Time domain internal multiple prediction on synthetic and field vertical seismic profile data

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ABSTRACT

Surface seismic methods represent the only technology capable of large scale 3D characterization of conventional and unconventional oil and gas reservoirs, monitoring of enhanced oil recovery, and water and CO2 injection. When seismic energy is injected into the earth, and the earth response recorded, two main type of events are seen, primaries and multiples. Primary energy arises from waves that have reflected once and returned to the surface to be recorded; multiples arise from waves that reflect more than once. Most seismic interpretation and processing workflows treat primary events as signal and multiples as undesirable noise. It is for this reason that the prediction and subsequent removal of multiple energy has become a popular research topic.

Multiple energy is classified into two main types, surface related or free surface multiples, and internal multiples. Free surface multiples are multiples in which at least one of the downward reflections occurs at the free surface of the earth. Internal multiples are multiples in which all downward reflections are restricted to the subsurface. Many successful schemes have been investigated to accurately predict and remove free surface multiples. The same cannot be said for internal multiples, although some important strides have been made in recent years. Weglein et al. (1997) proposed a wave equation based method of internal multiple prediction that is fully data driven, based on the inverse scattering series. The algorithm proposed by Weglein et al. was originally derived in the frequency-wavenumber domain. This paper reviews the time domain algorithm proposed by Innanen (2015) and then applies it to both synthetic and land zero offset VSP datasets. We also introduce a method of improving our predictions by converting the VSP data into zero offset sections.

INTRODUCTION

With many of the world's larger oil and gas plays already exploited, seismic exploration has moved defining subtle, less obvious features. As a result, multiples have attained a more important role in seismic interpretation, and because of this, in recent years' multiple prediction and attenuation has become an important field of geophysical research. Multiples come in two main types, free surface multiples, and internal multiples. Alam and Austin (1981) and Treitel et al. (1982) were among the first to recognize the periodicity of multiples in the tau-p domain. Yilmaz (2001) suggests that NMO correction and subsequent stacking of seismic data should attenuate multiples due to moveout differences. Velocity spectrums are also useful for identifying long period multiples. All of the methods identified above rely on some assumption about the difference between primaries and multiples. When the inherent assumptions in these methods are violated the algorithms no longer possess the ability to predict multiples accurately. While these assumptions typically hold well for free surface multiples, they are often violated by internal multiples.

In recent years wave equation based methods of internal multiple prediction have gained traction (Weglein et al., 1997; Jakubowicz, 1998; Berkhout, 1999). The inverse scattering series approach presented by Weglein et al. (1997) remains the most promising method of internal multiple prediction. In simple terms, their idea relies on the fact that every multiple is a combination of either primaries or primaries and other multiples. All first order internal multiples, in which only one downward reflection occurs, are a combination of three primaries. By combining these sub-event primaries in a lower-higher-lower relationship the algorithm proposed by Weglein et al. (1997) accurately predicts the traveltime and approximately predicts the amplitude of internal multiples.

The algorithm introduced by Weglein et al. (1997) performed the internal multiple prediction in the frequency-wavenumber domain. In recent years the CREWES project has been interested in carrying this algorithm into various domains to explore if an optimal domain exists for the prediction of internal multiples. One such algorithm proposed by Innanen (2015) examined prediction in the time domain. This algorithm, like many others has proven very successful on synthetic data sets. However, applications to real land data still remains a challenging exercise for reasons discussed by Luo et al. (2011). Land data sets are often complicated and noisy; in addition, land data sets commonly have interfering primary and multiple events.

The inverse scattering series approach to internal multiple prediction combines subevents that obey a lower-higher-lower relationship. One issue with this approach is that many other data types, aside from internal multiples, can obey this relation, including surface ghosts, free surface multiples, and noise. Therefore, it is important to remove surface ghosts, free surface multiples, direct waves, and as much noise as possible from data sets prior to predicting the internal multiples. Vertical seismic profiles (VSP) provide a unique opportunity to investigate internal multiple prediction. Fortunately, the upgoing wavefield component of a zero-offset VSP will be free of ghosts, direct arrivals, and free surface multiples, leaving only primaries, internal multiples, and noise in the data. In addition, **1**D algorithms can be applied to zero-offset VSP since each trace is essentially a zero offset, normal incidence wavefield response. This paper will apply the **1**D time domain algorithm introduced by Innanen (2015) to both a synthetic and a land VSP.

1D PREDICTION IN THE TIME DOMAIN

The algorithm proposed by Weglein et al. (1997) can be written in two dimensions as,

$$b_3(k_g, k_s, \omega) = \frac{1}{(2\pi)^2} \iint_{-\infty}^{\infty} dk_1 e^{-iq_1(\epsilon_g - \epsilon_s)} dk_2 e^{iq_2(\epsilon_g - \epsilon_s)} \times \varphi \tag{1}$$

where

$$\varphi(k_g, k_1, k_2, k_s | \epsilon) = \int_{-\infty}^{-\infty} dz\, e^{i(q_g + q_s)z} b_1(k_g, k_s, z) \int_{-\infty}^{z-\epsilon} dz'\, e^{-i(-q_1 - q_2)z'} b_1(k_g, k_s, z') \times \int_{z'+\epsilon}^{\infty} dz''\, e^{i(q_2 + q_s)z''} b_1(k_g, k_s, z'') \tag{2}$$

and where

$$q_x = \frac{\omega}{c_o}\sqrt{1 - \frac{k_x^2 c_o^2}{\omega^2}} \tag{3}$$

When $k_g = k_s = 0$ equation (1) reduces to the 1D frequency domain algorithm.

$$IM_\omega = \int_{-\infty}^{\infty} dz e^{i\frac{\omega}{c_0}z} b1(z) \int_{-\infty}^{z-\epsilon} dz' e^{-i\frac{\omega}{c_0}z'} b1(z') \int_{z'+\epsilon}^{\infty} dz'' e^{i\frac{\omega}{c_0}z''} b1(z'') \tag{4}$$

Equation (4) represents the 1D frequency domain internal multiple prediction formula, where the psuedo-depth $z = \frac{c_0 t}{2}$. The reference velocity c_0 is taken to be the velocity in the near surface, near the geophones. Epsilon is a parameter, setting the minimum distance two events must be separated in order to be combined.

