Illuminating paleozoic reservoirs in the Solimões basin with borehole seismic

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Abstract

In this case study we present a summary of the first Walkaway surveys acquired in Solimões basin, in the Amazon jungle, using a multi-levels versatile VSP tool and dynamite charges. The area presents unique operational, geological and geophysical challenges for seismic acquisition, processing and interpretation. The Walkaway images provided higher resolution images of the Paleozoic reservoirs, explaining some lateral variations between nearby wells, invisible in surface seismic data. In addition to the classical zero-offset calibration and well tie, the VSP surveys acquired provided additional information about VTI anisotropy, seismic multiples and attenuation.

Introduction

Petrobras acquired the first seismic survey in the Amazon forest in 1948, with an early oil discovery in 1955 but it was only in 1986 that commercial quantities were found in Carboniferous sandstones. This light oil discovery in the Solimões Basin was the first major one in Brazil's Paleozoic sedimentary basins. In order to develop the field, Petrobras had to overcome hurdles such as operating in a remote area, respecting the environment and coping with reservoir uncertainties. The latter included the reservoir extension and its internal reservoir architecture. Some wells drilled only 500 m apart did not communicate and the poor quality of the surface seismic made interpretation of the results difficult. The seismic data suffers from low fold and low resolution, being affected by surface statics, short period multiples and by some strong velocity contrasts. The first few hundred meters of low velocity Late Cretaceous and younger sediments, overlay fast Paleozoic rocks, unconformably, and can create pull-down artifacts in prestack time seismic data. The Paleozoic overburden includes diabase dikes and sills intruded into the upper Paleozoic evaporite sequence, with the cumulative sill thickness exceeding 1000 m (Figure 1).

Given those seismic challenges, Petrobras thought about a borehole seismic solution to image the targets around a development well being drilled and to obtain information about seismic multiples, anelastic attenuation and tilted transverse isotropy (TTI).

Method

One rig-source VSP and two Walkaway lines, with 241 shotpoints and 6 km each, were designed using 3D ray-tracing and reflectivity synthetics, keeping the incidence angles below 45 degrees and targeting a peak frequency of 40 Hz. The lines were acquired along the dip and strike directions, being adjusted to follow the well path. A dipole sonic was run in cased hole to record P- and S-wave slowness. A multi-level VSP tool with 21 shuttles spaced every 15 m, recorded triaxial accelerometer data at 1 ms sampling rate. Dynamite charges were deployed in 2 m deep holes, manually drilled. The Walkaway had 21 receivers deployed over 1500-1800 m, with two holes with 750 g charges shot simultaneously. The VSP had 80 levels over 1200-2400 m, with one 750 g charge per shot and 3 shots per stack.

The Walkaway data processing included trace selection, 3-C time picking and orientation, wavefield separation, deconvolution of upgoing by downgoing waves and migration. Travel time tomography velocity model calibration was a key step (Cao et al., 2000). The semblance-weighted deconvolution algorithm of Haldorsen et al. (1994) was used. Parametric wavefield decomposition produced scalar P and Sv-wavefields (Leaney and Esmersoy, 1989; Leaney, 2002). Model-based P-wave velocity filtering guided by ray-tracing, proved also to be an effective wavefield separation method. The reflected PrP waves and converted PrS waves were depth migrated using the Generalized Radon Transform algorithm (Miller et al., 1987).

The Walkaway TTI anisotropy measurement relies on the slowness and polarization of the P- and Sv-waves estimated for every shot by parametric wavefield decomposition (Leaney and Esmersoy, 1989). A best fit TTI model to the slowness-polarization data provides the Thomsen epsilon, delta and symmetry axis parameters (Horne and Leaney, 2000; Leaney and Hornby, 2007).

The VSP data were analyzed for multiples which may affect the surface seismic data. The multiples present in the VSP downgoing wavefield are analyzed first. Then we look for multiples in the upgoing wavefield. All multiples are present in the residual upgoing (= total minus downgoing) before deconvolution, while all interbed multiples generated within the VSP interval are present in the upgoing deconvolved by a shallow reference trace. Finally, no multiples should be present across the receiver interval in the trace-by-trace deconvolved upgoing waves. Different corridor stacks were also generated: internal (multiple contaminated) and external (the standard corridor stack, which without deconvolution will be affected only by very short period multiples).

