Improving Resolution in Complex Geological Areas with P and PS Imaging Using a Deviated Well Rig Source VSP – A Pre-Salt Case Study

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Abstract

In the pre-salt Deep Water complex reservoirs the salt causes distortion and loss of resolution of seismic images at reservoir levels, limiting the reservoir interpretation process. To face this challenge, a VSP data can provide the enhanced resolution necessary for better reservoir delineation using compressional and converted shear wave mode information. In this case study, a rig-source VSP was acquired in a deviated well of the Jubarte field in Brazil. This VSP provided reflection information below the borehole trajectory. Mode-converted PS-waves were also recorded. The PP and PS common depth point (CDP) mapping considerably improved the vertical and lateral resolution of the seismic image around the wellbore, which resulted in an improved well-to-surface seismic tie. The generation of the PS VSP seismic image was enhanced by using the VSP P-wave image, the Vp/Vs ratio, and the borehole imaging logs to improve the velocity model and imaging confidence.

Introduction

Imaging pre-salt, high-complex reservoirs in deepwater environments is a challenge. The salt causes distortion and often a loss of resolution of seismic images at reservoir levels, which can limit the reservoir interpretation process. Vertical seismic-profile (VSP) data can provide the enhanced resolution necessary for better reservoir delineation.

A conventional zero-offset VSP in a straight well can only provide rock properties and structure in the area around the Fresnel zone within the well (Chen et al. 1999). A methodology using a rig-source VSP in deviated wells has been developed to acquire the reflection information below the borehole in order to increase the benefits of VSP surveys and to improve the precision and resolution of P imaging. With the use of VSP-CDP transformation, the spread of reflection points resulting from non-vertical receiver alignment or by non-zero source offset can be exploited to image the subsurface structure near the borehole. The VSP-CDP stack can, thus, rectify ambiguities caused by source and receiver position (Karl et al. 1983). Conventional rig-source VSP surveys usually use compressional wave data to study the geological structure around the wellbore, but many of these surveys have the presence of converted shear waves as well. In most zero-offset VSP surveys, when examining the horizontal components the presence of secondary-arrival waves is noticed; this becomes more prominent after the three-component rotation analysis is performed. As a confirmation the moveout of these arrivals can be compared with the Vp/Vs ratio from the sonic logs to verify that these secondary waves are mode-converted shear waves. The shear results can be utilized to compare with the compressional results, provide quality control, confirm the well to surface seismic tie, and to compare the image variances and similarities to provide additional reservoir characterization information (e.g., hydrocarbon presence).

In this case study, a rig-source VSP was acquired in a deviated well, in the Jubarte field, Brazil. This provided reflection information below the borehole trajectory. Mode-converted PS-waves were also recorded. The PP and PS CDP (common depth point) mapping considerably improved the vertical and lateral resolution of the seismic image around the wellbore resulting in an improved well-to-surface seismic tie. The generation of the PS VSP seismic image was enhanced by utilizing the VSP P-wave image, the Vp/Vs ratio, and the borehole imaging logs to improve the velocity model and imaging confidence.

The well is located in the Campos basin, and the geological setting corresponds to the Lagoa Feia Group, which represents a large part of the sub-salt sequence. The lower part is composed of alluvial clastics; the middle part is composed of lacustrine carbonates; and the upper part is composed of marine evaporites. The rock succession is divided into six formations, including Itabapoana, Atafona, Coqueiros, Gargau, Macabu, and Retiro (Winter et al. 2007), but in the well area, only the Coqueiros, Macabu, and Retiro formations are present. The age of this group is Lower Cretaceous (Hauterivian to Aptian). The Coqueiros formation is one of the most important formations in the Campos basin, because the lacustrine shales are the main source rock, and the coquinas—the shelly limestones—is one of the reservoirs.

Method

By recording 3-component VSP seismic data, it allows for the use of a polarization analysis to rotate the two horizontal receivers to radial and transverse directions so as to study the vector nature of the seismic waves (Zhao et al. 2005). A polarization is first applied to the horizontal components on an Eigenvalue analysis, and the data are then rotated into horizontal-radial (HR) and horizontal-transverse (HT) components. Separation is performed on the vertical and horizontal-radial transformed components, projecting a combination of each component into the P-compressional wave mode and SV converted shear wave mode. The P- and S-wave data can be used independently to image the near-borehole geological structure. The commonly used VSP corridor stack is a time-domain imaging method and is convenient when comparing the VSP data with time-domain surface seismic. However, the time-domain P- and S-wave images cannot be directly compared because the two waves travel at different velocities. Therefore, a VSP-CDP transform and/or migration depth image are needed for this purpose (Zhao et al. 2005). A VSP-CDP transform generates a 2D reflection profile from the offset VSP geometry. Rays are traced from the source to reflection points in the subsurface and then to receivers to generate a mapping function that, for a given source-receiver pair, shows where a reflection point occurs in the subsurface and predicts the arrival time of that reflection.

