Utilizing PSSP Waves

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ABSTRACT

While the interpretation of reflected P-waves on seismic data remains the main vehicle for seismic interpretation, there are other signals in seismic reflection recordings that can be fully utilized in seismic inversion. There are reflection signals that are due to the conversion of P-wave energy to S-wave energy in transmission followed by conversion from S-wave to P-wave upon reflection. These waves, known as PSSP waves, have significant amplitude and normal moveout NMO), and are seen on reflection records at wide offset . We model PSSP waves by ray tracing and finite-difference wave equation computations. While PSSP amplitudes are essentially zero at normal incidence for flat reflectors, their energy is considerable at larger offsets. Also, the PSSP energy for non-flat reflectors will generally be nonzero at zero offset. In addition to identification of the PSSP modes, there is the challenge of utilizing this energy for estimation of seismic velocities. While the NMO for PSSP arrivals allows it to be suppressed through stacking in imaging P-wave reflections, it is feasible that full waveform inversion could be implemented for utilizing the PSSP energy as useful signal rather than treating it as undesirable "noise".

INTRODUCTION

Conventional seismic processing and interpretation has traditionally involved the analysis of P-waves that have undergone a single reflection. Converted mode seismic arrivals will generally not be handled appropriately with conventional seismic processing methods.

However, seismic recordings may often contain converted mode signals as shown by the examples from Jones (2014). Jones showed that reflections from chalk formations contain not only P-wave reflections but contain useful converted wave arrivals (PPSP+PSPP, and PSSP) arrivals as well.

Recently, David Gray of Nexen has provided us with examples of events on seismic data from the Long Lake region that show reflection events with considerably more NMO than P-wave reflections. The vertical component of these seismic recordings have large NMO suggesting that these are waves that involve conversion from P to S energy.

In this study we develop a layered model based on blocking dipole sonic logs from the Long Lake area (Lines et al., 2010), and use this model in the computation of elastic wave synthetic seismograms. The synthetic seismograms utilize elastic wave finite-difference codes as described by Levander (1988) and asymptotic ray theory codes as developed by Daley and Krebes (2015).

These seismic modeling codes are used jointly to identify converted seismic modes such as PSSP. We confirm and predict the location of converted modes on reflection seismograms. Traditionally, the converted wave energy has often been suppressed in conventionally processed through NMO-stacking to enhance the P-wave energy. We discuss how we might utilize the PSSP energy and other converted modes through the process of full waveform inversion.

METHODOLOGY AND RESULTS

To appreciate the nature of purely P-wave reflections (such as PPPP) and converted wave arrivals (such as PSSP), we model these waves by using asymptotic ray tracing and finite-difference wave equation modeling. It is instructive to perform both types of modeling since ray tracing allows us to isolate reflection events whereas finite-difference (FD) wave equation modeling gives all arrivals generated by numerical solutions to the wave equation. The ray tracing helps us to identify arrivals on the FD seismograms.

Ray traced paths are governed by Snell's Law while the amplitudes can be computed by the asymptotic ray tracing amplitudes described by Cerveny and Ravindra (1971). For these wave paths, it is easiest to identify the modes on the wave equation calculations using ray tracing.

The model for P-wave and S-wave velocities in this study is based on the blocking of sonic logs from the Long Lake area, as shown in Lines et al. (2010). The model basically has 3 layers based on the blocking of sonic logs and is shown in Figure 3(a) for the P-wave velocity and Figure 3(b) for the S-wave velocity. This velocity model is summarized in the Table below and shown schematically in Figure 3(c).

Formation	Formation Top Depth	P-wave velocity	S-wave velocity	Density
Post-McMurray	0 m	2000 m/s	800 m/s	2.073 gm/cc
McMurray	120 m	2400 m/s	960 m/s	2.170 gm/cc
Devonian	190m	3500 m/s	1750 m/s	2384 gm/cc

Table 1. Three-layer model for seismic modeling based on Long Lake dipole sonics.

