High-resolution images from 4-C horizontal-well VSP data

Volker Dirks*, Xin-Quan Ma, and Nick Randall, CGG, UK, Jacques Blanco, Michel Erbeta, and Jean-Luc Gomes, TotalFinaElf, Pau, France, Peter Dillon UK.

Summary

A VSP sonde equipped with a 4-component sensor package is a necessary and sufficient configuration for acquiring useful horizontal well data. A new processing methodology exploits the nature of the recorded data - achieving wavefield separation where the traditional procedures fail, due to lack of differential moveout.

This methodology was applied to data from the Angola Rosa-3 horizontal well. The data was successfully partitioned into three high-resolution wavemodes - P-wave, S-wave and tube wave, all of which contributed to an improved interpretation of the prospect.

Introduction

Drilling technology has advanced to the stage where horizontal-well completions are now common. The Rosa-3 horizontal well was designed to appraise an oligocene channel system within a graben structure in the deep Angolan offshore. This channel has been affected by a turtle-back anticline structure linked to a regional salt gravity tectonics. The mechanism has created an important conjugate faulting, which divides the structure into different fault blocks. Stratigraphically, the channel system consists of several channelised turbidite complexes. The objectives of the Rosa-3 well were to calibrate these turbidite complexes and check the feasibility of a sub-horizontal well to overcome the compartmentalization of the reservoir. More precisely, the aim of the VSP on the horizontal drain was to complete the calibration with the 3D surface seismic and to provide an accurate channel reservoir image below the drain trajectory for better compartment positioning with the associated faults.

Acquisition of VSP data in such wells calls for new techniques: The geophone no longer descends under its own weight and must necessarily be ‘pushed’ to its destination using TLC methods (Figure 1). The geophone must also be provided with a gimbaled tri-axial particle-motion sensor package, and a pressure sensor to meet the new processing needs.

Processing VSP data from such wells also calls for new techniques, and Figure 2 data shows why: It was recorded in a well (not Rosa-3) that has a vertical section and a horizontal section. In the vertical part of the well, the downgoing and upgoing wavefields can be distinguished through the difference of their apparent velocities. So, on this region, multichannel processing techniques such as median, parametric filtering, FK filtering etc. are effective in separating the two wavefields. In contrast, the horizontal part of the well exhibits no differential moveout at all (Mari 1989). In which case some other means of separating the wavefields is needed. That is, some other property of the wavefields must be exploited to achieve separation.
The Geophone-Hydrophone pair Concept

One solution to the separation problem is to take advantage of the different signal properties of the recorded pressure wave and the recorded particle-velocity vector. That is, the downwave and upwave amplitudes are in phase when recorded by a pressure phone (hydrophone), and are in anti-phase when recorded by a vector phone (geophone). Figure 3 shows how the difference can be turned to advantage.

Under summation, the in-phase downwaves appear in the ‘result’ trace, whereas the out-of-phase upwaves have summed to zero. Conversely, under subtraction, the in-phase upwaves survive, but the downwaves are eliminated. Thus the sum-and-difference method has separated the downwaves and upwaves.

Sum and Difference in Practice

The implicit assumption behind the method, is that the geophone impulse response and the hydrophone impulse response are identical. In practice they differ considerably: At low frequency (circa 10Hz), the spectral response of each device is known from manufacturers’ specification sheets, and can be expressed analytically. Indeed it is a simple matter to devise a deterministic transfer function to convert the low-frequency hydrophone response to the low-frequency geophone response.

Both devices should now be spectrally equivalent. It turns out that hydrophones are well-behaved, but all geophones suffer from spurious mechanical resonance at very high frequencies. The resonance is well above the useful seismic spectrum, but it does introduce phase changes within the seismic spectrum. The most reliable way to handle the phase difference is via least-squares wavelet matching between the two data sets – hydrophone and geophone. An additional advantage to least-squares matching is that it also equalizes the gain difference between channels.

