Super-Virtual Refraction Interferometric Redatuming: Enhancing the Refracted Energy

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SUMMARY

Complex near surface is one of the main challenges for onshore seismic data processing. Refraction tomography is becoming a common way to estimate an accurate near surface velocity model. One of the problems with refraction tomography is the low signal to noise ration in far offset data.

To improve, we propose using super-virtual refraction interferometry to enhance the weak energy at far offsets.

We use Interferometric Green's functions to redatum sources by cross-correlating two traces recorded at receiver stations, A and B, from a source at location W. The result is a redatumed trace with a virtual source at A and a receiver at B, which can also be obtained by correlating two traces recorded at A and B from different shots. Stacking them would enhance the signal-to-noise ratio of this "virtual" trace.

We next augment redatuming with convolution and stacking. The trace recorded at B from a virtual source at A is convolved with the original trace recorded at A from a source at W. The result is a "super-virtual" trace at B in the far-offset from a source at W. Stacking N traces gives a √N-improvement.

We applied our method to noisy synthetic and field data recorded over a complex near-surface and we could pick more traces at far offsets. It was possible to accommodate more picks resulting in a better subsurface coverage.

Key words: Interferometry, redatuming, cross-correlation, super-stacking.

INTRODUCTION

Complex geology in the near-surface is one of the most challenging issues for seismic reflection and refraction surveys. The classical processing cure to this problem is to redatum the data to a datum below these complex layers assuming a simple 1-layer, 2-layers, or even multi-layer velocity model. The remedy is to subtract from the seismic trace the time the seismic wave travels through these near-surface layers. The approximation used in this methodology is that the rays travel vertically.

Nevertheless, the assumption of vertical rays is losing its popularity because it is based on the wrong assumption especially if we consider a complex near surface geology where we cannot assume a simple velocity model to obtain ”static corrections”. Therefore, refraction tomography becomes essential and more useful for calculating the static time shifts, which gives better results than conventional static corrections.

The assumption of vertical rays fails when trying to correct far offset traces in the shot gather where the rays actually arrive to these traces at oblique incident angles. New redatuming techniques utilize the wave-equation but it requires an accurate velocity model. Relying on the raw shot gathers to characterize the near-surface cannot be used to build an accurate velocity model of the near surface. The first break picker will only be able to pick the first arrivals in the near-offset traces, which are associated with the shallowest part of the Earth model. It is the far-offset traces that contain information about the deeper part of the complex near-surface.

Static correction and redatuming data in the Middle East where the largest reserves are located is a ”must-do” part of the processing sequence. This is because the interpreter is looking for certain structure that could be altered by the near-surface complexity. The irregular time shifts caused by the complex near surface would distort these interesting structures that could be possible hydrocarbon traps. Similarly, these time shifts might create a wrong structure in the subsurface that could be misinterpreted as hydrocarbon targets.

Therefore, we need an accurate velocity model to do our ”tomographic” static correction or redatuming. This objective will not be achieved accurately if we cannot characterize the deeper part of the near-surface that requires picking the first arrivals of the far-offset traces usually obscured by a high noise level.

The problem we have is a complex field data with a low-velocity zone causing a refractor jump occurring at a large-offset where the traces becomes noisy and the signal is highly weakened by attenuation. A potential remedy is to apply super- virtual refraction interferometry to enhance the weak signal and suppress the noise. This will enable us to pick the far-offset traces and be able to construct velocity models that are more accurate and sample the deeper part of the near-surface associated with the far-offset traces.

METHODOLOGY

Assume a source at W and two receivers at A and B inside an arbitrary acoustic medium as shown in Figure 1. The surface is surrounded by a closed surface So + S∞ where So represents the shot line and S∞ represents a half circle surface far away at infinity. The reciprocity equation of correlation type in the far-field approximation in the frequency-domain (Wapenaar and Fokkema, 2006) is given as following:

$$Im[G(B|A)^{virtual}] = k \int_{shot\ Line} G(A|W)^{*} G(B|W) dW$$

The integration surface (So + S∞) reduces to So due to Wapenaar anti-radiation condition for sufficiently heterogeneous medium which assumes little interactions at infinity and the wavefield recorded there is negligible. The power of interferometry is utilized in this first step where we have moved our sources from the recording surface to a new datum without knowing the velocity model. Interferometry enables us to use the recorded Green's functions (i.e. data) as natural wavefield extrapolators. The phase associated with the common ray-path in G(A|W) and G(B|W) gets subtracted and cancelled as a result of cross correlating the traces (i.e. multiplication with the complex conjugate in the frequency domain). Then, the same redatumed green's function $Im[G(B|A)^{virtual}]$ can be obtained from another shot and the stacking (i.e. integration) over all possible shots containing this two-receivers pair will ensure the enhancement of the signal-to-noise ratio. However, this approach suffers from two major limitations:

