Cover Sheet

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Integrated Formation Attenuation and Multiple Generator Identification from Multi-well VSP Data

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Abstract. The Vertical Seismic Profile (VSP) is a widely used technique for extracting velocity information and seismic well tie purposes. However, the full potential of VSP data remains underutilized. This study explores the broader applicability of VSP data beyond its conventional usage by investigating its benefits for seismic data processing and interpretation. Advanced VSP products, incorporating features such as formation attenuation and multiple generator identification, play a crucial role in optimizing seismic data processing workflows.

In this paper, we present an extended workflow for zero-offset VSP processing that leverages the value of the downgoing wavefield. By utilizing a robust industry method, we estimate formation attenuation by analyzing the spectral ratio of the downgoing wavefield. The multispectral method is employed to compute the attenuation ratio, considering all receiver pair combinations. This results in the extraction of a 1-D attenuation profile along the well based on statistical coherence. To identify the multiple generators, we apply a separate deconvolution process involving trace-by-trace analysis and reference trace comparison. The adaptive subtraction method is utilized to compute the difference, outputting a wavefield exclusively containing multiple reflections. Additionally, we incorporate the available sonic and density logs from the well to calculate seismic multiples reflectivity modeling, which is then compared with the wavefields.

We demonstrate the effectiveness of our proposed workflow by applying it to Zero Offset VSP datasets from two wells in the Browse Basin, Australia. The integration of VSP datasets into the subsurface model highlights their value and contributes to subsurface interpretation and processing. The obtained results are can upscaled to a 3D field scale using property modeling, yielding valuable insights. Moreover, this study emphasizes the critical role of VSP data as an essential input for subsurface imaging and reservoir characterization.

Keywords: Multi-well VSP, Multiple Analysis, Q Analysis, and Seismic Processing

1. Introduction

This paper presents an integrated approach aimed at maximizing the total value of Vertical Seismic Profile (VSP) data. The Zero Offset VSP configuration is commonly employed to derive time-depth curves for seismic well tie purposes. In addition to providing time-depth information, Vertical Seismic Profile data contains wavefield recordings that offer valuable insights into wave properties, including frequency, attenuation, and the influence of formation reflectivity on wave transmission or reflection. By incorporating and integrating these measurements with seismic processing, seismic interpreters can enhance the quality and quantitative nature of seismic images derived from the data.

Two crucial parameters for seismic processing that can be obtained from VSP data are the Quality factor (Q) and seismic multiples identification. Typically, seismic data requires compensation for frequency attenuation to achieve higher resolution image, proper amplitude and phase correction. This compensation is commonly achieved using an inverse Q filter. VSP data allows for the estimation of the Q value by analyzing the frequency information recorded at each depth. Moreover, in many regions worldwide, the interpretation of primary and multiple reflection is hindered by the presence of seismic multiples, which also affect amplitude measurements. To address this issue, it requires the use of well data as a control point for surface multiple attenuations or interbed multiple attenuations. The VSP method, utilizing a receiver inside the wellbore, records wave propagation and provides an effective control point for this purpose.

Table 1. Seismic Processing Project Pain Points and Solutions from VSP.

Seismic Processing	Pain Points	Input from VSP
Multiple Attenuation (Interbed/Surface)	Difficult to determine multiple generator	Down/Up multiple generator identification
Multiple Attenuation (Interbed/Surface)	Lack of hard data to QC multiple attenuation workflow	Primary or multiple corridor stack
Inverse Q Filter	Required direct measurement of Q Value	Frequency or Q profile depth by depth
Q Tomography	Required stable and reliable initial/background model	Frequency or Q profile depth by depth

The VSP configurations allow for the simultaneous recording of both downgoing and upgoing wavefields. We demonstrate advanced processing workflows that aim to maximize the value of each wavefield. The initial processing sequences, including noise suppression, geometric and static correction, are applied to the data. Subsequently, wavefield separation techniques are employed to separate the downgoing and upgoing components. To estimate the Q profile as a function of depth, we utilize the multispectral ratio method, as proposed by Leaney (1999). For multiple identifications, we used a combination of deterministic deconvolution on the downgoing and upgoing wavefields, following the approach presented by Lesnikov et al. (2011). This approach enables the identification of zones with the strong multiple generators. To complement this method, we integrate the results with multiple modeling using the acoustic logs, following the methodology outlined by El-Emam et al. (2005). We apply this comprehensive approach to two sets of wellbore data, allowing us to obtain an overview of the lateral variation in Q estimation and multiple identifications.

