Seismic phase and amplitude calibration deep-water Brazil using VSP data

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Abstract

In this paper we review a case study where borehole seismic data acquired in a deep-water field offshore Brazil, was used to build a 1.5D-anelastic model that accurately predicts the seismic amplitude attenuation versus time and offset, due to the combined effects of geometrical spreading, transmission losses and anelastic attenuation (Q-factor). This borehole calibrated model is ray-traced to compute a seismic amplitude gain function that can be applied directly to surface seismic pre-stack gathers and the results compared to the geometrical spreading correction conventionally used. The Q(z) profile derived from the VSP data provides also very useful information for high-frequency enhancement of seismic data. Finally, we show the use of VSP data in assessing the phase of different vintages of surface seismic data and their degree of well tie.

Introduction

Seismic phase and amplitude are important parameters in reservoir studies but their control during surface seismic processing remains a difficult task. Downhole in-situ measurements of Vertical Seismic Profile data (VSP) and sonic and density logs, allow quantifying the effects of the earth filter on the seismic pulse phase and amplitude, and provide hard data to validate and enhance surface seismic data processing.

The present case study concerns an oil field situated in the ultradeep waters of the Campos Basin, offshore Brazil, in water depths ranging from 1500 to 2000m. During 2004-2005, new high-density surface seismic data was acquired with time-lapse (4D) objectives in mind and to allow better reservoir characterization. Calibration at boreholes of the new surface seismic data, in terms of phase and amplitude, was important (Morice *et al.*, 2003) and it represented a driver for acquiring the first VSP survey in this field in February 2005.

For the VSP acquisition, a tri-axial tool was used, fitted with accelerometer sensors. These sensors are omni-tilt, non-gimbaled, exhibiting a flat amplitude response from 3 to 200Hz, and a linear phase response over the seismic bandwidth. A linear Sodera G-GI airgun array was used, with two 250 cu.in. generator guns and one 105 cu.in. injector gun. The airguns were deployed with buoys from a semi-sub's crane, 50m from the wellhead, and fired at 5m depth and at 140bar. A reference hydrophone was deployed 5m below the guns in order to provide an accurate time reference for the survey and to monitor the source signature. A total of 45 VSP levels were recorded every 15m over the 3060-2350m MD interval, and six checkshot levels were recorded over 1800-2321m MD (Figure 1). Downhole data was recorded during 3.0s with 1.2s of blanking time. Surface hydrophone record length was 0.5s. All channels were sampled at 1ms.

The well had a 12.25" open hole section, a maximum deviation of 80.7° and a maximum temperature of 60°C. The 13.375" casing shoe was at 2494m MD and the 20" casing shoe at 1992m MD. Very good cementation conditions allowed recording quality seismic data behind two casings in this well. The maximum well deviation for the VSP survey was 51° at 3060m MD, with the horizontal displacement from the wellhead being only 261m. The maximum VSP source-receiver offset was about 220m. Therefore, this VSP was close to normal incidence.

Method

In order to model the seismic amplitude losses with propagation, a 1.5D-anelastic model is built from logs and VSP data. The amplitude decay due to geometrical spreading, Q-attenuation and transmission losses is computed by ray-tracing the borehole-calibrated model.

The 1.5D anelastic model extends from surface down to the reservoir and consists of the following blocked properties: P- and S-wave interval velocities, density and Q-factor values. If a VTI-anisotropy Walkaway VSP was acquired, Thomsen's ε and δ profiles could have been estimated versus depth and included in the 1.5D model (Leaney *et al.*, 2001). This additional data was not acquired due to cost considerations.

The compressional sonic log is drift corrected using the VSP times, extended to the sea floor using the shallow checkshot velocities and blocked at intervals about 3m thick using Backus averaging. The Gardner law is calibrated over intervals with both sonic and density logs and then used to extend the density log up to the sea floor. The mudrock Castagna law is calibrated over the intervals where both shear and compressional sonic logs are available and used to extend the shear velocity up to the seafloor from the compressional velocity. Shear velocities near the sea floor may be in error with this method. While this information is critical for OBC studies, it has a more limited impact on the study of amplitude losses. It contributes to the transmission losses terms, which are in general smaller than the spherical divergence and anelastic Q-attenuation.