Replacing $b_1(z)$ with $d(t)$ and z with t, equation (4) becomes,

$$IM_t = \int_{-\infty}^{\infty} dt e^{i\omega t} d(t) \int_{-\infty}^{t-\epsilon} dt' e^{-i\omega t'} d(t') \int_{t'+\epsilon}^{\infty} dt'' e^{i\omega t''} d(t'') \tag{5}$$

The product of the first and third integrals of equation (5) can be recognized as the product of two modified Fourier transforms over t and t''; therefore, this product represents a modified convolution. The second, integral being time reversed, represents a correlation; therefore, equation (5) represents the product of a modified convolution and a correlation, equation (5) then becomes,

$$IM_t = \int_{-\infty}^{\infty} dt' s(t'-t) \int_{\alpha(t,t')}^{\beta(t)} dt'' s(t'-t'') s(t'') \tag{6}$$

where,

$$\alpha(t,t') = t' - (t-\epsilon)$$
$$\beta(t) = t - \epsilon \tag{7}$$

Equation (6) is the 1D time domain prediction formula derived by Innanen (2015), equation (7) represents the limits of integration that forces the lower-higher-lower relationship. The integration limits of equation (6) can instead be invoked by a masking operator "O" consisting of two Heaviside step functions.

$$IM_t = \int_{-\infty}^{\infty} dt' s(t'-t) \int_{-\infty}^{\infty} dt'' [O(t,t',t'') s(t'-t'')] s(t'') \tag{8}$$

Where in equation (8),

$$O(t,t',t'') = H[t'' - \alpha(t,t')] H[\beta(t) - t''] \tag{9}$$

Let M_R be a correlation matrix of the trace, M_c be a convolution matrix of the trace, and "s" be the trace itself, then equation (8) in matrix notation becomes,

$$IM_t = M_R [O \circ M_c] s \tag{10}$$

where " $\circ$ " represents the Hadamard product of the masking matrix and convolution matrix. The masking matrix is a matrix that contains regions of ones and regions of zeros, therefore multiplying it by the convolution matrix results in a modified or partial convolution. Areas of the convolution matrix multiplied by a zero region of the masking matrix are not included in the convolution in a way that invokes the lower-high-lower relationship. The regional extent of the zeros and ones is determined by the limits $t'' = t' - (t - \epsilon)$ and $t'' = t - \epsilon$. For an in depth look at how the masking matrix is constructed refer to Innanen (2015).

Prediction on VSP data

As it turns out, zero-offset VSP data provides the perfect candidate dataset for application of 1D algorithms. The ease with which VSP data can be separated into its component downgoing and upgoing wavefields makes it easy to create a section that contains only primaries and internal multiples; the two event types needed for internal multiple prediction. The high-frequency nature of VSP data also puts fewer constraints on selection of the search limiting parameter epsilon in the algorithm. Each trace of a zero-offset VSP is essentially a zero offset, normal incidence trace, meaning that the data is well suited for the use of 1D prediction algorithms. In addition, internal multiples are typically identifiable from corridor stacks of VSP data (Lines and Newrick, (2004); Campbell et al., (2005)), thus providing a trace we can compare our predictions with.

SYNTHETIC EXAMPLE

We begin by assuming a zero offset vertical seismic profile obtained over horizontally layered, laterally homogenous geology.

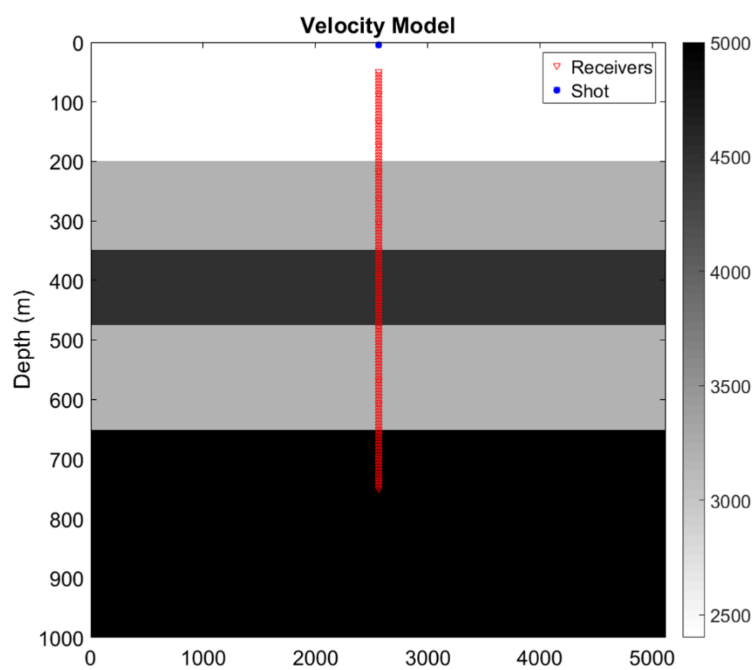

FIG. 1. Synthetic velocity model used to construct zero offset VSP, the red triangles represent the receiver locations (receiver spacing = 10m), blue circle indicates the shot location.

The velocity model in figure 1 was used to create the zero offset VSP dataset, this was accomplished using the CREWES function *afd_shotrec.m*, the data was constructed with a 70Hz ricker wavelet.

