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# Full Waveform Modelling for Converted Waves Seismic Reflections in Mountainous and Marine Environment

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**Abstract**

The application of seismic waves allows us to achieve adequate results by compressional wave (P-wave) surveys alone. However, in the presence of gas P-wave transmission disrupts and obscures underlying targets. Many reservoirs don't present sufficient impedance contrast to the overburden and not reflect P-wave strongly to produce an impedance image. High impedance rock such as basalt or hard volcanic rocks are difficult to image with P-wave. To overcome these challenges shear-wave (S-wave) or converted wave (P-S) surveys are used for last 20 years by making the use of down going P waves converting to upcoming S waves at the mode conversion boundaries. The processing of converted waves requires studying asymmetric reflection at the conversion point, difference in geometries and conditions of source and receiver, and the partitioning of energy into orthogonally polarized components. Interpretation of P-S sections incorporates the identification of P-S waves, full waveform modelling, correlation with P-wave sections and depth migration.

The objectives of this study is to model P-S wave reflections in onshore and offshore environment and to examine the major differences in processing of P and P-S wave surveys together with the identifying converted mode reflections by P-wave sources in anisotropic media. To achieve these, realistic mountainous and marine environment models have been developed and synthetic seismograms are generated by full waveform modelling technique. First a mountain foothill model was studied. A Kirchhoff-based technique that includes anisotropic velocities is used for depth migration of P-S waves. The results from depth imaging show that P-S section help in distinguishing amplitude associated with hydrocarbons from those caused by localized stratigraphic changes. Marine model shows a good correlation with identified converted waves. In addition, the full waveform elastic modelling proves useful in finding an appropriate balance between capturing high-quality P-wave data as well as P-S data challenges in a survey.

**Key Words:** Converted-waves (P-S); P-S Wave; Kirchhoff migration; Depth migration; Gas clouds; Shale diapers

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## INTRODUCTION

Conventional single component recording seismic methods have been widely used for hydrocarbon exploration since more than 70 years. A large number of conventional and unconventional reservoirs have been identified using 2D-3D P waves seismic data. But P wave seismic survey fails to provide better and adequate results in seismically and geologically challenging areas like shallow gas chimney, shallow drilling hazards, strong multiples, highly fractured, fluid discrimination, anisotropy etc. Most of these reservoir problems can be addressed using P and PS seismic data together. Therefore, additional shear wave data is required to overcome these challenges and many E& P companies discovered huge reservoirs based on the PP and PS datasets.

Multicomponent seismic survey records both P wave and S wave unlike only compressional-P wave in conventional survey. Under certain conditions, conventional energy source can be used for recording P and PS data using the fact that compressional (P) 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. Multicomponent ocean bottom cables (OBC) can be used to record PS data in marine environment[1]. These waves are called converted waves (PS). The direct measurement of shear waves in ocean studies has been attempted by several methods, mainly using ocean bottom seismometers (OBSs) and ocean bottom cables (OBCs), which consist of four components, each case includes a three component geophone (3C) and a hydrophone. Using OBCs have certain shortcomings, such as distortion of the shear wave component by the cable, non-coupling of the geophone to the ground in rugged terrain, drifting of the ship in rough seas, and higher expense. Some scientific organizations, therefore, have been using OBS data for the past two decades and have obtained promising results for deep marine environments[2-5]. OBS receivers also allow the recording of wide azimuth P wave data, thereby overcoming a major limitation of existing 3D practice. Since both the seismic source and the geology create a large variety of wave types, full multi component seismic recording and analysis techniques are needed to disentangle and use all of the seismic information available. By reducing ambiguities in interpretation, multi component data promotes an improved and more accurate evaluation of gas deposits[6,7]. P-S seismic data provides highly improved subsurface imaging as compared to conventional P wave data. Unlike P–waves, Shear wave is insensitive to the pore fluid with in reservoir and its amplitude does not attenuates due to presence of fluid (gas) therefore provides better subsurface image.

The focus of the petroleum industry is already shifted to the unconventional reservoir like deep water, tight reservoirs, heavy oil, shale gas/oil, HTHP reservoir, transition zones, very low permeable reservoir, structurally complex area and so forth. PS data is the key to exploit these reservoirs to full potential. The challenges in these areas are large heterogeneity in term of lithology, fluid characterstics, texture, porosity, permeability etc. Only conventional P wave data cannot solve the problem, it raises a strong need of PS wave data. Therefore most of the reservoir problems are handled by P and PS seismic data and it is going to be a standard tool for subsurface imaging of challenging reservoirs.

