Submission code: 6P8Q8WAYBZ

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Orthogonal contribution summation to build 3D internal multiple models

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Abstract Summary

This work revisits and explores benefits and practical aspects of employing inverse scattering series (ISS) based algorithms to predict internal multiples under a new forward prediction parameterization framework. The intricate nature and rapid vertical and lateral variability of multiple generating reflectors pose a limitation for methods relying on prior information about formations and/or boundaries responsible for creating major internal multiples at the reservoir level.

In some instances, thin layering with high impedance contrast makes every single sample of the seismic experiment a potential generator of internal multiples, requiring existing methods to perform a series of workarounds to fully capture and predict the internal multiple contamination pattern, unless a certain number of interpretation and/or boundaries are taken into consideration during the prediction process. Here we seek to incorporate computational efficient and spatial coverage when predicting internal multiples using the ISS method by leveraging the crossline contribution from adjacent 2D dimensional output multiple models.

Introduction

Internal multiple removal from recorded seismic is a major challenge for both onshore and offshore plays across different basins. Depending on the local subsurface conditions, contamination vary from clear and interpretable crosstalk to a relatively weak and conformable trend of short-period internal multiple, constructively and destructively interacting with primaries. The former type of internal multiple is generated by the longer-period reverberations between the overburden and at least on strong impedance formation, such as salt structures and seafloor reflectors; whereas the latter comes from intercalations with high impedance contrast generating multiple not necessarily associated with a single formation and any form of periodicity, commonly associated thin-layered effects in the overburden with small-scale intrusions that can also act as diffracted internal multiples generators.

The complexity of the multiple generator mechanism drives our understanding and effectiveness of modeling and removal of this coherent noise, especially around methods that rely on prior identification and interpretation of zones and boundaries responsible for generating most of internal multiples observed in the field data. For instance, boundary-related methods (Jakubowicz, 1998, Ikelle, 2006) could not be generally applied in all situations due to rapid geological setting variability, making the method either unsuitable or impractical for large-scale cases. Similarly, complex and fine layering stratigraphy with high impedance contrast makes every single formation a strong internal multiple generator. It becomes nearly impossible to assign a finite number of boundaries responsible to generate internal multiples and to assign a binary decision between generating and target zones.

The ISS approach for internal multiple prediction is a method that can predict all internal multiples at once without assumptions or estimation about subsurface (Weglein et al., 2003). However, the computational cost of the ISS for a 3D seismic experiment is prohibitive from a commercial standpoint, limited only to small scale and severely constrained examples in recent years.

In this work we propose a 2-step operation approach aiming to achieve a multi-dimensional ISS internal multiple prediction framework. The first step consists of producing a dense collection of 2D and true-azimuth predictions along the acquisition direction, followed by an orthogonal multiple contribution gather (MCG) formation and summation process designed to capture the crossline component contribution when building multi-dimensional internal multiple models.

The main idea of the proposed approach is to perform orthogonal summations from a collection of simpler projected inline models to produce computationally effective internal multiple predictions, incorporating relevant out of plane information not captured during the 2D modeling framework. Examples extracted from a narrow azimuth towed streamer (NAZ) acquired over the Santos Basin in Brazil shows noticeable kinematic improvements in the predicted process, capturing the spatial complexity of the internal multiple contamination pattern in the intra- and pre-salt regions.

Methodology

Starting from the prediction framework described different technical publications related to ISS for internal multiples (Weglein et al., 1997; Weglein et al., 2003, Wu et al., 2021), we start by performing a series of two-dimensional ISS predictions, expressed as (Kaplan et al., 2004):

$$b_3(k_g,k_s,\omega) = \iint dk_1 dk_2$$
$$\int_{-\infty}^{\infty} dz_1\, b_1(k_g,k_1,z_1)\, e^{+i(q_g+q_1)z_1} \int_{-\infty}^{z_1-\varepsilon} dz_2\, b_1(k_1,k_2,z_2)\, e^{-i(q_1+q_2)z_2} \int_{z_2+\varepsilon}^{\infty} dz_3\, b_1(k_2,k_s,z_3)\, e^{+i(q_2+q_s)z_3} \quad (1)$$

where $b_1(\vec{k}_g,\vec{k}_s,\omega) = 2iq_s D(\vec{k}_g,\vec{k}_s,\omega)$, D are acquired data; $b_1(\vec{k}_g,\vec{k}_s,z)$ is depth-domain data after a constant velocity (c_0) migration; $\vec{k}_g$and $\vec{k}_s$ are the horizontal wavenumber vectors at receiver and source sides, respectively. ω is temporal frequency. $|\vec{k}_i|^2 + q_i^2 = \frac{\omega^2}{c_0^2},\ i = g,s,1,2;$ q_i is vertical wavenumber; ε ensures that the sub-events meet the deeper-shallower-deeper relationship, defined as the wavelet length in pseudo-depth.