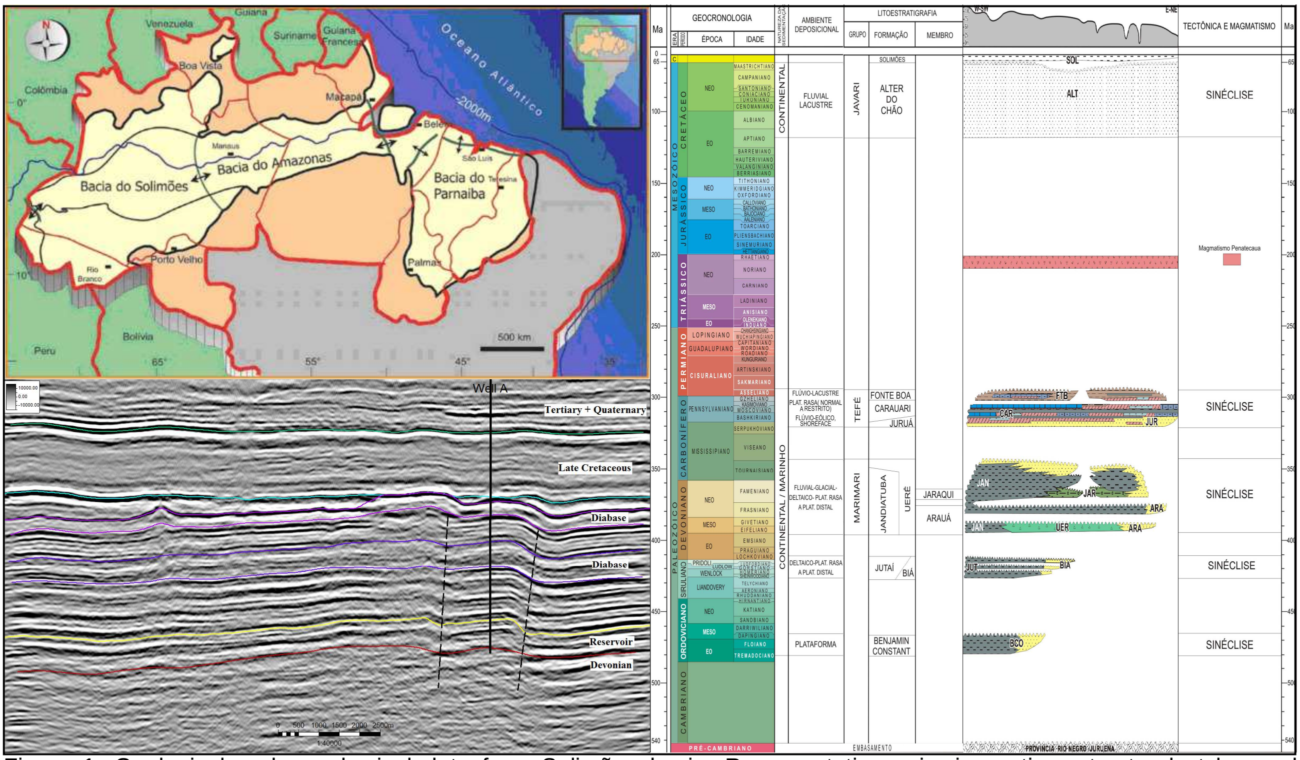

Figure 1: Geological and geophysical data from Solimões basin. Representative seismic section, structural styles and lithostratigraphic column for the basin (Filho et al., 2007).

Results

The Walkaway P-wave images achieved a frequency content of 5-85 Hz at the target level, compared to the existing surface seismic which is limited to 8-45 Hz, therefore almost doubling the surface seismic resolution at the reservoir level. A good tie was achieved between both walkaway images, surface seismic and zero offset VSP and also with the synthetic seismograms from both the logged well and the Well A, which was about 500 m away (Figure 2).