## 1. PRINCIPLES OF CONCERTED WAVES

### 1.1 Principles

Converted wave exploration is based on the theory of energy partitioning at an interface. There are many type of energy conversion takes place in subsurface. When a P wave energy incident at an interface of two acoustically different layers; the energy of incident wave get splitted into reflected and transmitted P and S waves. Here, the converted wave exploration is based on the principle that a down going P wave energy can be converted to upcoming S wave energy after reflecting from the deepest point of reflection known as converted point. Ray path geometry of down going P wave and upcoming S wave can be easily explained by Snell's law. Snell's law states that ratio of the sin of incident angle to the sin of reflection angle is equal to the velocity of incident wave energy to velocity of reflected energy. It means the angle of incidence will be equal to the angle of reflection for PP waves because incident and reflected P wave energy travels with same velocity and their reflection point is exactly below the midpoint of source receiver distance. Whereas the incident P wave energy and reflected S wave energy for converted wave exploration are travelling with different speed therefore the incident angle and reflection angle are different and the converted point does not lie below the midpoint of source receiver distance. Since S wave velocity is less than the P wave velocity therefore angle of reflection will be less than the angle of incidence, shear wave will be travelling more closely to the normal and converted point will shift towards the receivers. This way, Snell's principle is used to explain the ray path geometry for converted wave exploration and depicted in Figure 1.

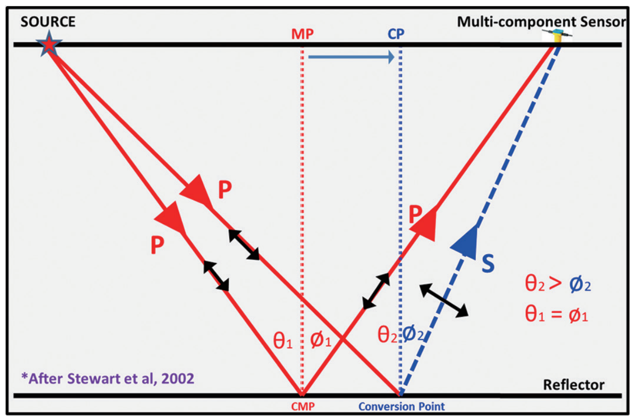


**Figure 1**
**PP and PS Reflection at Mid Point(MP) and Conversion Point (CP). P Wave Converted to S Wave at the Conversion Point and It is Shifted Towards the Receiver. Ray Geometry for Converted Wave Exploration is Asymmetric Instead of Symmetry Geometry as in Conventional PP Seismic. Black Arrows Show the Particle Motion Relative to the Wave Propagation**

The PS energy is being recorded at the receivers and the amplitude of PS wave energy is governed by the Aki-Richard equations[8]. It describes the variation of amplitude for PP and PS energy with angle/offset and shown in Figure 2. The amplitude variation for PS wave is in quasi sinusoidal pattern. At normal incidence i.e. zero angle of incidence, amplitude of shear wave reflectivity is zero, which means there is no wave mode conversion and it is purely PP reflections. The shear wave reflectivity amplitude increase with angle of incidence and at middle offset range the amplitude of the S wave reflectivity and P wave reflectivity become equal.

As explained, the converted wave exploration differs to conventional method only in asymmetrical ray geometry and quasi sinusoidal amplitude behaviour with offset. But it is different from conventional method in many ways like survey designing, recording, processing and interpretation.

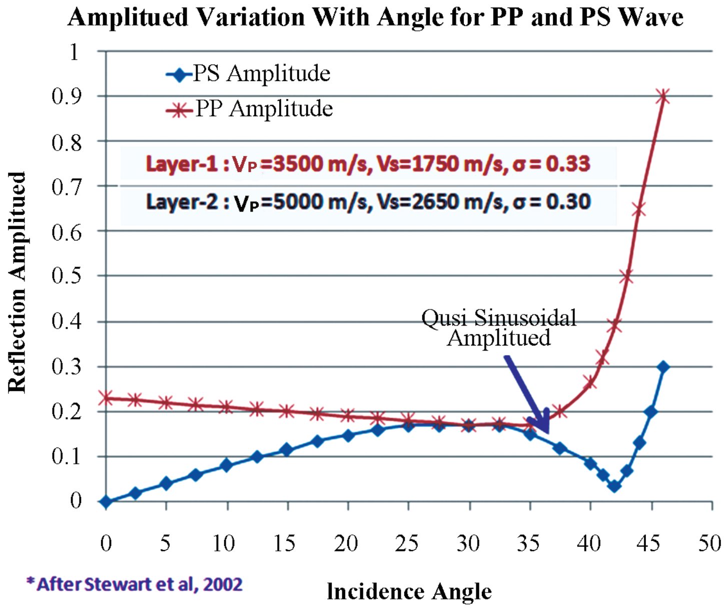


**Figure 2**
**PP and PS Plane Wave Reflection Coefficient as a Function of P Wave Angle of Incidence**
*Note*. Density is Constant and Absolute Value for PS Reflection Coefficient is Plotted.