Figure 1 gives the PPPP reflections for P-waves that travel through the top 2 layers before being reflected from the base of McMurray – top of Devonian interface.

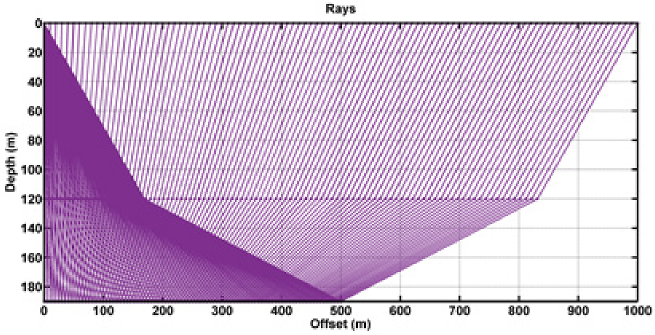


Figure 1. Reflected rays for the PPPP reflections from interface between layers 2 and 3.

Figure 2 gives the ray paths and traveltimes for PSSP waves. These are waves that pass through layer 1 as P-waves before being converted to S-waves in passing through layer 2 (McMurray) before being reflected from the top of the Devonian formation. These PSSP arrivals have considerably more NMO than the PPPP arrivals due to spending part of their journey as a lower velocity S-wave in layer 2.

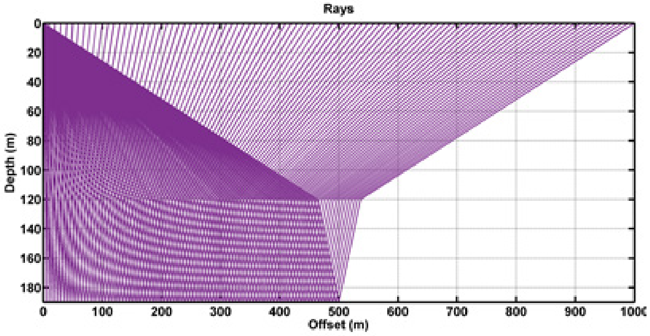


Figure 2. Reflected rays for the PSSP reflections from interface between layers 2 and 3.

Other converted waves of interest include the PSPP and the PPSP as shown in Figures 3 and 4. Both these waves spend only one part of their journey as S-waves in layer 2 – one wave (PSPP) has an S component on the way down and the other (PPSP) with an S component on the way up. Both waves will have exactly the same traveltime since the total distances are the same over ray paths lengths with the same velocity.

These waves will come in earlier than PSSP and will have NMO that is less than PSSP but greater than PPPP.

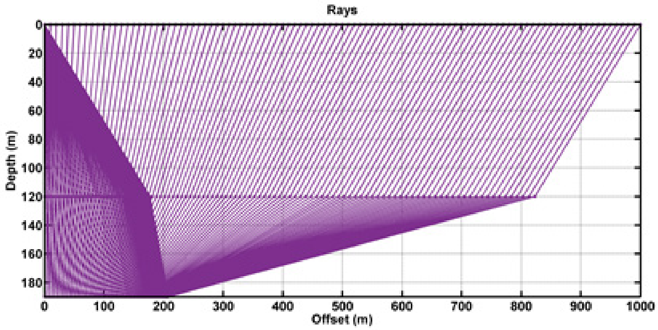


Figure 3. The PPSP rays for reflections from the interface between layers 2 and 3.