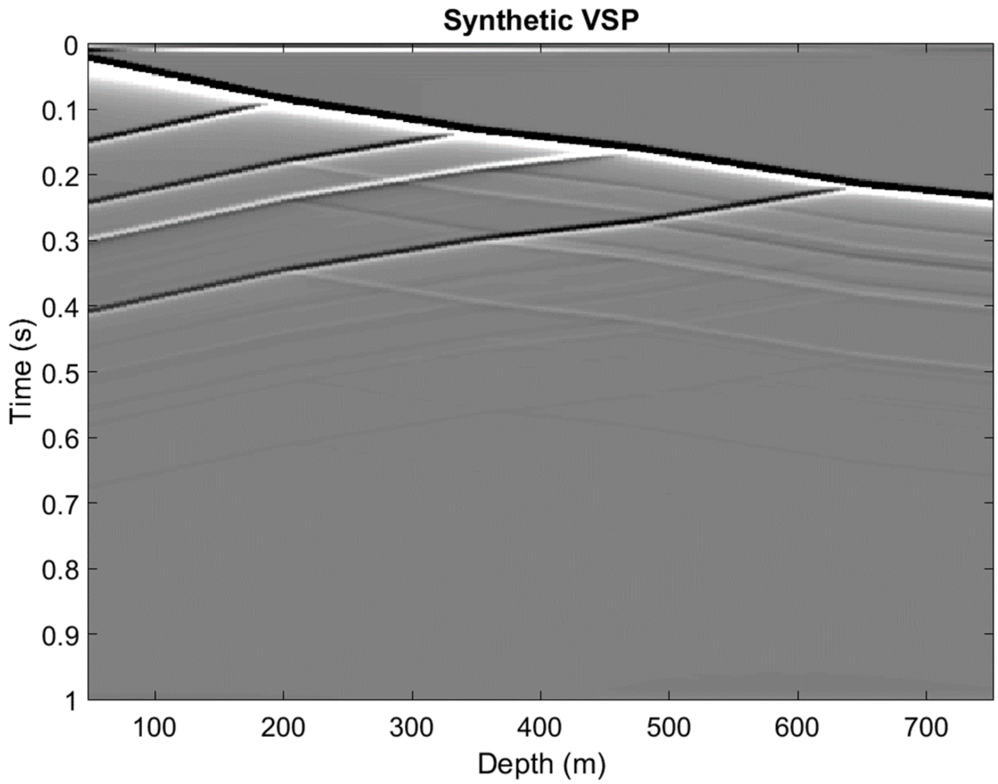

FIG. 2. Synthetic vertical seismic profile before processing.

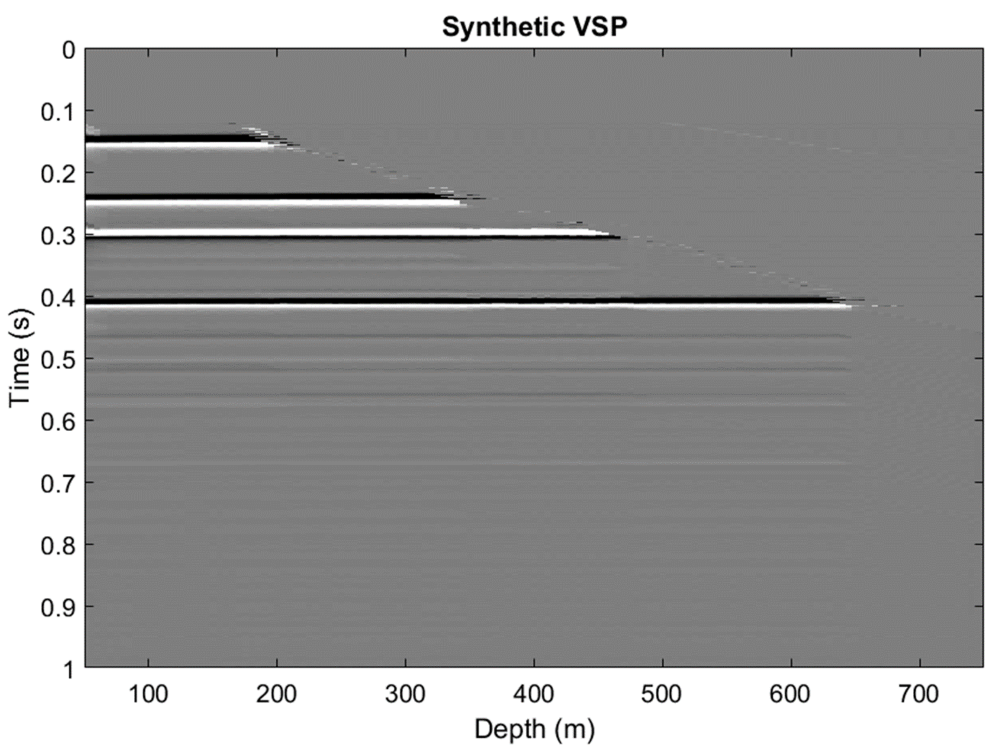

FIG. 3. Synthetic vertical seismic profile after processing.

Figure 2 shows the raw VSP dataset before any processing steps have been applied. It was noted in the previous section that the upgoing wavefield of the VSP data was a well-suited dataset for internal multiple prediction.

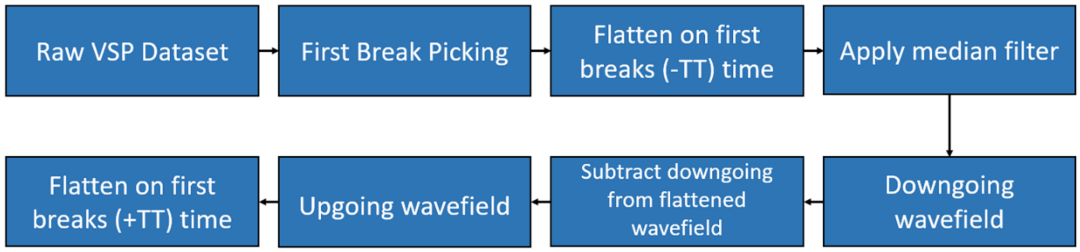

FIG. 4. Flow chart of the processing steps applied to go from figure 2 to figure 3.

Figure 4 represents a simplified form of the typical processing flow that is used to acquire the flattened upgoing wavefield from a raw VSP dataset. In this case a 9-point median filter was applied to acquire the downgoing wavefield. Figure 3 shows the resulting upgoing wavefield acquired by applying the above processing flow; containing only primaries and internal multiples. Multiples are easy to identify from the dataset in figure 3, the four brighter events are the primaries, while the fainter events represent multiples. In addition, multiples truncate at the same depth as their deepest generating interface, but arrive at later times, two such events are easily identifiable between 0.3 and 0.4 seconds.