The spectral ratio method (Gopa De *et al.*, 1994) is used in order to estimate an effective Q(z) profile from the VSP data. The VSP processing starts by first rotating the 3-C data to true vertical and true horizontal components, followed by velocity filtering to enhance the downgoing P-waves by means of a 7-level median filter. Predictive deconvolution is then applied: 1.0s operator with 100ms predictive gap. This aims to remove downgoing multiples and airgun bubble oscillations, while preserving the direct pulse. It also reduces the spectral notches and stabilizes the Q-estimation by the spectral ratio method. This method provides Q(z) over the depth interval between the top good checkshot level and the deepest VSP level, but not from the sea floor down to the top checkshot depth.

For the interval below the sea floor, we use the near-field gun signature measured by the monitor hydrophone as an estimate of the far field signature. By limiting the Q-analysis over a narrow frequency bandwidth (in this study from 30 to 90Hz), we show in Figure 2 that it is not required to deghost/reghost the near field measurement to simulate the far field signature. All our analyses are conducted in the far field, where the wavefront can be approximated by a plane wave and where the pressure field is in phase with particle velocity, their ratio being the acoustic impedance (Loewenthal *et al.*, 1985). This allows, for Q-estimation purposes, to compare the spectra of a far field hydrophone (pressure wave near the sea bottom) with that from a downhole VSP geophone. We recall that scaling factors (constant amplitude) differences between the two traces being analyzed by the spectral ratio method, do not affect the Q-estimation: the slope of the logarithm of the amplitude spectra ratio remains unchanged, and this slope is proportional to 1/Q.

In order to determine the average phase difference between the zero-phase VSP reference and the surface seismic traces, the method used here relies on time-shifting and phase rotating the surface seismic and cross-correlating it with the VSP. A two-parameter search looks for the optimum time-shift and phase rotation of the surface seismic traces that produces the maximum cross-correlation coefficient. The phase rotations are performed using the Hilbert transform. This method produces average phase values that are weighted towards the frequencies containing the most energy.

Results and Discussion

The borehole seismic data were processed (Figure 3) following the procedure described in the previous section to determine the Q-factor in the following intervals:

(i) VSP interval: 2400-3060m MD
(ii) Checkshot interval: 1800-2371m MD
(iii) Below sea floor: 1614-1800m MD

In Figure 4, we summarize the results of the Q-analysis conducted on these three intervals. For confidentiality reasons only relative values are indicated. A low Q-value was estimated over the interval below the sea floor. As explained in the previous section, the Q estimation between seafloor and the top checkshot, requires converting the downhole accelerometer trace recorded to its velocity equivalent (a 10Hz-geophone response was taken) before comparing it by the spectral ratio method to the hydrophone trace. The impulse responses of the different Schlumberger VSP sensors are characterized allowing transforming from one response to any other.

Using the VSP and log data, a 1.5D-viscoelastic model was built (Figure 5) by following the method described in the previous section. This model was ray-traced for the VSP geometry and the different contributions to amplitude decay were estimated, using a 30Hz central frequency for the Q attenuation. The amplitude decay results were compared with the decay observed in the VSP first arrivals (RMS amplitude in 100ms window). A relatively good match was obtained (Figure 6). We have then ray-traced the model for a surface seismic geometry to produce an amplitude gain map versus two-way-time and offset (Figure 7). This gain function can be applied directly to surface seismic pre-stack gathers in Well-Driven-Seismic studies (Morice *et al.*, 2003).

In Figure 8 we show the VSP CDP-Mapping two-way-time image superimposed on one vintage of surface seismic data. In Figure 9 we have estimated the phase difference and time shift between the two datasets. The average phase rotation is +16° and the time-shift is -3ms, but the correlation coefficient is only +0.55. The same phase analysis performed on another vintage of 3D seismic data resulted in a -4° phase-shift, a -3ms time-shift and a correlation coefficient of +0.70, providing a simple quality indicator about the level of surface seismic well tie.

