Submission code: 846L907847

See this and other abstracts on our website: https://home.sbgf.org.br/Pages/resumos.php

4D prestack image-domain least squares migration for presalt carbonate field in Santos Basin, offshore Brazil

Maria Shadrina (SLB), Alexey Sladkovsky (SLB), Maud Cavalca (SLB), Stefano Trezzi (SLB), Emmanuel Sargoussi (SLB)

4D prestack image-domain least squares migration for presalt carbonate field in Santos Basin, offshore Brazil

Summary

The geological complexity of the Santos Basin results in irregular illumination of the presalt carbonate reservoir. This variable illumination impacts the ability to interpret time-lapse seismic amplitudes, especially when looking at the amplitude signature in the angle domain where subtle production-induced changes are expected. The strength of the illumination footprint often dominates the time-lapse prestack signal and introduces uncertainty in further quantitative analysis, preventing confident appraisal of any elastic response. In this paper, we evaluate the impact that 4D prestack least-squares reverse-time migration (LSRTM) can have on the fidelity of the time-lapse signature. 4D prestack LSRTM is applied, using angle azimuth gathers, to three time-lapse seismic surveys acquired with ocean-bottom node (OBN) technology over a field in the Santos Basin. Initial quantitative attributes extracted from the derived time-lapse results demonstrate that, compared to standard reverse time migration, LSRTM delivers both 3D and 4D subsurface responses of higher resolution and superior amplitude fidelity.

Introduction

This study focuses on a deepwater presalt highly heterogeneous carbonate reservoir in the Santos Basin, offshore Brazil. The geological intricacy of the Santos Basin presents many challenges for seismic imaging and reservoir characterization, and moreover, for time-lapse analyses based on seismic response. Amplitudes at the reservoir are compromised by inconsistent illumination due to the highly variable structure of the salt layers present in the overburden. The illumination imprint is usually less pronounced in stacked images generated with wide-azimuth data. However, when data are decomposed into angle azimuth sectors, illumination variations become more prominent due to the narrow-angle, narrow-azimuth view of the complex subsurface, challenging amplitude fidelity.

A time-lapse seismic program was conducted with three vintages acquired using OBN technology, consisting of a baseline survey acquired in 2015 and two monitor surveys acquired in 2017 (M1) and 2023 (M2). The main objective of the 4D program is to monitor production and calibrate reservoir development planning. The most pronounced production-induced changes are expected to be in acoustic impedance (AI) with modeled changes varying from 1% to 2% (Cruz et al., 2021).

Tailored time-lapse OBN seismic processing and velocity model building workflows were employed to detect subtle 4D signals in the presalt section. To address the challenge of variable illumination, the workflow was completed with simultaneous 4D prestack LSRTM applied to 84 subsurface angle azimuth gathers within each vintage. Herein, we evaluate results through the prism of quantitative interpretation attributes and illustrate how compensating for illumination variations through 4D prestack LSRTM can enhance our interpretation of the reservoir behavior with time and production, especially when looking at the angle dependent 4D response.

Methodology

LSRTM is implemented in the image domain based on the use of point spread functions (PSFs) following the approach of Fletcher et al. (2012). Prestack application of image-domain LSRTM, also referred to as least-squares migration in the image domain (LSMi), has proven to be effective in handling 3D illumination variations and delivering prestack amplitude responses of higher fidelity (Shadrina et al., 2024). PSFs are explicitly modeled for each partial angle and/or azimuth gather, consistently with the seismic image decomposition, therefore capturing the angle- and/or azimuth-variant illumination pattern present in the seismic gathers. These effects are then mitigated through a global inversion (iterative deconvolution) process, involving all gathers. We extend this approach to perform simultaneous 4D prestack LSRTM. By enabling the use of constraints not only on the monitor and baseline reflectivities but also, when appropriate, on their perturbations, simultaneous inversion enables efficient 3D and 4D noise handling.