The interpretation of Walkaway line-1 clearly shows three faults F1, F2 and F3 (Figure 3). F1 is the principal fault of the structure, F2 is a normal fault and F3 is interpreted as a back-thrust fault. F3 may explain the different OWC between Well A and wells B and C. It also shows that the reservoir boundary to the East is defined by a flexure composed of several small-throw subseismic faults. These small faults may be associated with further reservoir compartmentalization.

In the Walkaway line-2 we have two faults (F2 and F4). F2 between wells B and C can be the same normal fault interpreted in the Walkaway line-1. The other normal fault F4, which was intercepted by the Well B, is recognized in the well logs as a layer repetition. It is possible that F4 may explain the different OWC between wells B and C (Figure 4).

As shown in Figure 5, an effective Q-factor of 110 was estimated over the rig-source VSP receiver interval from 1200 to 2400 m which includes the second sill, implying a moderate to low effective seismic absorption. The intrinsic attenuation of the Paleozoic rocks is expected to be low but their ensemble is responsible for significant stratigraphic filtering. TTI model fitting to the Walkaway downgoing P- and Sv-waves' slowness-polarization crossplot, resulted in average Thomsen parameters across the Walkaway receiver interval of epsilon=+0.10, delta=+0.07, with a vertical symmetry axis. We have therefore a nearly elliptical VTI medium, where the horizontal P-wave velocities are about 10% faster than the vertical (Figure 5).

Strong multiples present in the downgoing P-waves and which are continuous across their autocorrelogram, were all generated above the VSP receivers. The main multiple generators are the pre-Albian unconformity at about 600 m depth and the base of the weathered zone. Deeper in the geological section there are other important acoustic impedance contrasts that generate pegleg multiples with different periodicities. The multiple analysis was then performed on the upgoing waves before and after deconvolution in order to identify the interbed multiples generated across the VSP interval. Several strong multiples of periodicity larger than 50 ms were identified in the VSP data and in Figure 6, we have highlighted where they may affect the surface seismic data.

