Improving internal multiple attenuation in the Red Sea using enhanced two-dimension inverse scattering series modeling allied with multidimensional curvelet matching

Frederico Xavier de Melo*, Reham Yassein, Jing Wu, Zhiming James Wu, Clément Kostov, Cintia Mariela Lapilli, Zhimei Yan, Schlumberger

Copyright 2021, SBGf - Sociedade Brasileira de Geofísica

This paper was prepared for presentation during the 17th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 16-19 August 2021.

Contents of this paper were reviewed by the Technical Committee of the 17th International Congress of the Brazilian Geophysical Society and do not necessarily represent any position of the SBGf, its officers or members. Electronic reproduction or storage of any part of this paper for commercial purposes without the written consent of the Brazilian Geophysical Society is prohibited.

Abstract

The under-explored offshore Egyptian Red Sea area is made up of large, untested structures and well-established hydrocarbon systems. Advanced processing technologies are required to improve subsurface understanding and decrease risks associated with exploration and drilling new plays. Effective attenuation of internal multiples is a crucial step in mitigating the problems associated with earth model building and imaging processes over complex, highly stratified basins and pre-salt targets.

We propose an internal multiple attenuation workflow based on the 2D inverse scattering series (ISS) prediction followed by a multi-dimensional curvelet domain adaptive matching. Input point-source recorded seismic requires preconditioning as a requirement of the 2D ISS modeling assumptions. The modeling step also employs the obliquity factor and model post-conditioning for better amplitude fidelity, allowing a simpler matching condition in the multi-dimensional curvelet space.

The main goal of our work is to devise a general methodology that is data-driven and insensitive to underlying geological changes, providing a complete solution for a complex multiple contamination scenario. Results from one 2D line case study illustrate the robustness of the method for predicting and attenuating complex internal multiples without any prior information about the subsurface, while preserving the primaries.

Introduction

The Red Sea is one of the most challenging geologic settings in the Middle East, with a diverse range of significant features at local and regional levels, including complex subsalt structures and highly stratified basins. Such subsurface complexity translates into intricate coherent noise contamination trends, such as strong near-seafloor-generated converted waves, along with a spatially and geologically variant internal multiple contamination.

Internal multiple contamination is a well-known problem when dealing with any seismic data acquired in the Red Sea. Depending on the local subsurface environment, one may experience scenarios ranging from clear and interpretable internal multiples arriving inside the crystalline salt body structure, to a relatively weak, proximal and conformable trend of multiples perversely interacting with primaries. The former type of internal multiple is generated by the reverberation between the shallow top salt structures and the seafloor reflectors, while the latter comes from intercalations of limestone and evaporites that have high impedance contrast with sand and are a constant presence above the main target levels. Small-scale intrusions present in the area also act as generators for diffracted internal multiples.

Such complexity of multiple generators poses a limitation for prediction methods that rely on a priori identification of the multiple generators. For instance, a boundary-related methodology (Jakubowicz, 1998) could not be extensively applied due to the rapid variability of geological settings, making the method impractical for large-scale processing. Similarly, complex and finely layered stratigraphy with high impedance contrasts makes every single formation a strong internal multiple generator. It thus becomes nearly impossible to assign a finite number of boundaries responsible for generating internal multiples due to workflow complexity and high computational cost.

The task of matching the predicted model to the recorded internal multiple is also challenging given the proximal characteristics they have with recorded primaries. Besides, the process of predicting internal multiples typically generates models with amplitude and phase errors that depend on the scattering pattern of the internal multiples. Considering such interferences between different types of internal multiples or from primaries, simple filtering schemes cannot be effective even in high dimensions or in combination with data grouping, leading to extensive and non-generic processes in an attempt to achieve acceptable results.

In this work, we discuss a workflow developed to mitigate most of the internal multiple prediction and subtraction issues by performing the following:

- 2D inverse scattering series (ISS) prediction of internal multiples as a method to overcome the limitations associated with boundary-related methods and the requirement to specify generators of the multiples. Input recorded seismic data goes through a 3D-to-2D transform to incorporate a point-source dimension (3D) into a line-source (2D) assumption. The obliquity factor is also part of the modeling step.
- Adaptive matching is performed in the curvelet domain to give a compact and semi-sparse representation – promoting the orthogonalization between the wavefield components – of the recorded seismic data and the modeled multiples. This processing step is applied pre- or post-imaging depending on the subsurface complexity and target of interest. For this work, we chose to perform the curvelet adaptive matching after imaging both the

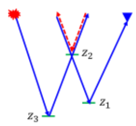
recorded seismic data and the predicted internal multiple model.