In this study, the 4D prestack LSRTM workflow was applied for three vintages using 84 reverse-time migration (RTM) 'dip-guided' subsurface angle azimuth gathers (DG-SAAGs) within each survey. These gathers were obtained following the approach described by Du et al. (2021), in which angle and azimuth decomposition is performed by analyzing the direction vector of the source wavefield in conjunction with a dip field estimated from the stacked image.

Evaluation of the baseline response

Firstly, we analyze the changes observed in the baseline amplitudes after the application of the process. The main amplitude differences are expected to occur in the prestack response, exposed to a stronger illumination challenge than the stacked response. Examination of the angle-dependent baseline amplitude signature for full-azimuth angle stacks reveals a reduction of the angle-dependent illumination footprint that was hindering amplitude variation with angle (AVA). Figure 1 exhibits AVA responses at the Well 1 location for RTM and LSRTM full-azimuth angle gathers. LSRTM gathers consistently present enhanced agreement with the modeled signature based on the borehole information, demonstrating the superior reliability of amplitudes due to the effective handling of illumination irregularities across angles.

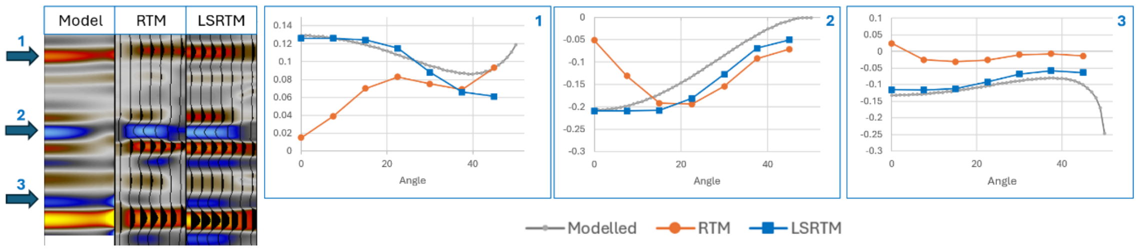

Figure 1: AVA analysis in the target window at Well 1 performed for full-azimuth RTM and LSRTM angle gathers. These are displayed next to the modeled signature based on the elastic well logs and 1D convolution with a representative wavelet, using Zoeppritz reflectivity equations. The right panels shows the AVA cross-plots associated with the events highlighted with arrows.

To further assess and visualize the effect of the illumination compensation achieved, AVA intercept and gradient attributes were extracted from both RTM and LSRTM angle gathers. The extraction was done using three-term Pan and Gardner (1987) re-parameterization of the Aki and Richards approximation. Near angles were excluded from attribute calculation due to very poor illumination in the RTM dataset. The results of these are displayed in Figure 2. As expected, the intercept attribute volumes derived from RTM and LSRTM are quite comparable, but the latter shows a more balanced response across the section and improved resolution and delineation of the formations. The broadening of the response after LSRTM can be attributed to the "deblurring" process that occurs during iterative deconvolution of the embedded, spatially variant 3D wavelet (estimated with PSFs). The gradient attribute exhibits greater differences after illumination compensation, with gradient volume derived from RTM struggling to capture property continuity for geologically complex and dipping structures. This suggests that the illumination irregularity is not only angle-specific, but also spatially and dip-variant, making it challenging for conventional angle-dependent 1D wavelets to accurately compensate for it. In contrast, the gradient distribution derived from LSRTM shows enhanced adherence to geological structures and borehole information.