Results

The following example of a rig-source VSP was carried out in January 2014 in the Campos basin, Brazil. 71 levels were acquired in the pre-salt zone in a 29º deviated well. Though it was a deviated well, the maximum angle of incidence at the bottom levels did not exceed 10º. In order to obtain the time to depth relationship a bent ray correction was used, which is more accurate than a simple vertical incidence approach. Figure 1 shows the well setting. Routine VSP data processing was followed to produce the optimum up-going wavefield data; a maximum frequency recovery of 84 Hz was achieved. A corridor stack and a synthetic seismogram were generated to assist in the time-depth match between the logs and the surface seismic.

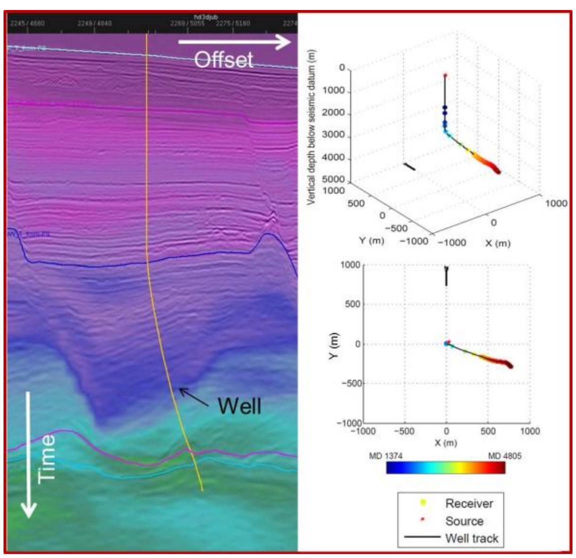

Figure 1: Well setting and survey geometry

Because of the steeply dipping nature of the layers around the well, the events in the deconvolved two-way time upwaves also displayed moveout, making it difficult to choose the best window for corridor stack generation. For this reason, there was some ambiguity in identifying the formation tops when comparing to the amplitudes between the corridor stack and the surface seismic (Figure 2).

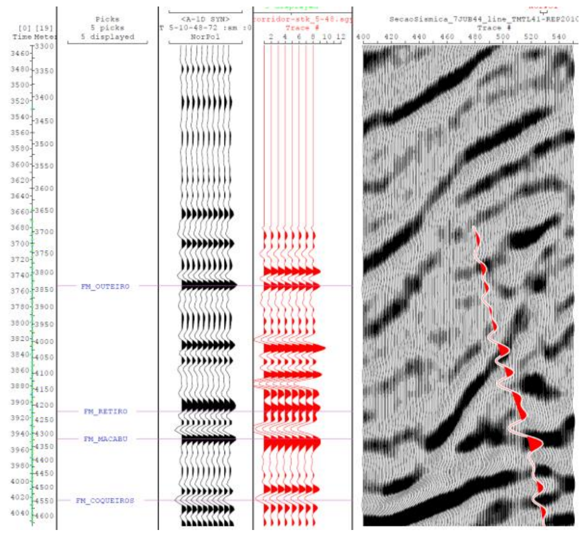

Figure 2: Corridor stack correlation with surface seismic along the well

In addition, the surface seismic has very poor resolution at the reservoir depth, with a maximum frequency content of 36 Hz. The presence of salt of variable thickness above the reservoir may be masking or attenuating the energy received at the target zone (Badri et al. 1997). To minimize these issues, a VSP-CDP transform was generated to put the VSP into its proper lateral position. Structural dips from imaging logs (OMRI, CAST) were used to improve the structure/velocity model. For future surveys, it is advisable to acquire the VSP levels higher up the well, at a minimum 10 levels above the kick off point of the deviation. This will increase lateral and vertical coverage as well as accuracy.