### 1.2 Survey Design

The process of survey designing for multi-component recording is same as for conventional P wave seismic but there is a challenge to handle the asymmetrical behaviour of PS ray path. The acquisition geometry attribute i.e. offset, azimuth and fold analysis becomes difficult as compared to conventional seismic. It requires a good understanding of the converted waves ray path geometry which took almost more than 30 years to establish the good practice for designing, acquisition, processing and interpretation of converted waves. Now we have more advanced software tools to design and select the best acquisition geometry parameters where good quality acquisition attributes can be obtained from the survey. Foldage, offset and azimuth distribution for the assigned bins should be uniform in order to relate the attribute changes with reservoir properties. Therefore designing of the survey parameters is of utmost requirement for the success of study. Better understanding of converted wave's behaviour, technology up gradation and advanced software made us comfortable to design the best acquisition geometry parameters.

### 1.3 Source Energy

The major difference between conventional and converted wave exploration is the recording of shear component in addition to P wave recording which add value to the exploration. A shear wave energy source can be used for propagating the energy in subsurface and recording the shear wave energy after reflecting from the deepest point of penetration. The problem with shear wave source is that it is very expensive with limited availability and very challenging for some environment like marine survey, transition survey etc. Additionally, SNR is poor for SS seismic section as compared to PP or PS section due to the near surface heterogeneity. Whereas a conventional P wave energy source can be used to record the shear component at the sensor which is easily available and have number of variety. Therefore PS exploration is better way to record the shear component with P component recording which is relatively in expansive, widely applicable and acceptable as a better source of shear recording.

### 1.4 Recording

In converted wave exploration, we record one vertical component and two horizontal component of the reflected energy using 3 component geophones/sensors on land survey whereas additionally one hydrophone is also required for marine survey. The involvement of huge amount of hardware which is almost three times of conventional seismic is a big challenge to handle and properly utilize it. A proper plantation and coupling is must for good quality seismic recording especially when we record shear component. The orientation of all the geophones should be similar otherwise it will degrade and attenuate the signal strength. Generally 3 component geophones are buried at the surface with one feet deep hole to make sure the 3 component are perpendicular to each other and properly coupled with earth surface. The vertical component will record P wave energy and both horizontal components of sensors record the two component of shear. It is very challenging to maintain the active acquisition spread noise free and record the data, but with times we have developed standard practices to record good quality data. It requires more logistics, more efforts, more hardwares & softwares and more recording time which in turn provide more data-three seismic sections (one vertical-P and two horizontal-S components) to better understand the subsurface.

Polarity of the three components recorded is also very important while recording, processing and interpretation of PS data. Some guidelines are given by Brown R. J. et al. 2002 on the polarity convention of PS data during acquisition.

### 1.5 Processing

PS wave exploration designing and acquisition differ to the PP wave exploration therefore the processing of PS waves is also different. It starts with asymmetric and anisotropic binning of the survey geometry. There are number of methods to perform trace binning according to common conversion point gathers domain[9]. The anisotropic rotation (Sh max and Shmin direction) of the shear component is also additional step in the workflow of PS processing. The static correction also differ from conventional PP seismic processing. S wave velocities is independent on fluid i.e. shallow water in weathering layer and have very low velocity for weathering layer[10]. The shear static correction is higher than normal component correction. A shifted hyperbolic velocity analysis approach is used to predict the shear velocity. The PS processing steps also differ in dip move out correction, stacking and migration of PS data. The challenges faced in converted wave processing are discussed by Gaiser[11]. The identification and picking of shear component on a 3C record is a challenging task and various algorithms/methods[12] are available to correlate PS event with PP event.

### 1.6 Interpretation

Ultimate objective of converted wave exploration is to provide a good structural framework and its constituents i.e. rock matrix and pore fluid. P and S waves alone are inefficient to characterize the rock because different rocks can have same properties. It provides two independent measurements and variables which together provide better control for reservoir characterization. P wave and S wave properties together discriminate the fluid type and rock type which is the ultimate objective of exploration. We do extract shear information from the PP seismic data also through AVO analysis. The amplitude of P wave depends on shear velocity (Vp/Vs) for different offset and does not provide independent shear information. Secondly, the main recording parameter for seismic survey is two way travel time which is absent for shear wave in PP survey. Therefore PS provides us travel time of shear wave and an independent section. Isochron maps from these two sections can be used to get VpVs ratio which is excellent attribute to characterize the reservoir.PS AVO analysis can be used to estimate the density of the rock in a reservoir from the PS amplitude versus offset. Another advantage over PP AVO is that it provides density information with shorter offset information in the PS gathers. The density and shear wave reflectivity can be measured with more confidence from PS seismic data[13].

Synthetic generation and forward modelling for PP and PS waves are useful to better understand the recorded seismic. Converted exploration provides anisotropic solution through the two anisotropy volume generated using fast shear and slow shear wave. The multi-component survey has wide variety of applications to solve the uncertainties beneath earth.