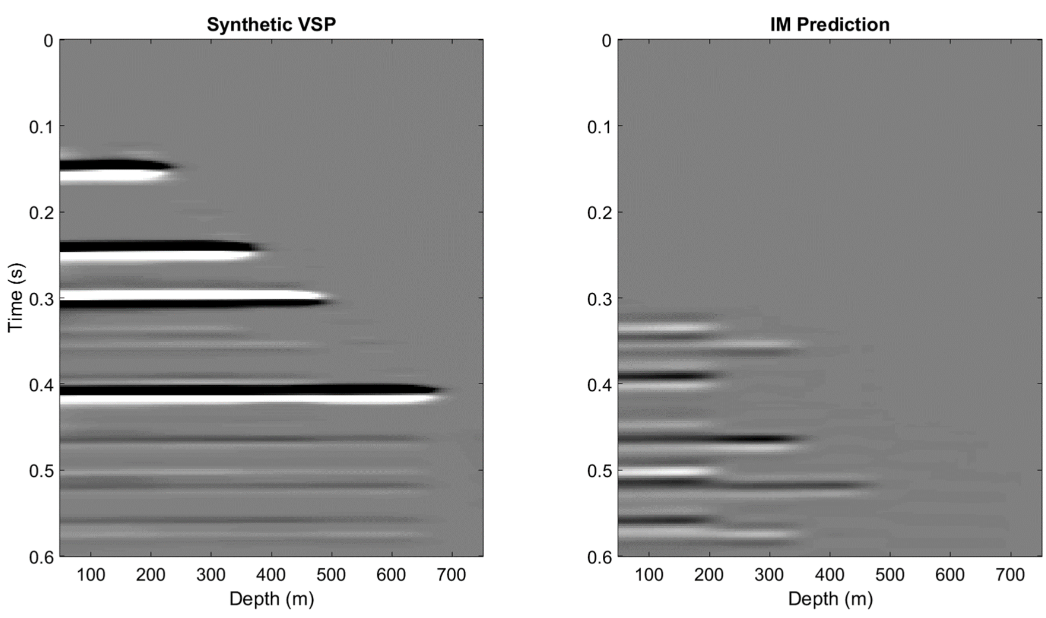

FIG. 5. Flattened upgoing wavefield (left), internal multiple prediction (right).

Figure 5 (left) shows the dataset of figure 3 restricted to the interval where most of the prominent internal multiples exist. Figure 5 (right) shows the resulting internal multiple prediction. Figure 6 below shows the same information as figure 5, however on the left plot a trace containing only primaries has been added to accentuate the primaries and multiples. On the right plot of figure 6, a trace has been added of only first order internal multiples to indicate how well the prediction has matched the actual multiples, in addition dashed blue lines representing the arrival times of primaries have been added to show that the algorithm has not erroneously predicted primaries.

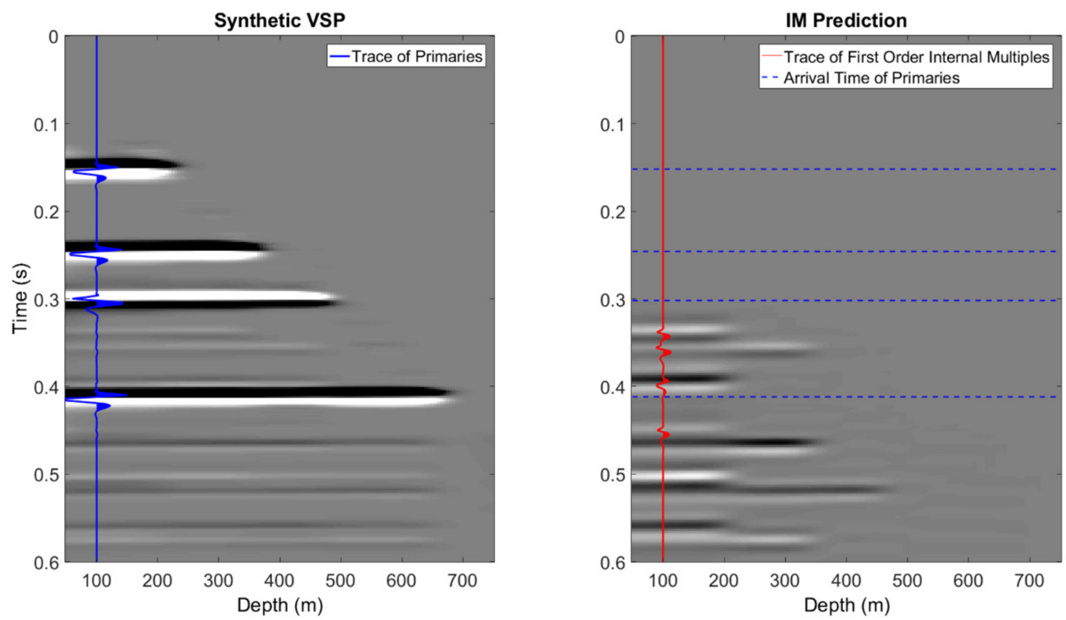

FIG. 6. Flattened upgoing wavefield (left), internal multiple prediction (right). The blue trace shows the trace containing only primaries, while the red trace shows the trace of first order internal multiples. The dashed blue lines indicated the arrival time of the primaries.

The predictions in figures 5 and 6 show a strong correlation between the actual and the predicted internal multiples. In addition, the primary events have not been predicted, even for the closely spaced multiple and primary around 0.4 seconds. The events that do not correlate with events in the red trace, are second order internal multiples. It was mentioned previously that VSP data provides a unique opportunity by providing an additional method of internal multiple prediction that helps to validate our result; corridor stacking. Looking at figure 3 it can be seen that multiples truncate at the same depth as their deepest generator, but at a later travel time. If we define a region that includes only events after the truncation of multiples and stack (sum) the data over this region, then we should acquire a primaries only trace; this is referred to an outside corridor stack. If we then stack over all traces, we will acquire a trace of primaries and multiples; this is referred to as inside corridor stacking. Comparing the two stacks, any points that do not agree between the two can be recognized to be internal multiples. This is a well understood method and has proven to provide accurate results, thus providing a trace to compare our multiple prediction to. The main issue with corridor stacking is that it only results in one trace, our method provides an entire section of predicted internal multiples.

