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Integrated Multiple Attenuation Across the Shelf Edge – a Colombian Caribbean Case Study

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Summary

Due to well-known limitations of data-driven SRME in shallow-water environments, multiple attenuation methods applied to date on seismic towed-streamer datasets acquired in shallow waters of the Colombian Caribbean shelf have been heavily dominated by gapped Tau-P deconvolution techniques. In this paper, a successful application of integrated multiple attenuation, including a model-driven shallow-water implementation of 3D SRME, is presented for an offshore Colombian Caribbean case with highly variable bathymetry. This model-driven, shallow-water 3D SRME is based on convolution between input data and Green`s Function propagator gathers representing forward-modelled water-bottom primary reflection data, thus avoiding the issues with conventional SRME in shallow-water areas.

On the shallow-water continental shelf, the multiple attenuation effectiveness of the presented integrated approach consistently outperforms that of gapped Tau-P deconvolution. In addition, we achieved a seamless merge with conventional deeper-water 3D SRME in a survey area with bathymetry ranging from shallow-water continental shelf to slope, rise down to deep-water abyssal plain. Thus, model-driven SRME methods have the potential of "bridging the shelf-break demultiple gap", and of replacing Tau-P deconvolution as the workhorse in shallow-water demultiple sequences.

Introduction

For towed-streamer configurations, successful application of SRME remains one of the key processing challenges in shallow waters due primarily to two root causes: (1) the near-offset acquisition source-to-receiver gap, and (2) cross-talk between water-layer related multiples (WLRMs). Success of SRME techniques depend on the availability of broadband water-bottom primary reflections (WBPRs) on input data, with sufficiently high signal-to-noise ratio from zero offset up to critical angle in order to accurately predict WLRMs. To address the near-offset acquisition gap, a conventional SRME workflow typically includes in-line NMO- and Radon-based extrapolation of available nearest-offset traces to extrapolate to nominal zero-offset traces. This procedure aims to reconstruct the near-offset WBPR wavefield prior to SRME multiple prediction.

At the nearest available offsets, the recorded WBPRs in shallow-water surveys are generally contaminated by acquisition noise and other "early" near-seabed arrivals. Combined with NMO-correction related wavelet stretch at high angles of incidence, this severely distorts this required moveout-based near-offset extrapolation to zero-offset. Due to this stretch and distortion, the extrapolated WBPRs at near offsets in shallow waters are typically low-frequency, which decreases the bandwidth of the WLRM models predicted by the SRME convolutional process, relative to the recorded WLRMs present in the data. In general, least-squares adaptive filtering of the SRME model does not sufficiently account for this bandwidth difference. In addition to bandwidth issues for *extrapolated* WBPRs, the *recorded* shallow-water WBPRs are relatively low-amplitude at high to near-critical angles due to mode conversions and angular directivity. WLRMs are typically recorded at lower angles of incidence with significant amplitudes up to high orders compared with the primary signal in the same (adaptive filtering) time window. Cross-talk between WLRMs can additionally deteriorate SRME results in shallow-water, even in the hypothetical case where the WLPRs have been sufficiently recorded at near-offsets, or perfectly extrapolated to zero-offset. This is due to overlap of short-period WLRMs in the SRME convolution.

To address these shallow-water SRME challenges, Wang et al (2011) proposed a model-driven implementation of SRME that convolves input data with Green`s function propagator gathers representing forward-modelled WBPRs rather than with the WBPRs actually recorded in the data, as is the case in conventional SRME. In this paper, the method and results of a similar Shallow-Water Multiple Elimination (SWME) approach described by Zhai et al (2015) are discussed. Here, we integrate the model-driven approach with conventional SRME techniques across the shelf edge.

Colombian Caribbean Case Study

In Colombian Caribbean shelf areas (figure 1), the shallow seafloor is often hard and structural attenuation and absorption in the near-seabed zone can be high, posing additional difficulties for the application of SRME. Gapped Tau-P deconvolution relaxes the dependency on WBPRs for SRME. However, Tau-P deconvolution attenuates events with periods from gap length to gap length plus operator length, including non-seabed related free-surface multiples generated in the near surface, inter-bed multiples, and primaries. This undesirable attenuation negatively impacts the internal consistency of the wavefield. In turn, the (partial) attenuation of longer-period free-surface and inter-bed multiples compromises subsequent non-WLRM SRME (on water-bottom muted input) and any inter-bed demultiple methods. Finally, Tau-P deconvolution methods are inherently 2D in nature, leading to suboptimal results at outer-cable gathers and subsequently to footprint due to differences in demultiple efficiency between inner and outer cables.