### 1.7 Advantages Over Conventional Method

Converted wave exploration proved itself an effective tool to overcome the difficulties or challenges where conventional method fails[14]. The some of the applications of Multicomponent recording are mentioned below:

- An independent image in addition to PP section;
- Better subsurface imaging beneath gas clouds where PP section fails to image due to more attenuation;
- Improved subsurface mapping where acoustic impedance contrast is low and high shear impedance contrast;
- It also provides better subsurface image below High velocity layer[15];
- Improved resolution at shallow depth;
- Anisotropy analysis and fracture identification;
- It helps to map gas zone, identify fluid type and in reservoir characterization.

As per shear wave specialist survey at SEG workshop-2000, converted wave exploration has potential solution for other geological and geophysical problems as well. These problems are listed as below:

- Imaging faults;
- Imaging below salts;
- Density estimation;
- Pore pressure prediction;
- Stress characterization;
- Reservoir monitoring;
- Detection of shallow water flow;
- Lithology delineation i.e. carbonate, evaporates and so forth;
- Coal bed methane, Gas hydrates;
- Imaging complex structure, that is, overthrust.

Conclusively, converted wave exploration will be adopted as standard practice as the world is moving towards oil and gas explorations in non-conventional field or to find small hydrocarbon pockets in conventional field where shear wave play a significant role for the success of exploration.

## 2. FULL WAVEFORM MODELLING

Exploration oriented seismic modelling requires accurate and efficient methods. Various seismic modelling algorithms incorporates analytical methods, semi analytical methods (e. g., reflectivity method), ray geometric methods (e. g., ray tracing method), and direct methods (finite difference and finite element methods). Conversely, elastic wave equation modelling accounts for direct waves, primary and multiple reflection waves, converted waves, head waves, and diffraction waves. It therefore overcomes the shortcomings of the raytracing approach, which fails in many cases; for example, at the edges where the calculated amplitude is infinite or in the shadow zone where the amplitude is zero. Full waveform modelling takes the complete wave field and structure effect into account and it generates the shot gathers instead of the common midpoint (CMP) gathers. The synthetic data needs to be treated as recorded data and taken through a processing sequence. In elastic modelling, field acquisition parameters can be used and three component data can be generated. Since the present aim is to calculate the seismograms of the full wave field for a rocky mountain foothill model (Figure 3) the finite difference technique of direct methods is used[16]. An optimised processing technique has been applied on the simulated seismic data. Each component has been processed separately but using Pwave data to constrain parameters in areas where it is most reliable. The vertical (Z) and horizontal component (X) data for the rocky mountain foothill model is shown in Figure 4. 2D synthetic seismograms for a realistic rocky mountain foothills model were studied.

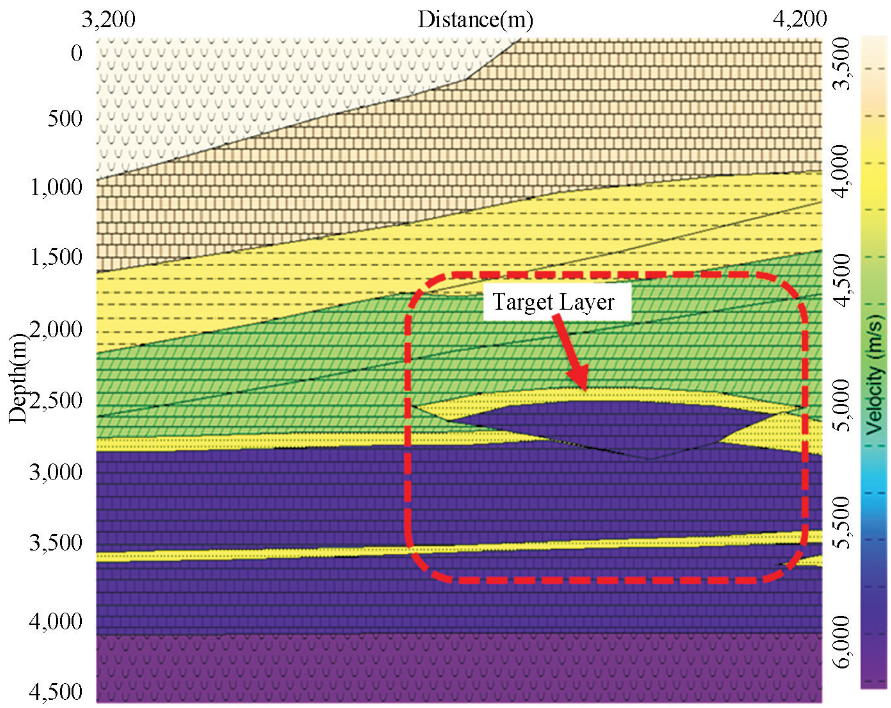


**Figure 3**
**Velocity Model for a Rocky Foothill Mountain, Which Is Used for Synthetic Calculation. Target Layer Is Marked**

Figure 4 shows that the S/N of the converted wave is lower than that of the P-wave reflection and partly overlaps the noise in low lying frequencies. To get satisfying processing results, it is critical to identify and attenuate the various noises. Furthermore, static correction builds the foundation for later subsurface imaging in the area of complicated near surface structure. Therefore, an iterative and integrated approach for noise removal and static correction was setup, comprising of a series of de-noising and static correction methods step by step. Amplitude recovering and deconvolution processes were also included in the procedure.