The proposed workflow validation uses a complex and challenging 2D towed-streamer seismic experiment from the Red Sea. Results show the stability and efficacy of the process. The proposed workflow accurately predicts and removes internal multiples across varying geological settings present in the Red Sea area.

Method

For an underlying 2D earth assumption, the ISS internal multiple attenuation algorithm (Weglein et al., 1997; Kaplan et al., 2004) can be expressed as follows:

$$b_3(k_g, k_s, \omega) = \iint dk_1 dk_2$$



$$\int_{-\infty}^{\infty} dz_2\, b_1(k_1, k_2, z_2)\, e^{-i(q_1+q_2)z_2}$$
$$\int_{z_2+\varepsilon}^{\infty} dz_1\, b_1(k_g, k_1, z_1)\, e^{i(q_g+q_1)z_1}$$
$$\int_{z_2+\varepsilon}^{\infty} dz_3\, b_1(k_2, k_s, z_3)\, e^{i(q_2+q_s)z_3}, \qquad (1)$$

where b_1 are the input data after a constant velocity (c_0) migration; b_3 is the predicted internal multiple and k_g and k_s are the horizontal wavenumbers at receiver and source sides, respectively. ω is temporal frequency. $k_j^2 + q_j^2 = \frac{\omega^2}{c_0^2}$, $j = g, s, 1, 2$, and q_i is vertical wavenumber. ε ensures that the subevents meet a deeper-shallower-deeper relationship. The main advantage of this algorithm lies in the assumption that each sample acts as a multiple downward generator, overcoming the limitation commonly present in boundary-related methods. Constraints aiming to limit the computational cost while preserving the geophysical significance are part of the process. These can be a combination of the selection of the z_2 interval and the maximum values of z_1 and z_3, along with dip and opening angle limits, as proposed by Terenghi and Weglein (2012) and validated by Wu et al. (2019).

Sources in seismic experiments fall under the point-source (3D) regime regardless of the acquisition type (2D or 3D geometries). In contrast, the 2D ISS algorithm assumes that the experiment is based on a line source (2D). We apply a transform operation prior modeling, adjusting the point source closer to a line source representation. The 3D-to-2D data transformation follows the Auer et al. (2013) proposition. The 2D ISS algorithm better incorporates the amplitude-angle dependency of the internal multiple by using the obliquity factor as part of the prediction process. By doing so, internal multiple models will present an improved bandwidth accuracy and reduced artifacts due to crosstalk between events. Wu et al. (2020) presented details about the 3D-to-2D transform and obliquity factor application.

Although arrival times of internal multiples from the ISS method are accurate, adaptive matching algorithms are required to correct for amplitude and phase distortions in the predicted internal multiples. Interference between internal multiples and primaries, or between internal multiples requiring different matching schemes, creates conditions where simple filters are not effective (Spitz, 1999). We aim to address this limitation by splitting the recorded data and predicted model into components to better constrain the matching process. Applying a multi-dimensional curvelet transform represents the recorded data and the multiple model in a multiscale, compact, and semi-sparse sense (Candés and Demanet, 2005). This makes the curvelet representation sparse and well-suited for our task, enhancing components that are present in both data sets (multiples) while allowing us to exclude from the matching process components that only exist in one of the data sets (e.g., primaries, thus leading to better preservation of primaries). The multidimensional curvelet transform process follows the method proposed by Ying et al. (2005), with discrete curvelet coefficients defined by

$$c^D(j,l,k) := \sum_{n_1,n_2,n_3} f(n_1,n_2,n_3)\, \overline{\varphi^D_{j,l,k}(n_1,n_2,n_3)}, \qquad (2)$$

where j, l, and k represent scale, angle, and position of the coefficients. $f(n_1,n_2,n_3)$ is the input data, which is multiplied by the complex curvelet element $\overline{\varphi^D_{j,l,k}(n_1,n_2,n_3)}$.

The forward transform process maps the data into almost orthogonal localized events with a spatial and temporal component. The adaptive-matching process runs in this semi-sparse domain, followed by the inverse transform of the matched model, later subtracted from the recorded field data.