The term b_3 in Equation (1) is the predicted internal multiple, followed with a correction by a factor of $1/\ 2iq_s$, back to the data domain as $IM_3 = \frac{1}{2iq_s} * b_3$. In this case, we perform the prediction IM_3^{3D} over a number of two-dimensional lines, normally associated with an acquired subsurface line $IM_{(3,\mathrm{ssl})}$.

Assuming we have a given number of predicted subsurface lines from the 2D ISS framework, we obtain the extra dimensional component by aggregating adjacent subsurface line models over a defined crossline aperture N. This can be translated as

$$IM_{3,ssl}^{3D}(x_g,x_s,t) = \int_{-N/2}^{N/2} IM_3(x_g,x_s,t,y_i)\,di, \quad (2)$$

where d_{i} represents the spatial sampling of the summation over a crossline aperture N. This 2-step process provides an additional dimension to the modeling process, improving the kinematic and focal response of internal multiples when capturing the orthogonal contribution not considered when solely considering the 2D ISS framework.

Examples

We applied the proposed prediction workflow to a NAZ acquisition acquired over the Santos Basin, offshore Brazil, with water varying from 1450 m to 2650 m. The complex stratigraphy above the pre-salt reservoir target in the Santos Basin, composed of structural trend variations, evaporites with variable thickness amongst other formations, creates the perfect condition to create strong internal multiple reverberation crosstalk at the reservoir level.

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Figure 1 shows a mid-offset common channel (CTG) and common midpoint comparisons between the recorded data and models from equations (1) and (2). We can observe visible kinematic improvements when moving from a two-dimensional prediction to a model that incorporates orthogonal contributions. The interleaved portion of Figure 1b shows a correction in the kinematic response of the predicted multiples, along with an improved response coming from the proposed approach model.

