them are expected to be very close in location and to have the same waveform (from the same fracking mechanism), while others further apart on the hydraulic fracture have rather different waveforms. This is reflected in the tight clustering of source locations of waveforms having high correlation with the master waveform. However, the clustering of locations does not necessarily imply any fixed distribution of event times. What we observe is a long-tailed distribution, with most appearing at the early stages of the treatment. This we attributed to such events being due mostly to the initial opening of the fracture, with some later slippage as pressures vary during later stages of the treatment.

Due to the high correlation values obtained in most cross-correlations, deciding what the threshold for what constituted a match/multiplet was not possible without visual inspection. We conservatively opted to only include in a given multiplet those records with nearly perfect correlation to the multiplet master.

DISCUSSION AND CONCLUSIONS

From our results, we see that receiver-by-receiver shifting is better than bulk shifting as it produces larger signal amplitude and overlap as demonstrated by the higher amplitudes of the stacked reflections. We note that fractional shifting did not help much to improve alignment in these examples, that is, whole samples were sufficient, but we will continue to use this method in order to develop and mature it for general application to microseismic data that may well need fractional shifting for sufficient alignment.

Finally, although shear reflections are sufficient for imaging, that fact that we were able to identify later P-arrivals that encourages us to not abandon our search for P-reflections.

ACKNOWLEDGMENTS

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APPENDIX A

FRACTIONAL SHIFTS

By first taking the seismograms to the Fourier domain, padding with zeros with a certain factor (interleaving), we obtain fractional shifting. This is because the sampling interval is reduced by that factor, which we call super-sampling of data. Then, we apply the receiver-by-receiver alignment program to align all multiplets with the master seismogram reflection, as will be discussed in the coming section. Fractional shifting does not change a seismogram visually, but it multiplies its sampling density.

APPENDIX B

TRAVEL TIMES AND GRADIENTS

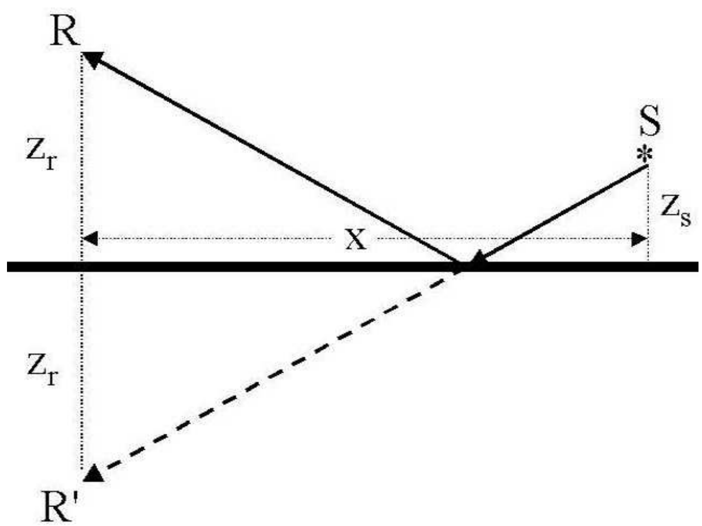

Figure A-1: Diagram showing source-receiver relative locations with respect to the reflector. [**NR**]

Referring to Figure A-1, the direct arrival time, T_D, is given by

$$T_D = \frac{\sqrt{x^2 + (z_s - z_r)^2}}{V}$$

and the reflected arrival time, T_R, is similarly

$$T_R = \frac{\sqrt{x^2 + (z_s + z_r)^2}}{V} \quad .$$

To calculate the relative effect of small shifts in source or receiver location on these arrival times, we compute the gradients ∇T_D and ∇T_R with respect to changes in source location:

$$\begin{aligned}
V \frac{\partial T_D}{\partial x} &= \frac{x}{\sqrt{x^2 + (z_s - z_r)^2}} \\
V \frac{\partial T_D}{\partial z_s} &= \frac{z_s - z_r}{\sqrt{x^2 + (z_s - z_r)^2}} \\
V \frac{\partial T_R}{\partial x} &= \frac{x}{\sqrt{x^2 + (z_s + z_r)^2}} \\
V \frac{\partial T_R}{\partial z_s} &= \frac{z_s + z_r}{\sqrt{x^2 + (z_s + z_r)^2}}
\end{aligned}$$

and with respect to changes in receiver location:

$$
\begin{aligned}
V\frac{\partial T_D}{\partial z_r} &= \frac{z_r - z_s}{\sqrt{x^2 + (z_s - z_r)^2}} \\
V\frac{\partial T_R}{\partial z_r} &= \frac{z_s + z_r}{\sqrt{x^2 + (z_s + z_r)^2}}
\end{aligned}
$$

With these gradients in hand, let $\mathbf{f}$ be a unit vector aligned with the fracture and $\mathbf{g}$ be a unit vector aligned with the receiver array. Then the directional derivatives $\nabla T_D \cdot \mathbf{f}$ and $\nabla T_R \cdot \mathbf{f}$ give the relative sensitivities of the direct and reflected arrival times to source displacement along the fault that gave rise to some set of multiplets. Similarly, the directional derivatives $\nabla T_D \cdot \mathbf{g}$ and $\nabla T_R \cdot \mathbf{g}$ provide the arrival slopes of the direct and reflected arrivals respectively.

With the above, not only can we estimate where to look for weak reflections behind a direct arrival (or, conversely, how far from the microseismic source a clear reflection arose), but we can also begin to understand how much or little reflections within multiplets misalign when their associated direct arrivals are aligned. For example, the limiting case of the receiver just above the reflector has the reflected and direct arrivals arriving at the same time and changing at the same rate as the source is displaced whereas if $z_s = z_r = x/2$ the reflected arrival displaces $\sqrt{2}$ times further than the direct arrival. Both of these cases are serendipitous in the sense that aligning the direct arrival across channels also aligns the reflected arrival.

Let us apply these formulas to analyze the shear reflection we spotted in our Bonner multiplet example.

In the example of Figure 1, the receivers are at about 12,800 ft depth and the microseismic source was computed to be at about 13,100 ft depth and an offset of about 300 ft from the monitor well. The dipole sonic log shows a compressional velocity of about 13,750 ft/sec and a shear velocity of about 8,000 ft per second in that depth range. The difference between the direct P and the direct S arrivals would be 22 msec, in good agreement with the actual record. The delay of about 220 msec to the later shear arrival corresponds to a reflector depth of about 13,800, i.e., a thousand feet below the receivers and, sigh, well below the reservoir depth.

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