Conclusions

A method of building a complete Q(z) model in deep-water from zero-offset VSP data was presented. The Q(z) profile together with VSP calibrated sonic and density logs, allow building a detailed 1.5D anelastic model of the subsurface. By ray-tracing through this model, amplitude gain functions can be computed and used to compensate surface seismic pre-stack gathers for amplitude decay due to geometrical spreading, transmission losses and anelastic attenuation. The validity of the amplitude gain functions derived was tested positively against measured VSP first arrivals amplitudes. In addition to amplitude calibration, we have shown how the high-resolution VSP traces, which are true-amplitude, zero-phase and multiple free, can be used to assess the degree of well tie of different surface seismic vintages and to determine their deviation from true zero-phase.

Acknowledgments

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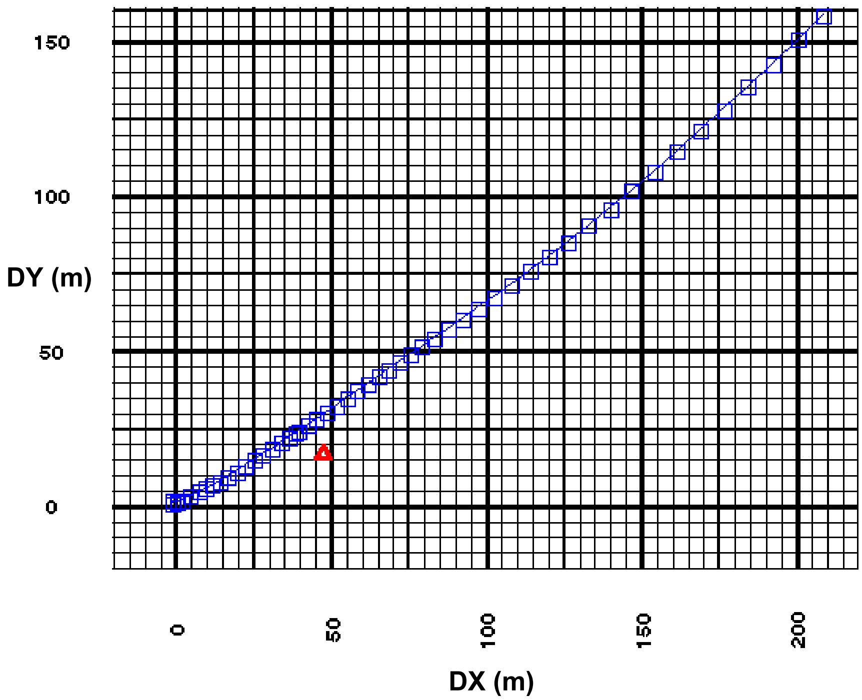

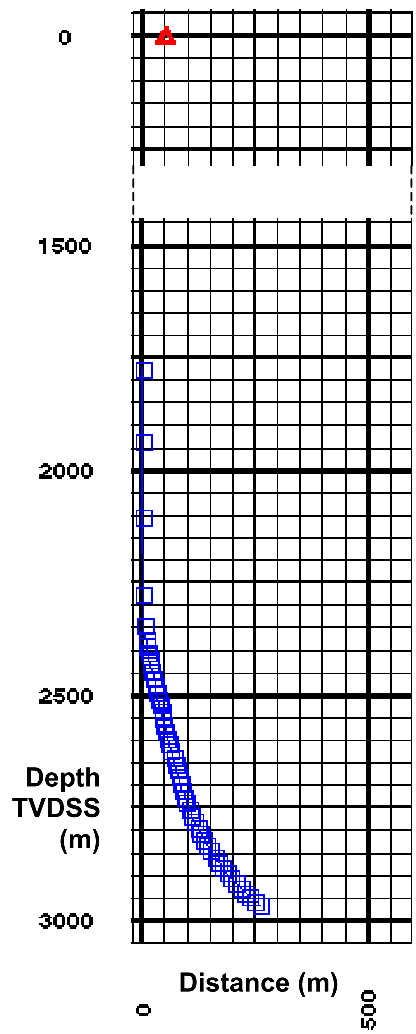

Figure 1 - Acquisition geometry for the rig source VSP survey. The wellhead is located at (0,0). The VSP source was deployed from a rig crane along N70°, at 50m offset and 5m depth, and it is shown as a red triangle. The receivers are shown as blue squares. A total of 45 VSP levels were recorded every 15m over the 3060-2350m MD interval. Six checkshot levels were recorded over 1800-2321m MD.