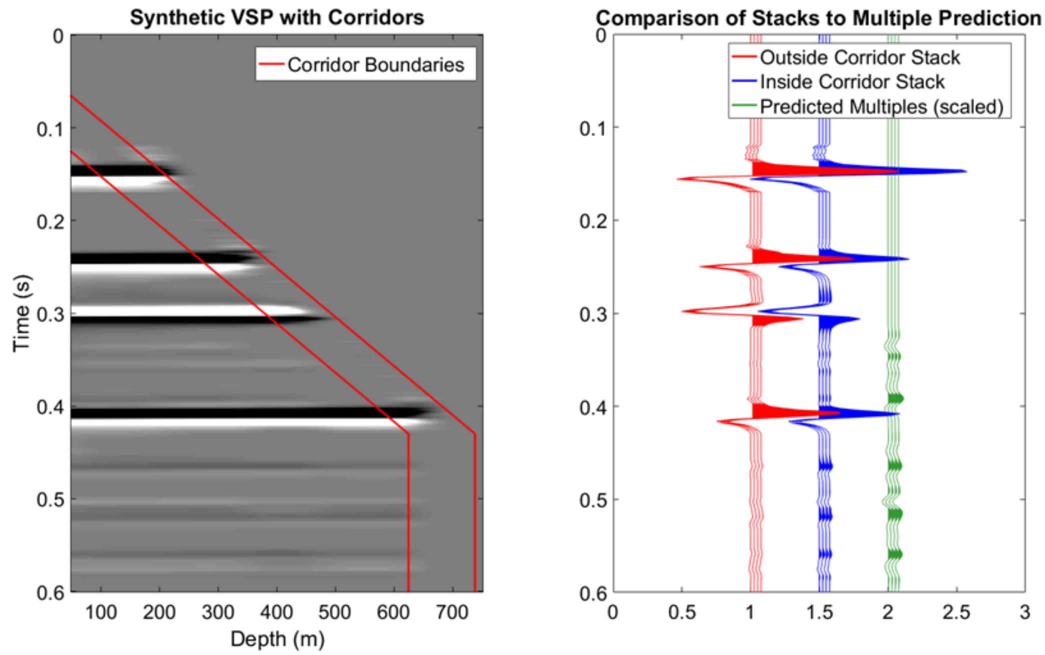

FIG. 7. VSP dataset with overlain corridors (left), outside corridor stack (red), inside corridor stack (blue), internal multiple prediction (scaled, green).

The two red lines in figure 7 (left) represent the chosen outside corridor for our dataset, the right image of figure 7 shows the outside corridor stack (red), inside corridor stack (blue), and a predicted internal multiples trace from a depth of 100 meters (green). Figure 7 (left) shows that the outside corridor stack should contain only primaries, while the inside corridor stack will contain both multiples and primaries. Therefore, any differences in the two can be interpreted to be multiples. This result means that we can compare our prediction to the inside corridor stack, and our resulting prediction should match the multiples in the stack. Figure 7 (right) shows that we have accurately predicted the traveltime of all the multiples, and approximately predicted the amplitudes. Furthermore, the outside corridor stack shows that we have not predicted primary energy.

One of the issues with predicting internal multiples from VSP data is event truncation. As discussed earlier, inverse scattering series internal multiple prediction searches through the data and combines events that obey a lower-higher-lower relationship. Looking at the VSP data in figure 3, as the section increases with depth we begin to lose events, we can say the events truncate. As VSP geophone strings are lowered down the hole, the geophones will pass interfaces, once all the geophones have passed a given interface, the response of that interface is no longer recorded. Furthermore, when a geophone lies directly at an interface the direct arrival and the reflection arrive at the exact same time, therefore events truncate exactly at the depth of the interface. Looking at figure 3, we see a multiple arrives at 0.33 seconds, this multiple being the first internal multiple must be generated by the first and second interface that creates them. This is further confirmed by the fact that the multiple truncates at the same depth as the second reflector. When this multiple is predicted the algorithm combines the traveltimes of the first and second reflector. However, we can see that the first reflector truncates far before the second one. After the first reflector truncates the multiple is no longer predicted as indicated by figure 5. Therefore, on VSP datasets we cannot predict multiples to their full lateral extent.

Extension to zero offset sections

We propose to artificially extend events past their truncation point so that we may accurately predict the multiples at every depth. This is realized by defining a window in depth, at a given time, and calculating the mean value over that window. This mean value is then injected at that given time for each depth value for which no data exists. In this way we transform our VSP data into a zero offset section.