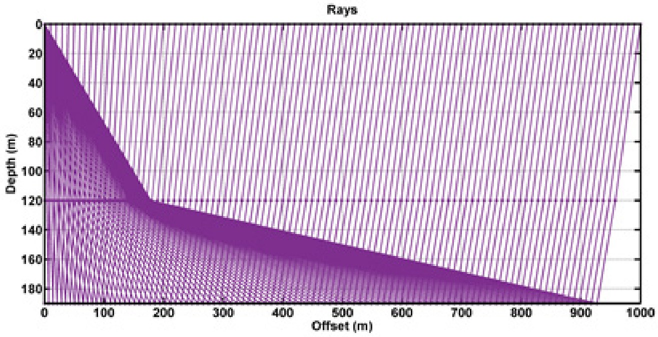


Figure 4. Ray paths for the PSPP reflections from the interface between layers 2 and 3.

We have computed the ray paths for the P-wave reflections (PPPP) and the various converted wave modes (PSSP, PPSP, PSPP). With ray reflectivity methods (Daley and Krebes, 2015), we can compute the amplitudes of converted modes. We do this for the recorded vertical component amplitudes. The converted wave amplitudes for PSSP and PSPP+PPSP are shown in Figure 5. As expected from the boundary conditions for 2-D elastic media, there is zero amplitude associated with converted waves for a normally incident wave on a flat boundary. Therefore, for source-receivers with zero offset, the amplitudes are zero for these normally incident waves. As seen in Figure 5, the amplitudes for the converted modes all increase with offset. We will now examine the seismograms for waves computed using FD wave equation calculations.

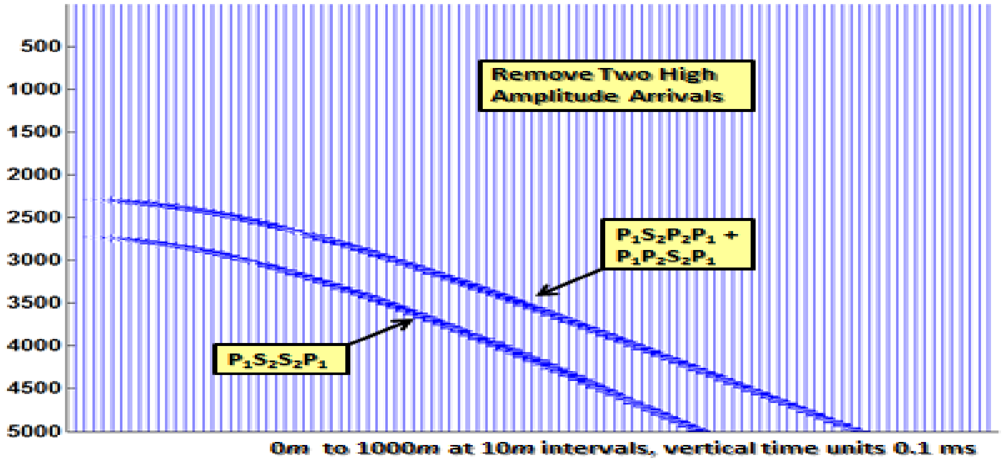


Figure 5. Ray reflectivity amplitudes for the converted wave modes as a function of offset for surface source. Range of traces is from 0-1000 m at 10m receiver intervals. Vertical time samples are in units of 0.1ms. Note the zero amplitudes at zero offset and the increase in amplitude with offset for both modes.

For modeling of P-SV waves, we use the 2-D modeling code for fourth-order finite-differencing of the wave equation, as described by Levander (1988) and modified by Luo and Schuster (1989 private communication). The complete mathematical description of the staggered grid calculations for this code are described in Levander's paper.

In order to upscale the reflections, we can choose to filter out the direct arrivals and head waves to emphasize the reflection events in the filtered seismogram of Figure 6. The PSSP event (labelled in this figure) has very dim amplitudes at near offset with reflection energy being strong at far offset. According to the ray trace and the FD wave equation modeling, the PSSP reflections have considerably more NMO than the P-wave reflections. The PSSP reflection amplitudes are dim at near offset but are strong at far offset for flat reflectors.