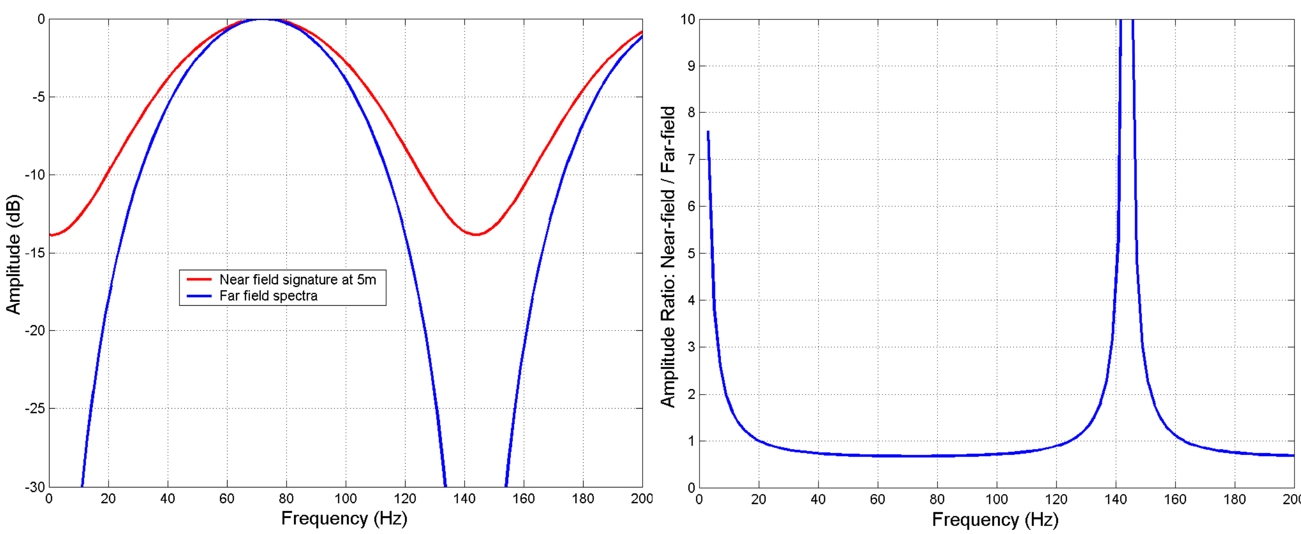

Figure 2 – Amplitude spectra of modeled near field and far field source signatures. The VSP source ghost effects were modeled and compared at the near- and far-field. To model the far-field trace, amplitude was set to +1 at the first sample and it was set to '-1' at sample number eight (1ms sampling was used). All other samples are zero. For the near-field trace, the amplitude was set to +1 at the first sample and '-1/3' at the eighth sample to simulate the ghost from a 5m gun depth. The plot on the right shows that the amplitude spectra of far field and near field source signatures should be similar over the bandwidth from 30Hz up to 110Hz.