1. These redatumed Green's functions are short offsets and we are interested in far offset events.
2. The virtual sources are placed at the refractor and fired at non-physical time prior to the firing time. In other words, this virtual source at the refractor is excited at the pre-zero time of $-\tau_{YA.}$

This can be resolved by utilizing the reciprocity equation of convolution type, which is analogous to surface-related multiple elimination (SRME) technique. We can predict multiples by convolving two primaries. Unlike cross-correlation, the convolution of two Green's function adds the phase representing the traveltime whereas correlation subtracts the phase. In the frequency domain, the convolution turns into a multiplication of the two Green's functions.

Thus, the reciprocity equation of convolution type in the far-field approximation gives the new redatumed gather $G(B|W)^{super}$ as following:

$$G(B|W)^{super} = 2ik \int_{virt\_shot\ Line} G(A|B)^{virtual} G(A|W) dA$$

The superscript in the new redatumed green's function $G(B|W)^{super}$ is to indicate that this trace is different from the original recorded green's function G(B|W) used in the reciprocity equation of correlation type. This new green's function is a result of two-redatuming steps and involves two stacking operations: one in the correlation process and one in the convolution process. Hence, the SNR for $G(B|W)^{super}$ is larger than both $(G(B|A)^{virtual}$ and G(B|W). Figure 2 shows how to construct the super-virtual gather.

NUMERICAL EXAMPLES

We generated pressure traces using the finite difference solution to the two-dimensional acoustic wave equation. We tried to simulate the real data by using similar velocity model shown in Figure 3 and acquisition geometry where, the shot and receiver spacings are of 10 meters. The velocity model contains a low-velocity zone impeded in-between the layers that causes the refracted energy to abruptly jump (i.e. shingle). A typical shot gather along the profile is shown Figure 4. The red arrow in the figure indicates where the refractor singles. After the addition of random noise, the noise level obscures the refractor and it becomes hard to distinguish between the noise and the signal especially where the refractor jump is occurring as illustrated in Figure 5.

Super-virtual refraction interferometry seems to be a potential remedy to this problem. After applying the method described above, we noted a remarkable increase in the signal to noise ratio by a factor of √N where N is the number of contributing shots (Maillinson *et al*, 2011)

We managed to pick far-offset refraction arrivals that we could not pick in the noisy gather and capture the refraction jump that was masked by a high noise level as illustrated in the super-virtual shot gather in Figure 6.

Applying super-virtual refraction interferometry to the field data shows promising results. Figure 7 shows a typical shot gather along a seismic profile acquired in the Middle East over a complex near surface. The gather is windowed around the first arrivals and we were not able to pick arrivals beyond 1000-meters offset. However, after the application of the interferometric transformations, the SNR increased remarkably as shown in Figure 8. Moreover, we managed to pick more first breaks at far offsets and Figure 9 shows both the first break picks on the raw and super-virtual shot gather. Due to wavelet distortion, there exists a discrepancy between the super-virtual picks and raw ones but it is no more than T/4 where T is the dominant period. We found out that this difference is much less than one sample point and therefore, considered this difference to be negligible.

CONCLUSIONS

The power of interferometric methods is their ability to redatum sources and receivers without knowing the velocity model. We basically use the recorded data as natural wavefield extrapolators (i.e. natural green's functions) and use them to move the sources and receivers unlike model-based redatuming.

We showed how super-virtual refraction interferometry can enhance the signal to noise ratio of the refracted arrivals at mid- and far-offsets in both synthetic and field shot gathers with oil-industry type of acquisition geometry. This would make picking first breaks at far offsets associated with the deeper part of the near surface, an easier task. As a result, the near-surface velocity model would more accurate.

