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Full Waveform Modelling for Subsurface Characterization with Converted-Wave Seismic Reflection

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Abstract. While a large number of reservoirs have been explored using P-waves seismic data, P-wave seismic survey ceases to provide adequate result in seismically and geologically challenging areas, like gas cloud, shallow drilling hazards, strong multiples, highly fractured, anisotropy. Most of these reservoir problems can be addressed using P and PS seismic data combination. Multicomponent seismic survey records both P-wave and S-wave unlike conventional survey that only records compressional P-wave. Under certain conditions, conventional energy source can be used to record P and PS data using the fact that compressional wave energy partly converts into shear waves at the reflector. Shear component can be recorded using down going P-wave and upcoming S-wave by placing a horizontal component geophone on the ocean floor. A synthetic model is created based on real data to analyze the effect of gas cloud existence to PP and PS wave reflections which has a similar characteristic to Sub-Volcanic imaging. The challenge within the multicomponent seismic is the different travel time between P-wave and S-wave, therefore the converted-wave seismic data should be processed with different approach. This research will provide a method to determine an optimum converted point known as Common Conversion Point (CCP) that can solve the Asymmetrical Conversion Point of PS data. The value of γ (Vp/Vs) is essential to estimate the right CCP that will be used in converted-wave seismic processing. This research will also continue to the advanced processing method of converted-wave seismic by applying Joint Inversion to PP&PS seismic. Joint Inversion is a simultaneous model-based inversion that estimates the P&S-wave impedance which are consistent with the PP&PS amplitude data. The result reveals a more complex structure mirrored in PS data below the gas cloud area. Through estimated γ section resulted from Joint Inversion, we receive a better imaging improvement below gas cloud area tribute to the converted-wave seismic as additional constrain.

1. Introduction
The presence of rock saturant will change elastic properties of the rock depending on the type and quantity of the pore fluid. Gas cloud existence prone to contribute in bad imaging of the conventional P-wave seismic below the gas cloud area. Similar characteristic also found in Sub-Volcanic imaging, both gas cloud and Sub-Volcanic triggers an imaging quality degradation caused by energy scattering and attenuation in its high-contrast velocity zone. When conventional P-wave surveying fails to provide adequate seismic image, additional S-wave data might be just the solution. Shear wave is generally less sensitive to the rock saturant [1], so it is possible to use S-wave surveying to penetrate this gas cloud layer.

There are several ways to obtain shear wave information from seismic data. The easiest way and certainly cost less is by using multicomponent seismic survey. As the source was compressional, multicomponent seismic survey allows propagation of converted-wave or PS images that derives from a downgoing P-wave which converting to an upgoing S-wave at the reflector point. The PS data is the
key to assist conventional PP seismic imaging in case such as gas cloud. By reducing ambiguities in PP seismic, multicomponent data assist in creating more accurate evaluation of imaging through gas cloud [2]. The PS seismic data provides highly improved subsurface imaging as compared to conventional P-wave data. Different rocks and its saturant could have a similar P-wave response, therefore create indistinguishable PP images. The joint usage of S-wave and P-wave seismic could help to characterize the rock structure, lithology type, and pore fluid [3]. Acknowledging this common practice, most of the unconventional reservoir problems are handled by P and PS seismic data. This combination is going to be a standard tool for subsurface imaging of challenging reservoirs.

However, there are several stumbling blocks that hinder a widely use of PS seismic data in assisting conventional PP datasets. The most prominent problem is related to the different event times between PP and PS seismic data. Although both of them derived from a same reflector, PP and PS seismic data show different reflectivity at different time. This condition leads to the necessity of applying different approach both in converted wave seismic processing and also in its further use in aiding conventional PP seismic data for reservoir characterization purpose. This paper will present a series of tricky processing flows for multicomponent seismic data, also the benefit of using converted-wave seismic in assisting conventional PP seismic data to solve seismic imaging below gas cloud area through Joint Inversion process.

2. Methodology
This research is intended to better understand the converted-wave seismic reflection using Full Waveform Modelling starts from the converted-wave seismic data processing to the application for reservoir characterization through Joint Inversion of PP-PS seismic data stack. To achieve this objective, the study is comprised into three main focus of workflow as described below.

2.1. Full Waveform Modelling
Full waveform simulation in seismic study is a common method to use in learning about seismic wave propagation through layered medium. For such a high risk reservoir, it is preferred to do modeling first before the real acquisition done in order to get the best design parameter for maximum result. Seismic data used in this research is a synthetic data derived from a real case of gas cloud recorded in its well log data. The purpose of modeling is to get better knowledge about wave propagation of seismic converted-wave with full wave seismic simulation. This modeling process used 2D approach to simulate converted-wave propagation and to produce synthetic data which consist of two-component receiver – vertical and horizontal component. The model builds using velocity model recreated from seismic velocity picking model of a real converted-wave seismic data processing. The velocity model consists of P-wave velocity model and S-wave velocity model of seismic line GOG004 crossing well ALPHA-01. The full model created by extracting the correlation between density and P-wave from the well log data and applying the correlation to create the low-frequency subsurface model (Figure 1). The presence of P-wave velocity decreasing is shown in the model relating to the purpose of this modeling that intend to study about the effect of seismic imaging below gas cloud zone.