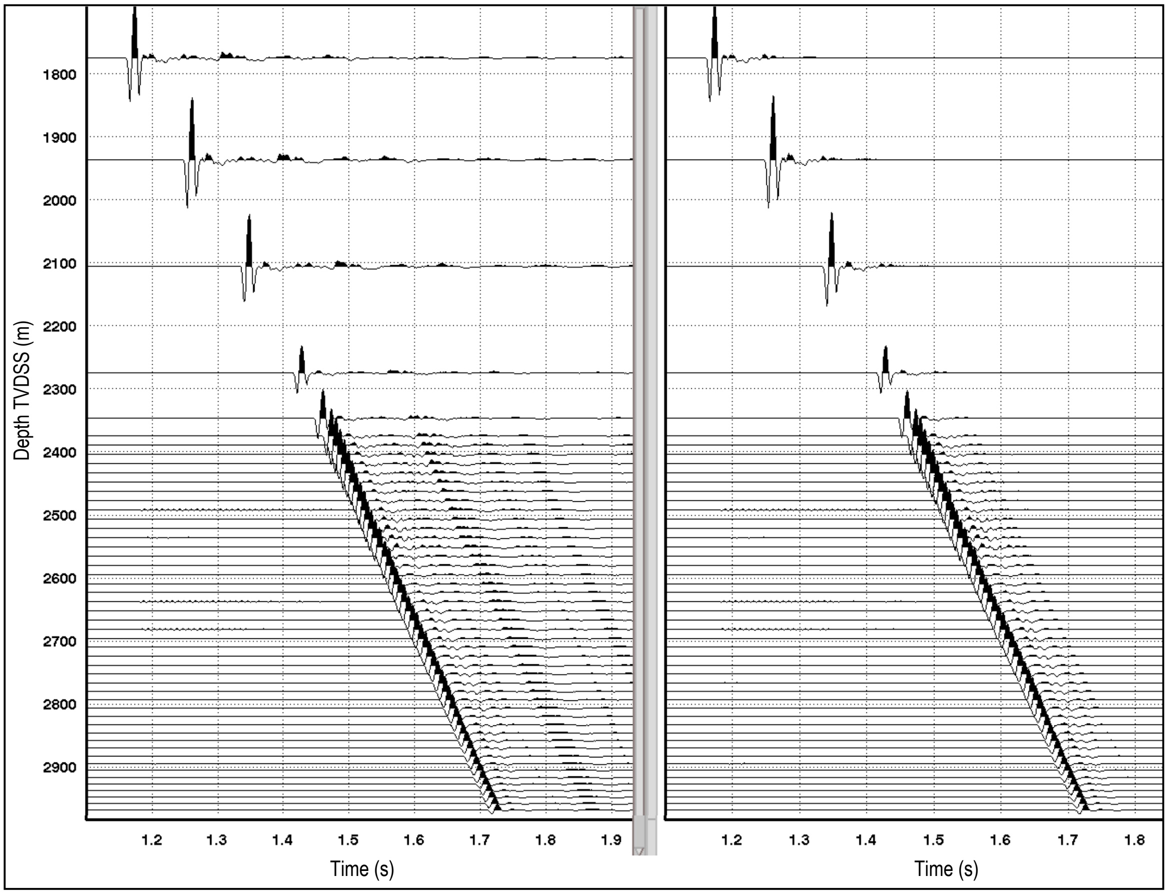

Figure 3 – VSP downgoing waves before (left) and after predictive deconvolution (right).
The oriented vertical component stacks were first velocity filtered to enhance the downgoing P-waves (left panel). Predictive deconvolution was then applied using a 1.0s operator with a 100ms gap, preserving the first arrival wavelet and attenuating downgoing multiples (right panel).

