Improved subsalt imaging in Brazil Campos basin - cascaded application of hybrid interbed demultiple, P- and S-salt velocity joint migration, and subsalt converted wave suppression

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Summary

The pre-salt play of Brazil Santos and Campos Basins has been the hot-spot for oil and gas companies since 2006 due to significant discoveries made and large volume of Yet-to-Find to chase. Seismic imaging plays a critical role in the success of companies from exploration to development of this major play. The pre-salt play is capped by thick salt with highly variable geometries and stratigraphy that leads to significant imaging and illumination challenges. It requires seismic data acquisition and processing programs specially tailored based on those challenges and learnings from the pre-salt imaging. In this abstract, we present the cascaded application of three critical technologies to improve the subsalt imaging in Brazil Campos basin data: hybrid interbed demultiple, P- and S-salt velocity joint migration, and subsalt converted wave suppression. We will showcase in detail through examples the significant benefits of these cascaded applications to ensure subsalt images are more accurate and the true geology can be revealed, rather than being distorted through interbed multiples and converted waves related, particularly, to the stratified salt and carbonate layers.

Introduction

In conventional P-wave oriented imaging, interbed multiples and converted waves are not imaged correctly. Both appear as coherent noise and may distort the identification of the true structures (Alai et al., 2021). Therefore, elimination of these kind of coherent noises would significantly benefit emerging plays in Brazil and major subsalt plays in the Gulf of Mexico and West Africa. In addition to the attenuation of interbed multiples and converted waves, we showcase the significant benefits of using converted waves in improved imaging of the salt flanks, base-salt, and entire salt bodies. We showcase in our narrow azimuth acquired data, the significant values of the converted waves in improving the quality of the salt flank images, especially on the cross-line direction which suffer from illumination limitations. In the following, the subsequent applications we propose, will be further discussed in more detail.

Hybrid interbed demultiple

In the Campos basin, offshore Brazil, carbonate layers on top of the stratified salt generate a large number of complex interbed multiples. Interbed multiples cannot be correctly imaged through conventional prestack depth migration algorithms (Wang, 2009). Many authors have proposed different methods to estimate and suppress them (Weglein et al., 1997; Jakubowicz, 1998; Griffiths et al., 2011; Hung and Wang, 2012; Wapenaar et al., 2014; Van der Neut and Wapenaar, 2016; Pereira et al., 2018; Krueger et al., 2018; Zhang et al., 2019; Staring and Wapenaar, 2020; Xavier de Melo et al., 2020). In structurally complex carbonate and salt bodies environments, optimal interbed demultiple remains a challenging task. Therefore, we are suggesting a hybrid interbed demultiple workflow being a combination of both Jakubowicz and Marchenko methods. In our approach we estimate the interbed multiples in 3 regions defined by horizons as follows:

- Jakubowicz method – below water bottom
- Jakubowicz method – below Top of Salt
- Marchenko method - between Top and Base of Salt

and through a simultaneous Least-Squares matching with the data, the estimated interbed multiples are combined and adaptively subtracted from the data. Both methods use cross correlations and convolutions to optimally estimate interbed multiples. The adaptive multi Least-Squares simultaneous subtraction algorithm introduced by Alai and Verschuur (2003) has proven to be valuable and effective for suppression of interbed multiples, especially in very complex geological settings like Brazil. For both the estimation and subtraction of interbed multiples, mathematically justified cross correlation displays have been generated, which allow very accurate quality control, ensuring that the estimated interbed multiples are optimal prior to any subtraction. Similarly, the estimated multiples are cross correlated with the data after adaptively matched subtraction, ensuring no leakage allowance in the optimal subtraction processes. A data example of the hybrid interbed demultiple approach is shown later.

P- and S-salt velocity joint migration

Another refinement we emphasize in this abstract are the specific values of mode-converted waves related to salt body imaging (Wu et al., 2001; Jones and Davison, 2014). There is a significant advantage to utilize mode-converted waves in the early stages of salt velocity model building. In the conventional acoustic salt velocity model building schemes, the top of the salt is picked followed by P-salt flood migrations to image the base-salt. Performing additional S-salt flood migrations provides significant improvements in the salt body definitions, especially in the areas with highly complex top salt and base-salt geometries. This phenomenon becomes more important during the processing of a narrow azimuth data with significant illumination deficiencies around salt bodies, especially along the cross-line direction.