The majority of Colombia`s Caribbean offshore blocks covering the shallow-water continental shelf with relatively flat seabed also include seabed conditions with highly variable bathymetry, morphology, complexity, and structural dip *within the same block*. For these blocks and covering seismic surveys, a seamless integration of shallow- to deep-water multiple attenuation methods is required. Tau-P deconvolution assumes an approximately flat seabed within the gather spread, and will not effectively attenuate multiples in shallow-waters with a variable, non-flat, and complex water bottom. Therefore, Tau-P deconvolution is typically limited to areas of shallow bathymetry on the proximal side of the continental shelf break. For reasons mentioned above, SRME generally yields suboptimal free-surface multiple attenuation results in water depths less than about 200-400 m. This means that for cases where the continental shelf break is located in water depths less than 200-400 m, SRME and Tau-P deconvolution techniques cannot be seamlessly integrated.

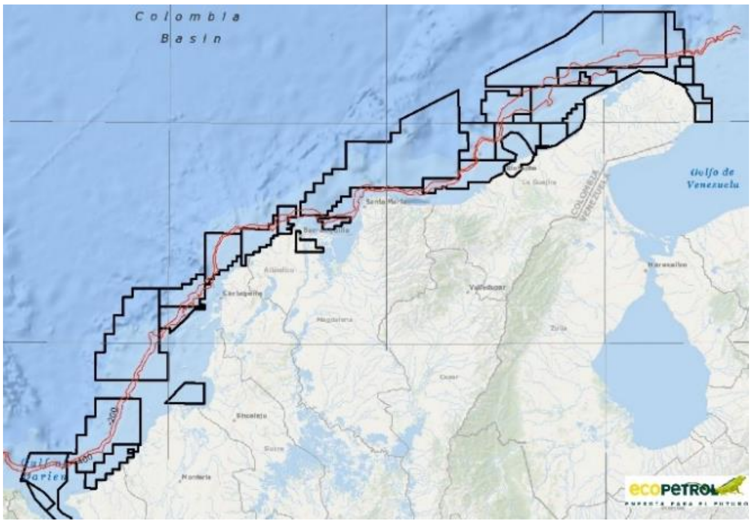


Figure 1 *Colombian Caribbean Coast; Offshore licence blocks with shallow-water zones are annotated in black. The 200m & 500m bathymetry contour lines (red) indicate the water depth range at shelf edge where conventional SRME methods tend to break down.*

Fortunately, SWME-type methods have the potential of bridging this “shelf-break demultiple gap”, in areas that contain bathymetry ranging from shallow-water continental shelf down the slope, rise and deep-water abyssal plain. SWME techniques, however, exclusively address WLRMs, which are a mere subset of the free-surface multiples targeted by SRME. With the aim to eliminate the remaining non-WLRM, longer-period free-surface related multiples, the SWME workflow is often integrated with SRME applied on input gathers with the seabed reflection muted. Moreover, 3D SRME is expected to always outperform 3D SWME in deep-water settings, since 3D SWME is highly dependent on the accuracy of the water-layer velocity and picked seabed horizon on migrated data. Therefore 3D SRME is still the preferred deep-water demultiple technique.

This paper describes a hybrid SWME technique applied to offshore Colombia`s Caribbean coast, with the aim of outperforming and replacing Tau-P deconvolution, which has traditionally been employed on datasets in this region, while providing seamless integration with deep-water 3D SRME.

