Improved presalt imaging using innovative model-driven imaging technology

Sriram Arasanipalai[1*], Alejandro Valenciano Mavilio[1] and Hermann Lebit[1] outline the impact of advanced modelling and inversion technologies on seismic data reprocessing to support exploration and production objectives in a prolific presalt play offshore Brazil.

Introduction

The foundation for a wide range of exploration and production decisions is built on assessing seismic data. The objectives are wide ranging, from capturing hydrocarbon prospects, characterizing and monitoring the reservoirs, to well planning and completion design including geo-hazard assessments. With this focus, the seismic industry is striving for the most sophisticated acquisition techniques to provide acoustic data. Optimized processing technologies that use advanced modelling techniques to generate accurate high-resolution models and seismic images are as important. In addition, reducing turnaround time for the development of hydrocarbon production while maintaining safe and secure operations relies strongly on accurate seismic modelling and imaging of the subsurface.

Modelling is the core tool that estimates high-resolution earth models. Both Full Waveform Inversion (FWI) and high-resolution tomography, model and invert for seismic velocities, but the former is emerging as the preferred tool as its access to data enables higher resolution and an increased accuracy in the modelled results. The algorithm uses the wave equation to model the data, mimicking the recordings from a seismic survey. It generates an earth model by solving a nonlinear inverse problem that minimizes the difference between field and modelled data (Tarantola, 1984). The initial applications of FWI were mostly in shallow water settings using refractions. Recent advances in FWI technology have made it practical to incorporate seismic reflection data as well. Obtaining high-fidelity earth models is a critical step in generating high-resolution estimates of the earth's reflectivity, and therefore in improving data interpretability.

Conventional migration techniques such as Kirchhoff Migration and Reverse Time Migration (RTM) provide an estimate of the earth's reflectivity, and are used to capture hydrocarbon reservoirs and outline prospects. Least-squares migration (LSM), another technology that uses modelling, has emerged as a new standard in high-end imaging, improving the level of resolution and amplitude fidelity necessary for prospect risk mitigation, reservoir characterization and well planning. LSM builds on detailed earth models, created by using the modelling and inversion

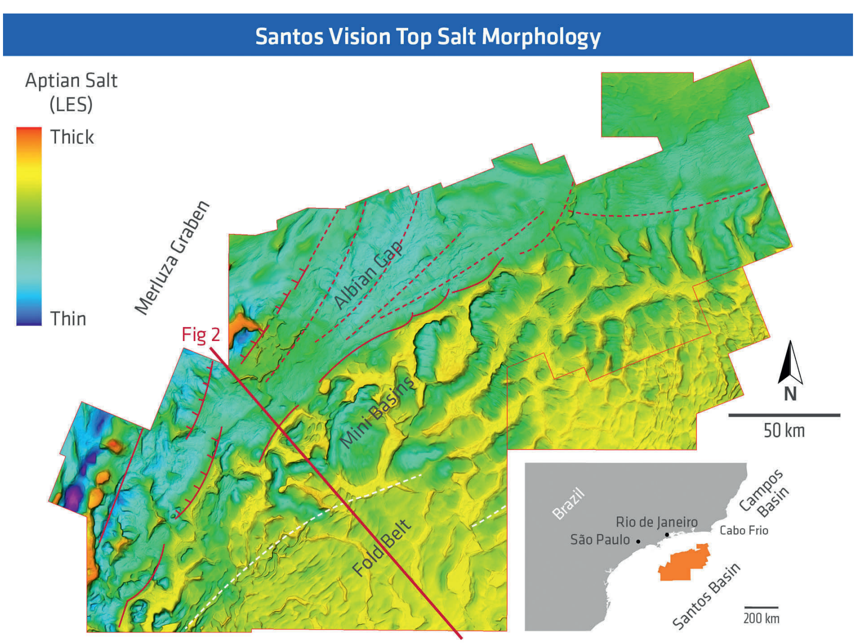

Figure 1 Regional map of the Albian Top Salt (Layered Evaporite Sequence). The Top Salt morphology indicates the major tectono-stratigraphic domains over the São Paulo Plateau, Santos Basin, Brazil.