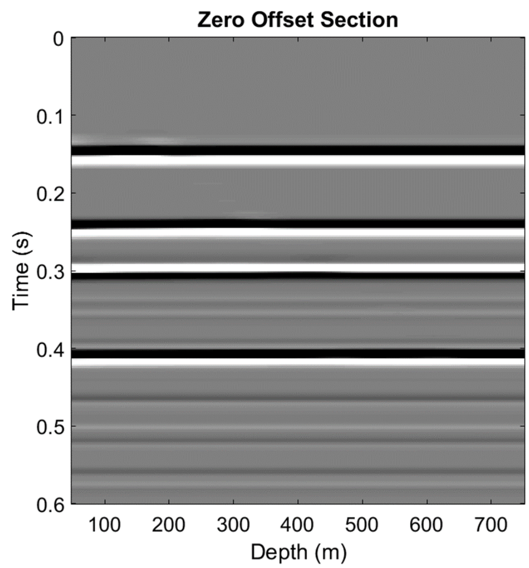

FIG. 8. Zero offset section

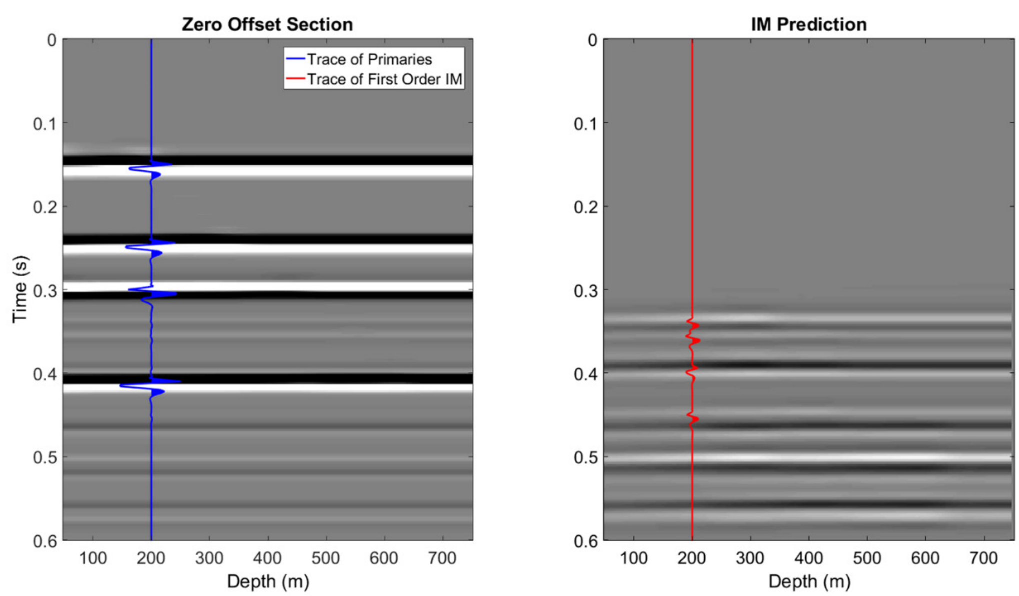

FIG. 9. Zero offset section (left), internal multiple prediction (right). The blue trace shows the trace containing only primaries, while the red trace shows the trace of first order internal multiples. The dashed blue lines indicated the arrival time of the primaries.

Figure 8 shows the results of extending the events laterally past their truncation point, creating a zero offset section. Figure 9 shows the result of the prediction from the zero offset section. The resulting prediction is just as accurate as was the prediction on the VSP data, however now the multiples are predicted correctly at all depths, the resulting section is more continuous, and easier to understand and interpret.

INTERNAL MULTIPLE PREDICTION ON ZERO OFFSET VSP LAND DATA

The zero-offset VSP dataset used in this paper was graciously provided by an anonymous company. Wu (2016) processed this VSP data set as a component of her MSc. thesis as a member of the CREWES project. The data set used represents the zero-offset VSP after first break analysis, wavefield separation, deconvolution, and NMO and static corrections. The downgoing wavefield was extracted by first flattening the data on the first breaks, then applying a 19-point median filter to remove the upgoing wavefield. The upgoing wavefield was then calculated by subtracting the downgoing wavefield from the flattened wavefield. Once the upgoing wavefield was extracted it was flattened by applying the +TT time correction (Lines and Newrick, 2004). For a detailed explanation of the entire VSP processing workflow, refer to Wu (2016).

It was indicated earlier that noise can be a major issue when predicting internal multiples, therefore it is important to reduce noise as much as possible before attempting to predict internal multiples. Figure 10 shows the VSP data set before filtering (left) and after the application of a high cut Butterworth filter with a corner frequency of 100 Hz, and an order of 3.

Figure 11 shows the amplitude spectrum of a 50 Hz Ricker wavelet (top), and the raw and filtered amplitude spectrums (middle, and bottom respectively). In addition to the previously discussed Butterworth filter, a notch filter was also applied to the anomalous spike around 140 Hz. It is evident from figures 10 and 11 that much of the noise has been removed from the data. Now that the separated upgoing wavefield has been filtered it is fully primed for the prediction of internal multiples.

For equation 10 to be fully realized on actual datasets, it must be carried out row by row. A companion paper (Eaid et al., 2016) in this CREWES report provides an in depth explanation of how to implement this algorithm in MatLab.

$$IM_t(j) = M_R(j,:)[O(t(j)) \circ M_c]s \tag{11}$$

Equation (11) is then repeated for every trace of the filtered data.

The search limiting parameter (ϵ) can be made to vary with time; that is, it can be made nonstationary. A simple scheme proposed by Innanen (2015) calculates the envelope of the trace, and then lets epsilon grow large for large values of the envelope, and smaller for small values of the envelope. When the envelope takes on a larger value it is assumed that the trace is dominated by primaries, epsilon then grows and the prediction becomes more cautious. The opposite is assumed at small envelope values and epsilon shrinks causing a more aggressive prediction. This is the scheme that was used in this example, epsilon was set to have a minimum value of 70 samples and was allowed to grow to a maximum of 210 samples.

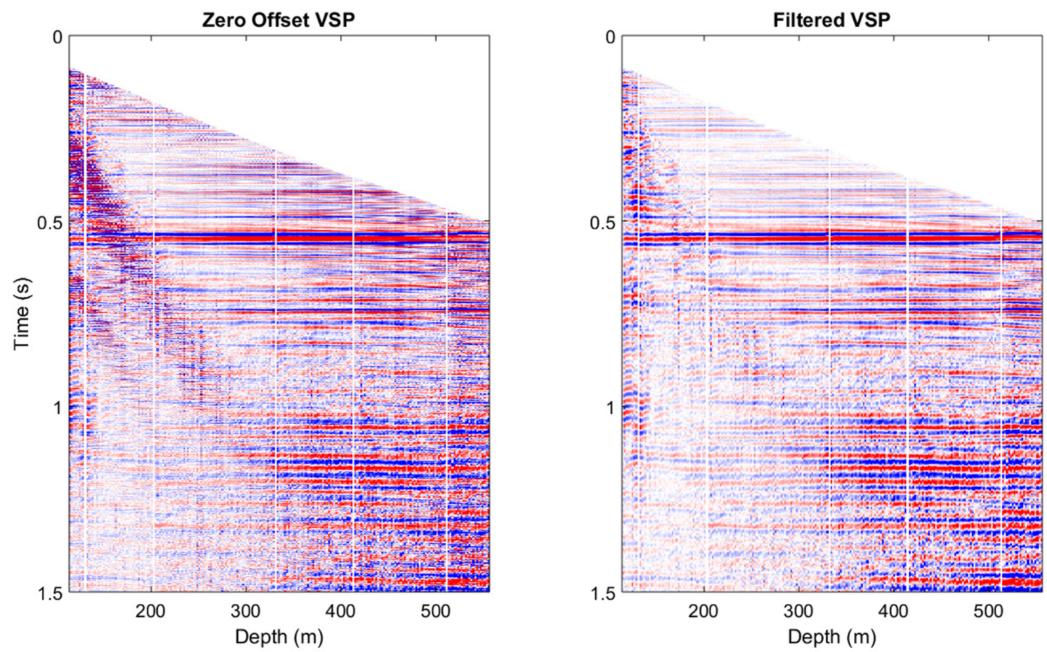

FIG. 10. Zero offset VSP data (left), and VSP data filtered with a high cut Butterworth filter (right).

