Full Waveform Modelling for Subsurface Characterization with Converted-Wave Seismic Reflection: Residual PP Removal on PS Component Using $F-K$ Filter

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Abstract. The application of converted-wave seismic method in hydrocarbon exploration has increased significantly. Since the conventional seismic ceases to provide an adequate image in complex geology area and it often provides an ambiguous bright spot response. The main principle is that an incident P-wave produces reflected and converted P and SV wave on an interface. Converted-wave seismic uses the multicomponent receiver that records both of vertical component and horizontal component. The vertical component is assumed to correspond to the compressional PP wave and the horizontal correspond to the PS converted-wave. In this and previous research (Viony and Triyoso, 2018), a synthetic seismic data with the shallow gas and the salt dome model are constructed by the full-waveform modelling. The purpose of this study is to improve the imaging quality on the PS section and the PS AVO curve due to the existence of the residual PP events on the horizontal data in the previous study (Viony and Triyoso, 2018). The PS gather has been NMO corrected by the PP velocity. Therefore, the residual PP reflections are well-corrected and the PS reflections are under-corrected. To obtain the more reliable PS data, the residual PP reflections have been removed by rejecting the well-corrected data in $f-k$ filtering process. The results of this study present that the imaging quality and the AVO of the filtered PS is better and more reliable than the un-filtered PS in the previous study (Viony and Triyoso, 2018).

Keywords: AVO, converted-wave, $f-k$ filter, salt dome, shallow gas.

1. Introduction

The primary method in hydrocarbon exploration is the P-wave seismic reflection. Because the compressional wave usually has high signal-to-noise ratio, propagate faster in all environment, and easily generated by a variety of sources (Stewart et al., 1996). However, the P-wave survey ceases to provide adequate results in complex geology area and sometimes provide an ambiguous brightspot response. Different rocks and its saturant could have a similar P-wave response, therefore create indistinguishable PP images (Triyoso et al., 2017).

With the same P-wave frequency bandwidth, S-wave has a shorter wavelength. Therefore, the vertical resolution of the S-wave is higher than the P-wave. However, it is difficult to generate the S-wave and
it is vulnerable to be absorbed by the deep layer. Along with technological developments and increasing object complexity in hydrocarbon surveys, a new method known as converted-wave seismic exploration was discovered. This method has a principle of recording the propagation of converted-wave that derives from a down going P-wave which converted to an upgoing S-wave at a reflector point. This survey uses multicomponent receivers that capable to record seismic signals both on vertical and horizontal components.

This method successfully provides better information than conventional seismic surveys. The brightspot response generated from the conventional seismic survey still has ambiguity, whether brightspot is caused by pore fluid like gas or as the result of lithologic changes like coal. Both gas and coal could produce the brightspot response on conventional seismic image. But, unlike the converted-wave seismic which has a characteristic that is not sensitive to rock saturant, the brightspot ambiguity problem can be solved. In addition, usually the conventional seismic section cannot provide a good result in area under the gas cloud due to attenuation and diffraction. Shear wave is generally less sensitive to the rock saturant (Danbom & Domenico, 1986). This made the converted-wave capable to resolve the area bellow the gas cloud better than the conventional seismic did.

In the previous study (Viony and Triyoso, 2018), the converted-wave present that due to the existence of the shallow gas, the reflectors underneath especially the salt dome cannot be imaged by the conventional PP section, while the PS section can clearly produce the better image. It is because the diffraction and attenuation effect of P-wave while propagating through the gas column. For the shallow gas characterization, the PP AVO curve present the class 1 AVO anomaly. However, the PS AVO curve does not refer any anomaly because the S-wave is not sensitive to the existence of rock saturant.

In this paper, due to the existence of the residual PP events on the PS data, we will present the further process as an improvement to obtain the more reliable and the better PS image quality and PS AVO curve by removing the residual PP on the PS horizontal data.

2. Methodology
The aim of this study is to improve the imaging quality on the PS seismic section and to obtain the more reliable PS AVO curve for subsurface characterization, especially the effect of a shallow gas cloud existence. To achieve the goal, this study is divided to three main processes; full-waveform forward modelling, seismic data processing (including $f-k$ filter), and AVO analysis.

2.1 Full waveform forward modelling
Minimizing the high risk of hydrocarbon exploration, it is preferred to do the forward modelling first before doing the real acquisition to get the framework parameter for the best result. Synthetic model is used in this and the previous study (Viony and Triyoso, 2018) of the shallow gas with complex geology structure and the salt dome bellow the shallow gas zone (Figure 1). The configuration of shot geometry has 80 shot points and 181 geophone groups with split-spread geometry. Interval for each group and shot interval is 50 m, 25 m for near offset and 4525 m for far offset. The source wavelet is designed as a ricker wavelet which the dominant frequency is 15 Hz.

Simulation used 2D elastic modelling to generate the full waveform propagation from the sources to the receivers. The synthetic data contained vertical and horizontal particle velocity, normal stress and stress shift. The vertical particle velocity is merged to obtain the compressional PP gather data. While to get the converted-wave PS gather data, the horizontal particle velocity is merged. After obtaining the synthetic data, both of conventional PP and converted-wave PS seismic data are then processed.
2.2 Seismic data processing

Both vertical PP and horizontal PS converted-wave data processing is performed. Before processing the horizontal PS converted-wave data, the vertical PP has to be fully-processed first to get the value of RMS velocity. The RMS velocity from PP data is used to construct the initial PS velocity in horizontal processing. The workflow for processing the seismic data is showed in Figure 2.