2. Data and Methodology

The example dataset used in this study was the open-source Poseidon 3D data obtained from the NW Shelf, Australia (Browse Basin), which was provided by GEOscience Australia. The dataset was downloaded from the following source: https://terranubis.com/datainfo/NW-Shelf-Australia-Poseidon-3D. The Browse Basin, which forms part of the Westralian Superbasin, is a northeast-trending depocenter containing up to 15 km of Paleozoic to Cenozoic sediments (Government of Western Australia, 2014).

Within the available dataset, a total of six wells has VSP (Vertical Seismic Profile) datasets. For the purpose of demonstrating the workflow, two wells were selected for analysis: Poseidon-1 and Pharos-1. These wells are located approximately 12 km apart. Figure-1 provides an overview of the seismic section encompassing both wells. It is worth mentioning that the dataset was affected by casing noise. To enhance the signal-to-noise ratio of the data, casing noise removal was applied as a preprocessing step before conducting advanced processing techniques.

2.1. Multi-Spectral Ratio Q Analysis

The Q value was determined using the multi-spectral ratio method (Leaney, 1999), which involved computing all possible combinations of receivers. This method was employed to enhance the statistical significance of the Q estimates. Along the 1-D profile of the wellbore, we extracted the inverse covariance-weighted Q from various spectral ratios. To estimate Q, we focused on the frequency range of 7-100 Hz at the binned mid receiver's positions. Following the testing of several parameters, Q estimation was performed within the 7-100 Hz frequency range. The multi-spectral ratio method generated a color-coded plot of Q values against mid-values between receivers' pairs, representing the estimation with varying levels of confidence. The level of confidence was indicated by a color scale, with smaller confidence levels depicted in blue and higher confidence levels in red.

2.2. Multiple Waveform Identification Processing and Modeling

The downgoing and upgoing wavefields are processed through deterministic deconvolution to identify the wavefield that only contains multiples (Lesnikov, 2011). The simplified method combines deterministic deconvolution to identify the wavefield that only contains multiples (Lesnikov, 2011). A series of deconvolution methods were applied to this processing sequence:

1. Apply trace-by-trace deconvolution using an operator determined directly at each receiver level. This step yields a wavefield comprising only primaries.
2. Utilize deconvolution with an operator derived from a shallower trace. Based on Molyneux (1996), this reference trace deconvolution preserves primaries and interbed multiples while eliminating surface-related multiples.
3. Subtract the results obtained from reference trace deconvolution (step 2) from the outcomes of trace-by-trace deconvolution (step 1) to obtain a wavefield containing all interbed multiples reverberating between the two reflectors.

In addition to VSP multiple waveform processing, several modeling runs were conducted using blocked sonic and density logs. The logs were blocked to create a layered model at the well location. This model estimates the total combined reflectivity of all potential first-order interbed multiples (El-Emam et al., 2005; Ras et al., 2012). The cumulative reflectivity from VSP multiples is a qualitative measure of the strength of the reflector in generating multiples and results from the upward and downward reflectivity experienced by the interbed multiples. The modeled reflectivity was then convolved with a wavelet to obtain the seismic response of primaries only, primaries and multiples, and multiples only.