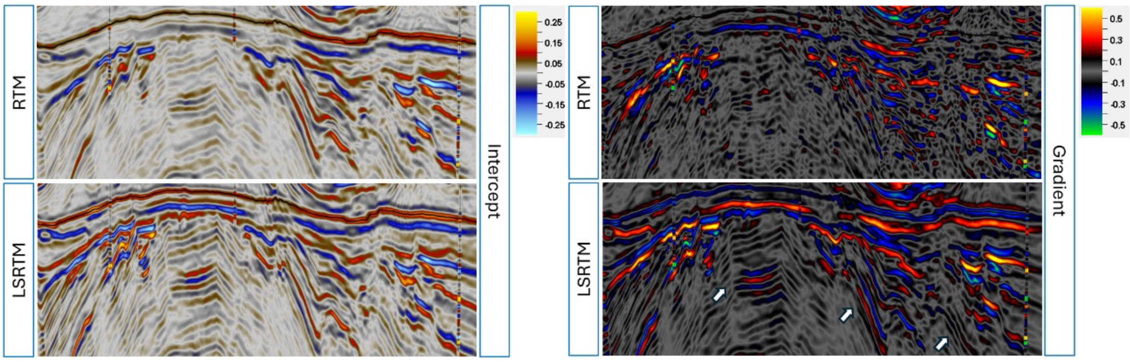

Figure 2: Intercept and gradient volumes obtained using RTM and LSRTM datasets, with associated modelled response based on the borehole logs overlaid at the three well locations.

Evaluation of time-lapse results

Following validation of the amplitude changes for the baseline vintage, the time-lapse response was studied. Figure 3 illustrates the stacked seismic 4D difference between M2 and baseline volumes before and after the application of 4D prestack LSRTM. It can be noted that, although generally the two images are akin, the time-lapse difference derived with LSRTM is characterized by better continuity and clarity of the 4D signal, as well as by a decrease of the noise level, supported by the reduction of mean normalized root mean square (NRMS) in the target interval from 4.7% to 3.3%.

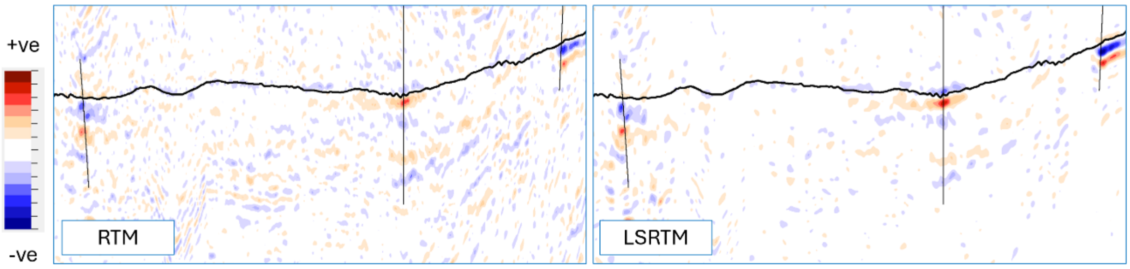

Figure 3: Intersection line across three injection wells through 4D difference volume between M2 and baseline (M2 minus baseline) before and after LSRTM. Difference in the response at the wells is expected as some are water injection wells while others are WAGs (water alternating gas) injection wells.

This observation is also reflected in the intersection line through the intercept 4D response between M1 and baseline, as shown in Figure 4. These demonstrate similar patterns, both being in fair adherence to the expected changes based on the production history, with the time-lapse response after LSRTM exhibiting improved continuity of the 4D signal and lower 4D noise level.

Gradient changes with time are also shown in Figure 4 and, as expected, raise a bigger challenge. The 4D perturbation distribution derived from RTM data is sporadic. No clear correlation can be observed between the derived 4D changes and the well locations or areas of expected production-induced changes. Additionally, considering that for tight carbonate reservoirs, Vp/Vs 4D changes are expected to be very small and potentially undetectable, it is natural to disregard these gradient changes as noise. Nevertheless, when we look at the 4D gradient changes after LSRTM, we observe a more plausible distribution. Areas with higher magnitude change are now contained in proximity to the water and WAG injection wells and areas of expected production-induced 4D changes. As shown by Hindriks (2024), gradient and curvature carry significantly more uncertainty and sensitivity to noise than intercept, and these uncertainties propagate into the relative rock physics parameter estimates. Therefore, robust recovery of elastic rock physics parameters, especially for time-lapse analyses, is highly dependent on high-quality seismic compensated for non-geological effects over a large angle range.