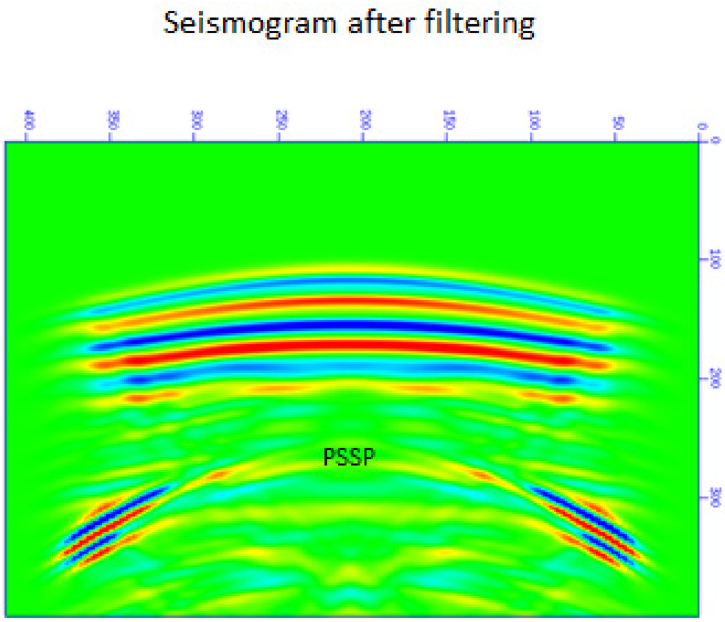
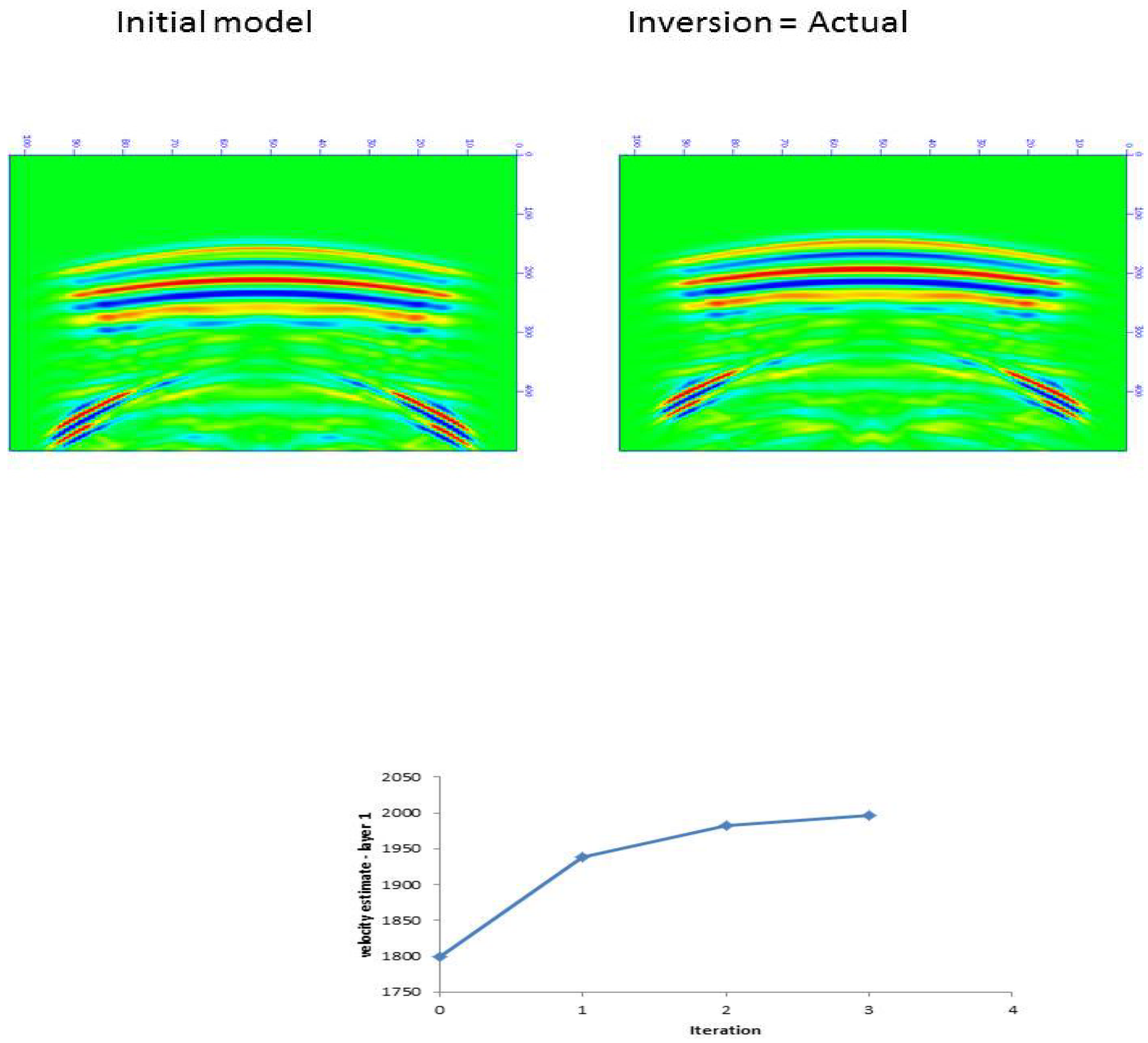