Finally, VSP downwave deconvolution is applied, between the two wavefields from the sum-and-difference procedure. The result is an estimate of the earth’s P-wave reflectivity below the wellbore.

Other Wavefields

The main thrust so far has been in generating the P-P reflectivity wavefield. There are, however, other wavefields present:

In open hole (no casing) permeable formations and fissures induce tubewaves into the borehole in response to the high amplitude body-wave first arrival (Beydoun et al., 1984). The mode conversion is sometimes referred to as the ‘squirt’ mechanism. Only the hydrophone records these waves. They are usually seen as ‘chevrons’ in the data, the apex of the chevrons indicating the point of generation. In Figure 4 (upper panel) the chevrons have been unfolded in an attempt to pinpoint permeable zones. Note that the downgoing tubewave is very low amplitude because it must propagate between the borehole and the drill stem.

In both open-hole and cased-hole surveys, P-S mode conversion occurs. Only the geophone records these waves. The mechanism here is the direct P-wave arrival exciting.
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Figure 5: Surface-seismic section with VSP insert. The upper and lower markers indicate the zone of VSP illumination.

Figure 6: Dual interpretation of VSP and surface-seismic images
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the surface of steeply dipping horizons at high angles of incidence. The excitation generates both transmitted and reflected S-waves. Again, they are usually seen as ‘chevrons’ in the data, the apex of the chevrons indicating the intersection of the horizon with the borehole. The unfolded chevrons in the figure show convincing continuity across the borehole. Note that the borehole has been straightened to the horizontal for display purposes

Wave Equation Migration of the Reflectivity Estimate

The migration procedure is:

(i) Kirchhoff depth migration with aperture +/-15 degrees with respect to the local model dip.

(ii) Bisector weights (Miller et al., 1987) to account for simultaneous movement of sources and geophones.

(iii) Depth-to-time conversion

In Figure 5 there is a good structural tie between the VSP and surface-seismic data, but in detail they differ. Perhaps the most significant difference is in the surface-seismic multiple activity, which is not present on the VSP (See for example the seabed multiple at about 3700 ms, on both sides of the image).

The VSP data does not suffer from free-surface multiples (the major source of multiple activity) because the horizontal well is in a deep marine environment. That is to say, the seabed is at 1850 ms TWT, ensuring that free-surface multiples will not appear on the VSP downwave until 1850 ms after the first arrival. In other words the VSP sees its’ first free-surface multiple at about 5000 ms TWT!

Interpretation

Due to the complexity of the fault system and its impact on the reservoir compartmentalization and consequently, on the lateral dynamic connectivity, a reliable structural interpretation is needed. Efficient evaluation of the structural pattern should be performed by integrating all data giving information about the internal architecture and the fault system. Actual information to be integrated could firstly be extracted from tubewaves originating at fractures, connected to faults crossing the horizontal drain, and secondly from shear waves converted on the same faults. A good correlation between both should reinforce the fault system interpretation. Despite the difficulty in validating and comparing all the results, a fault interpretation was made and compared to the surface seismic one. The 3-D surface seismic image is exceptionally high quality, and its bandwidth is similar to that of the VSP. In Figure 6 both data sets have been interpreted. The main faults interpreted by the subsidiary were superimposed on the surface seismic (lower panel). These main faults are visible and validated by VSP data (upper panel). Moreover, the VSP significantly improves the interpretation allowing more accurate and more detailed structural and reservoir models.

Conclusions

VSP acquisition technology now provides the two sensor types needed for P-wave VSP processing in horizontal wells. The objective of a high-resolution P-P migrated image below the borehole has now been met.

The additional wavefields provided by the technology are a bonus. The P-tubewave conversion is indicative of permeable zones, and P-S reflection and transmission from dipping horizons may be diagnostic of cross-cutting faults (Dupal et al., 1993).

At the moment TLC arrangements are needed to achieve the survey objectives, but future advances are expected from other techniques such as PipeSeis™, in which the geophone is deployed inside the drillpipe.

References


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