Case study: 2D seismic line from the Red Sea

We applied the proposed workflow to one marine seismic 2D line acquired in the Egyptian waters of the Red Sea. The acquisition parameters are: 3500 m cable length, 260 m lead-in, 25 m shot spacing with 12.5 m receiver interval. Source and receiver depths are 6 m and 8 m, respectively, with a fold coverage of 68 traces after migration. The average water depth is 750 m and the recorded data was free of ghosts and surface-related multiples.

The inverse-scattering multiple prediction consisted of defining a downward internal multiple generator region between the seafloor down to Top Zeit formation (top of anhydrate layer, maximum two-way-time of 2200 ms). The parameter ε was set to 23 samples and the modelling was constrained to a maximum reflector dip angle of 20° and a maximum opening angle of 80° in the pseudo-depth domain. The maximum frequency considered in the internal multiple modelling was 60 Hz with the obliquity factor correction as part of the prediction process. Modeling preprocessing consisted of the 3D-to-2D transform prior to 2D ISS, followed by the inverse operation (2D-to-3D) applied to the predicted internal multiple model.

We imaged input seismic data and predicted internal multiple using Kirchhoff prestack time migration prior to the adaptive matching in the 3D curvelet space. The forward transform process consisted of time, midpoint, and offset as transform axes, with a window of 351 locations, 301 offsets, and 1200 temporal samples (approximately 433 tiles per window with 48 angles on scale 2, and 192 angles on finer scales). For each window, an adaptive matching scheme was applied to match the predicted internal multiple model from the recorded seismic data, with the final subtraction taking place in the time-space domain.