[1] PGS
[*] Corresponding author, E-mail: Sriram.Arasanipalai@pgs.com
DOI: 10.3997/1365-2397.fb2020023

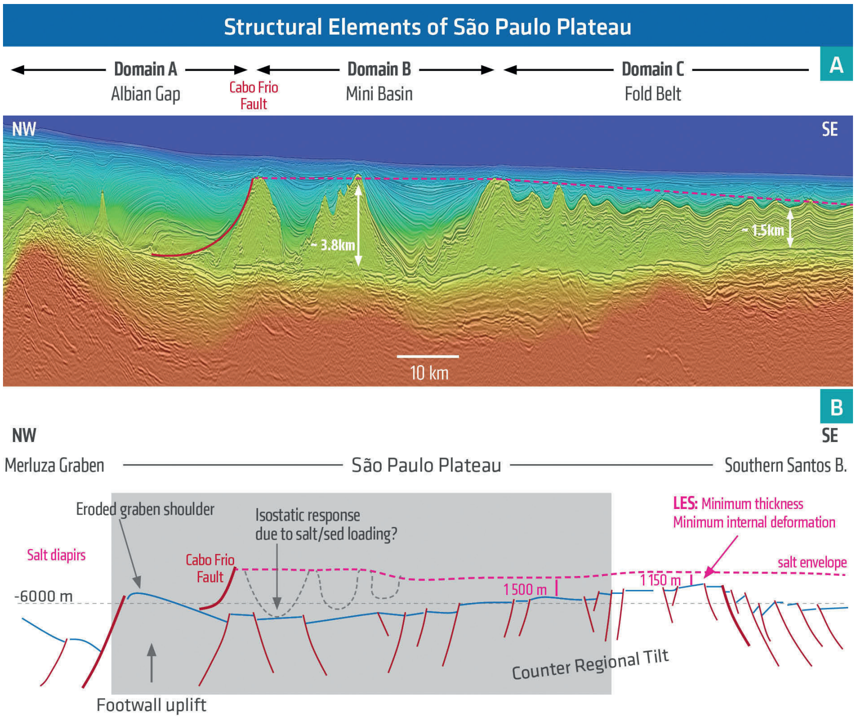

Figure 2 (A) Seismic section of the São Paulo Plateau. For orientation, see Figure 1. (B) Regional section of the São Paulo Plateau outlining the major structure elements for the presalt section. The blue horizon outlines the base of the Aptian salt (LES) and the underlying presalt carbonate build-ups.

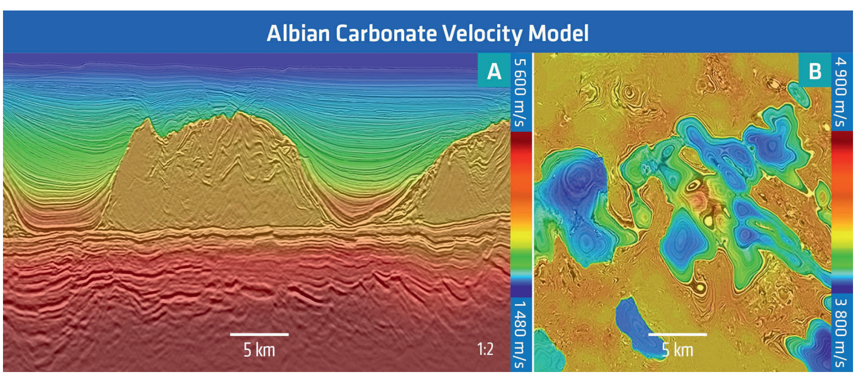

Figure 3 (A) Seismic section with rendered velocity model updated with tomography and FWI showing the variability in the seismic velocity of the postsalt Albian carbonates which are key for accurate presalt imaging. (B) Depth slice through the mini-basin domain illustrating the structural conformity of the Albian carbonate velocities.

engine of FWI and geological constraints, to iteratively obtain an optimal image of the earth's subsurface.

Accurate images of the subsurface using imaging technologies like FWI and LSM can aid critical decision-making processes. In this paper, we demonstrate such an application of model-driven imaging technologies using data from the Santos Basin, offshore Brazil.