The main limitation of super-virtual stacking is the wavelet distortion but it doesn't seem to affect severely our traveltime picks in both synthetic and field data.

In conclusion, super-virtual interferometric stacking seems to be a potential remedy to enhance the weak refracted energy at far offsets that could lead to a better characterization of the near-surface model.

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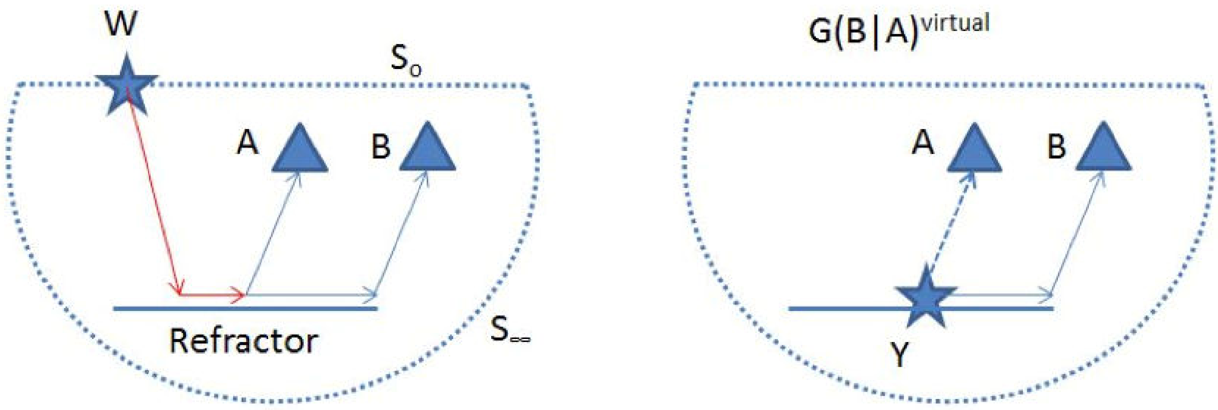

Figure 1: Geometry for calculating a redatumed Green's function recorded at receiver B due to a source at A. Cross-correlating the trace recorded at A and B due to a source at W results in a trace recorded at B due to a virtual source at Y but advancing in time it takes the wave to travel from Y to A (τ_{YA})

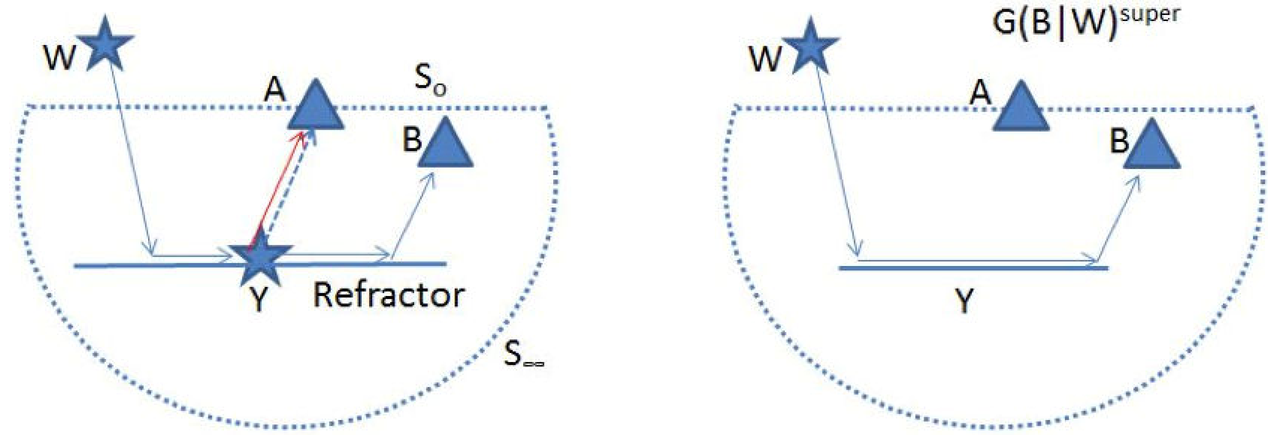

Figure 2: Geometry for calculating a new redatumed shot gather recorded at B due to a source at W. Convolving the virtual trace recorded at B due to a source at A and a trace recorded at A due to a source at W results in a super-virtual trace recorded at B due to a source at W.