 

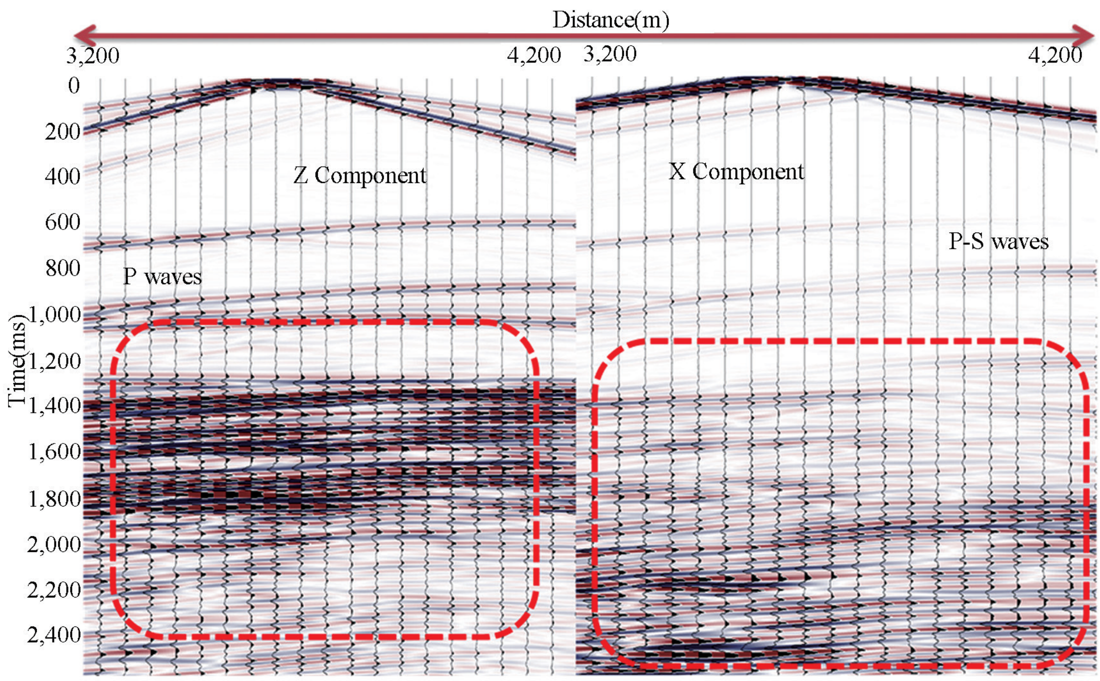


**Figure 4**
**Display Shows Synthetic Seismograms for Z Component (Left) and X-Component (Right). The S/N Ratio for X Component Is on the Lower Side**

Through these iterative processing steps, the statics is corrected and the S/N is improved. Seismic wavefronts are spherical and their curvature deceases with distance from the source such that they can be approximated as plane waves. These seismic wavefronts can be defined as the surface at which particles are vibrating with the same phase. Rays are perpendicular to the wavefronts and parallel to the propagation direction.

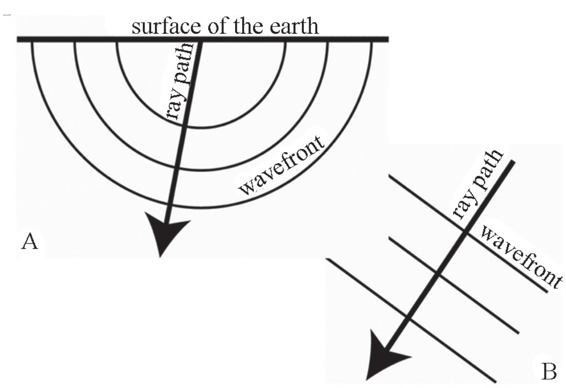


**Figure 5**
**Display Shows the Wavefront Propagation for Spherical Wavefront in A and Plane Wavefront in B. The Direction of Wave Travel Is Always Perpendicular to the Wavefront**

Figure 5 shows the illustration of the principle of seismic wavefronts and rays where the wavefronts are spherical and perpendicular to the ray path. To study the wavefront propagation for P and P-S waves the snapshots have been captured at different time with 100 ms interval. The main observable difference is the time for reflected energy as shown in Figure 6.