Santos Basin geological setting

The PGS Santos Vision survey covers the São Paulo Plateau, which represents a zone of relatively shallow presalt rift architecture underneath the Aptian Layered Evaporite Sequence (LES) in the Santos Basin offshore Brazil (Mohriak et al., 2008; Figure 1). At the plateau, the average LES base is about 6000 m, while its western edge is delineated by a major graben/half-graben system that has down-thrown the salt base to depths of > 9000 m and is named Merluza Graben (Figures 1 and 2). On the São Paulo Plateau, three major tectono-stratigraphic domains are distinguishable based on the Aptian salt (LES) architecture and the morphology of the postsalt Albian carbonates (Lebit et al., 2019; Figure 2A), which are the Albian Gap, the Mini-Basin domain and the Fold Belt domain. The Albian carbonate sequence has a significant impact on the velocity model and hence the imaging quality of the underlying sequences. This is due to the large velocity variability within the Albian carbonate sequence, which primarily depends on the overburden (Figure 3).

The Albian Gap

Domain A represents the Albian Gap, an approximately 40 to 50-km wide zone containing only minor remains of Aptian evaporites and widely lacking the Albian carbonates. Those units are replaced by large clinoforms comprising Upper Cretaceous clastic sediments, and are distally bound by the Cabo Frio Fault, a lystric counter-regional normal fault rooting into the base of the postsalt sequence (Figure 2A).

Mini-basins

Outboard of the Cabo Frio fault system, Domain B is dominated by Aptian evaporites (LES) forming salt walls and reactive salt diapirs approximately 3.5 to 4 km in thickness separating sedimentary mini-basins. The LES reveals complex internal folding which is well imaged due to the impedance contrast of the component evaporite layers (Halite, Anhydrite, Carnallite etc.). The intervening mini-basins contain convex mega-flaps of postsalt Albian carbonate layers that commonly terminate laterally against sets of normal faults as part of the reactive diapirs, and rarely drape across the LES 'domes'. It is assumed the mini basins are dominated by the down building process, and the disruption (elongation) of the Albian carbonates reflects the arc length change during this process. Evidence for active diapirism is absent on the São Paulo Plateau. The Albian postsalt carbonate is important for the seismic velocity model building as this lithological sequence is prone to significant velocity changes depending on the confining pressure (overburden, depth).

The Fold Belt

The transition from Domain B to the distal Domain C is gradual in nature as the salt thickness reduces and the significance of mini-basins diminishes (Figure 2A). The domain is characterized by well-imaged layering in the evaporite sequence (LES) and a continuous Albian carbonate cover. The LES' internal fold complexity gradually reduces as it approaches simple harmonic folds at the distal section in the east/southeast of the plateau, where locally little to no internal deformation is evident by well imaged undisturbed concordant evaporite layers of about 1.2 to 1.5 km in thickness (Figure 2B).

The primary reservoir targets are situated in presalt carbonate build-ups (Barremian) beneath heterogeneously layered evaporate sequences (LES) (Figure 2B) and are interbedded with volcanic rocks. The paralic/lagoonal depositional environment was affected by late stage faulting during the sag-phase representing a final rifting interval prior to the opening (seafloor spreading) of the South Atlantic. The geologically challenging setting of laterally changing reservoir facies disrupted by fault patterns (Figure 6) requires seismic processing solutions to mitigate exploration risks and development uncertainties for these presalt prospects.

Improving the reliability of seismic data

Velocity model building workflow, the key for enhanced presalt imaging

Having an accurate postsalt velocity model is the first key step in achieving an accurate presalt image, and in turn a more reliable interpretation and reservoir characterization. The post-salt sediment velocity model building (VMB) workflow used a combination of tilted transverse isotropy (TTI) tomography and FWI; the later proved to be an important tool within the earth model building workflow.