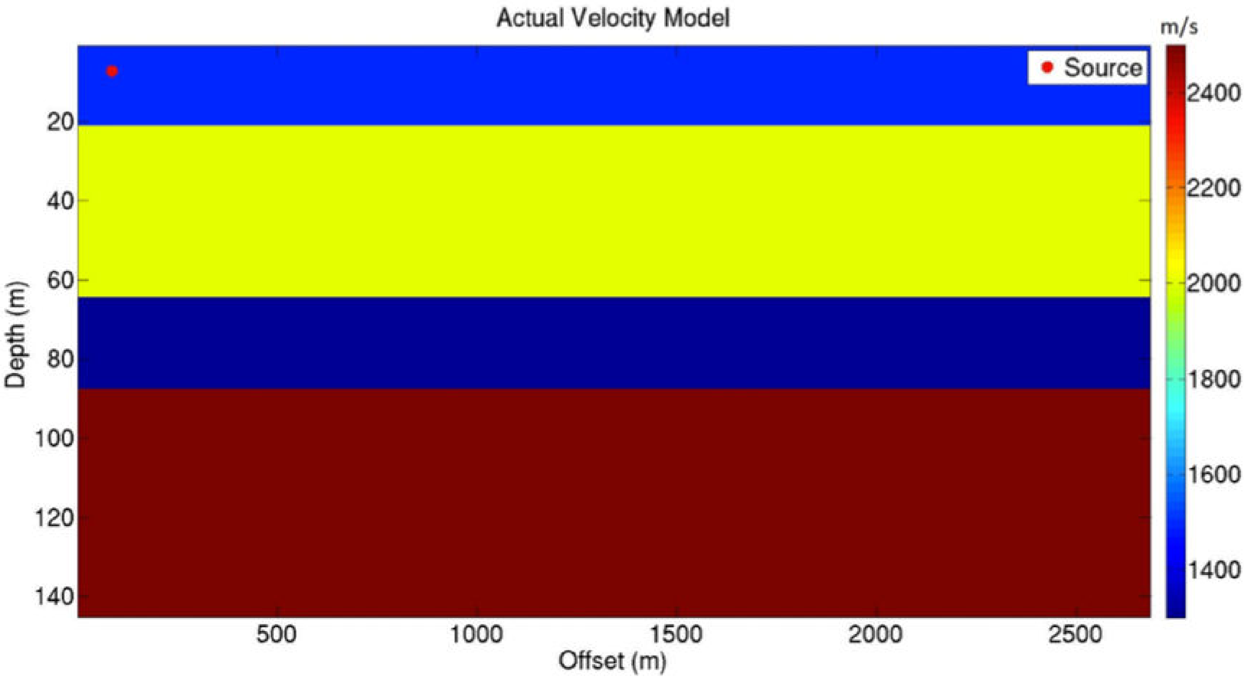

Figure 3: The velocity model used in the finite difference simulation. Note the low-velocity layer with a thickness of about 25 meters causing a jump in the refracted energy in the shot gather.