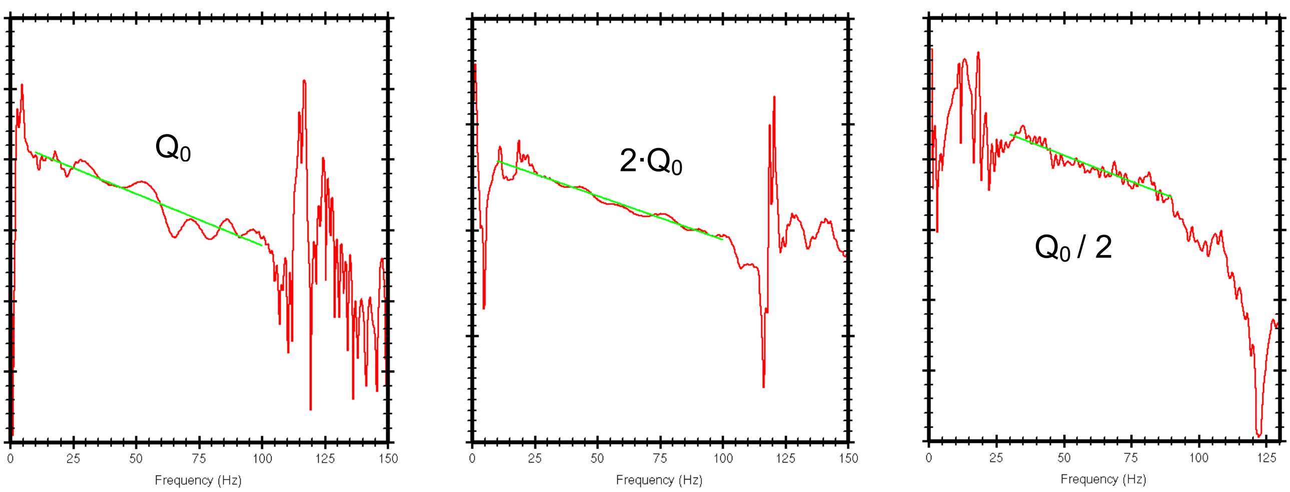

Figure 4 – Q-estimation by the spectral ratio method over three intervals: VSP, Checkshot and seafloor.
In the VSP interval 2400-3060mMD (left panel), a value Q_0 was estimated from top and bottom interval traces, with a correlation coefficient c.c.=0.938 over 10-100Hz. In the Checkshot interval 1800-2371mMD (middle panel), a value of $2Q_0$ was estimated, with c.c.=0.970 over 10-100Hz. Below seafloor over 1614-1800mMD (right panel), a value of $Q_0/2$ was estimated from the top checkshot accelerometer trace (geophone transformed) and the surface hydrophone trace, with c.c.= 0.946 over 30-90Hz. For confidentiality reasons only the relative Q-magnitudes are indicated.

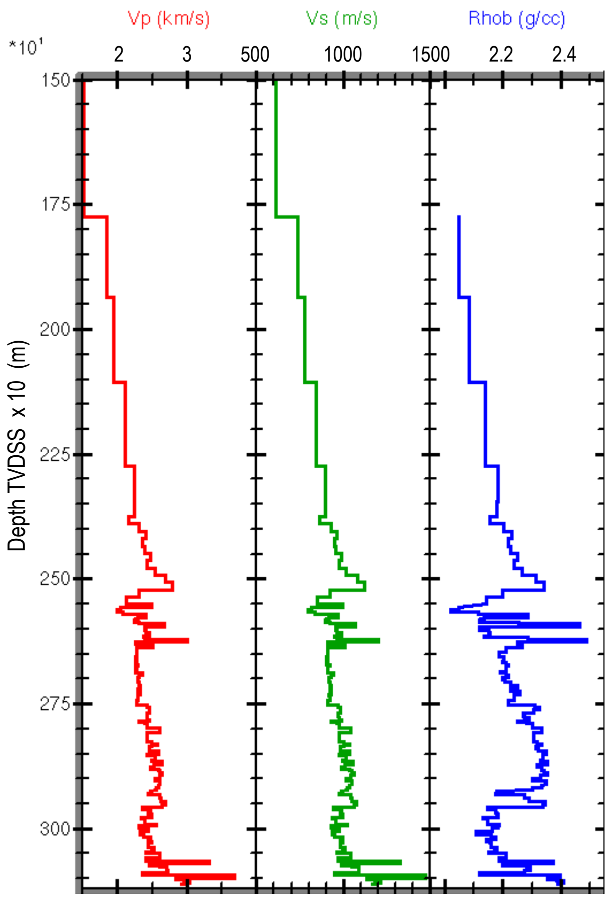

Figure 5 – Viscoelastic 1.5D model generated from logs and VSP data.
The P-wave velocity Vp was obtained from sonic drift corrected with VSP times. A calibrated Gardner law was used to extend the density up to the seafloor from Vp. A calibrated Castagna law was used to extend Vs up to the seafloor from Vp. For confidentiality reasons the Q(z) profile derived from the VSP data is not displayed.

