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Efficient 3D Internal Multiple Attenuation in the Santos Basin

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Summary

Internal multiples constitute a major challenge for imaging. Artefacts generated by incorrectly imaging internal multiples interfere with targets, affecting the interpretation and contaminating amplitude analyses in the reservoir. The Santos basin is a particularly challenging example of this problem because of the presence of stratified salt. We implemented a method recently proposed by Van der Neut and Wapenaar (2016) to attenuate internal multiples and successfully applied it to a data set from the Santos basin.

Introduction

Internal multiples pose a major challenge for imaging. Standard imaging algorithms assume that the data is composed of primary reflections only. In the presence of strong subsurface reflectors, artefacts will be created by incorrectly imaging internal multiples. The Santos basin, offshore Brazil, constitutes a particularly challenging example of this problem (Cypriano et al., 2015) due to the presence of stratified salt. The strong reflectors inside the salt act as generators for internal multiples that are imaged in the pre-salt area. These spurious events can affect the interpretation of pre-salt primaries and contaminate amplitude analyses in the reservoir.

The method of Jakubowicz (1998) is considered as a main tool for modelling internal multiples. It is based on the cross-correlation and convolution of three wavefield components. The wavefield components are obtained by truncating the recorded data such that the upward reflectors are below the downward generator. To obtain a complete set of internal multiples, one would need to scan the data for all possible downward reflectors in a top-down approach. A window-based approach to perform this top-down scan has been proposed by Hung and Wang (2012). Alternatively, a method based on the inverse scattering series (ISS) has been proposed by Weglein et al. (1997). These authors propose to use the third term of the inverse scattering series subject to a truncation in depth to ensure the low-high-low (LHL) condition is satisfied. The advantage of this class of methods is that it does not require identification of the multiple generators, but it comes at a high computational cost.

Recently Van der Neut and Wapenaar (2016) introduced a new method for modelling internal multiples by rewriting the Marchenko equations. We consider a particular set of multiples proposed by the authors. We posit that this set is sufficient for most practical applications, providing an alternative method to catalogue the multiples in the data. Similar to ISS, this method does not require explicit identification of generators and has a cost comparable to Jakubowicz's method (1998). We show the results of this approach applied to a field dataset from the Santos basin, which is known to contain strong interference of internal multiples with pre-salt primaries.

Method

We start by separating the data into an overburden region and a target region. Figure 1a shows a typical section from the Santos basin and an example of this separation. The overburden region contains the multiple generators, while the target region is where the internal multiples are imaged. For a given horizon h separating the data into overburden and target, we consider the following set of internal multiples (Van der Neut and Wapenaar, 2016):

$$M_h\,(x_B, x_A; t) = -\left\{\Theta_{t_h}^{\infty}\mathcal{R}\Theta_{t_0}^{t_h}\mathcal{R}^{\star}\Theta_{t_0}^{t_h}R\right\}(x_B, x_A; t)\,. \qquad (1)$$

In this equation, x_A and x_B are either shot or receiver positions at the acquisition surface, t is the output two-way traveltime of the multiple, and R is the recorded reflection data. We assume that the data have been properly deconvolved, so that the source wavelet and source and receiver ghosts have been removed. $\Theta_a^b(t)$ is a muting operator defined to be equal to 1 for $t \in (a, b)$ and zero otherwise. $\mathcal{R}$ and $\mathcal{R}^{\star}$ are operators defined respectively as the multi-dimensional convolution and cross-correlation of the reflection data acting on a given wavefield. Note that in this formulation, the data are seen both as a wavefield and as an operator. Similar to SRME implementations (e.g., Dragoset et al., 2010), in order for these operators to be well defined, the data must (1) be dense in both source and receiver grids, (2) have enough aperture in both inline and crossline directions, and (3) have the near offsets. We fulfil these requirements by properly interpolating/extrapolating the data prior to the calculation of the multiple model. The key acquisition parameters controlling the quality of this interpolation are sailline spacing, crossline spacing, and crossline aperture in the case of a streamer acquisition, and shot interval and density of nodes/cables in the case of an OBS acquisition.