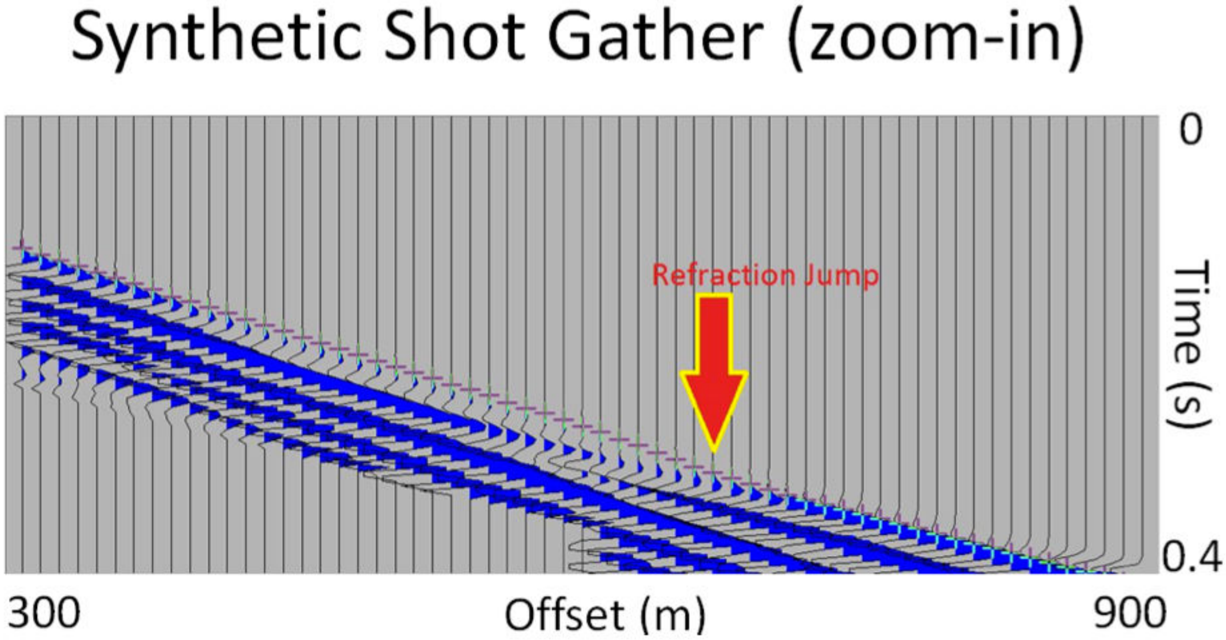

Figure 4: A raw shot gather resulting from the velocity model windowed around the refracted first arrivals. The abrupt refraction jump marked by the red arrow meters offset is due to the existence of the low-velocity layer. The red crosses denote first break picks.

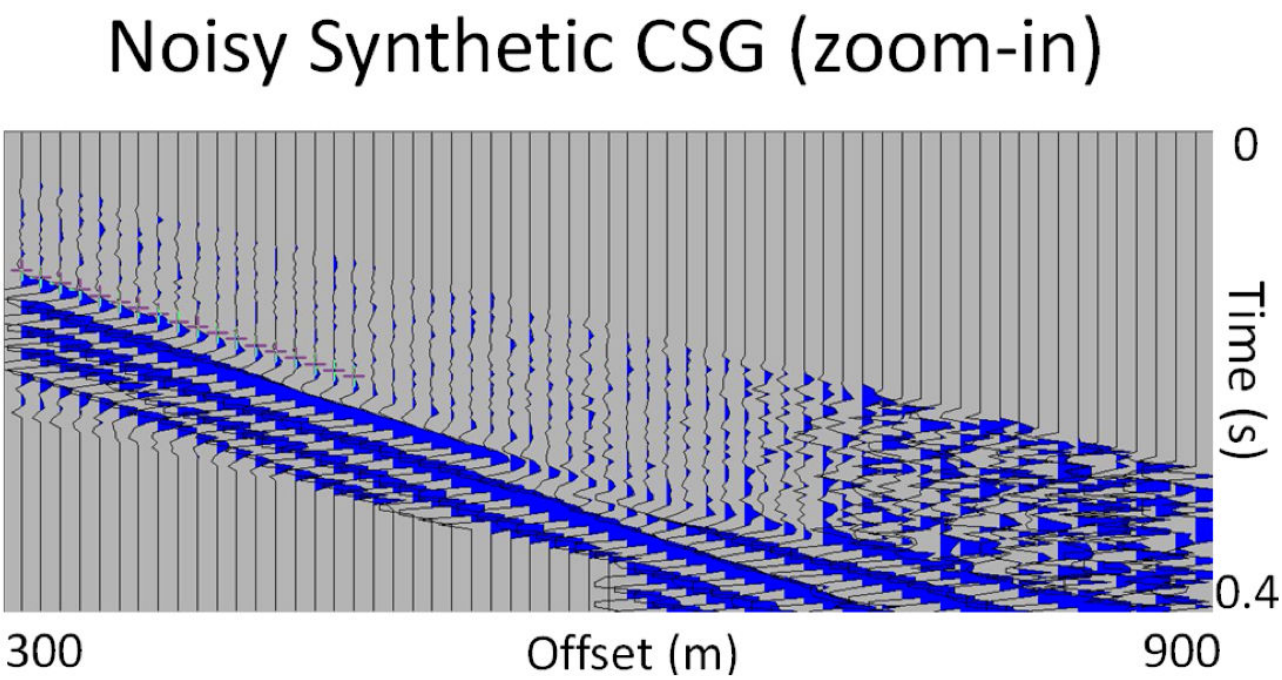

Figure 5: The synthetic shot gather after the addition of random noise. The amplitude of the refracted signal in the vicinity of the refraction jump is highly deteriorated. Also, the high noise level masks the first break at far offsets. The red crosses mark the first arrivals.