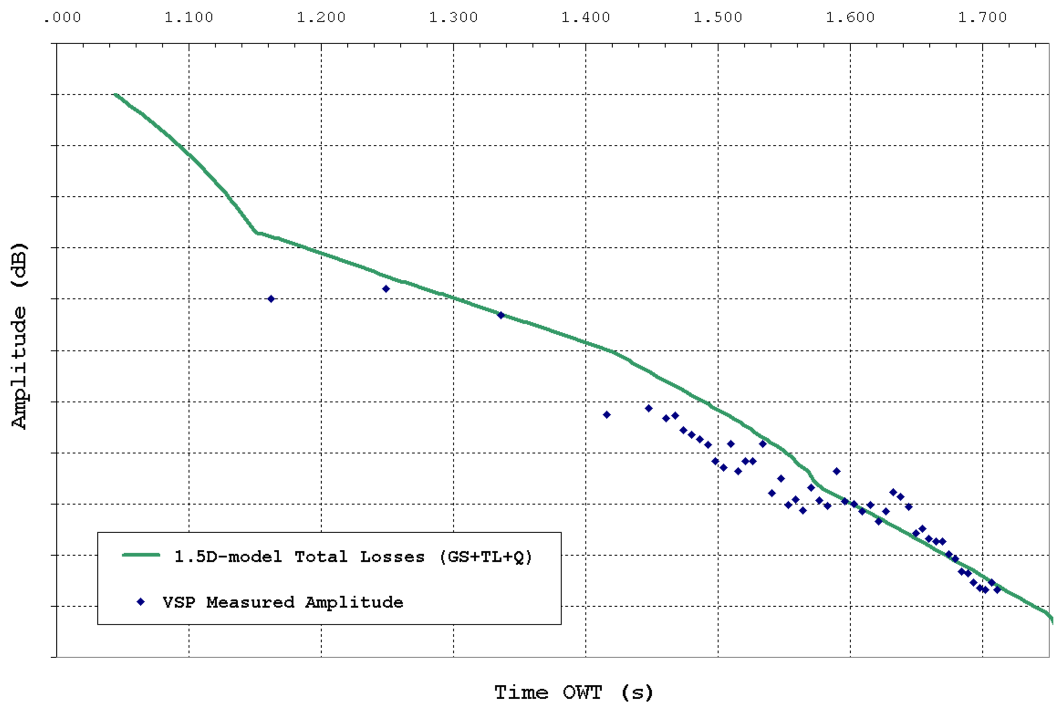

Figure 6 – Seismic amplitude decay in dB with propagation time: modeled versus VSP measured.
The dB-scale was normalized to zero at seafloor's one-way-time. The model in figure 5 was used to compute the total amplitude decay (green curve) due to spherical divergence, transmission losses and Q-absorption (estimated at 30Hz central frequency). The blue dots are the direct VSP amplitude measurement. Due to the lack of logs in the shallow sediments, the transmission losses are underestimated. For confidentiality reasons the decibel scale was omitted.

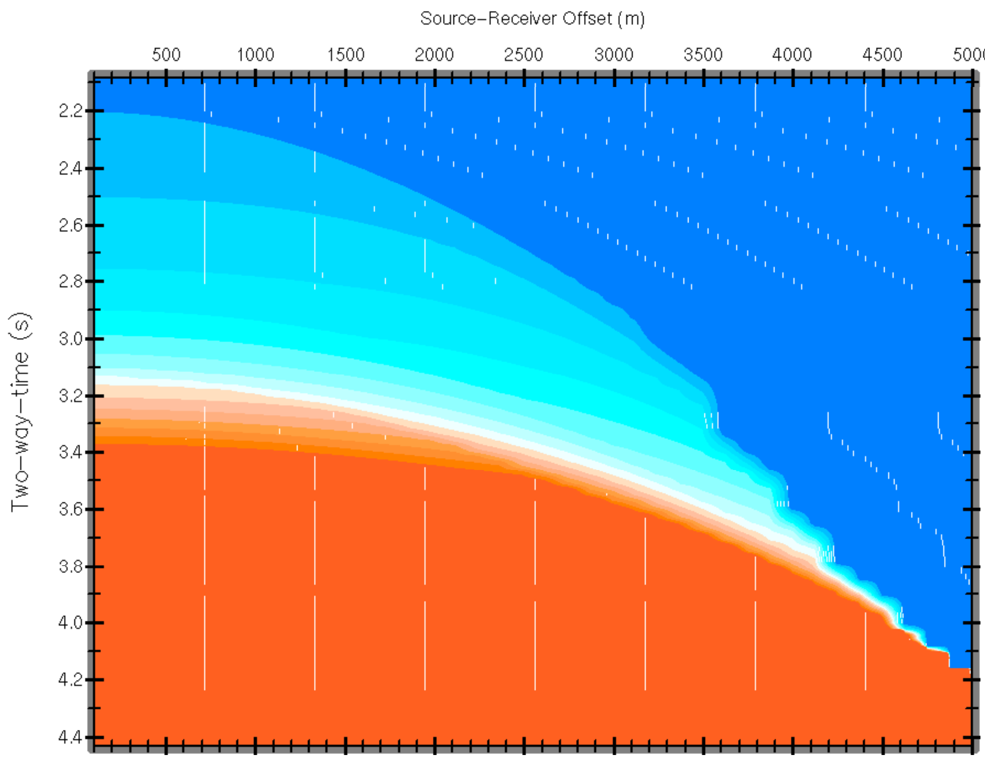

Figure 7 – Amplitude gain function to compensate surface seismic gathers for total amplitude decay. The gain function was computed by ray-tracing the model in figure 5 and it includes the effects of spherical divergence, transmission losses and Q. The modeled interval runs from the seafloor at 1589m down to 3110m TVDSS. Dark blue corresponds to a minimum gain and red corresponds a maximum gain. The color scale was omitted for confidentiality reasons.