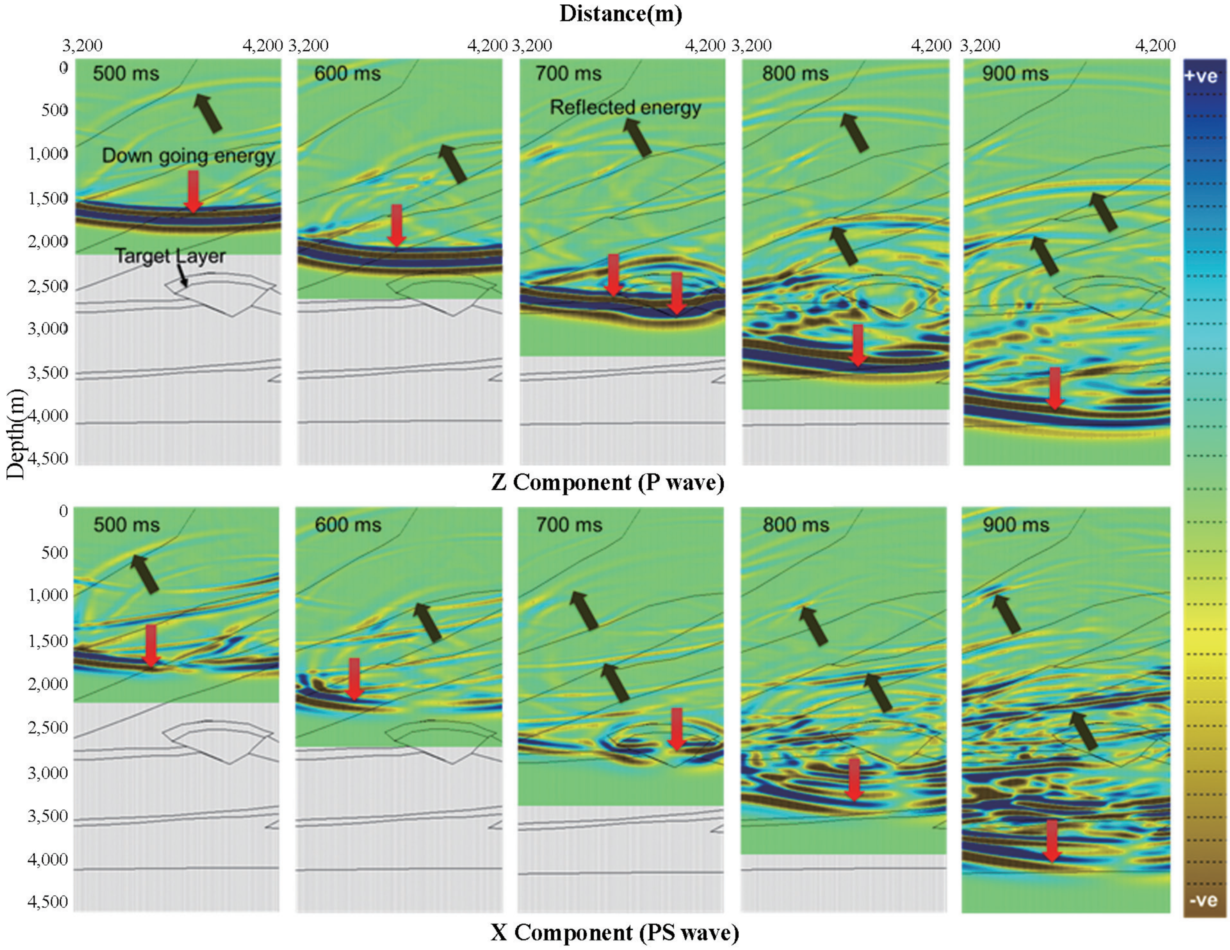


**Figure 6**
**Display Shows Comparisons of Wave-Front Propagation for P-Wave and PS-Wave for a Single Source. The Upper Part of the Figure Shows Down-Going and Reflected Energy Propagation for P-Waves From 500 ms to 900 ms at 100 ms Interval. The Lower Part of the Figure Shows Down-Going and Reflected Energy Propagation for PS-Waves From 500 ms to 900 ms at 100 ms Interval**