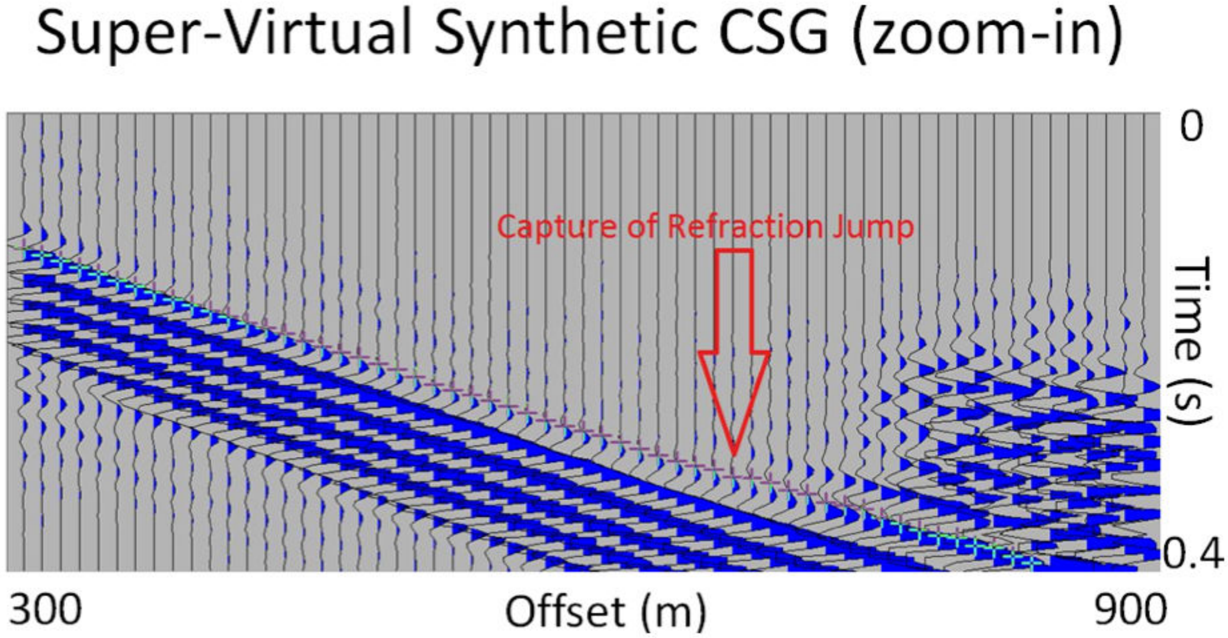

Figure 6: The noisy synthetic shot gather after the application of super-virtual stacking method. The amplitude in the vicinity of the refraction jump due to the low-velocity layer is enhanced and we managed to pick more traces at further offsets.