![Figure 1. 2D synthetic model. Reproduced from Viony and Triyoso (2018, Fig. 3)](image)

**Figure 1.** 2D synthetic model. Reproduced from Viony and Triyoso (2018, Fig. 3)

**Figure 2.** The workflow of the PP and PS seismic data processing. Adapted from Viony and Triyoso (2018, Fig. 7)

Generally, both PP and PS processing have similar basic flows. Those are geometry assignment, preprocessing (trace muting and bandpass filtering), velocity analysis, etc. However, in PS processing there are some additional flows such as ACP binning, constructing PS initial velocity, reversing polarity, $f$-$k$ filtering and depth variant stacking. In ACP binning, an average $V_p/V_s$ value is estimated from the optimum ACP fold diagram (**Figure 3**). Then the $V_p/V_s$ is used to construct PS initial velocity from the RMS Velocity from PP data. Reversing polarity is a must due to the acquisition configuration in this study is a symmetrical split-spread. This makes the azimuth from the source to the receiver between the negative and positive offset differ by 180° and the polarity of these two offsets should differ by 180° (Hardage et al., 2011).
In the presence of the residual PP events in PS section between the two-way-time 600-800ms, $f-k$ filtering may be the solution to clear the PS section from the residual PP. The PS gather has been NMO corrected by the PP velocity. Therefore, the residual PP reflections are well-corrected and the PS reflections are under-corrected. To obtain the more reliable PS data, the residual PP reflections have been removed by rejecting the well-corrected data in $f-k$ filtering process. In ACP binning only one value of Vp/Vs is used, this makes the stack section is unfocused and unreliable. So, the flow of depth variant stacking is important to make a better image. In this step, Vp/Vs value of each layer is estimated using this following equation:

$$\frac{V_p}{V_s} = \frac{2T_{ps}}{T_{pp}} - 1$$

(1)

**Figure 3.** Comparison of ACP fold diagram for each Vp/Vs value. The red square shows the Vp/Vs value which is used in this study. Reproduced from Viony and Triyoso (2018, Fig. 8)

**Figure 4.** Comparison before (A) and after (B) $f-k$ filtering
2.3 AVO analysis
PP-PS simultaneous AVO analysis may improve estimation of rock properties by combining extracted attributes to yield fractional contrast in P-wave, S-wave and density, and discriminate between reservoir and non-productive lithology (Sun and Innanen, 2014). AVO analysis is done to characterize the shallow gas response in PP data and PS data. The synthetic well across the shallow gas is constructed to tie with the seismic data. Well data consists of Vp, Vs and density log. The flow of AVO analysis is followed by the flowchart in Figure 5.

Figure 5. Workflow for PP and PS AVO analysis. Adapted from Viony and Triyoso (2018, Fig.9)

3. Result and Discussion
3.1 Horizon Interpretation
Comparing the PS section with the PP section, there is a time delay in PS section. It is because S-wave takes a longer time to propagate through the layers than the P-wave. So, the same reflector occurred at different two-way-time in both PP and PS section. The gas anomaly response (brightspot) in PP section does not appear in PS section. It is because S-wave is not sensitive to fluids. Moreover, PS section can clearly image the reflectors below the gas zone especially the salt dome while PP section cannot provide a clear image of salt dome due to the attenuation and diffraction effect when P-wave propagates through the gas.

However, PS section still contains of some unexpected events such as the residual PP data. After applying the f-k filter, the PS section is relatively clear from the residual PP events (at two-way-time between 600-800ms). This provides a reliable image that can ease the better horizon interpretation and gas characterization.
3.2 AVO analysis

PP AVO curve from seismic data shows the consistency from the response of synthetic AVO curve for gas model and shows the opposite response from the brine synthetic AVO model. PP AVO curve present a class 1 AVO anomaly. However, in PS AVO especially the f-k filtered PS from seismic data, the curve relatively presents the better and more similar curve to both of brine and gas model than the unfiltered PS AVO curve, as the impact of the presence of the residual PP data on the unfiltered PS data.

Figure 7. (A) Synthetic PP AVO curve from well data for brine model. (B) Synthetic PP AVO curve from well data for gas saturated model. (C) AVO curve from PP seismic data. Reproduced from Viony and Triyoso (2018, Fig. 13)
4. Conclusion
In the presence of the residual PP events in PS horizontal section between the two-way-time 600-800ms in the previous study (Viony and Triyoso, 2018), application of f-k filter could be used to eliminate the residual PP component in the PS horizontal component. The more reliable result of both image quality of PP and PS could be produced as well as AVO curve. This concludes that f-k filter can effectively reject and remove the residual PP data on the PS horizontal component. Therefore, the more reliable and the better results diminish the ambiguity of horizon interpretation and gas characterization.

Reference
[1] Danbom, S. H. and Domenico, S. N., 1986. Shear-wave exploration. Society of Exploration Geophysicists.
[2] Hardage B.A., DeAngelo M.V., Murray P.E., SAVO D., 2011. Multicomponent seismic technology. Society of Exploration Geophysicists, Tulsa.
[3] Stewart, R. R., Gaiser, J. E., and Lawton, D. C., 1996. P-S Seismic Exploration: A mid term overview. CREWES Research Report 8.
[4] Sun, J. and Innanen, K., 2014. A review of converted wave AVO analysis. CREWES Research Report, 26.
[5] Triyoso, W., Oktariena, M., Sinaga, E., and Syaifuddin, F., 2017. Full waveform modelling for subsurface characterization with converted-wave seismic reflection. IOP Conference Series: Earth and Environmental Science, 62.
[6] Viony, N.C. and Triyoso, W., 2018. Study of converted-wave modelling: AVO application for shallow gas models. Jurnal Geofisika, 16(2), 19-24.