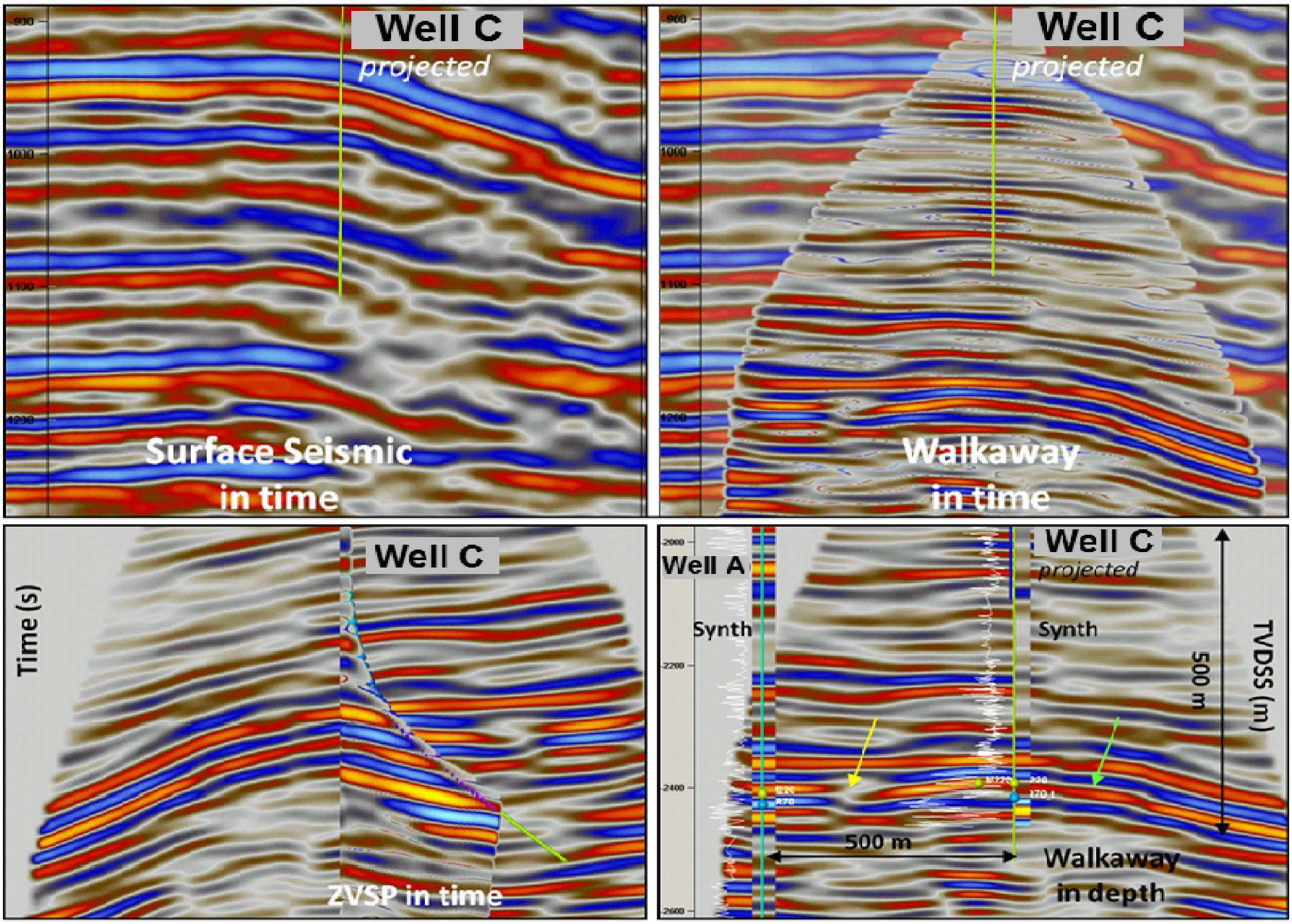

Figure 2: Walkaway images tied to the surface seismic, to deviated well ZVSP and to the synthetics. The Walkaway resolution (5-85 Hz) is higher than the surface seismic (8-45Hz). The yellow arrow shows a small fault that may explain the different OWC in Well A and Well C. The green arrow shows that the Eastern reservoir boundary flexure is probably composed of a series of small subseismic faults.