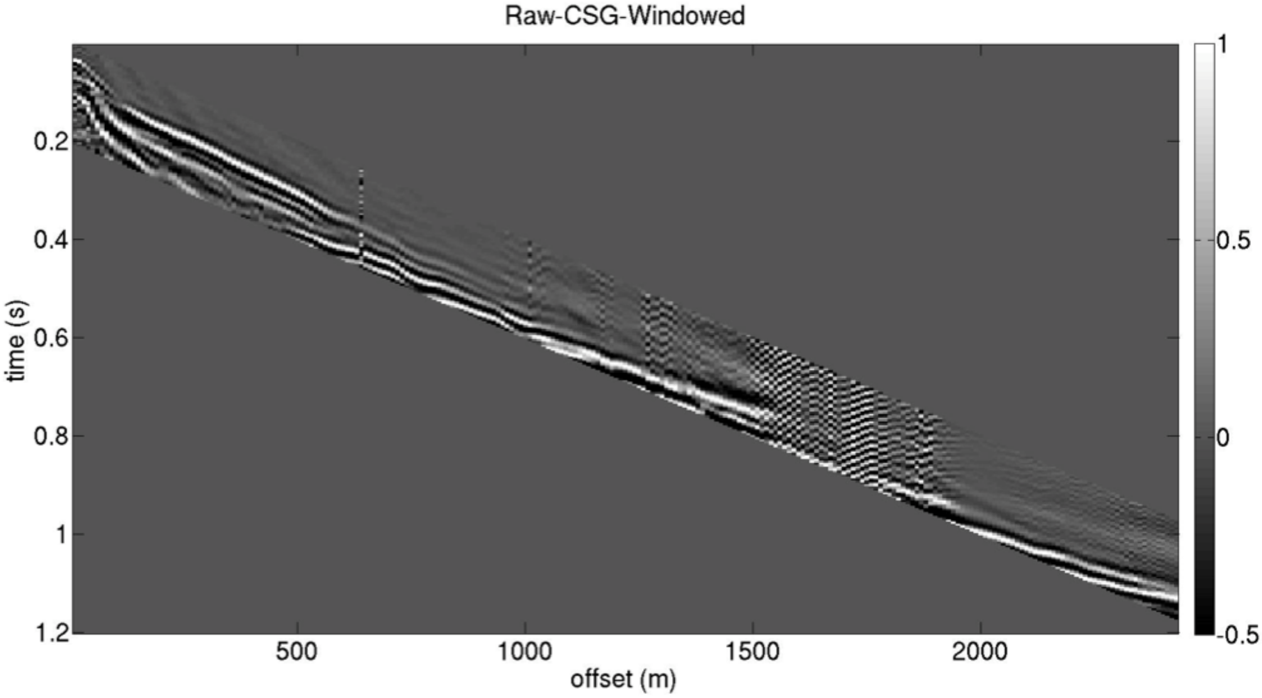

Figure 7: A representative field raw common-shot gather along the profile. The field shot gather shows a significant deterioration in SNR at far offsets larger than 500 meters. It is hard to locate the refractor jump caused by the regional low-velocity layer present in this area.