FWI's evolution for improved earth models in challenging regimes

Most FWI applications have targeted shallow water environments where recorded refracted waves enable the inversion to resolve small-scale geological features up to the deepest turning point (e.g. Sirgue et al., 2009; Zhou et al., 2015). Recently, the use of FWI technology has been pushed to deep-water scenarios where refracted energy may be missing due to limited offsets in conventional towed-streamer acquisitions (Martin and Long, 2019). Consequently, there has been a growing demand for acquiring better data for FWI, e.g., longer offsets from ocean bottom seismic (Shen et al., 2017) and lower frequencies with a high signal-to-noise ratio in order to reduce cycle-skipping between recorded and modelled data (Dellinger et al., 2016). Alternatively, FWI developments have focused on better inversion solutions (e.g. Alkhalifah, 2014, Ramos-Martinez et al., 2016, Gomes

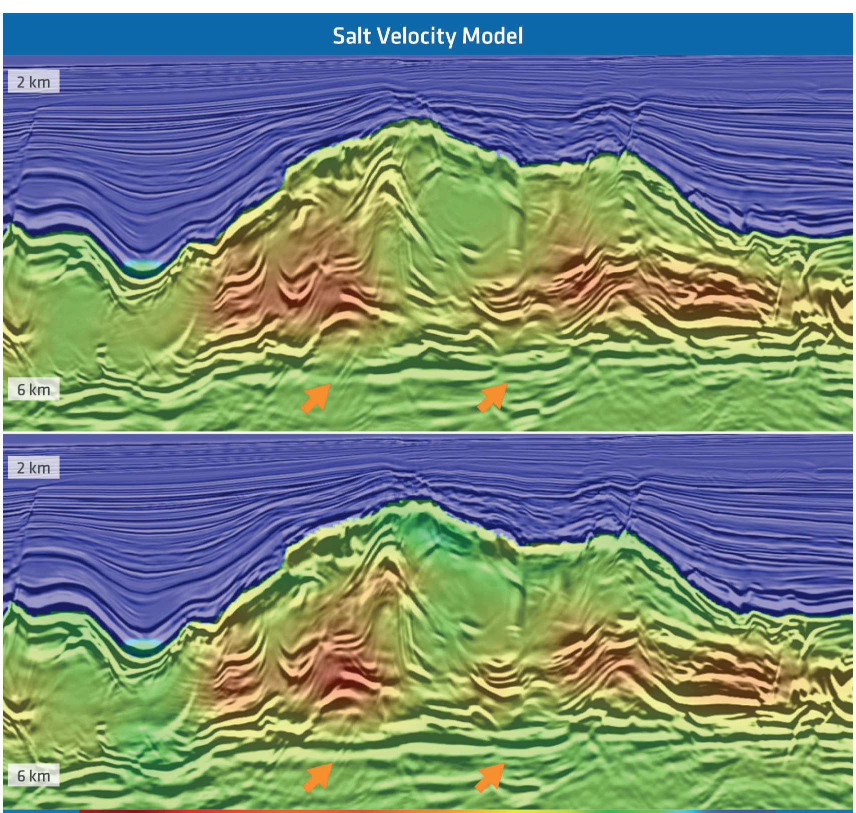

Figure 4 Example of velocity updates within the LES. (A) Tomographic velocity model prior to reflection FWI update. (B) Reflection FWI update illustrating the increased focusing of presalt imaging.