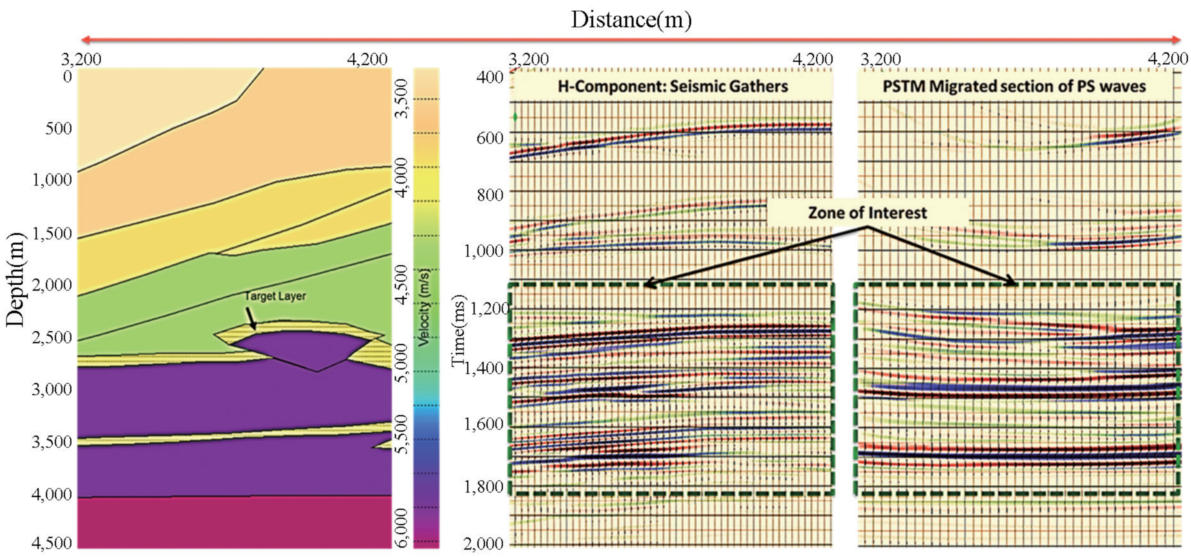


**Figure 7**
**Display Shows the Model on Left, H-Component Gathers in the Middle and Time Kirchhoff Migrated Seismic Section on the Rightmost Panel. Zone of Interest is Shown by Green Dotted Boxes**

Through these iterative processing steps, the statics is corrected and the S/N is improved. Pre-Stack Kirchhoff based time migration techniques is applied for PS-wave migration and shown in Figure 7. Kirchhoff prestack migration is based on a model of the subsurface as an organized set of scattered points. The model assumes that energy may come from a source located anywhere on the surface to all receivers. The location of energy on a recorded trace is the total travel time along the ray path from the source down to the scatter point and back up to the receiver. Kirchhoff prestack migration assumes an output location, and then sums the appropriate energy from all available input traces. Figure 7 show seismic gathers for horizontal component and corresponding PSTM migrated seismic section over geological model. The imaging quality for the zone of interest is good as highlighted by green box on PS gathers and migrated section. A Kirchhoff-based technique that includes anisotropic velocities is used for depth migration of converted waves (Figure 8).

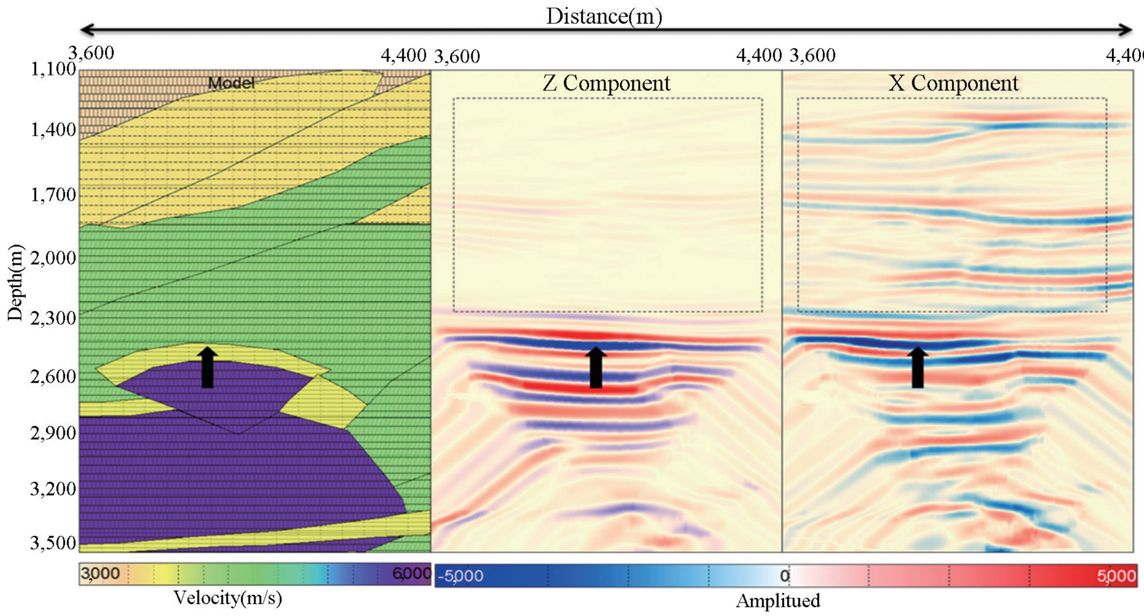


**Figure 8**
**Display Shows the Model on Left, Depth Migrated P-Wave in the Middle and Depth Migrated P-S Seismic Sections on the Rightmost Panel. Shallow Reflectors Are Better Imaged in P-S Seismic Section**