Subsalt converted wave suppression

During data acquisition over salt structures, P-waves may be converted to S-waves at salt interfaces, propagate through the salt and being converted back to P-waves prior to reaching the hydrophones (Lu et al, 2003; Alai and Verschuur, 2006; Alai and Verschuur, 2007). Conventional acoustic migration schemes will not be able to position the images of the converted reflections correctly, and these may mask important primary subsalt structures as coherent strong signal and distort critical images of possible prospects. To ensure that true geology is exposed for accurate interpretation of seismic images, it is recommended to suppress the subsalt converted waves (Kessler et al., 2002; Huang et al., 2013; Kobylarski et al., 2015; Hegazy et al., 2017; Alai et al., 2021). However, with the complex geology offshore Brazil, it is preferable to first estimate interbed multiples followed by adaptive subtraction of migrated interbed multiples in the image domain. Then, we can estimate and suppress mode-converted waves.

Examples

In the following, some data examples from the Campos Basin are showcased for improved subsalt imaging. In Figure 1a, a simplified velocity model [left] and impedance model [center] are depicted, emphasizing carbonate layering and stratified salt in the Campos basin offshore Brazil. Numerical modeling has been performed for the purpose of optimally testing the hybrid interbed demultiple scheme. In Figure 1a [right], the input stack is shown with large number of interbed multiples generated between all high impedance layers. Figure 1b showcases the 3 different methods we are combining into an optimal hybrid interbed multiple estimation scheme. Note that in all the 3 different displays the amount of interbed multiples is significant. In Figure 1c, three reverse time migrated (RTM) sections are displayed with interbed multiples (color overlays on sections) showcasing their existence and distribution. These displays show clearly the critical necessity of interbed demultiple in offshore Brazil data for improved subsalt imaging. The large amount of interbed multiples observed in all sections are possibly causing signal distortions and masking prospective subsalt target zones. Figure 1c [right] shows base-salt scattering and multiple generation of a secondary source (red dot at high amplitude base-salt edge). Scattering is observed when the waves propagate through the salt (indicated in blue) and reach the discontinuous high amplitude diffraction point. All the swings observed in this section are caused by the secondary source energy propagation. It is interesting to observe that the hybrid interbed demultiple has estimated these swings accurately. Adaptive subtraction methodologies in the curvelet domain (Chang et al., 2000; Yang et al., 2020) allow optimal suppression of these high amplitude swings. Figure 2a [left] shows an RTM image following conventional acoustic migration schemes, and Figure 2a [right] is the result for which the P-salt velocities (C_P) have been replaced by S-salt velocities (C_S). In offshore Brazil, the ratio of C_S/C_P~0.57 (obtained from well data). It is interesting to observe the improved salt flank image (increased confidence for salt flank prospectivity, indicated by red arrow). Figure 2b showcases a similar comparison for improved imaging of the salt flanks of the two salt bodies connecting to each other (indicated by the red arrows). Figure 2c shows another example, in which a "possible" subsalt basin [left] is mapped to base of salt [right] using S-salt velocity replacement. Due to limited illumination of S-waves inside the salt, the base-salt is partly imaged (the blue arrows indicate the salt flank image improvements in utilizing S-waves in the salt). In Figure 2d [left] partly zoomed images are shown of Figure 2c at the salt flanks. Figure 2d [center] depicts schematically the possible mode-converted wave propagations (PPSP, PSPP, PSSP) through P- and S-salt velocity models. Figure 2d [right] shows the combined Least-Squares matched mode-converted wave models (Figure 2e) that have been suppressed in the subsalt zones (color overlay RTM section). Note that all these mode-converted waves are distorting the true geology of the subsalt structures, if not optimally estimated and suppressed.

Conclusions

This abstract highlights subsalt imaging improvements through cascaded application of hybrid interbed demultiple, P- and S-salt velocity joint migration and subsalt converted wave suppression. We have demonstrated through synthetic and narrow azimuth field data from the Campos Basin in offshore Brazil, the applications, and critical values of removing all possible signal distortions in the subsalt section, revealing true geology for the purpose of optimal well placements. Mode-converted waves provide improved images of salt flanks, base-salt, and entire salt bodies.