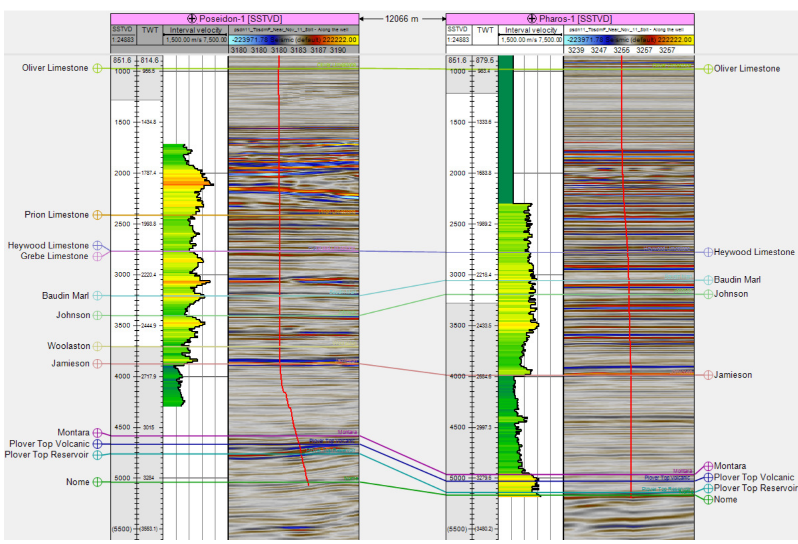


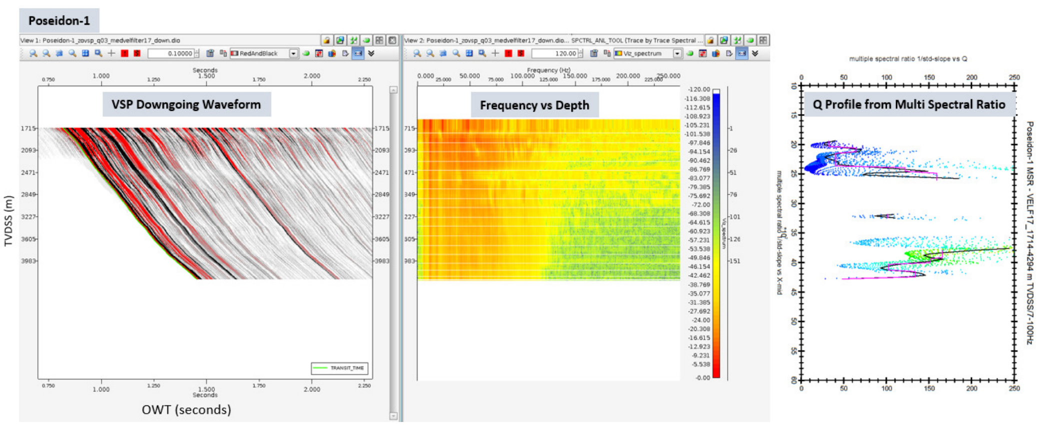
Figure 1. Well Section crossing studied well Poseidon-1 and Pharos-1 along with the interval velocities.

3. Results and Discussion

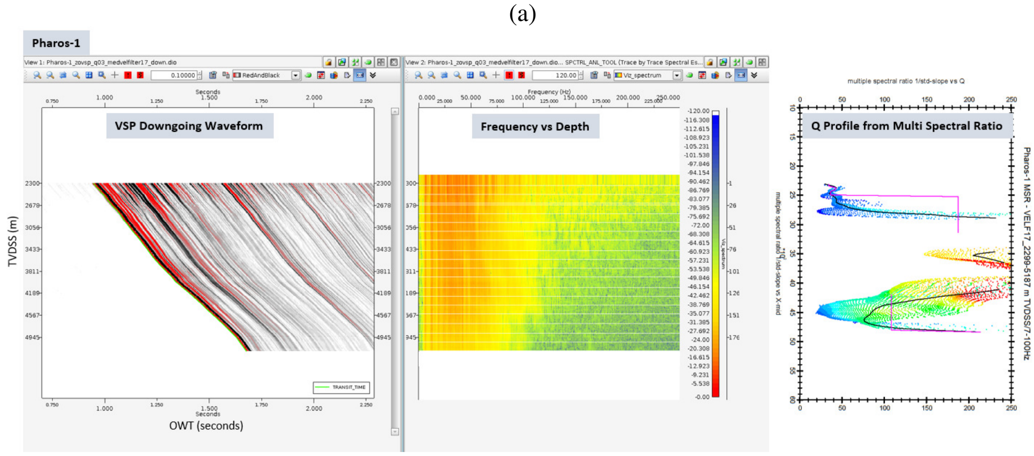
3.1. Q Estimation Results

In both wells, the Vertical Seismic Profile (VSP) data was affected by casing noise, particularly in the shallower section. To enhance the total wavefield data (Z component), a series of noise removal techniques was applied. The resulting data was then utilized to compute the end Q results, using the downgoing wavefield after the removal of casing noise.

The figure below illustrates a comparison between the downgoing waveform and its corresponding frequency spectrum map as a function of depth. Although efforts were made to remove noise, some residual noise remained evident in the spectrum. The Q estimation was performed using frequencies ranging from 7 to 100Hz. It is noteworthy that Poseidon-1 exhibited a more issue with noise compared to Pharos-1. The right panel of the figure displays the Q results map. Within the depicted zone in the middle, an invalid Q profile estimation is observed, indicating a lack of accurate data. However, the deeper interval of the map reveals a Q profile estimation characterized by decreasing Q values.



(a)



(b)

Figure 2. Downgoing waveforms (left), with frequency vs depth spectrum (middle), and map of Q vs Xmid overlaid with blocked Q profile. Top figure (a) is for Poseidon-1, and bottom figure for Pharos-1 (b).