The definitions of the muting times t_0 and t_h are fundamental to understanding this implementation. t_h is the two-way traveltime of horizon h extrapolated for non-zero offsets, based on an estimation of the RMS velocity around this horizon. Note that the horizon can be quite arbitrary, as long as it does not cut through any strong reflectors; otherwise, truncation artefacts may occur. t_0 is a mute close to zero time and needs to be at least equal to the support of the data wavelet, in order not to introduce primary energy in the multiple model. t_0 also controls the shortest period allowed for the predicted internal multiples.

Given a choice of t_h and t_0, the algorithm for computing M_h is described as follows. For each shot gather located at x_A, (i) mute the interpolated data R with $\Theta_{t_0}^{t_h}$; (ii) apply the operator $\mathcal{R}^\star$ (the result of this operation is the cross-correlation of the result of (i) with the fully-interpolated data); (iii) mute the cross-correlation output with $\Theta_{t_0}^{t_h}$ (the mute at t_0 will remove the events that are too close to zero); (iv) apply operator $\mathcal{R}$, and (v) mute with $\Theta_{t_h}^{\infty}$ (only multiples arriving later than t_h are predicted).

The construction above is similar to the one proposed by Jakubowicz (1998) in the sense that it is based on a cross-correlation and a convolution of the data and thus is fully data-driven, but it differs from it in the way the truncations are applied. Note that the second and third mutes are applied after the cross-correlation/convolution steps, while in Jakubowicz (1998), the wavefields are truncated from the beginning. Each method will predict a different set of multiples. To see this, let us come back to Figure 1a. We are interested in predicting all internal multiples with the three generating reflectors in the overburden region, which is formed by the series of reflectors from the water bottom down to the strong package seen around the top of salt. This can be achieved by computing M_h for the horizon shown in the figure. This model contains, as a subset, the multiples that we are interested in. Note that in order to do the same using the approach of Jakubowicz (1998), we would need to scan all possible generators in the overburden and compute a different model for each one of them.

Examples

We apply the method described above to a dataset from the Santos basin, which is known to contain strong interference of internal multiples. The acquisition consisted of six flat streamers with 150m cable separation and 6km cable length. The sailline separation was 450m and the nearest offset was at 213m. Basic pre-processing steps consisted of denoise, designature, source and receiver deghosting, and SRME. The data were then interpolated to a regular shot/receiver grid and the near offsets were reconstructed.

This dataset presents a very strong reflector at the top of salt and a series of reflectors forming the stratification inside the salt. In addition, the post-salt region contains a few strong reflectors as well. The most dominant internal multiples are generated by the water bottom together with the top of salt (Cypriano et al., 2015). One possible choice of horizon is shown in Figure 1a. As explained above, all internal multiples that fall within the target region and have generating reflectors in the overburden are included in the model corresponding to this horizon.

The results of adaptively subtracting this internal multiple model from data can be found in Figures 1 and 2. The multiple model was migrated with the same algorithm as the data and subtracted in the image domain for each offset cube. Curvelet filters were used in the subtraction (Wu and Hung, 2015). In Figure 1c and 1e, internal multiples appearing in Figures 1b and 1d have been attenuated (green arrows). Note that adaptive subtraction can be very challenging due to similar kinematics of internal multiples and primaries.

Conclusions

We have implemented a recently proposed method for modelling internal multiples and applied it to a 3D dataset from the Santos basin. While we were able to attenuate a good portion of the multiples present in the pre-salt area, adaptive subtraction remains very challenging.