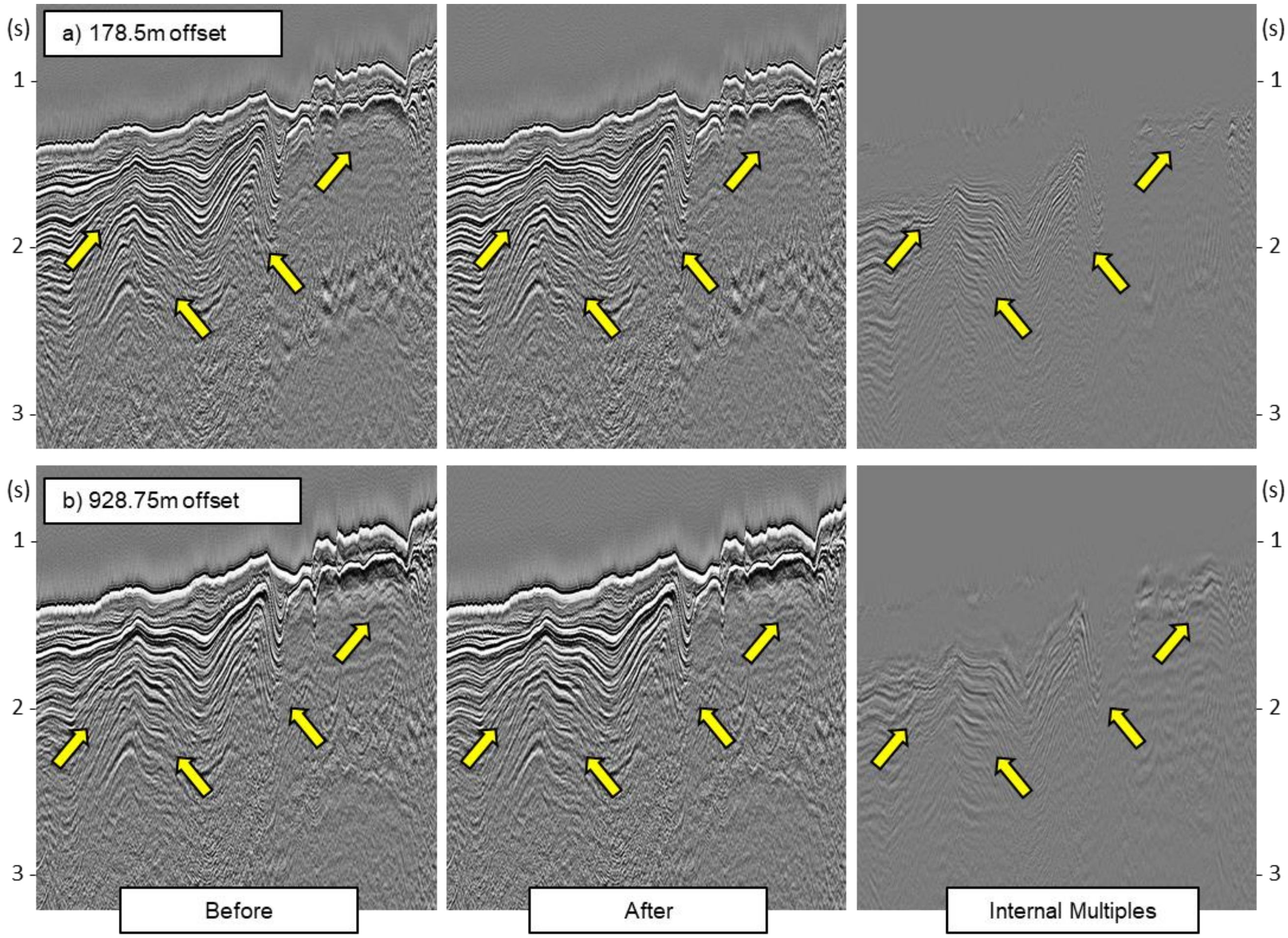


Figure 1 – Kirchhoff time migration of two common offset planes in rows a) and b) before internal multiples attenuation (left column), after internal multiples attenuation with the proposed workflow (middle column), and their difference (right column). The yellow arrows show significant improvements in the results due to the internal multiple removal process.

The same primary response improvements are visible when looking at the full image displayed in Figure 2. The zoomed section highlighted in light blue shows an accurate prediction and effective attenuation of a strong internal multiple formed between the reflection of the seafloor and Top Salt formations. Green and orange sections highlight the performance of the proposed workflow in a finely stratified basin situation, where primaries and internal multiples are proximal and the generation pattern does not come from specific formations. The combination of the inverse scattering series prediction method with a constrained matching in a semi-sparse domain representation allowed high fidelity of attenuation of internal multiples while preserving primaries. The overall performance is assured by closely examining the final image and estimated internal multiples after applying the proposed workflow.

Conclusions

We presented a case study showing a robust and effective attenuation of internal multiples over an area of the Egyptian Red Sea that comprises a range of geological features covering complex, highly stratified basins and pre-salt targets. The proposed workflow makes use of an inverse scattering series-based algorithm to predict internal multiples, followed by a post-imaging multi-dimensional curvelet domain adaptive matching.

The combination of these two processes resulted in a workflow capable of accurately attenuating internal multiples, regardless of the underlying geological conditions present in the overburden. The proposed workflow does not have prior assumptions about generating formations; it is data-driven and insensitive to spatial changes and provides a complete solution for different internal multiple contamination scenarios. Our case study applied over a 2D seismic survey elegantly attenuated a wide range of internal multiple interference, varying from weak to strong internal multiples, while preserving the primary response. The process improved the overall interpretability in the subsurface, reducing the uncertainty when identifying potential hydrocarbons plays.

Acknowledgments

We thank WesternGeco Multiclient for granting permission to publish this work.