P-to-S wave-mode conversion was observed in the horizontal components. This conversion was probably generated at the sea bed as well as at the boundary of the evaporitic complex and the carbonates below. These arrivals were selected after horizontal rotation and parametric separation of the three-component data (Figure 3). These time arrivals were then compared to the DTS times from the sonic log to confirm that they were shear traveling times. A Vp/Vs ratio was calculated to build a velocity model. The converted shear-wave mode was then processed using a conventional VSP-processing flow to obtain the deconvolved up-going wavefield (Figure 4). This data was then used as the input for the VSP-CDP 2-D shear wave image.

Both P and PS images were filtered down to the surface seismic-frequency bandwidth to obtain the correlation.

Figure 5 shows the correlation between the well logs and the P-wave image. Figure 6 shows the correlation of the PP and PS image with the surface seismic. The 2D image significantly helped to identify the time-depth match between the borehole seismic events and the surface seismic events.

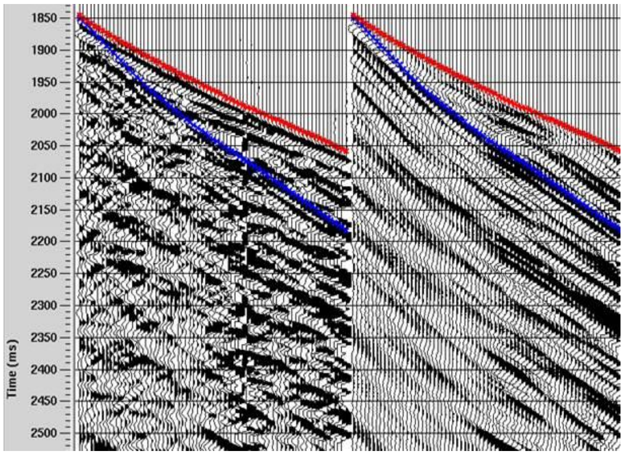

Figure 3: Converted shear-wave mode separation.
Left: H-Radial component, Right: down-going PS waves. Red lines correspond to P travel time and blue lines correspond to PS travel time

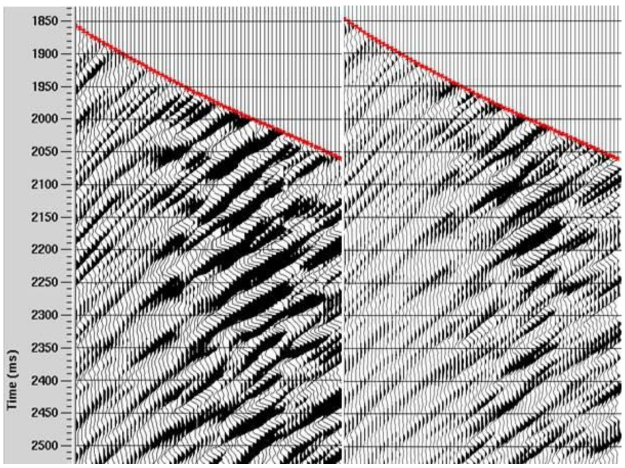

Figure 4: Converted shear-wave mode separation.
Left: up-going PS waves, Left: up-going deconvolved PS waves. Red lines correspond to P travel time

P and PS VSP images show better reflectivity coherency and event definition than the surface seismic. The P image provides more lateral coverage than the PS image; however, the PS image appears to better follow the structural attributes of the surface seismic, especially below Outeiro Fm top. It can also be noticed that there is little amplitude contrasts at the Macabú and Coqueiros seismic interfaces on the PS VSP image. This could be attributed to an attenuating effect from the salt in the converted wave modes, or it could infer the presence of hydrocarbons, which could help to complement the petrophysical analysis.