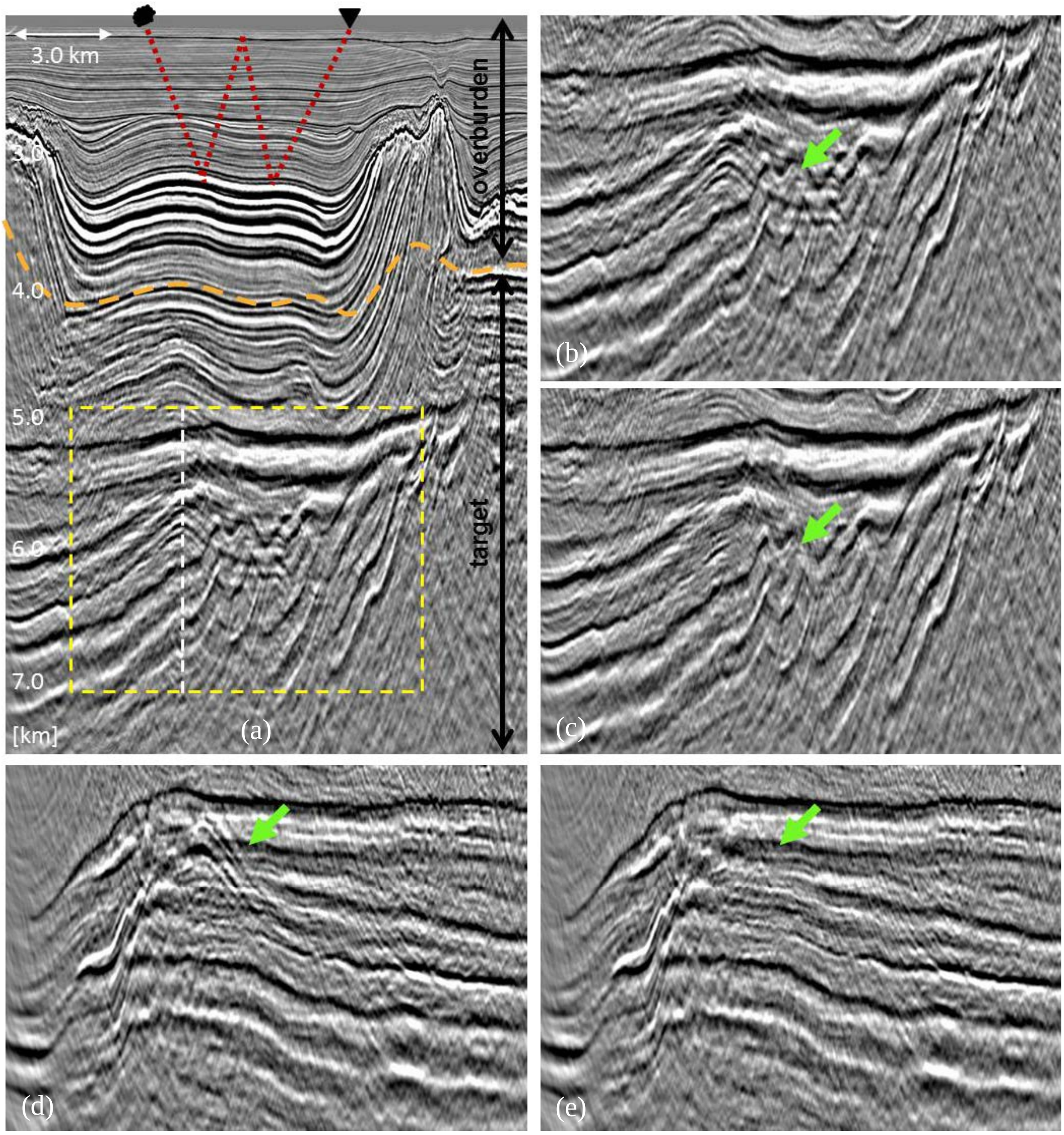

Figure 1 *a) Section from the Santos dataset. Choice of horizon separating target/overburden regions is shown by the dashed orange line. An example of an internal multiple ray path is shown in red. The yellow box shows the zoom area for b and c, and the white line shows the crossline position for d and e. (b) and (c): Zoomed inline from near offset cube before and after internal multiple attenuation, respectively. (d) and (e): Zoomed crossline from near offset cube before and after subtraction, respectively. Arrows indicate internal multiples.*