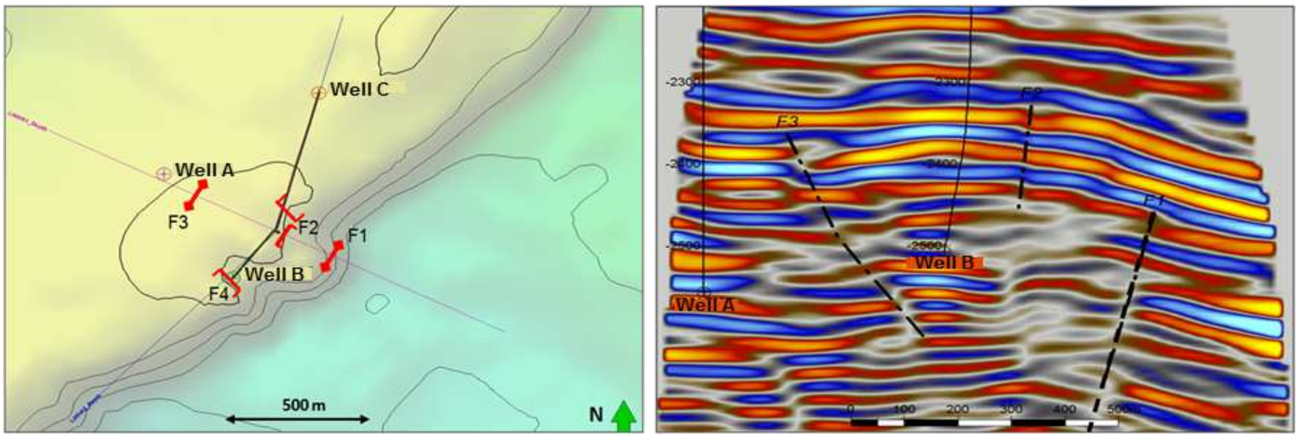

Figure 3: Position of interpreted faults in the two walkaway lines (left) and faults interpreted in the Walkaway line 1 (right). F1 is the principal fault of the structure, F2 and F4 were interpreted as normal faults and F3 is a back-thrust fault responsible for the different OWC observed in Well A and Well B. The horizontal scale is compressed relative to the vertical scale.

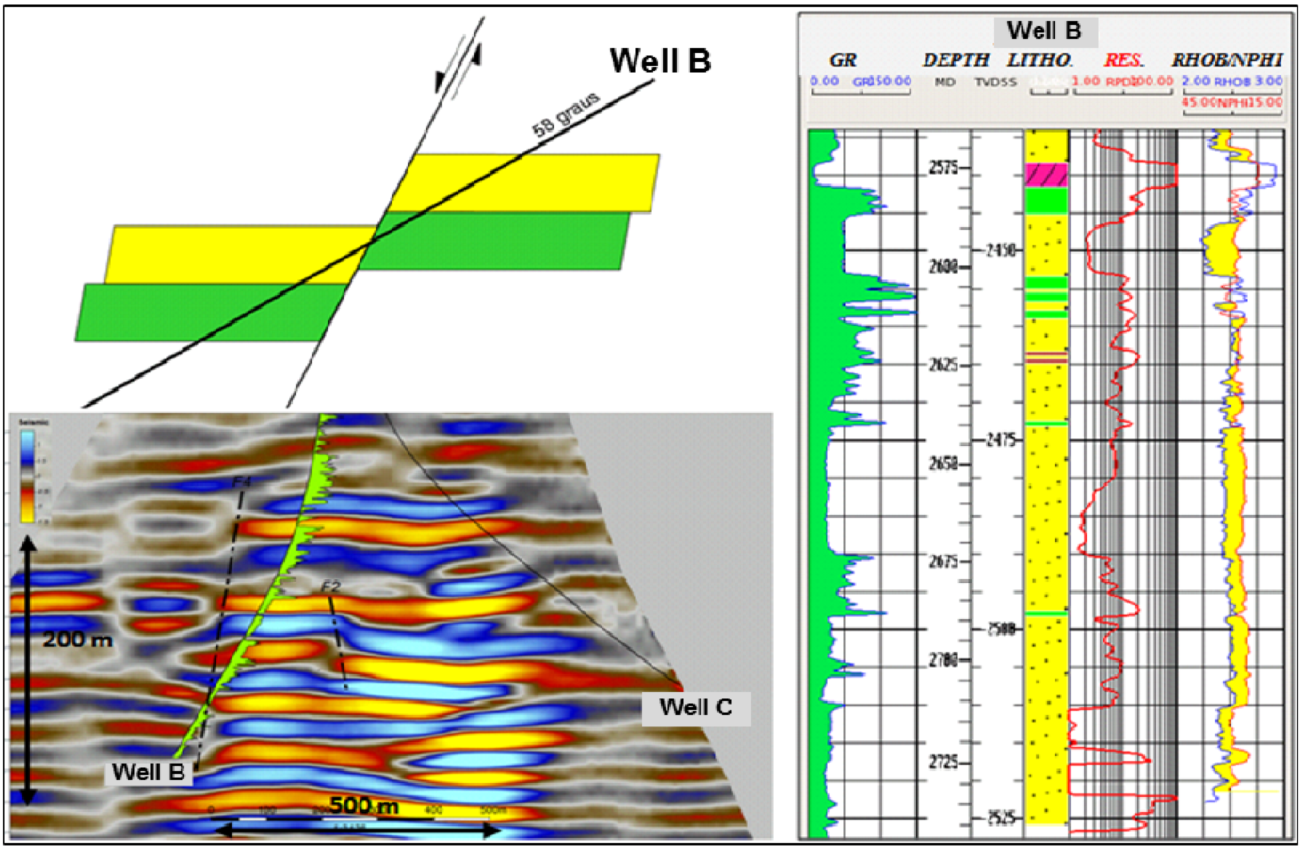

Figure 4: Faults interpreted in the Walkaway line 2. Fault F2 is the same fault observed in the Walkaway line-1 and F4 can be recognized in the well logs by the presence of a repeated layer. Fault F4 may explain the different OWC between wells B and C.