Methodology

Multiple model M can be obtained by convolving the recorded input data D with primary reflections P, followed by source deconvolution S (Verschuur *et al*., 1992):

$$M = D \otimes P \div S \qquad (1)$$

with symbol $\otimes$ denoting multi-dimensional convolution in space and time. As P and S are unknown in practice, equation 1 can be achieved iteratively by conventional SRME:

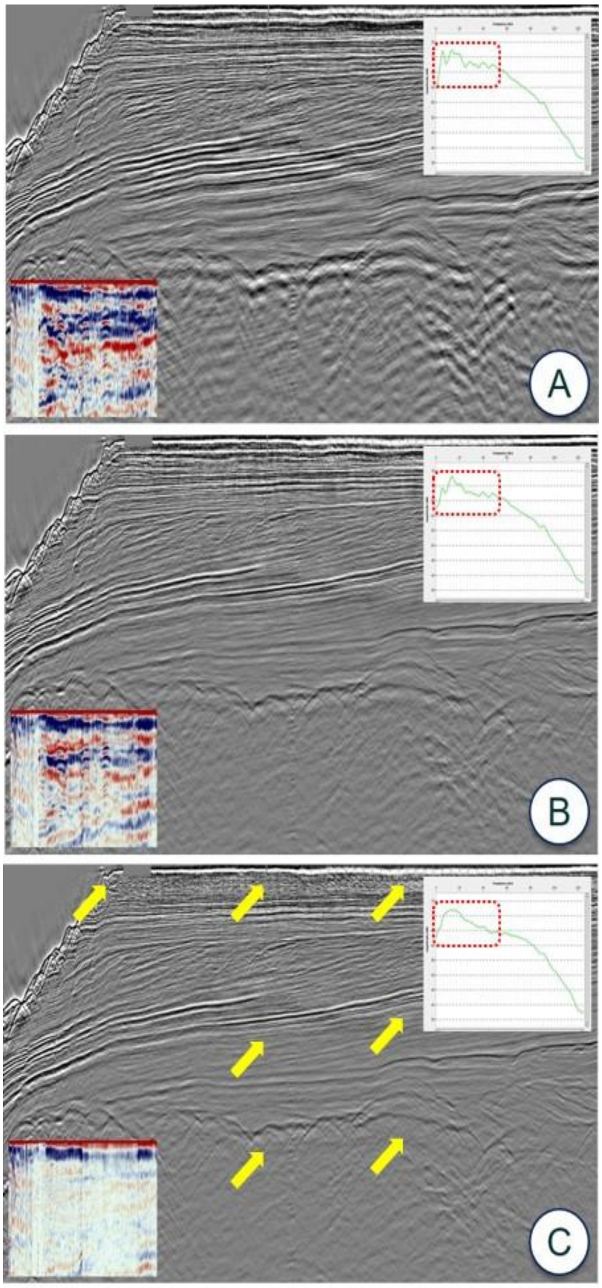
$$\begin{cases} M_{i+1} = D \otimes P_i, \\ P_{i+1} = D \Xi M_{i+1}, \end{cases} \qquad i = 0,1,\ldots, \qquad (2)$$

where $P_0 = D$, and the operator Ξ is the so-called adaptive matching and subtraction which is required as the predicted multiple model carries an extra source signature and amplitude errors due to cross-talk. The first iteration usually gives a good result P_1 when the water depth is deep (e.g. > 400m). However, as the water depth becomes shallower the iteration in equation (2) has difficulty in converging to a satisfactory result, as summarized in the previous sections.

Wang et al. (2011) proposed a model-driven implementation of SRME that uses Green`s functions $G$ of water-bottom primaries rather than actual seabed reflections $P$. The proposed 3D SWME method replaces $P \div S$ in equation (1) with an idealized representation of the water bottom event, known as a Green`s function propagator G. The propagator gathers can be calculated by any WEM method, given an average water velocity depth trend and accurate seabed horizon. To predict WLRMs for a shallow water dataset, 3D SWME is used to convolve data D with the propagators to predict multiples that have a reverberation on both the source and receiver sides of the DRP. This method overcomes cross-talk issues, since each trace is simply shifted in SWME before stacking to produce a multiple model. Substituting Green`s function G into $P \div S$ for equation (1), and following Kostov *et al* (2015) and references herein, the WLRM model M is given by:

$$M_{WLRM} = G_R \otimes D + (D - D_W) \otimes G_S - G_R \otimes D \otimes G_S \tag{3}$$

where D_W denotes the water-bottom primary reflection in the data, and G_R and G_S are the receiver and source-side Green`s function propagators.