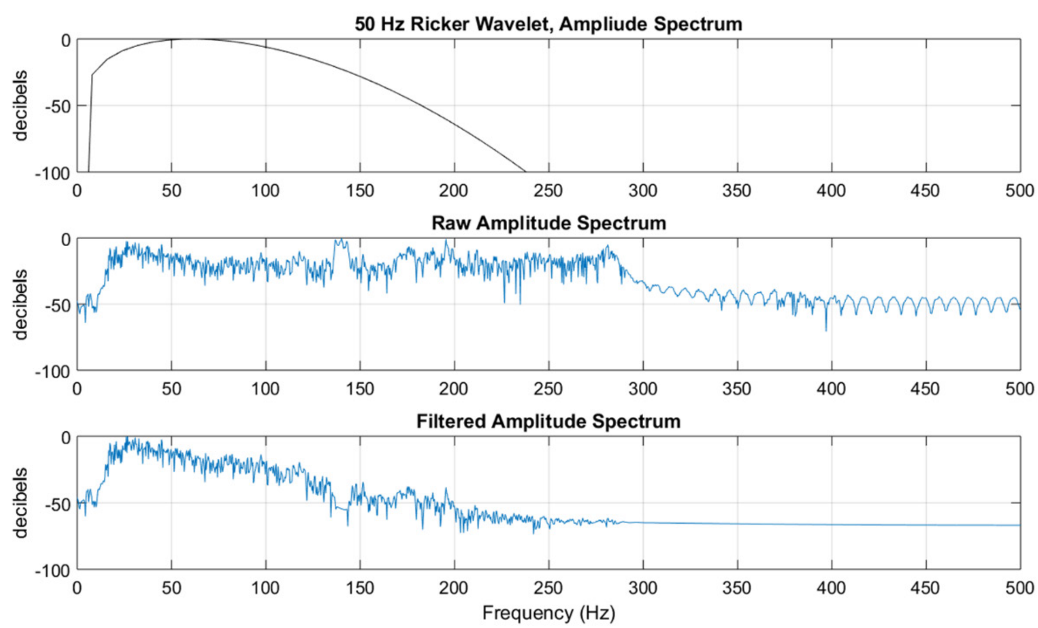

FIG. 11. The amplitude spectrum of a 50 Hz Ricker wavelet (top), amplitude spectrum of the unfiltered amplitude spectrum (middle), filtered amplitude spectrum (bottom).

Figure 12 shows the same filtered data of figure 10 on the left, and the resulting time domain internal multiple prediction on the right. Figure 13, below shows the result of carrying out the conversion to a zero offset section. The left image of figure 13 shows the newly created zero offset section, while the rightmost figure shows the new prediction carried out on the zero-offset section. Figure 14 below shows the two predictions as well as the difference section.

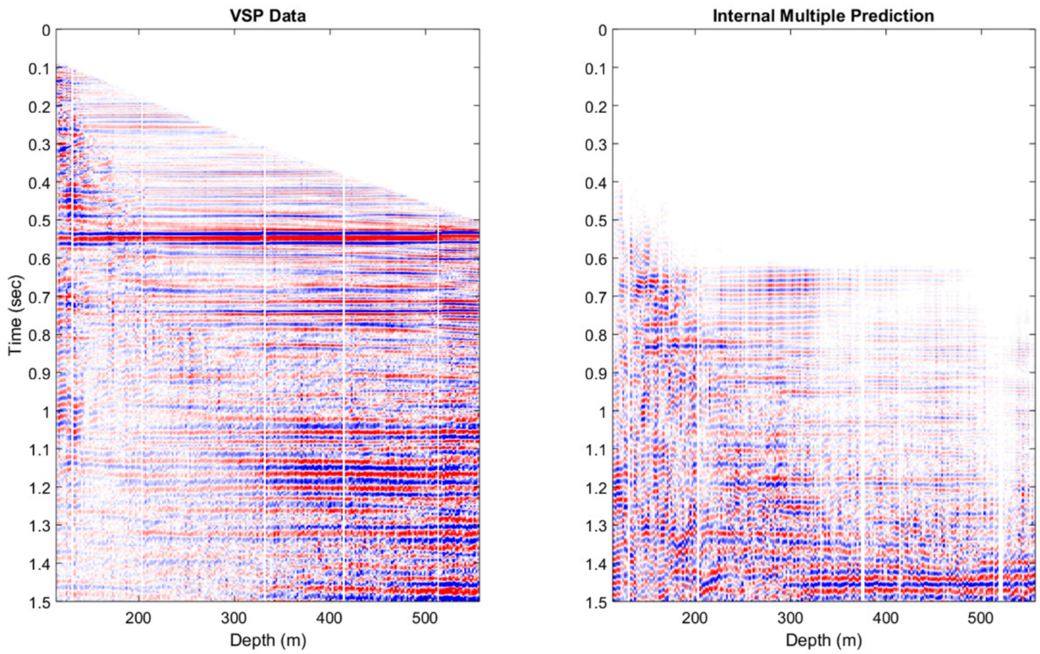

FIG. 12. Filtered zero-offset VSP data (left), time domain internal multiple prediction (right).