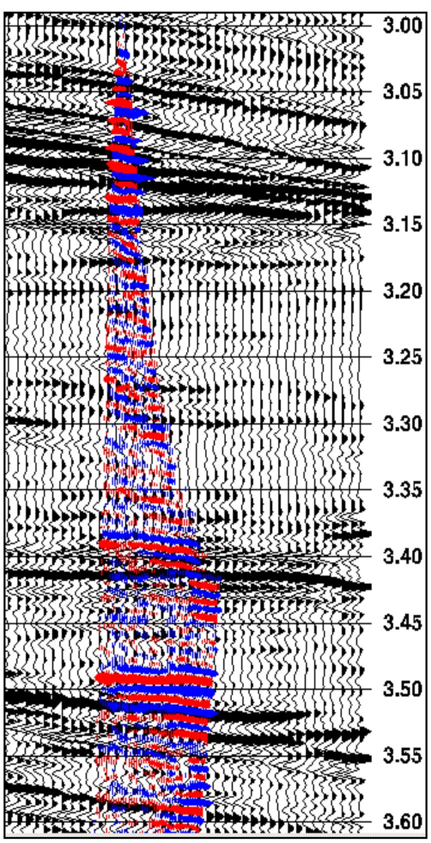

Figure 8 – Surface seismic and VSP CDP-Map results in two-way-time.

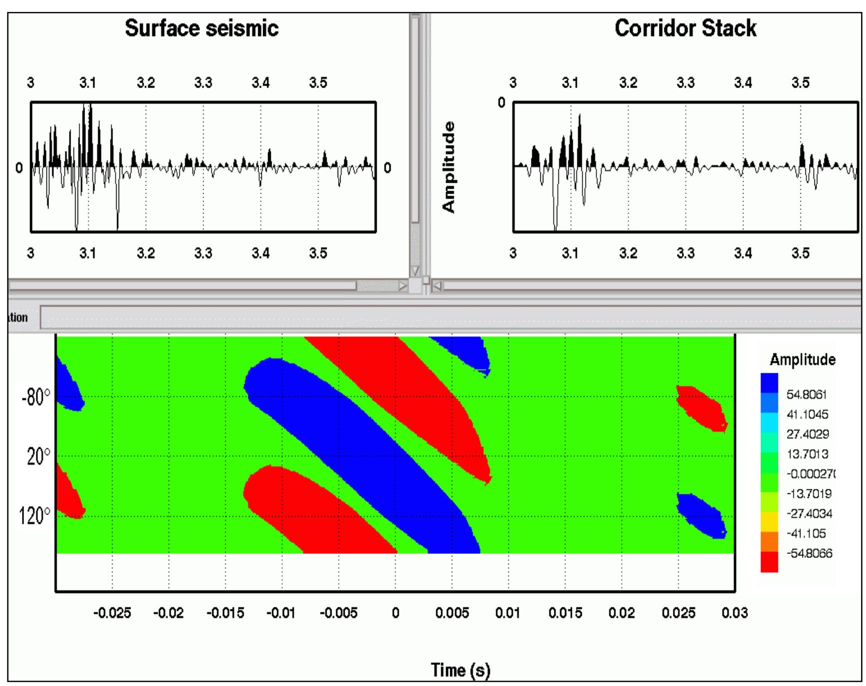

Figure 9 – Phase rotation and time-shift analysis between zero-phase VSP and surface seismic. The analysis was conducted in a time window from 3.0 to 3.6s two-way-time. The time shift to apply to the surface seismic traces to better match the VSP is '–3ms' and the phase rotation is +16°. The correlation coefficient is only +0.55 in this case.