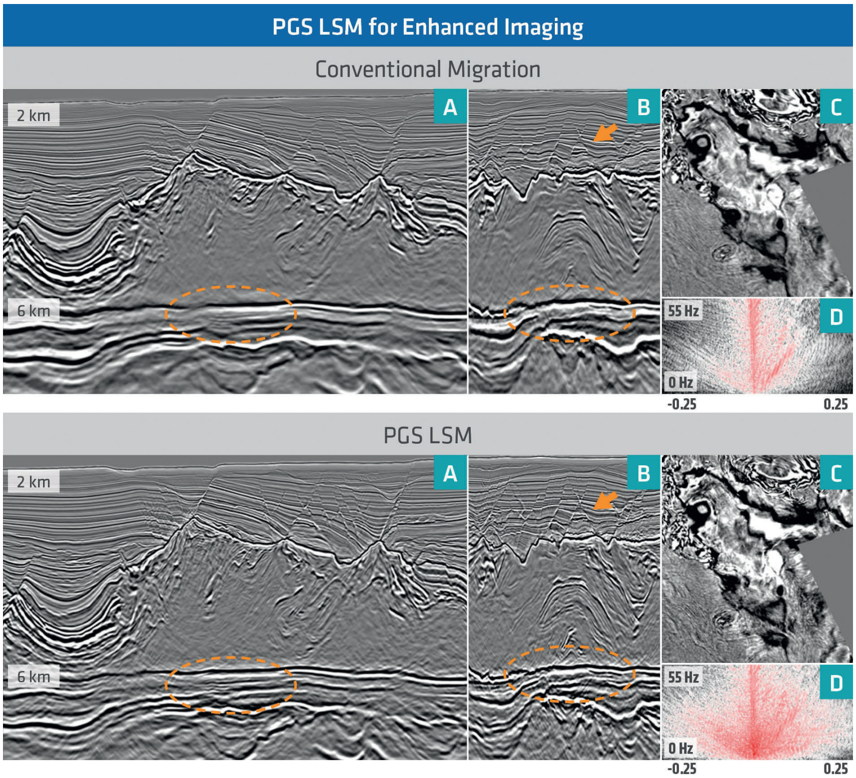

Figure 5 Comparison of conventional migration (top) images vs. LSM (bottom) images, each with a N-S line (A), an E-W line (B) and a depth slice at 5750 m (C). The LSM images clearly reveal enhanced postsalt imaging of fault patterns, cap rocks and sedimentary structures. Resolution of the entire section and especially that of the presalt reservoir sequences has improved significantly with LSM.

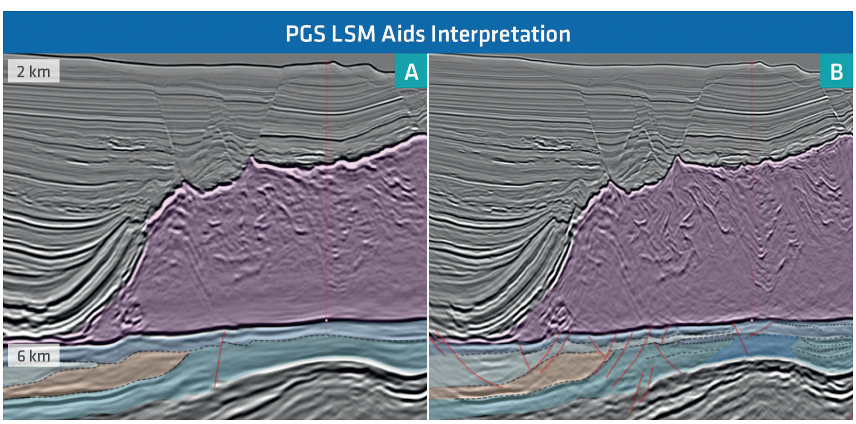

Figure 6 Geological interpretation of the presalt reservoir architecture based on (A) Conventional migration and (B) LSM. Note the increased reflector resolution outlining various seismic facies at the presalt reservoir, including better definition of the fault population.

and Chazalnoel, 2016) that can reduce the dependency on data requirements and produce deep velocity model updates. These efforts have targeted combinations of modified gradients, robust norms for measuring the data misfit, and *a priori* model constraints to enable utilization of all wave modes in the data (refractions and reflections).

Advanced model building in the Santos Basin

An implementation of FWI, utilizing refractions and reflections, was deployed in the Santos Vision program to obtain an accurate model to the presalt section. The FWI algorithm utilized reflections to produce low-wavenumber updates when refracted events are not available (Ramos-Martinez et al., 2011, Ramos-Martinez et al., 2016). To achieve accurate modelling of the data, free of numerical dispersion, the FWI engine is based on an efficient pseudo-analytical extrapolator (Crawley et al., 2010).

Availability of refracted energy in the data was limited due to the water depths of approximately 2 km and the maximum acquisition offset of 8 km. Careful modelling and QC of the match between modelled and field data guided the process of selecting the appropriate input for FWI in each of the model building units. In the shallow sections, just below the water bottom, refractions were used to obtain the FWI updates whereas in the Albian carbonates section reflections were used to obtain the FWI updates. The result of this workflow was a postsalt sediment velocity model capturing the depth-dependent velocity variability of the Albian carbonates and the mega-sequences of the Upper Cretaceous clastic sequences. Examples of the application of the postsalt VMB workflow are shown in Figure 3.