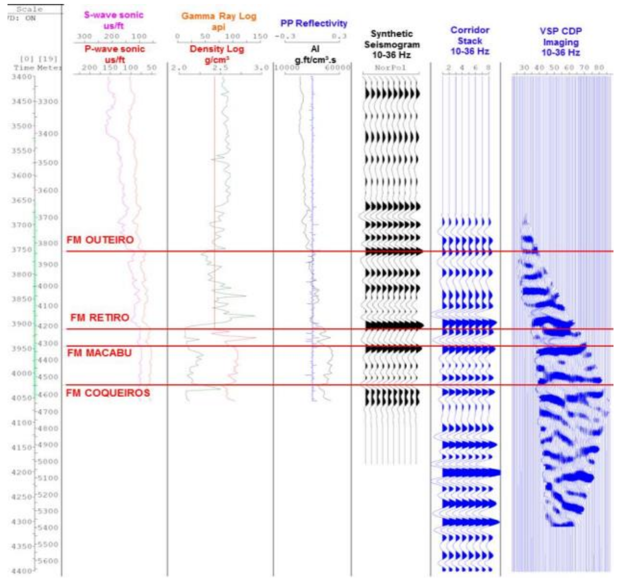

Figure 5: Well logs and borehole seismic correlation

Conclusions

Converted wave information has been recorded on the horizontal VSP components, and the Vp/Vs ratio was obtained. The PS VSP image compares well with the P image. The vertical and horizontal resolution of the VSP images reveals valuable structural and stratigraphic details at the reservoir, which were not clearly imaged by the surface seismic data. This highlights the importance of 2D VSP images to improve resolution in complex geological areas and the advantage of using both P and PS information. A VSP corridor stack is an excellent tool for tying the VSP to the surface seismic data when there is minimal geometry move out or geologic structure. However, it may not be the best approach for the surface seismic – well tie correlation in deviated wells or structural complex areas.

The importance of pre-survey planning and modeling is critical to optimizing the data acquisition survey parameters, including the geophone level placement to ensure the survey objectives are achieved. This data can also be used to complement log interpretation, petrophysical analysis, and reservoir geometry delineation.

Acknowledgments

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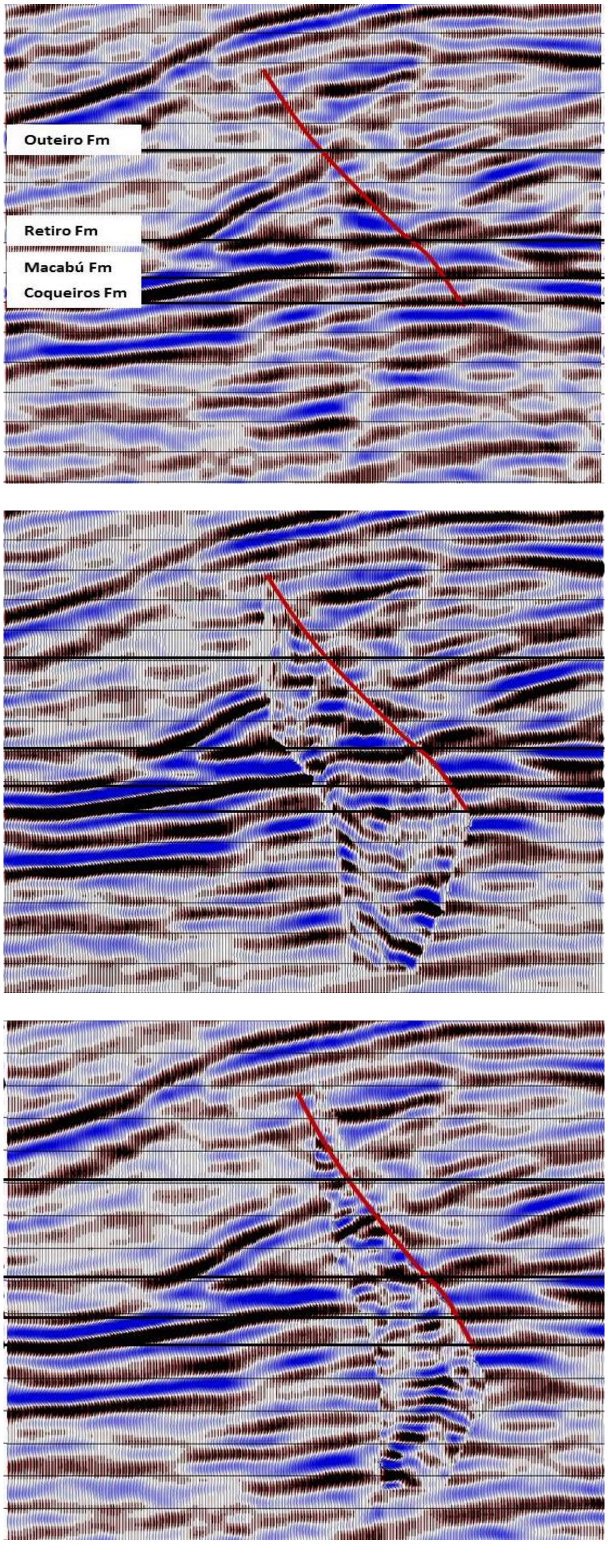

Figure 6: Surface seismic (Top) compared to VSP P-wave image (Middle) and VSP PS-image (Bottom)

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