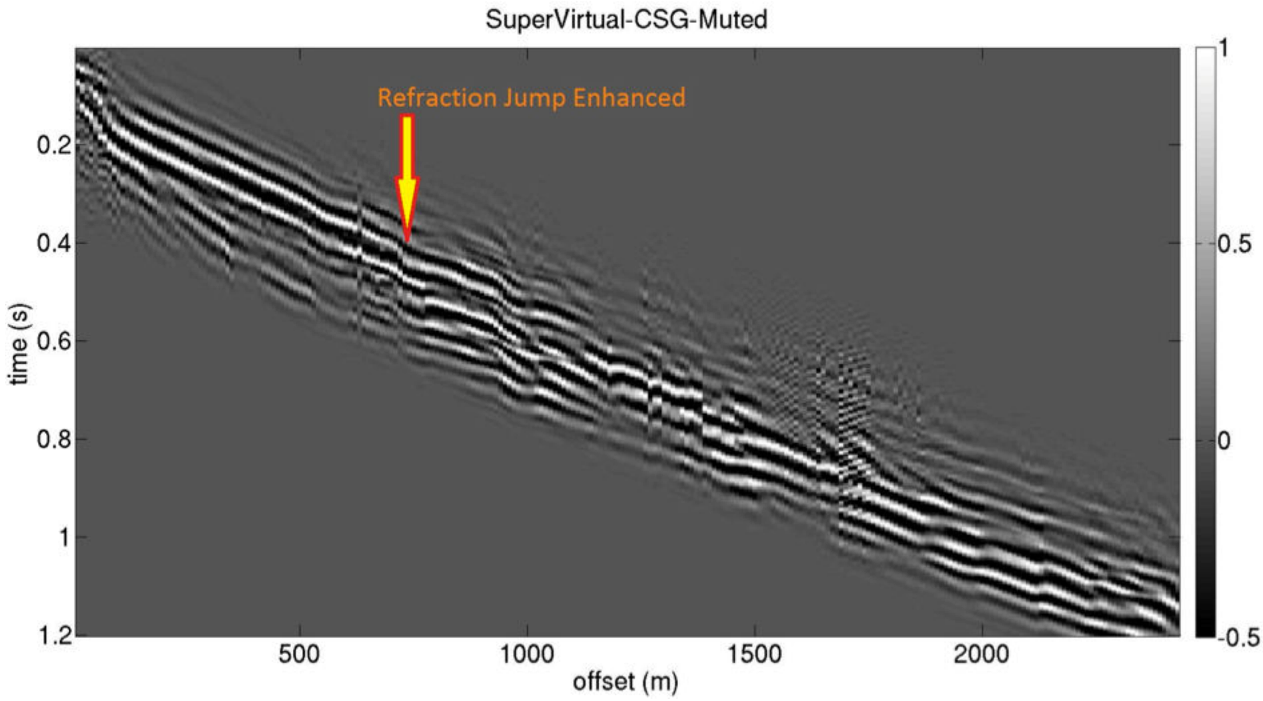

Figure 8: The field shot gather after the application of super-virtual stacking. The super-virtual gather confirms the existence of the refractor shingle we modeled and noted in the raw data. It also enabled us to pick the refractor at further offsets.

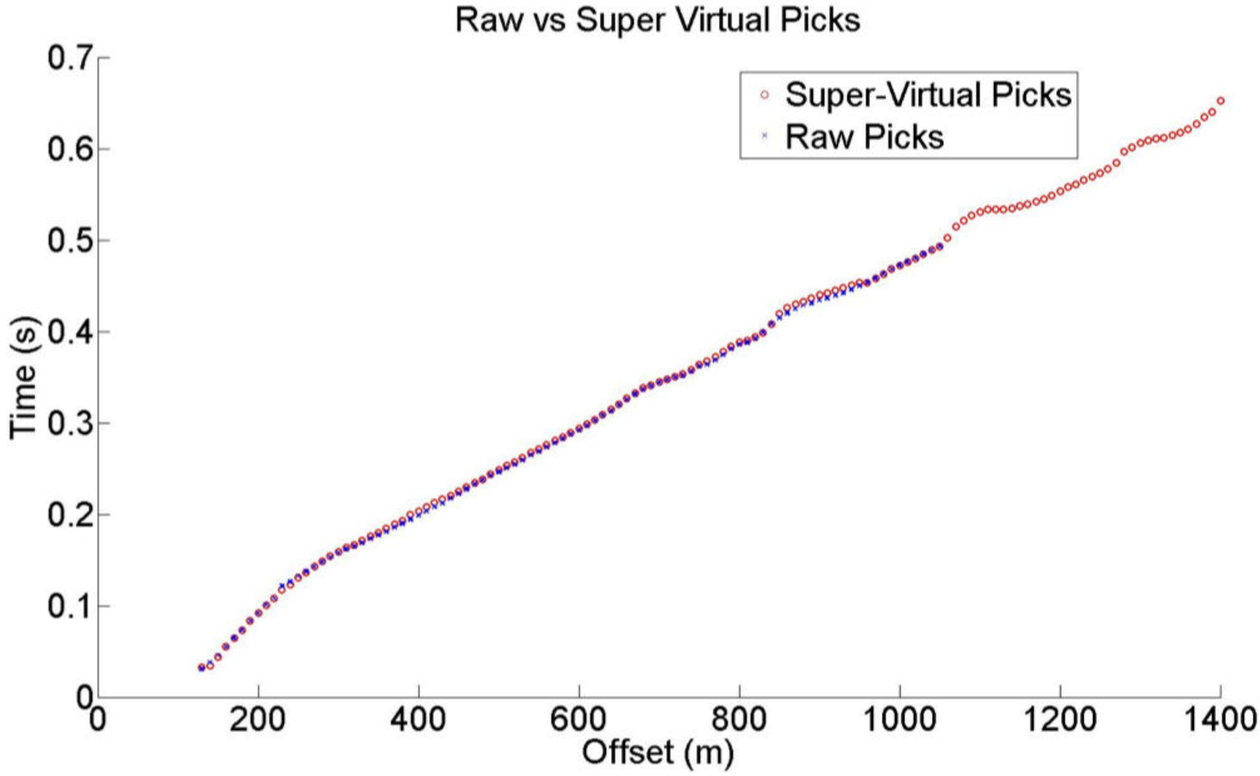

Figure 9: Traveltime picks for the field shot gather before and after the application of super- virtual interferometry. For the same offset range, the differences between the picks are negligible (i.e. within a quarter of a period). Also, we were able to pick more first arrivals at further offsets.