The convolution of shot-ordered input gathers with receiver-side Green`s propagators in the first term of equation (3) produces the receiver-side contribution $M_R$ of the WLRM model, i.e. water-bottom peg-legs at receiver side. The second term represents the source-side model $M_S$ given by convolution of receiver-ordered, seabed-muted data with source-side Green`s propagators. The third term is referred to as the "common" or "source-receiver" term, and represents a class of WLRMs with a short-period water-layer bounce on *both* the source and receiver-side. The first and second terms (M_R and M_S) both include the common term and would be predicted twice in case of simple summation of source- and receiver-side models. Thus, the common third term is subtracted to avoid overestimating the combined WLRM model.

Calculating this source-receiver correction term involves an additional SRME-type convolution. Aiming to reduce the number of convolutions to two, an iterative simultaneous adaptive subtraction of the source- and receiver-side WLRM models described by Zhai *et al* (2015) is implemented as alternative approach. Output are broadband, artefact-reduced, source- and receiver-side WLRM predictions, which are simultaneously, adaptively subtracted from input. Compared with equation (2), equation (3) partially resolves cross-talk between multiples and does not suffer from spectral distortion caused by the extra source wavelet, i.e. no $M \otimes M$ operation is performed during convolution. The input data spectrum is preserved within the predicted SWME multiple dataset when convolving data with a band-limited propagator dataset that is assured to have a wider frequency spectrum than input data.

Figure 2 *Inline stack sections with amplitude spectra (dB) and autocorrelations of a) input, b) Tau-P deconvolution and c) Integrated SRME-SWME demultiple.*

Finally, after integration between SWME and deeper-water 3D SRME outputs in a blend zone between 200-500 m bathymetry contours, conventional SRME is applied sequentially in shallow water on the water-bottom muted SWME output gathers to attenuate longer-period non-seabed related free-surface multiples, followed by a residual pass of gapped Tau-P deconvolution as "clean-up" step.

Results

The proposed multiple attenuation sequence has been successfully applied to a 3D narrow-azimuth streamer survey, acquired in 2009 off the Colombian Caribbean coast where bathymetry varies from 20 m to more than 1500 m. The area of interest is mainly covered by a shallow water column (<100m) on the current continental shelf. The 8-streamer acquisition configuration has a ~156 m inline gap between the source and nearest channel. For a 100-m deep seabed, this acquisition gap corresponds to a minimum angle of incidence of the recorded WBPR of 38 degrees for the central cables. The main focus of reprocessing was on source- and receiver broadband deghosting and bandwidth enhancement prior to the described integrated shallow- to deep-water multiple attenuation workflow. Figure 2 shows inline stack sections of a) input, b) Tau-P deconvolution and c) integrated SWME output, with respective amplitude spectra and autocorrelations. Here, a consistent, albeit subtle, improvement of multiple attenuation effectiveness and primary preservation can be observed for the integrated SWME results, compared to Tau-P deconvolution output (yellow arrows). This is most pronounced at seabed and basement levels and at and beyond the shelf edge, with some improved results at reservoir level. Autocorrelations and spectra confirm this enhanced multiple attenuation by the described integrated multiple attenuation approach, where the autocorrelation is cleaner and spectral undulations due to multiple contamination are more efficiently eliminated by the hybrid demultiple sequence (figure 2c).

Discussion & Conclusions

This hybrid demultiple approach relies heavily on adaptive subtraction techniques due to various implementations of SRME multiple prediction. The risk of primary attenuation in each adaptive subtraction step could be as large as primary leakage in Tau-P deconvolution. Therefore, we highly recommend a set of meticulous adaptive subtraction test and QC procedures, as integral part of the presented demultiple workflow.

We have shown successful integrated multiple attenuation based on a model-driven implementation of 3D SRME, for an offshore Colombian Caribbean case with highly variable bathymetry. In the shallow-water shelf area of interest, the multiple attenuation effectiveness from the presented approach consistently outperforms that of conventional Tau-P deconvolution, from overburden down to basement. In addition, we achieved seamless integration with conventional deeper-water 3D SRME in areas covering bathymetry ranging from shallow-water continental shelf down to the deep-water abyssal plain. Hence, SWME methods show potential of bridging the "shelf-break demultiple gap", and of replacing the Tau-P deconvolution method as the workhorse of shallow-water demultiple. Model-driven SRME implementations in shallow-water environments and in areas with highly variable bathymetry produce broadband WLRM prediction models close to input data bandwidth. Thus, SWME techniques are well-suited for any broad-band (re-) processing project.

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