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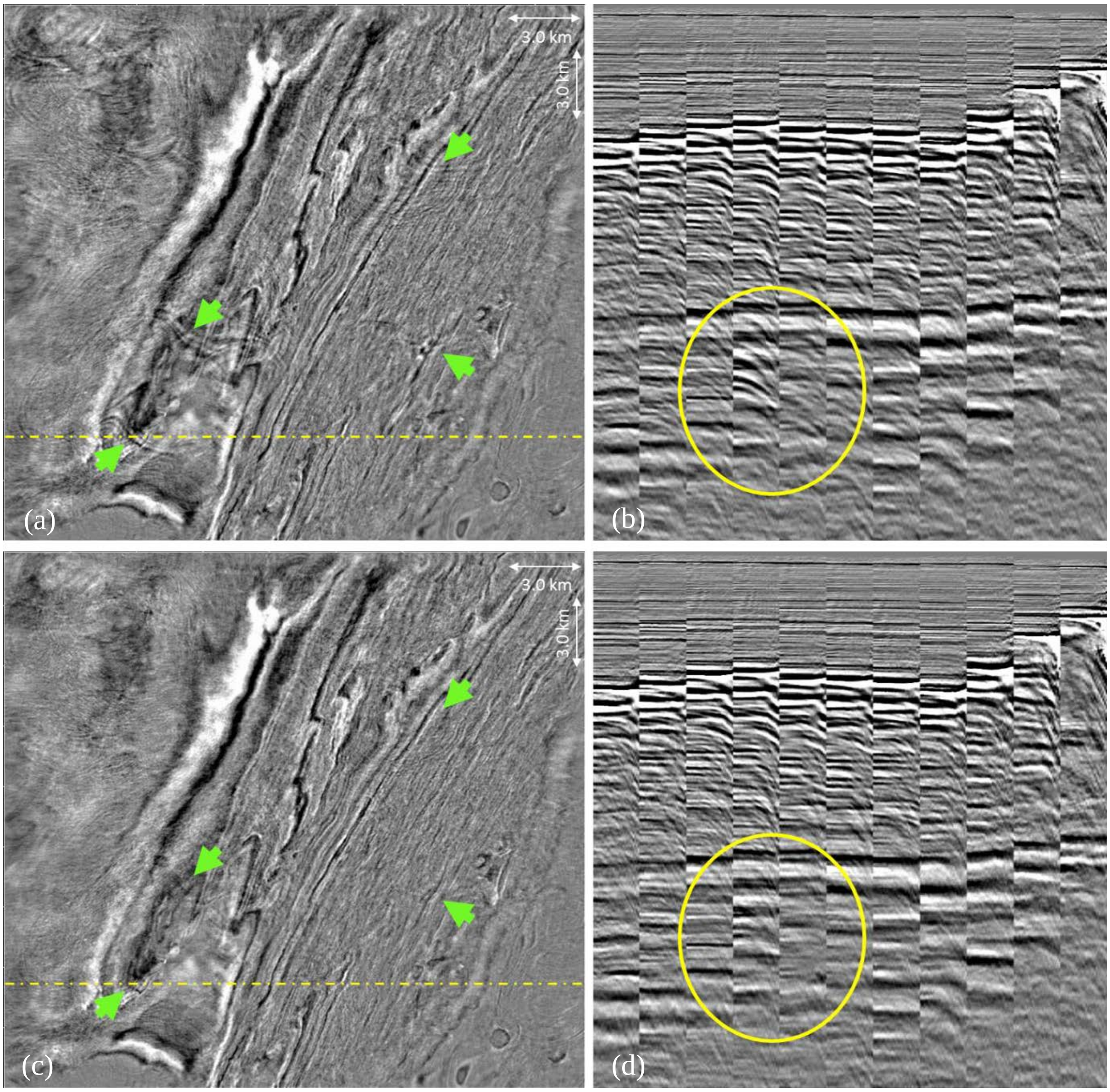

Figure 2 *Depth slice from near offset cube and CDP gathers. (a) and (b): depth slice and gathers before internal multiple attenuation. (c) and (d): depth slice and gathers after internal multiple attenuation. The depth slice was taken at 5km. CDP locations are indicated by dashed line in the depth slice. Arrows indicate internal multiples.*