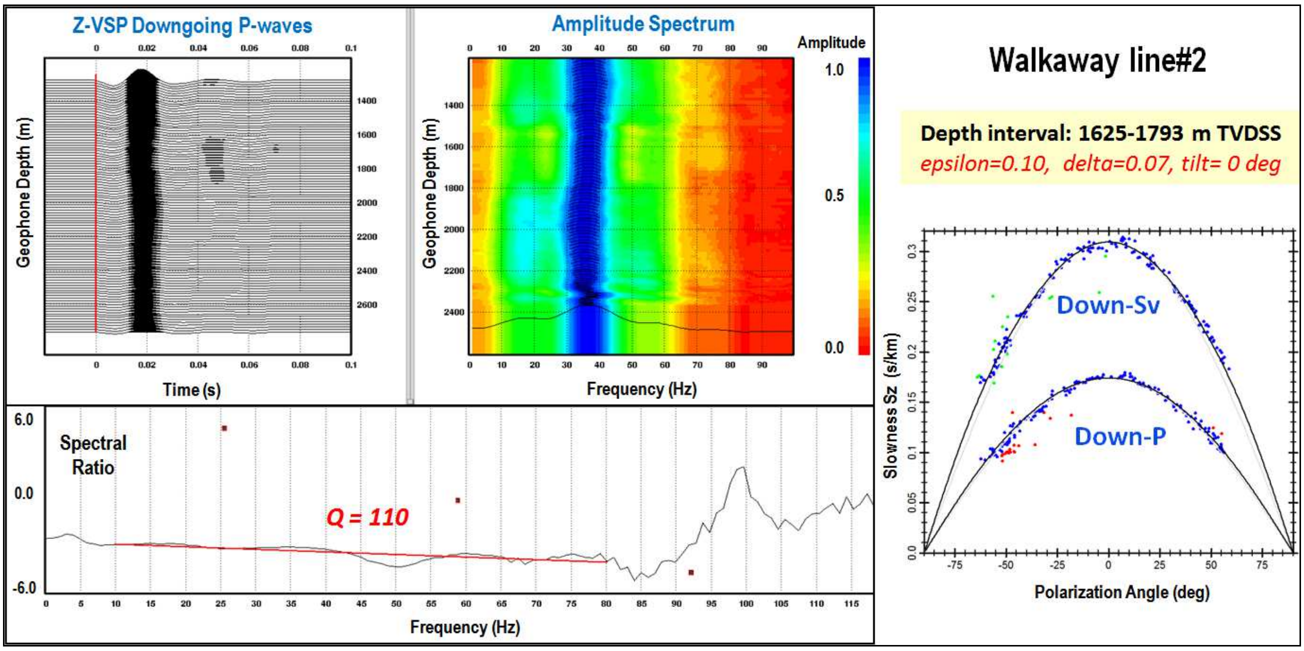

Figure 5: Q-factor from the rig-source VSP and TTI anisotropy results from the Walkaways. An effective Q=110 was estimated over 1200-2400 m TVDSS using the spectral ratio method. The Walkaway polarization and slowness crossplot for P- and S-waves are shown on the right panel. The inverted Thomsen parameters were epsilon=+0.10, delta=+0.07, with a vertical symmetry axis (VTI medium).