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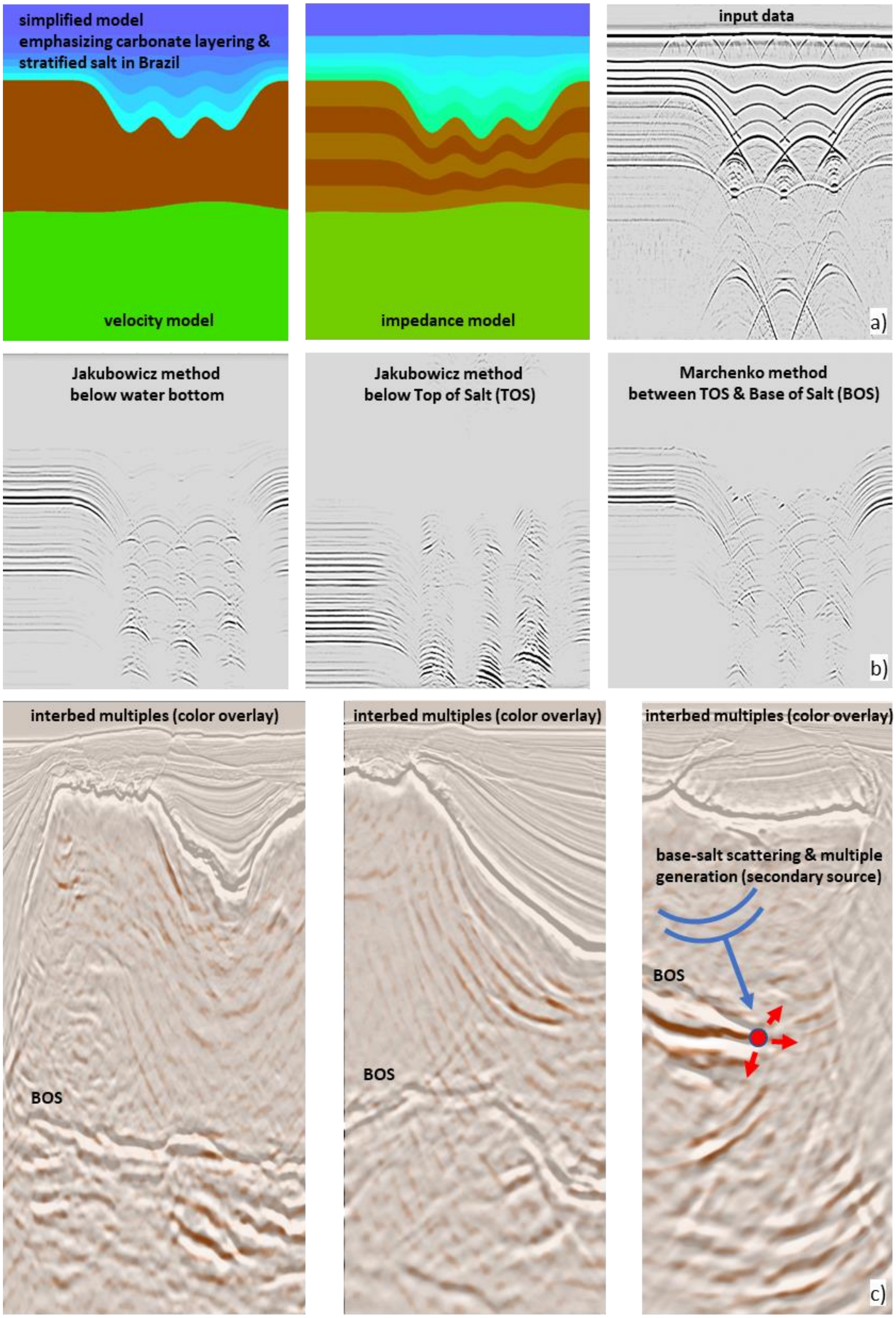

Figure 1: a)simplified velocity model, impedance model and input stack for interbed demultiple testing, b)interbed multiple models for three methods, c)adaptive Least-Squares matched estimated interbed multiples (color overlays on RTM sections) showcasing their existence and distribution.