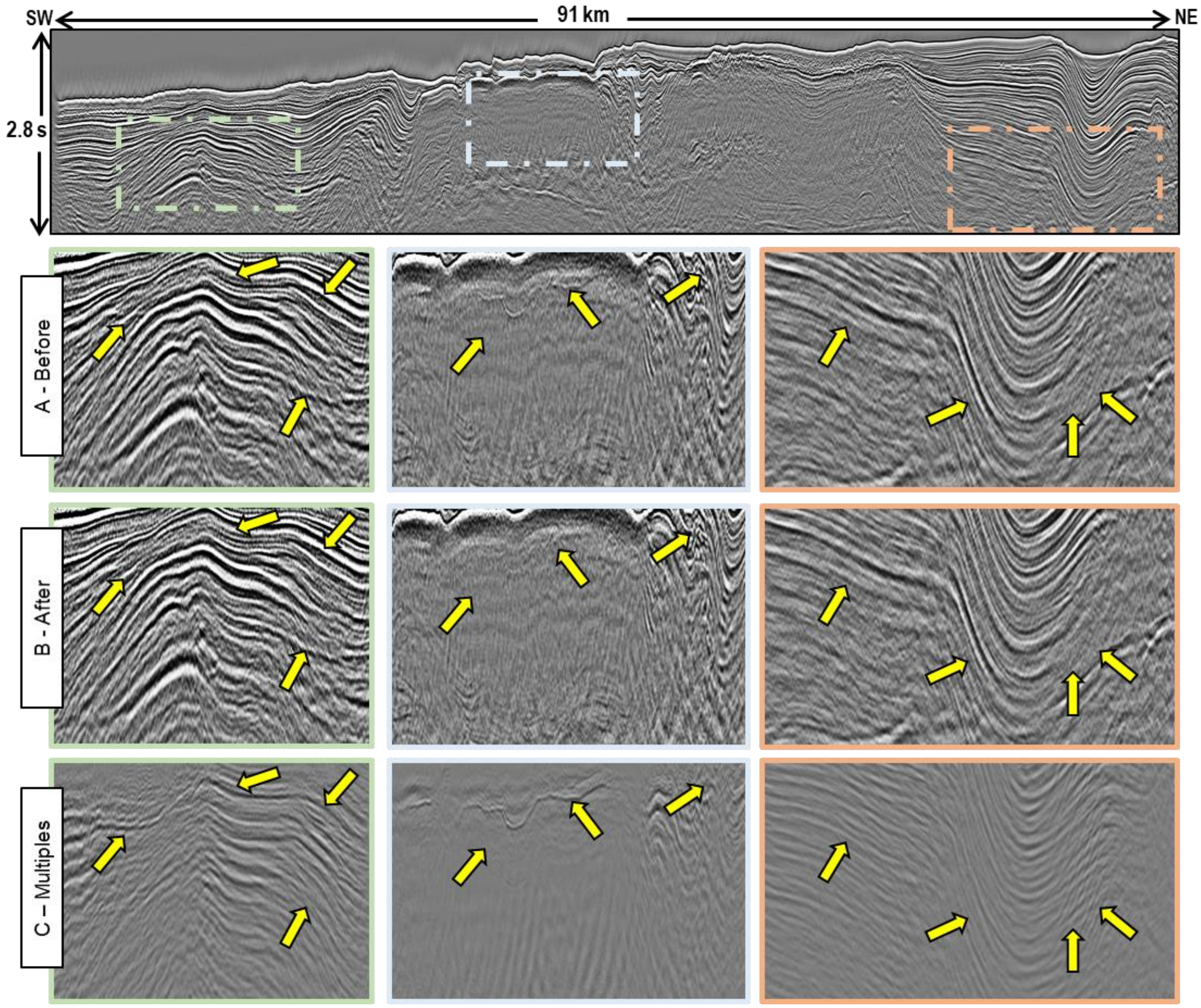


Figure 2 – Kirchhoff prestack time imaging results before (A), after (B), and estimated internal multiples (C) obtained with the proposed workflow. Highlighted areas from the full image (above) show in more detail the subtle, but significant, improvement when applying the inverse-scattering series prediction combined with multi-dimensional subtraction in the 3D curvelet space.

References

Ala′i, R., and D. J. Verschuur, 2003, Simultaneous adaptive least-squares subtraction of multiples: 65th EAGE Conference & Exhibition, Extended Abstracts, P193.

Candès, E. J., and L. Demanet, 2005, The curvelet representation of wave propagators is optimally sparse: Comm. Pure Appl. Math, 58-11: 1472-1528.

Jakubowicz, H., 1998, Wave equation prediction and removal of interbed multiples: SEG Technical Program Expanded Abstracts, 1527-1530.

Sun, D., K. Jiao, X. Cheng, and D. Vigh, 2018, Keys to robust reflection-based full-waveform inversion: SEG Technical Program Expanded Abstracts, 1283-1287.

van der Neut, J., and K. Wapenaar, 2016, Adaptive overburden elimination with the multidimensional Marchenko equation: Geophysics, 81, T265-T284.

Verschuur, D. J., 2006, Seismic multiple removal techniques: Education tour series, EAGE.

Weglein, A. B., F. A. Gasparotto, P. M. Carvalho, and R. H. Stolt, 1997, An inverse-scattering series method for attenuating multiples in seismic reflection data: Geophysics, 62, 1975-1989.

Wu, Z. J., S. Sonika, and W. Dragoset, 2011, Robust Internal Multiple Prediction Algorithm: 81st Annual International Meeting, SEG, Expanded Abstracts, 3546-3549.