After the postsalt velocity updates and interpretation of the top salt horizon, the intrasalt velocity updates capture the heterogeneity in the section, which is due to the complex folding of the evaporite layers (e.g. anhydrite). While a traditional top salt interpretation was still necessary to delineate the boundary of the model building unit, manual interpretation of the base of the salt sequence, (LES in the Santos Basin) was not required due to data-driven tomography and FWI updates of the combined salt and presalt section. The entire velocity model building workflow therefore comprises of two major model building units: the post-salt section, including the Albian carbonates, and the salt and presalt section. This approach reduced the need for interpretation of the base of salt over a large swath of the Santos Basin. The VMB workflow optimized the initial tomographic model by pushing the reflection-based FWI velocity updates to the presalt section (Figure 4). No refraction events are expected in the salt and presalt section due to limited offsets and the water depth. The reduction in human interpretation efforts plus demands of intermediate migrations, while favouring a data-driven VMB efficiently improved the earth models, which result in more reliable images for interpretation and reservoir characterization.

Optimized model building leading to enhanced reflectivity – Least-Squares Migration

Using advanced modelling and inversion tools can create accurate velocity models. However, conventional depth migration only produces an approximation of the earth's true reflectivity. The main limitations are attributed to imperfect acquisition and variable illumination beneath a complex overburden (e.g. salt, carbonates, and volcanics). Therefore, migrated images often suffer from limited wavenumber content and reduced granularity, especially in presalt sections. Using modelling, Least-Squares Migration (LSM) tackles these limitations by posing seismic imaging as an inversion process (Nemeth et al., 1999) seeking optimal images closely representing the earth's reflectivity.

While most commercial LSM algorithms are implemented in the image-space, data-domain LSM algorithms solve for the earth's reflectivity by means of an iterative modelling and data-fitting workflow similar to FWI (Lu et al., 2017). More than one iteration of data modelling and migration are often necessary to obtain an optimal image. The engine of LSM efficiently propagates high-frequency seismic data using the detailed earth models derived from FWI and in-depth interpretation. This results in high-resolution images with balanced amplitudes and reduced illumination variations. The amplitudes of the reflectivity models are more suitable for reservoir characterization as it minimizes illumination effects (Valenciano et al., 2019).

Improved amplitude fidelity and interpretability in the Santos Basin

An iterative, data-domain LSM was applied in the Santos Basin to demonstrate the uplift for presalt reservoirs. The objective was to address presalt imaging limitations and enhance the resolution of presalt carbonate build-ups and associated fault patterns at reservoir level. Figure 5 shows an application over the Buzios field. The comparison between the conventional migration and LSM shows an uplift throughout the section with improved postsalt imaging of faults and cap rocks, better imaging of fold interference pattern within the LES, and an improvement in resolution of the reservoir sequence. It enables easier identification of various seismic stratigraphic units. For instance, the Coquina facies at the lower reservoir section is better delineated by the LSM revealing a sediment bar geometry, aiding the reservoir characterization.

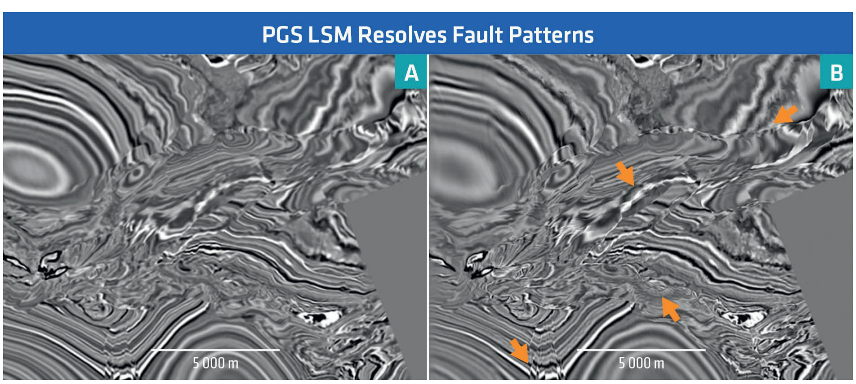

Figure 7 Depth slice showing fault patterns within the shallow postsalt section (at 2750 m) that represent a drill hazard. Notice the enhanced fault resolution when comparing (A) Conventional migration with (B) LSM that reveals increased resolution of fault patterns (examples are indicated by orange arrows).