The simulation shoots using elastic wave. The configuration of shooting geometry has 153 point shot numbers. The receiver uses 161 geophones with split-spread geometry. Each group interval ranges 25 m and 50 m for the shoot interval. The synthetic shot gather data of the full wave modelling is recorded in two components. They are vertical and horizontal component. Each component addresses a different purposes. The vertical component which common in conventional seismic reflection method is used for PP velocity analysis in the converted-wave seismic processing. The horizontal component is where the converted wave or PS seismic data well-recorded. After synthetic data is created, it is time to move on to next stage of this research, the converted-wave seismic data processing.
2.2. Converted-Wave Seismic Data Processing

A series of processing flows for both vertical component (PP) and radial component (PS) are applied to synthetic line GOG004. Among several purposes of this step, one of them is to eliminate the event time difference between PP and PS seismic data. Several assumptions are made in this 2D converted wave processing. First assumption, both PP and PS seismic data have the same geometry. Second assumption, in order to provide the final PP RMS Velocity, the vertical component (PP) should already fully-processed before converted-wave seismic processing begins.

The processing flow will be focused on providing more reliable estimation of Vp/Vs value through Asymptotic Conversion Point (ACP) Binning for each input of Vp/Vs. The next step is to register the PP RMS Velocity into the PS Data that are already processed through the ACP Binning. The general processing workflow are shown in Figure 2 below.

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**Figure 1.** P-wave and S-wave velocity model is taken from converted-wave PSDM seismic processing. Subsurface model building is more reliable derived from shear wave velocity with adjustment in the near surface low velocity anomaly to support this research objective.

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**Figure 2.** General processing workflow for PP and PS seismic data processing.
The processing flow between the PP and PS data are focusing on similar basic sequences, such as Geometry Assignment, Velocity Analysis, Pre-processing, Final Velocity Analysis, Stacking, and Post-Stack Time Migration. Additional sequences for PS processing are ACP binning and Converted-Wave Stacking. The reflection point of PS data is not at the Common Mid-Point (CMP) like in conventional PP seismic data. In order to predict the PS reflection point, converted-wave processing uses Asymptotic Conversion Point. In this step, an estimation of Vp/Vs is essential in order to investigate the Common Conversion Point (CCP) Fold. Arguably the optimum CCP Fold achieved at Vp/Vs value of 2.2 as shown in Figure 3 below. The later step is the extraction of RMS velocity from the PP Data which will be registered and applied into the PS data.

![Figure 3. Comparison ACP Fold for each value of Vp/Vs](image)

2.3. Joint Inversion of PP-PS Seismic Data Stack

There are several practical difficulties that should be addressed before applying Joint Inversion method to PP and PS seismic data. First and foremost is the need to ensure that the PP and PS reflections that will be combined in the inversion model coming from the same reflection point below the earth surface. This problem already addressed in converted-wave seismic data processing and would be furthermore enhanced the accuracy during Joint Inversion process.

Joint Inversion is an inversion that runs simultaneously. It is a model-based inversion that estimates the P- and S-wave impedance sections that are consistent with the PP and PS amplitude data [4]. The objective of simultaneous inversion is to invert directly from several seismic traces to multiple inverted results. The process also includes some form of coupling between the input variables [5]. Coupling of the PP and the PS data is based on the fact that the S-impedance and the density should be related to the P-impedance [6]. There are several conditions that should be fulfilled to ensure that the input data is suitable for the Joint Inversion process. First, the input data must have the same number of trace and geometry position. Second, the PP and PS seismic must be carefully processed preserving the amplitudes and using a valid velocity volume.

There are two step of the Joint Inversion process that need a special attention. Part one is Domain Conversion. The purpose of Domain Conversion is to ensure that both seismic sections are matching well before joining the two different domain data into one model in the next step. The Domain Conversion of the PS data to PP time is initially based on assumed Vp/Vs ratio of 2. Since this ratio does not represent the actual velocity structure, the converted PS data does not properly align with the PP data. Therefore, we correlate the P and PS well logs with the seismic data in the PP and PS domain and use the well velocities to correctly define the relationship between the two datasets to bring them into alignment at the well location. Part two is Joint Model Building. The purpose of Joint Model Building is to build a joint model from the two PP and PS domains and perform a Model Based Inversion that delivers results which are consistent with the PP - PS seismic amplitude volumes. The step by step procedure of Joint Inversion workflow is shown through Figure 4.
Figure 4. Flowchart shows the Joint Inversion PP-PS seismic workflow used in this research.