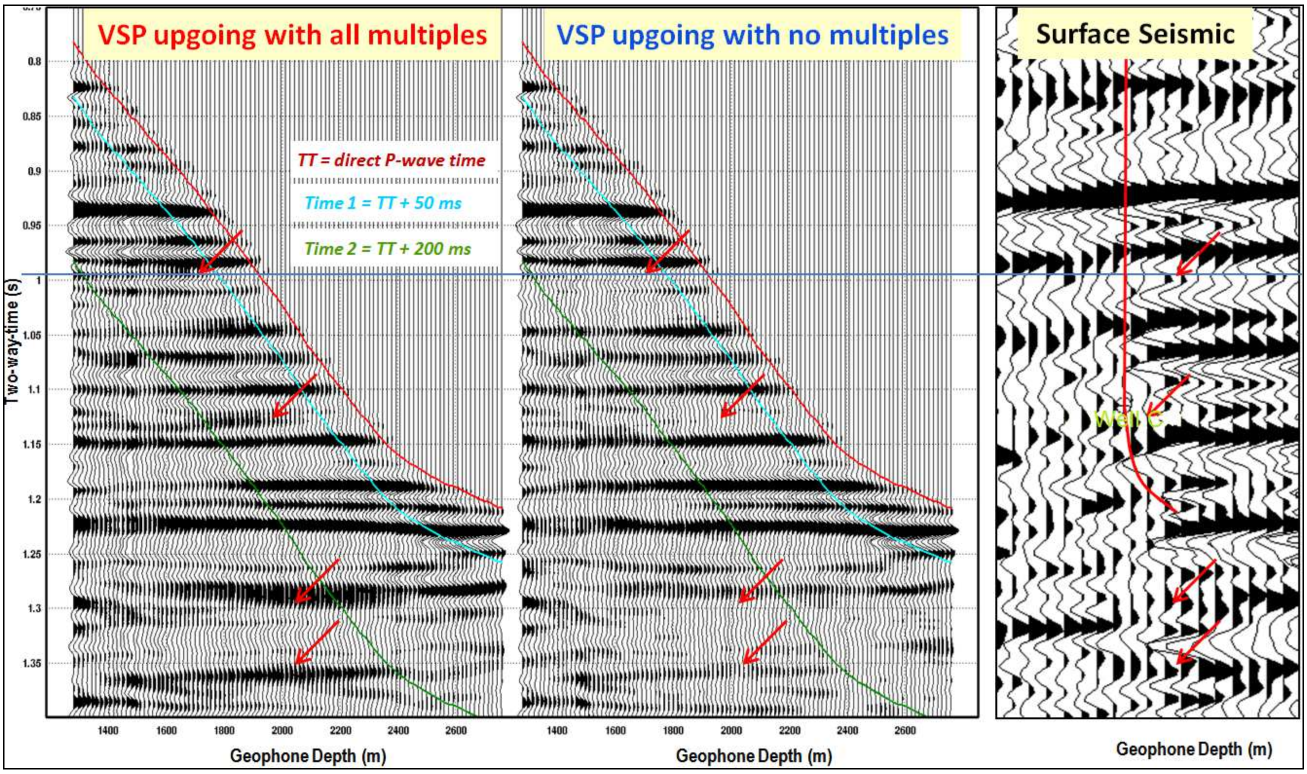

Figure 6: Upgoing waves in VSP without deconvolution and after trace by trace deconvolution. All multiples (surface generated and interbeds across the VSP interval) were highly attenuated by the deterministic deconvolution of upgoing by downgoing. The intervals that might be more affected by multiple energy interference were highlighted in the surface seismic panel on the right. Note that the VSP data inside the 50 ms external corridor does not change with deconvolution, indicating that the stronger multiples have a larger period.

Conclusions

The Walkaway VSP surveys delivered improved images of the reservoir Eastern boundary and of its internal architecture and lateral variation. The borehole seismic data assisted in the well to seismic tie and in understanding the true seismic response in the area. Several geophysical measurements were obtained that can be used during data processing to enhance the surface seismic data quality in the area. The VSP multiples identified have a direct use for the seismic interpreters.
Given the good results of the VSP surveys, Petrobras is now evaluating other applications of the borehole seismic technology in this remote area of the Amazonian jungle.

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