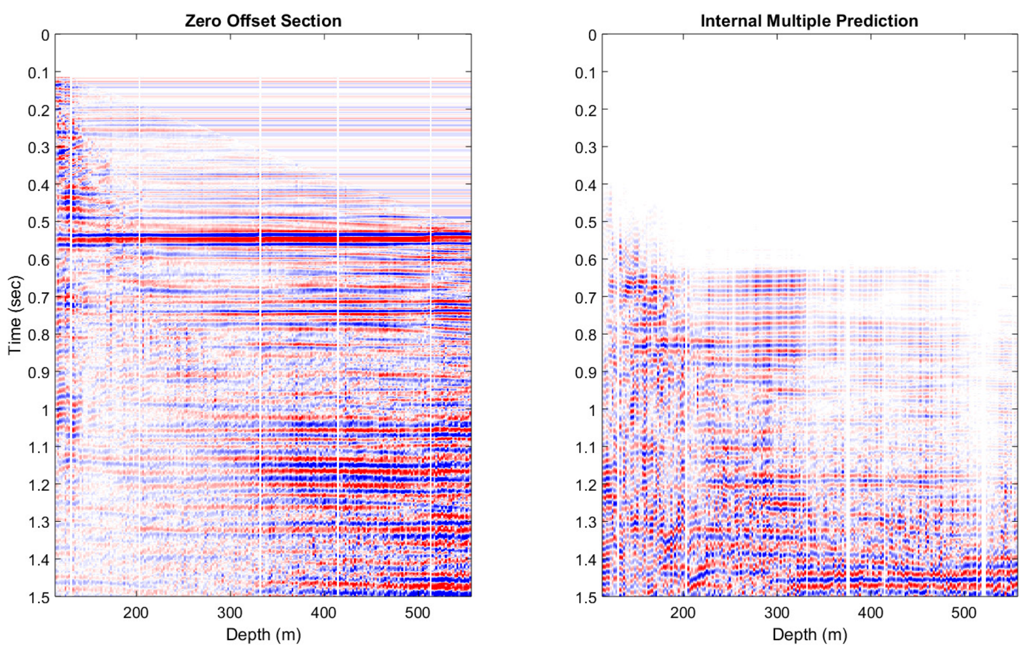

FIG. 13. Filtered zero offset section (left), time domain internal multiple prediction (right).

While the prediction of figures 12 and 13 are quite noisy, some bona fide multiples have been predicted. Significant multiple energy is predicted at approximately 0.85 seconds; this is similar to twice the travel time of the large primary at 0.55 seconds minus the traveltime of the primary at 0.25 seconds. In addition, the multiple energy around 0.65 seconds arrives at a traveltime that is similar to the traveltime of the primary at 0.55 seconds plus the traveltime of the primary at 0.375 seconds minus the traveltime of the primary at 0.25 seconds.

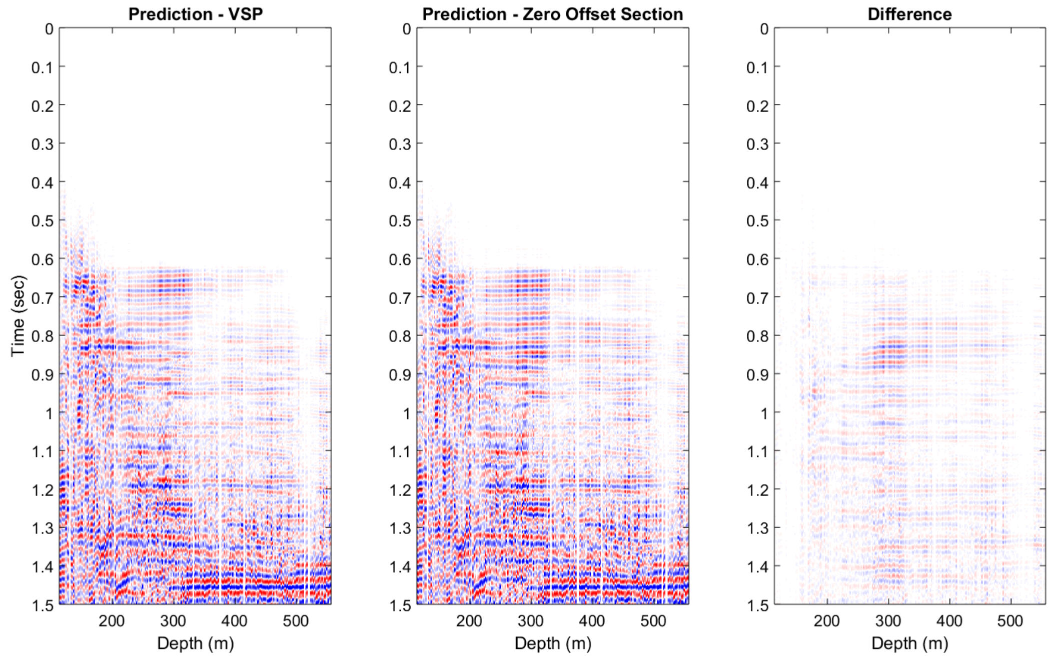

FIG. 14. Prediction from the VSP data of figure 12 (left), prediction from the zero-offset section of figure 13 (middle), and the difference section (right).

What is more is that when we extended the primary at 0.25 seconds we see more multiple energy predicted at depths greater than 300 meters at both 0.85 seconds and 0.65 seconds, as seen on the difference section. The primary at 0.25 seconds truncates around 300 meters so the fact that more multiple energy is predicted after 300 meters when we extend this event proves that it is a multiple generator for the energy at 0.85 seconds and 0.65 seconds.

CONCLUSIONS

In this paper, we review internal multiple prediction based on the inverse scattering series. A brief review of the time domain prediction algorithm introduced by Innanen (2015) is given and then an application to both synthetic and land data VSP examples are shown. A method for extending VSP events past their truncation depth is introduced, and then the prediction scheme is carried out. The difference between the predictions on the VSP and zero offset section are then compared.

Although the prediction on the land data is noisy, we have shown that it has predicted bona fide internal multiples. What is more impressive is that we have shown that by extending these events according to the workflow introduced here, the prediction is greatly improved at deeper traces, as indicated by figure 14.

FUTURE WORK

Future work will focus on applying adaptive subtraction to VSP predictions to see if the prediction can be further improved. We would also like to re-apply this workflow to a less noisy VSP to see if the prediction can be further improved. Another interesting line of research will be to use the outside corridor stack to guide the selection of epsilon.

ACKNOWLEDGEMENTS

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