Introduction

Besides primary P reflection waves, PS converted reflection waves from VSP data can also carry equally useful information on subsurface geology. However, due to the relative complexity of PS converted wave propagation, it is much more challenging to process and image PS converted reflection waves than conventional primary P reflection waves. The processing tools developed for PS converted reflection waves are still very limited. Here we first develop a normal moveout (NMO) correction for processing PS converted reflection waves in VSP data. We introduce two parameters \( V_c \) (PS converted wave NMO velocity) and \( \xi \) into the new three-term NMO formulation. Then, we use semblance coherence analysis on the VSP common receiver gather domain to search for the two parameters. That is, the PS converted reflection events are horizontally aligned and the coherent semblance-analysis coefficient is maximized after NMO correction. Through the synthetic example, we demonstrate that our PS NMO formulation is accurate for multi-layered media with a large source offset (up to a ratio of \( \sim 2.5 \) of offset to reflector depth) in VSP survey. Based on the new NMO correction formulation, we also develop a new methodology to improve signal to noise (S/N) ratio and the final imaging quality of PS converted reflection waves in VSP data. The methodology consists of three major processing steps in the common receiver gather domain: NMO correction for flattening/aligning PS converted wave reflection events, median filtering for attenuating coherent and incoherent noise, and reverse NMO correction prior to imaging. We use a field walkaway VSP dataset to demonstrate the effectiveness of our methodology in improving the imaging quality of PS converted reflection waves.

Methodology

**VSP PS converted reflection NMO formulation**

Due to the asymmetry of the conversion points of PS converted reflection waves, an exact analytical equation of PS NMO correction does not exist even for a single constant layer velocity model under both surface seismic and VSP survey geometries. A few approximation formulations for PS converted waves NMO correction have been developed in surface seismic (e.g. Yuen and Li 1998, Thomsen 1999). Based on these formulations and the principle of mirror symmetry of VSP survey to surface seismic survey (Lou and Simpson 2017), we have derived a three-term NMO correction approximation, shown as equation (1) for PS converted reflection waves in multiple layered media in VSP survey:

\[
t^2(x) = t^2_{c0} + \frac{x^2}{V_c^2} - \frac{\xi x^4}{4(\xi + 1)t^2_{c0} V_c^4 + \xi(\xi + 1)V_c^2 x^2}
\]  

(1)

where \( x \) is source offset to wellhead, \( t_{c0} \) is one-way zero-offset time summation of vertical P wave down to a reflector, and then converted S wave up from the reflector to a borehole receiver, \( V_c \) is PS converted reflection wave NMO velocity, and \( \xi \) is an coefficient related to ratio of P-wave velocity to S-wave velocity in the multi-layered media.

In the following Examples section, we show that the equation (1) is accurate for multi-layered media with a large source offset (up to ratio \( \sim 2.5 \) of offset to reflector depth) in VSP survey.

**Coherence semblance analysis to search for \( V_c \) and \( \xi \)**

We employ the coherence semblance analysis to search for the two parameters \( V_c \) and \( \xi \) in equation (1). That is, a coefficient of semblance analysis is maximized if a PS converted reflection event is correctly NMO corrected and flattened in a common receiver domain. The coefficient of semblance analysis is defined as:

\[
CE = \frac{1}{M} \sum_{i=1}^{M} \frac{\sum_{t=1}^{T} (f_{t(i)}}{\sum_{t=1}^{T} \sum_{i=1}^{M} f_{t(i)}}^2
\]

(2)

where \( f_{t(i)} \) is the amplitude value on the \( i^{th} \) trace at NMO corrected time \( t(i) \), \( M \) is the number of traces in a common receiver gather, and \( T \) is the window length of semblance analysis.
**Attenuating noise through VSP NMO correction**

Similar to primary P reflection wavefield, the upgoing PS converted wave reflection wavefield is often contaminated by numerous residual wave modes, refracted interface waves, and other random noise. The coherent or incoherent noise can result in severe migration artifacts and therefore degrade the final image quality of PS converted reflection waves. To compress/attenuate the noise, we utilize a three-step processing flow similar to P wave NMO correction (Lou and Simpson 2017) which consists of PS wave NMO correction, median filtering, and reverse PS wave NMO correction. After applying the NMO correction, the PS converted reflection events are approximately horizontally aligned. Therefore, we then can apply a median filter to attenuate/compress any unaligned coherent or incoherent noise. Finally, we employ a reverse NMO correction to the median-filtered wavefield prior to imaging. The effectiveness of this application in the field PS converted reflection wavefield has been demonstrated in the following Examples section.