3. Results and Discussions
A comparison between the final stack of PP and PS seismic processing is needed to analyze whether these methods work in PS seismic processing. PP and PS Data is similar and suitable to be compared as shown in Figure 5 below. The effect of gas cloud is well-captured on synthetic PP seismic data. This phenomenon reducing the quality of the seismic image sub-layers below the accumulation, which is in term of structural image fault plane become blur and in term of amplitude level become shadowed as it is effected by presence of gas accumulation. Reflections from interfaces within and below the gas-charged channels are extremely poor on the stacked P-wave section, exhibiting reverberations and attenuation of high frequencies. As shown in Figure 5, amplitude level of the horizontal component show weaker than vertical component by comparison of the synthetic data.

The PS Seismic data could shows subsurface layering image more clearly. Notice the complex structure of seismic waves shown in each data circled with yellow line. The presence of the gas cloud does not affect the quality of seismic image. In term of structural image, PS seismic data could show discontinuity better than PP seismic data. The amplitude level of the PS seismic data shows more balance compare to PP seismic data in term of capturing the lithology contrast. The PS Data is better in the shallow time domain, and the PP Data is the opposite. This result is aligned with the fact that the PP seismic data has a higher energy level than the PS seismic data. The PP seismic stack appears more low frequency than the PS seismic stack which has a noticeably richer in number of event aspect as well as the ability to define structural edges despite the presence of gas cloud.
Figure 5. Comparison between PP and PS Processing results before migration. Notice the differences in structure details between PP and PS Data inside the dashed yellow circle.

The superiority of PS seismic data imaging is further proofed through the impedance result (Figure 6). While P-impedance section appears coherent as a flat layer cake around fault area below gas cloud zone, S-impedance section shows a sub-layer imaging that is quite similar to the synthetic model in term of discontinuity position. This is the main reason of the resulted Vp/Vs section more similar appearance to the S-impedance section rather than the P-impedance section. The S-impedance section achieves a better resolution and contains higher frequency content compared to the P-impedance section. This result shows that the S-impedance obtained through converted-wave datasets could be a useful alternative to assist P-impedance when it fails to map subsurface because of challenging phenomenon such as gas cloud or sub-volcanic. Vp/Vs ratio result from Joint Inversion also compared to Independent Inversion result (Figure 7) to showcase the benefit in simultaneously involved the converted-wave seismic through parameter estimation and calculation process. The main different between Independent Inversion and Joint Inversion located on the method of producing inverted PS Seismic Section. The Independent Inversion creates S-Impedance by secondary approach based on Acoustic Impedance inversion. The Joint Inversion creates S-Impedance by dealing Well-to-Seismic Tie directly in PS Domain and creating a model that involved the PS Seismic Stack on the building process. So, it is inevitable that the result from Joint Inversion, particularly the Vp/Vs section shows a better delineation and value stability tribute to the converted-wave seismic data complementing the conventional PP seismic data.

Figure 6. Comparison of impedance section from Joint and Independent Inversion. The critical area which is prone to imaging degradation triggered by gas cloud existence is pointed by the yellow arrow.
Figure 7. The variable coupling between Vp, Vs, and density which build the initial model of Joint Inversion results in a more stable Vp/Vs value, better delineation (pointed by black arrows), and the ability to define a clearer structural images compared to result from Independent Inversion. As can be seen through dashed black line, Joint Inversion could distinguish an additional fault planes sharply.

4. Conclusions

Answering the seismically and geology challenging area, the converted-wave seismic is just the right alternative in aiding the conventional PP seismic image which is sensitive to the rock characteristic and its saturant. The different in event time also reflectivity characteristic between the PP and PS seismic data sure is deemed to be a setback but not impossible to break through in order to enjoy the benefit of clearer seismic imaging. Through a full waveform modelling, the synthetic PP and PS seismic data shows that the PP seismic image is heavily affected by the presence of gas cloud while the PS seismic image shows a sharp fault boundary and more event recorded despite of having a same gas cloud problem as the PP seismic image. Although the converted-wave seismic data processing could be quite tricky because a different calculation of travel time between downgoing P-waves and upgoing S-waves, the Asymptotic Conversion Point Binning is helpful to accommodate the PS seismic data aligned with the PP seismic data. Joint Inversion method is applied in order to reap the superiority of PS seismic imaging by inverted it simultaneously with the PP seismic data. Using the fact that the PS seismic data related to PP seismic data, the Joint Inversion result creates a better imaging in delineation and stability value aspect compared to Independent Inversion.

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