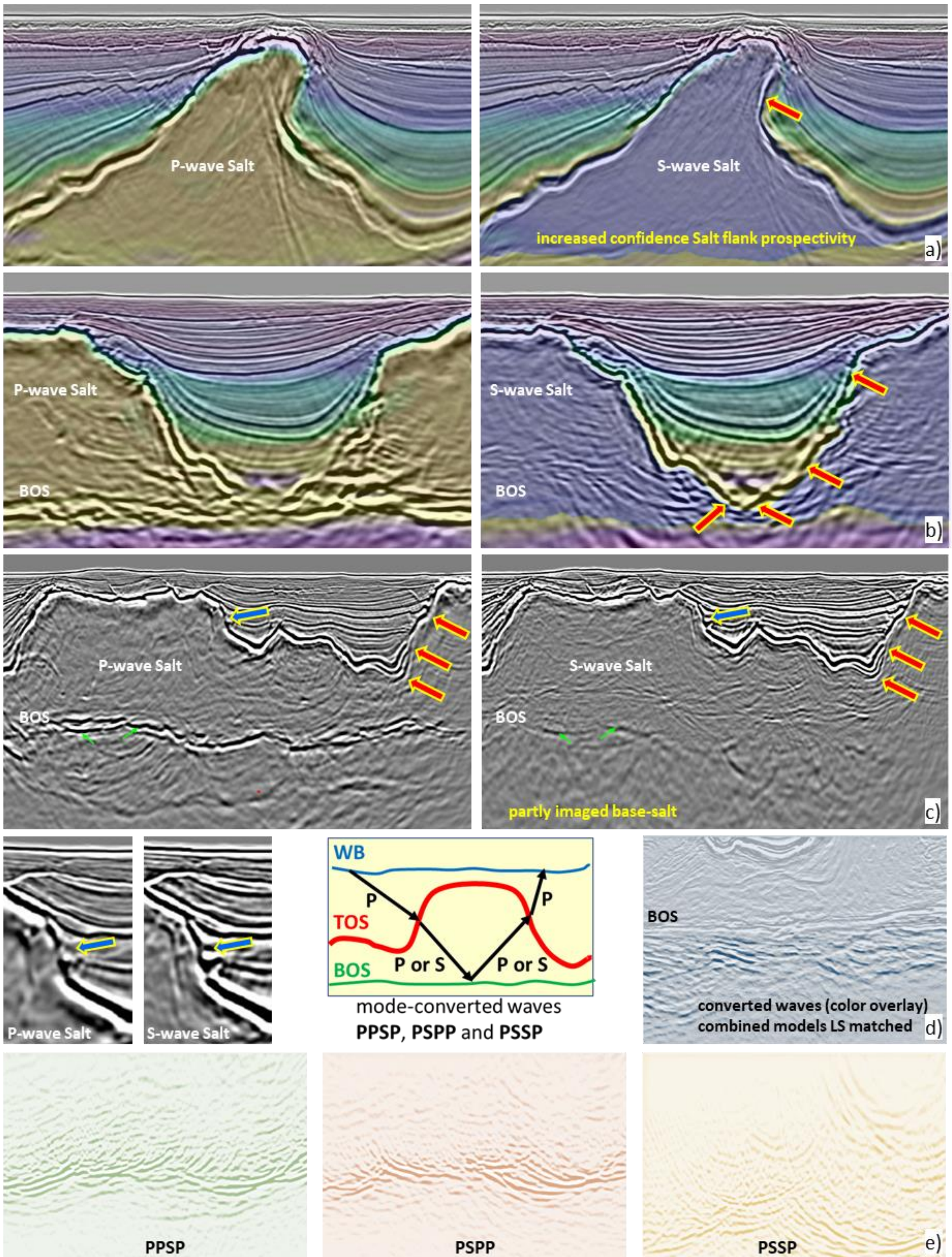

Figure 2: S-salt imaging providing improved salt flanks [a) and b)] and improved base-salt [c)]. d)[left] partly zoomed displays of c). d)[center] illustration of mode-converted waves. d)[right] combined Least-Squares matched converted wave models with color overlay on RTM. e)mode-converted PPSP [left], PSPP [center] and PSSP [right] models.

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