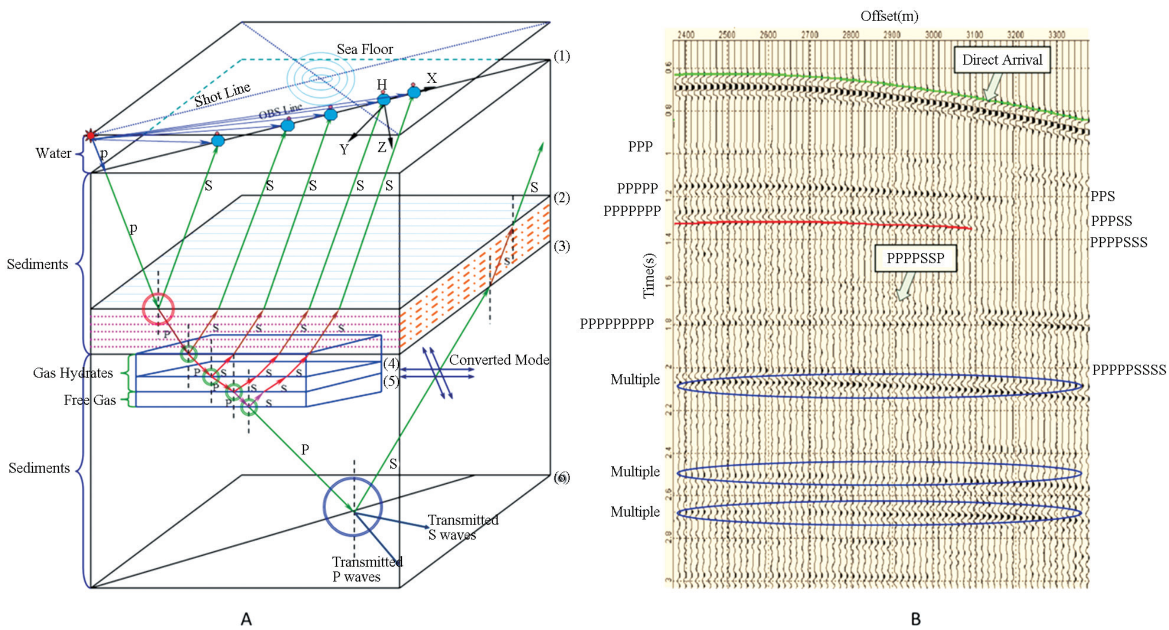


**Figure 9**
**Marine Environment Model and Generated Synthetic Seismogram With Identified P-S Wave Reflections. (A) The Model Consists of Water, Sedimentary Layer Target Layers Consist of Gas Hydrates and Free Gas. (B) Display of Identified P-S Wave Reflections That With Correlation of the Model. PPP Refers to Down-Going PP-Wave and Reflected P-Wave. PPS Refers to Down-Going PP and Reflected S-Wave**

To identify the converted waves a realistic marine environment models is developed. Multicomponent receivers are assumed at the ocean bottom and a 35 Hz central frequency used to simulate the synthetic seismograms. A target layer is assumed below the sedimentary layer. The 3D representation of the model is shown in Figure 9.

## DISCUSSION AND CONCLUSIONS

Except for some important differences, converted wave processing steps follow similar approach to that of compressional wave surveys. Following are the major differences between processing of P-S wave surveys and pure P wave surveys:

- Different geometries for compressional and converted wave surveys;
- As the P-S waves have slower velocity than P waves therefore asymmetric reflections at conversion boundary are observed;
- Difference in condition of source and receiver and partitioning of energy into orthogonally polarized components.

The result from depth imaging for a rocky mountain foothill model reveals that converted wave reflections help in distinguishing amplitude associated with hydrocarbons from those caused by localized stratigraphic changes. In addition, the full waveform elastic modeling is useful in finding an appropriate balance between capturing high-quality P-wave data as well as P-S data challenges in a survey. The identification of P-S arrivals has been demonstrated with the help of a marine environment model and a good correlation is observed. The identification of converted wave arrival on a seismic section has always been challenging and needs significant level of experience in this area. Some challenges always remain such as the need of advance interpretation techniques to support the evolution of multicomponent data to the next level. Integration of data from different sources will be the key to new and more advanced interpretation techniques. More experiments for acquiring P-S wave data are needed to develop the innovative techniques.

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