Figure 6. FD wave equation vertical component synthetic seismogram after filtering out the direct arrivals and head waves. Horizontal scale is in m for source at x=204 m and depth 40m. Vertical samples are in units of 1 ms. PSSP amplitudes build up with offset.

By showing how modeling has described the converted wave energy, including PSSP arrivals, we have actually developed to tools for utilizing this converted wave energy in an inversion. Full waveform inversion attempts to match all the model response values to the data values by adjusting the model parameters such as velocities. If **d** represents a vector containing data amplitudes and **f** represents a vector containing the model response values, we find the values of the model parameters, **x,** that will minimize the sum of squares of errors between **d** and **f** values, $S = \|\mathbf{d} - \mathbf{f}\|^2$ by setting $\frac{\partial S}{\partial x_j} = 0$ for all j. This FWI inversion technique was applied for seismic-Q estimation by Lines et al. (2014).

A simple example of FWI inversion for using the vertical component data in our problem is illustrated in Figure 7. For this example, we perform FWI on the synthetic data in Figure 6. In this example we start with a an initial velocity estimate for layers that is too small by 10%. That, is the P-wave velocity of layer 1 is estimated to be 1800 m/s rather than 2000 m/s. The model response of the initial model shown in the upper left part of Figure 7. The desired data seismogram is in Figure 6. By adjusting the velocity to minimize the difference between the model and data, the FWI inversion needs three iterations to adjust the velocity, as shown in the bottom part of Figure 7. After 3 iterations, FWI reaches the correct velocity and the converged model response, as shown in the upper right of Figure 7, which is virtually identical to the desired data result of Figure 6.

While this is a simplistic result, it would seem that the fitting of an elastic model to the data by an iterative FWI procedure should allow us to estimate the model velocities by fitting the P-wave and converted wave arrivals.



Initial model

Inversion = Actual

Figure 7. (Upper left) Initial model response for velocity error of 10%
(Upper right) Converged model. (Lower right) Velocity estimates and iteration to convergence – 3 iterations.

CONCLUSIONS

In wide offset seismic recording, there are seismic events of far offset recordings with significant amplitude NMO that are due to converted waves. These arrivals can be PSSP waves as predicted by ray tracing and wave equation modeling. While traditionally, these arrivals have been suppressed and treated as “noise” in conventional NMO stacks, it may be worthwhile to treat these converted waves as signal and use them in full waveform inversion to improve our Earth models.

ACKNOWLEDGEMENTS

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