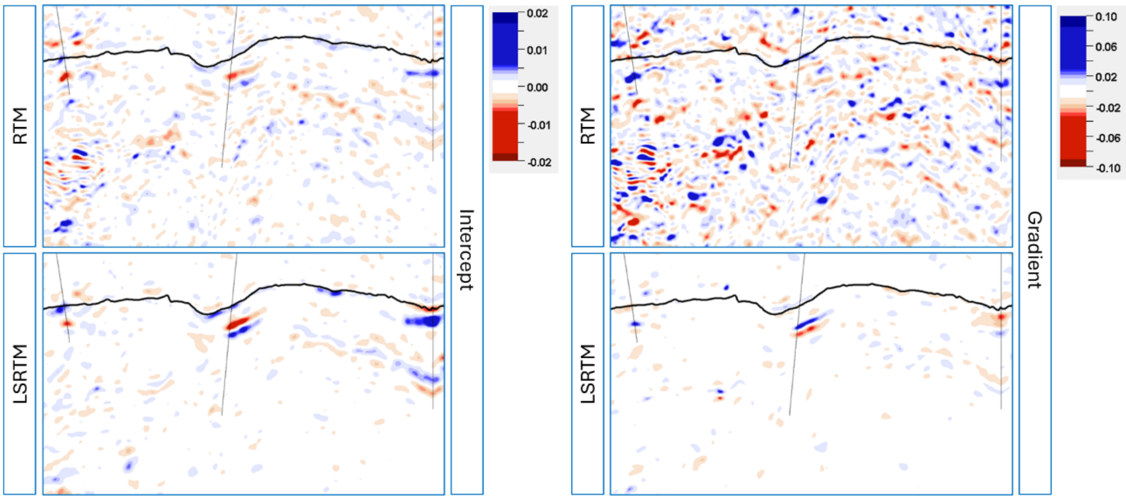

Figure 4: Intersection line across three injection wells through intercept and gradient 4D difference volumes between M1 and baseline (M1 minus baseline) before and after LSRTM. Difference in the response at the wells is expected as some wells were injecting water, while others were injecting gas between M1 and baseline time stamps.

Conclusions

4D prestack LSRTM was applied to three seismic vintages acquired over the Santos Basin field, in a challenging presalt environment, and delivered promising results. By handling the illumination variability with angle and azimuth, 4D prestack LSRTM facilitates the use of prestack data in 4D analysis. Analysis of angle- and azimuth-dependent 4D changes can now be envisaged with more confidence in complex areas. These analyses can provide valuable insights into reservoir elastic properties for a deeper understanding of the production-induced changes.

Acknowledgments

The authors thank Petrobras, Shell, Galp, and SLB for permission to publish this study.

References

Cruz, N.M., Cruz, J.M., Teixeira, L.M., da Costa, M.M., de Oliveira, L.B., Urasaki, E.N., Bispo, T.P., de Sá Jardim, M., Grochau, M.H. and Maul, A., 2021, Tupi Nodes pilot: A successful 4D seismic case for Brazilian presalt reservoirs: The Leading Edge, 40, pp.886-896.

Du, X., Fletcher, R.P. and Cavalca, M., 2021, Prestack least-squares reverse-time migration for elastic property estimation: SEG Technical Program Expanded Abstracts, 196-200.

Fletcher, R.P., Archer, S., Nichols, D. and Mao, W., 2012, Inversion after depth imaging: SEG Technical Program Expanded Abstracts, 1-5, Society of Exploration Geophysicists.

Hindriks, F.M., 2024, AVA Parameter and Relative Rock Physics Sensitivities: 85th EAGE Annual Conference & Exhibition, Vol. 2024, No. 1, pp. 1-5.

Pan, N. D., and Gardner, G.H.F., 1987, The basic equations of plane elastic wave reflection and scattering applied to AVO analysis: Annual Progress Review 19, Seismic Acoustic Laboratory, University of Houston.

Shadrina, M., Cavalca, M., Saragoussi, E., Monteiro, J., Mathewson, J., Dias, B.P., Sperandio, E.F., Braga, M.R., Bezerra, M.D.S. and Costa, T.N., 2024, Pre-Stack LSRTM-Illuminating the Subsurface for Advanced Reservoir Understanding-Campos Basin Case Study: 85th EAGE Annual Conference & Exhibition, Vol. 2024, No. 1, 1-5.