3.2. Multiples Waveforms Identification Processing Results

The presence of casing noise significantly affects the various extraction processes in both data sets. To mitigate this issue, we chose the deconvolution operator deeper than the recorded shallowest receiver. In Figure 3, the VSP downgoing multiples and VSP upgoing multiples are obtained as a result of the reference trace deconvolution at 2602 m. This deconvolution process highlights distinct multiple activities occurring at approximately 2.6 s and 3 s intervals. To aid in identifying the start of a multiple, a dashed orange line is used to indicate a 60 ms delay from the first arrival curves.

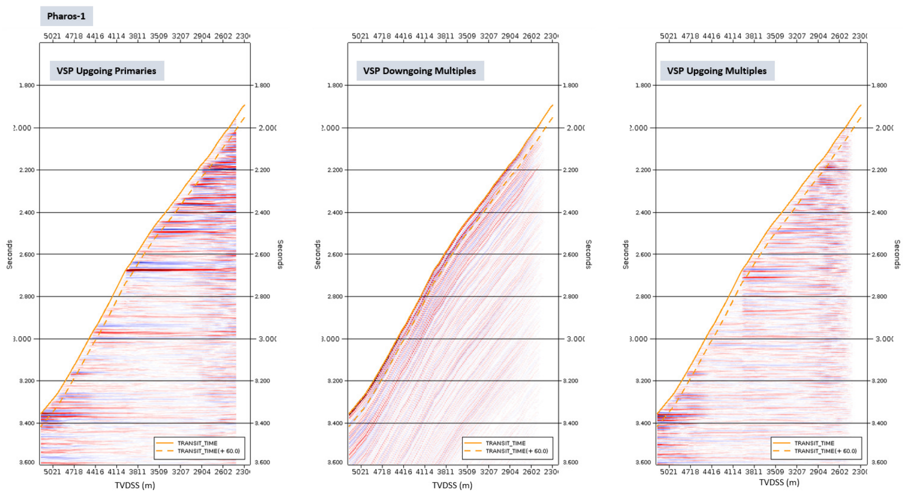


Figure 3. Multiple extraction process, VSP upgoing primaries (left), VSP downgoing Multiple (middle), and VSP upgoing multiples). The dashed orange line can be used to indicate start of multiple.

3.2. Multiples Modeling from Acoustic Logs

The open dataset used in this study includes a limited interval of sonic and density logs. In the case of Poseidon-1, the available sonic logs were below the Vertical Seismic Profile (VSP) interval, therefore the modeling using Poseidon-1 is not feasible. In the case of Pharos-1, the sonic logs and VSP interval velocity were spliced and extended to the seabed using a compaction trend, resulting in a more realistic layer model. To assess the quality of the combined reflectivity, Figure 4 displays the annotated total combined reflectivity that aligns with the primary generators. Notably, at a specific reflector (~2.755 ms), the difference observed in the primaries, multiples only, and primaries+multiples synthetic seismogram can indicate the presence of multiples influencing the data. As demonstrated in Figure 4, a correlation between the upgoing interbed VSP multiple waveforms is apparent in the interval near 2.75 s Two-Way Travel Time (TWT).

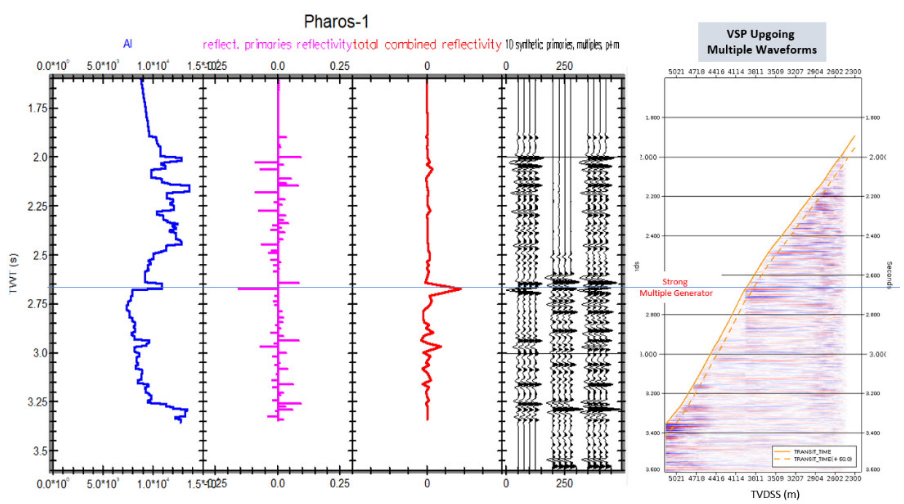


Figure 4. Acoustic Impedance (AI), primaries reflectivity, and total combined reflectivity. Peaks in total combined reflectivity correspond to potential multiple generators. Correlated with synthetic waveforms and VSP upgoing multiples waveforms.