**Examples**

We first test our PS converted reflection wave NMO correction equation using a four-layered model and a walkaway survey geometry shown in Figure 1. The walkaway survey geometry consists of 101 surface sources with an inter-shot spacing of 50 meters offset from -2500m to +2500 meters from the wellhead. Figure 2 shows the synthetic common-receiver gather of three PS converted reflection events from three interfaces (at depth 1000m, 1500m, and 2000m) received by a borehole receiver at depth 500m. Note that around zero offset the amplitudes of the synthetic PS converted waves diminish, as no conversion takes place at the zero offset. After applying the NMO correction equation (1), all the three PS converted reflection events are correctly aligned/flattened as shown in Figure 3. Figure 3 also demonstrates that the equation (1) is accurate up to at least ratio 2.5 of source offset to reflector depth.

To test the effectiveness of our methodology in attenuating noise, we have added random noise into

![Figure 1](image1.png)  
**Figure 1** A multi-layered model and a walkaway VSP survey geometry for synthetic PS converted reflection wave.

![Figure 2](image2.png)  
**Figure 2**. Three synthetic PS converted reflection events from the model and walkaway VSP survey geometry of Figure 1.

![Figure 3](image3.png)  
**Figure 3**. The three PS converted reflection events in Figure 2 flattened/aligned after applying the NMO correction equation.

![Figure 4](image4.png)  
**Figure 4**. Random noises added into the synthetic seismograms in Figure 2.
the synthetic PS converted reflection waves (Figure 4). After applying the NMO correction and then an eleven-points median filtering, the random noise has been largely reduced while the three PS converted reflection events have been flattened and preserved as shown in Figure 5. After reversing the NMO correction to the seismograms shown in Figure 5, the three PS converted reflection events shown as in Figure 6 have been restored to the correct position and compare very favorably with the pre-contamination state (Figure 2).

Moreover, we have used an offshore walkaway VSP field dataset to test the effectiveness of our methodology in attenuating noise and improving the imaging quality of PS converted reflection waves. The walkaway survey geometry is shown as in Figure 7, which consists of total 120 shots covering offsets from -4000m to +4000m, and 28 receivers with 15m interval positioned from depth 2680m to 3085m in a nearly vertical well. Figure 8 shows the PS converted wave reflection wavefield in a common receiver gather at depth 2680m after wavefield separation with parametric inversion. After applying the PS converted reflection wave NMO correction, the major PS converted reflection events in Figure 8 have been horizontally aligned as shown in Figure 9a. However, some noticeably coherent and incoherent random noise present in the separated PS reflection wavefield are not aligned. An eleven-point median filter was accordingly applied to the NMO corrected receiver gather to attenuate the unaligned noise. Figure 9b shows the median-filtered result of the receiver gather of Figure 9a, which clearly demonstrates a significant improvement of S/N ratio after the median filtering. For imaging the PS converted reflection wavefield, the reflection events in Figure 9b are reverse-NMO corrected as shown in Figure 9c. Finally, Figure 10 shows the Kirchhoff migration result of the PS converted reflection wavefield after the insertion into the corresponding surface seismic imaging section. Comparing the imaging result without (Figure 10a) and with (Figure 10b) attenuating the noise, the imaging quality of PS converted reflection waves has been significantly improved after applying our methodology. The two ovals in Figure 10 highlights the major improvement zone by showing better ties with the surface seismic and higher S/N ratio after attenuating the noise.

Figure 7 A nearly 2D walkway VSP survey geometry with 28 receivers and 120 shots offsetting from -4000m to +4000m. The receivers are positioned at a nearly vertical borehole from depth 2680m to 3085m with 15m interval.

Figure 8. The PS converted reflection wavefield in the common receiver domain at depth 2680m.
Conclusions

We have developed a new formulation of normal moveout (NMO) correction for PS converted reflection waves in VSP data. The formulation is accurate for multi-layered media with a large source offset (up to ratio ~2.5 of offset to reflector depth) in VSP survey. Based on the new NMO correction formulation, we also developed a new methodology to improve signal to noise (S/N) ratio and the final imaging quality of PS converted reflection waves in VSP data. The methodology consists of three major processing steps on common receiver gather domain: NMO correction for flattening/aligning PS converted wave reflection events, median filtering for attenuating coherent and incoherent noise, and reverse NMO correction prior to imaging. We use a field walkaway VSP dataset to demonstrate the effectiveness of our methodology in improving the imaging quality of PS converted reflection waves. The field data example shows that the imaging results of VSP PS converted reflection waves have better ties with surface seismic and higher S/N ratio after attenuating noise by using our methodology.

Acknowledgement

We thank Baker Hughes for the permission to publish this work.

References


Thomsen, L., 1999, Converted-wave reflection seismology over inhomogeneous anisotropic media, Geophysics, 59, 1,290-1,304.