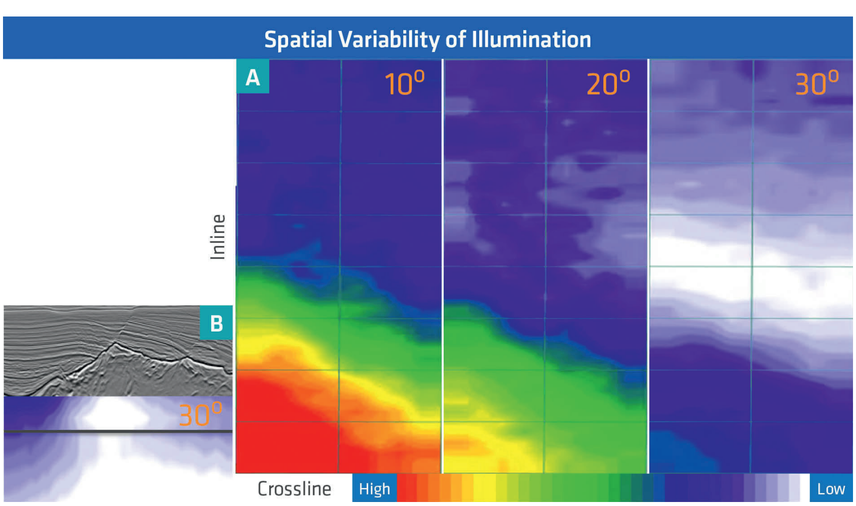

Figure 8 (A) Illumination maps of 10, 20 and 30 degree angles at the presalt section. (B) Note the low illumination at about a 30-degree angle below the complex salt.