4. Values Added from Seismic Processing

VSP techniques play a pivotal role in the quantitative calibration and reservoir description within Reservoir Geophysics. However, the limitations of uniform observation geometry and a small migration aperture necessitate the integration of VSP data with seismic data to establish a well-driven seismic data processing approach (Shufang et al., 2015).

In seismic processing, the estimation of Q (quality factor) and the identification of multiple reflections are crucial parameters. These inputs can be effectively utilized for multiple attenuations and inverse Q filtering, thereby enhancing the accuracy and quality of seismic data processing. To facilitate this integration and streamline the seismic processing workflow, an integrated approach is developed as outlined below.

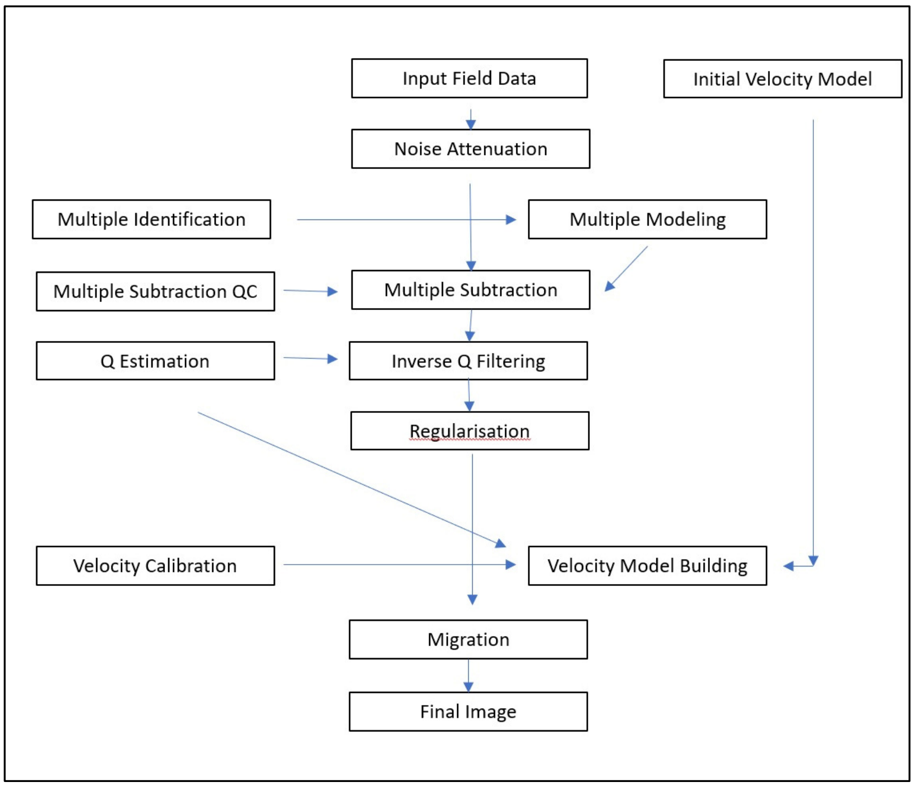


Figure 5. Integrated workflow through the utilization of VSP information to elevate seismic processing

5. Conclusions

This paper has demonstrated an integrated workflow for estimating formation attenuation (Q value) and identifying multiple generators using VSP data. The correlation analysis between the modeled total combined reflectivity derived from Acoustic Impedance logs combined with VSP multiples waveform processing has proven effective in determining the presence of multiple generators. Notably, it was observed that beyond this interval, a decrease in Q values was observed, suggesting that the presence of multiples may influence formation attenuation. In future studies, it is recommended to extend the workflow to include the generation of a corridor stack, which can be instrumental in calibrating amplitude during the multiple suppression process. Furthermore, the workflow can be expanded to investigate the impact of seismic multiples to formation attenuations. Including this workflow as an end product would emphasize the essential role of VSP as an input for well-driven seismic data processing. The integrated workflow presented in this study has the potential to advance our understanding of formation attenuation and improve the overall effectiveness of seismic data processing.

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