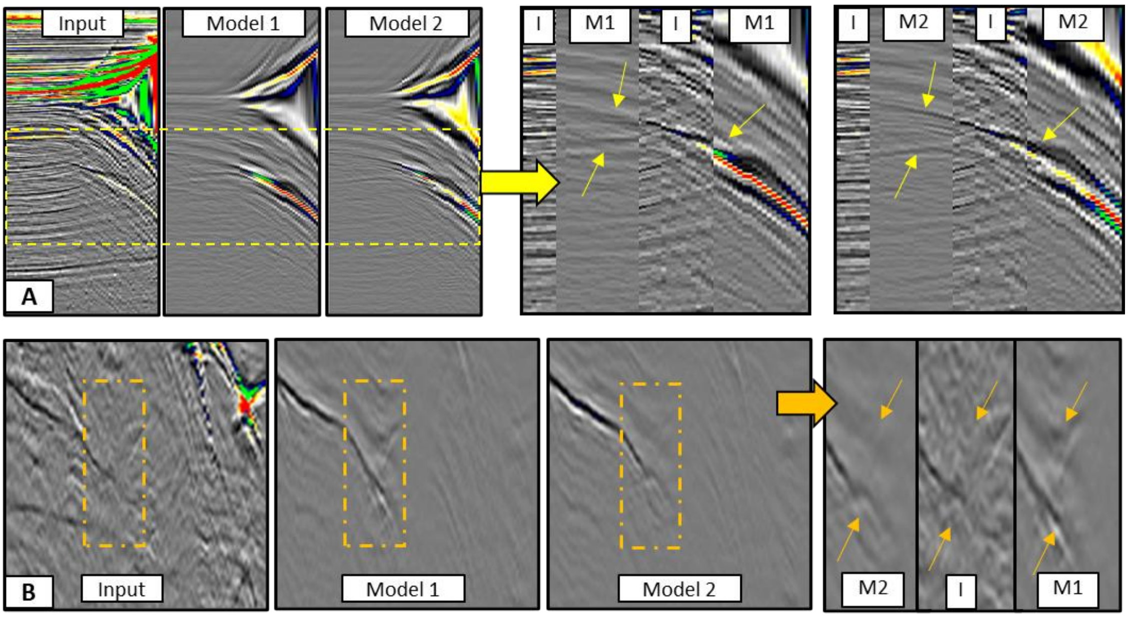

Figure 1: Side-by-side CMP gather (A) comparison between the input (left), 2D (center) and proposed (right) ISS models. Interleaved displays below between input and models demonstrate resolution and kinematic improvements when adding the orthogonal contribution. Similar behavior can be observed when looking at a mid-offset common channel gather (B). Arrows point key places where the proposed model provides better correspondence with recorded events associated with internal multiples, including the ones with a shifted apex effect (A).

Although the improved model gives better focal and kinematics response relative to the input, final multiple attenuation still requires an adaptive matching step designed to adjust for dynamic effects not considered in the prediction process. The final suppression step was done in the data space (prior imaging) using least-squares filters and adaptive masking operators computed in the complex curvelet space. Post-stack migrated images before, after and estimated model using the enhanced ISS prediction and data domain matching are in Figure 2. Highlighted areas focus the results over pre-salt regions across heterogeneous overburden settings, clearly reducing the focused crosstalk related to strong and complex internal multiples and improving lateral interpretation over deep formations (pointed by the arrows).

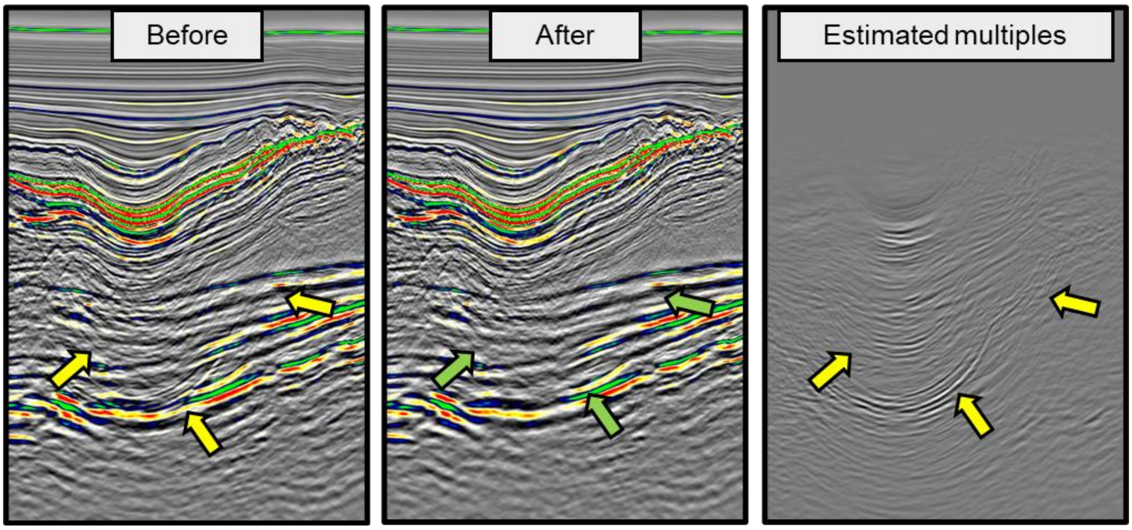

Figure 22: Post-stack image before, after and difference of the proposed internal multiple attenuation with ISS process (as noted). Highlighted arrows show the noticeable improvement of the image after the application of the proposed internal multiple attenuation process.

Conclusions

This work introduced a multi-dimensional internal multiple prediction framework by performing a 2-step prediction approach. The process consisted of building a set of 2D forward ISS predictions followed by spatial collection from this pool of existing models to create MCGs orthogonally and symmetrically defined from the initial 2D models.

We showed a viable framework solution when predicting complex internal multiples in the Santos Basin region, with the proposed approach kinematically capturing complexity at the captures post- and intra-salt multiples that negatively affect the seismic response at the pre-salt reservoirs.

Acknowledgments

The authors thank SLB Exploration Data for their permission to publish this work.

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