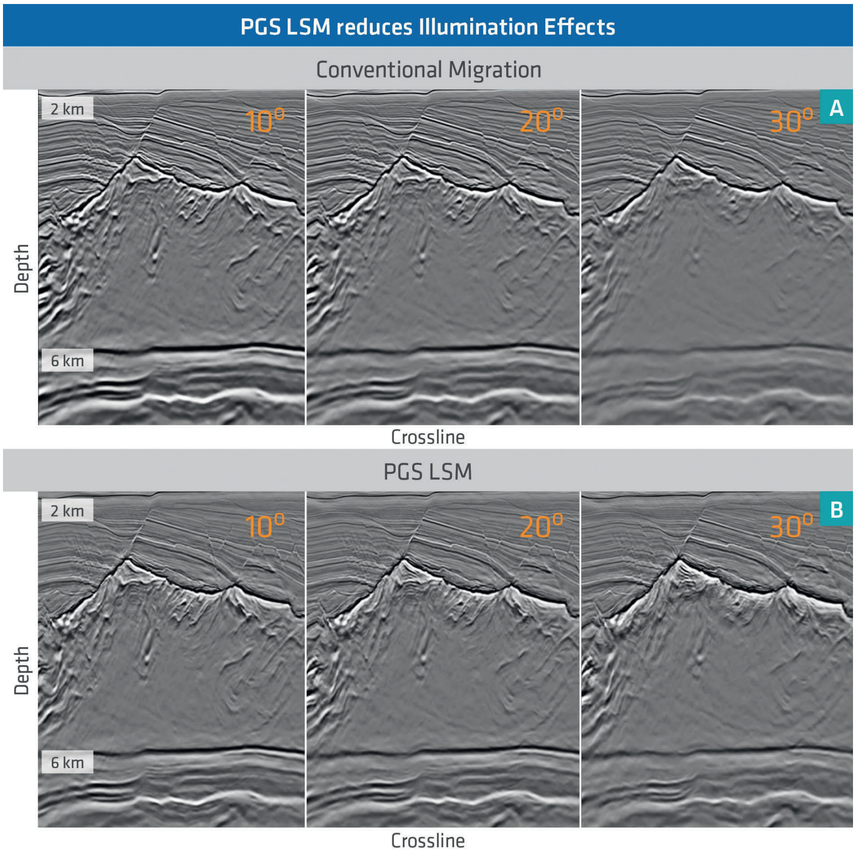

Figure 9 Comparison of angle stacks from (A) Conventional migration and (B) LSM, showing the compensation for illumination, improvement in resolution and amplitude fidelity with angle.

The higher granularity in the definition of the fault patterns helps to mitigate the compartmentalization risk (Figure 6). The latter is also significant for well placement and well completion, while the high-resolution shallow data enables better fault interpretation, which may mitigate drilling hazards (Figure 5B – orange arrow, Figure 5D increase in bandwidth of f-k spectra and Figure 7).

Non-uniform illumination with angle may be an issue especially at presalt reservoir depths. As an extension to the study, an image-domain LSM using point spread functions (Valenciano, 2008) was performed to correct for illumination effects. Figure 8 shows the result of modelling the illumination for different angles at the reservoir level. The modelling was achieved using optimized wavefield extrapolation. Note the spatial variability of the illumination for different angles. Consequently, the gathers and the angle stacks from a conventional migration may not produce reliable amplitudes beneath complex overburden. LSM reduces illumination effects and generates data that are more suitable for amplitude analysis and interpretation (Figure 9).

Discussion

Using modern modelling and inversion techniques, the Santos Vision dataset delivers improved seismic imaging quality. Rigorous benchmarking of the velocity model against geological subsurface information enabled a more accurate model build and more reliable seismic images. An integrated and streamlined workflow using technology and expertise was significant for the successful outcome that combined 13 surveys into a seamless 3D seismic volume over more than 50,000 km^2.

A major focus was on the imaging of the presalt sequence that contains some super-giant hydrocarbon reservoirs in this prolific basin. The velocity model was built on a two-layer concept comprising a postsalt section and a salt to presalt section. It does not have a boundary at the base of the salt due to the absence of significant velocity contrasts between the salt (LES) and the underlying rocks. The base of the salt or top of the presalt reservoir sequence was imaged by a data-driven model using tomography and FWI updates throughout the combined salt and presalt section. The remaining model building boundary besides the water bottom was top of the salt (LES).

The postsalt model was constrained by the seismic imaging and the impact on the presalt architecture. For instance, velocities that were too fast in the mini-basins led to push-downs within the presalt sequence and a defocused presalt image. Therefore, the image was optimized by an interpretative feedback loop. Other interpretation geological constraints include the continuity of stratal reflectors and their sedimentary geometries, the definition of fault patterns and the morphology of volcanic layers in the presalt section and well-tie analysis.

An important element of the postsalt seismic velocity model is the Albian carbonate which is prone to significant velocity changes depending on the confining pressure (overburden, depth). The Albian carbonates form megaflaps in the mini-basins (Figure 3) and reveal highly variable velocities depending on their burial or depth in these mini-basins. Delineating the Albian carbonate velocities was important for the image quality of the presalt section and this was achieved by using the modelling engines of tomography and FWI in combination with the aforementioned interpretative geological constraints.

The Santos Basin seismic data were limited in offset and low frequency content and that made the model building in the salt and presalt section challenging. A good starting velocity model is important to avoid cycle-skipping in FWI. The starting model for FWI updates in the salt to presalt section was achieved by using TTI tomography. The initial tomographic velocity model was optimized by extending the reflection-based FWI updates into the presalt section (Figure 4), resulting in purely data-driven imaging of the base salt and underlying sequences.

Having a good velocity model is fundamental to obtaining a high-fidelity seismic image, which enables a more reliable interpretation. However, conventional migrations are based on approximations that do not correct for imperfect acquisition and variable illumination under complex overburdens. A conventional migration may result in inconsistent amplitudes and a loss of resolution in the target section, particularly with increasing angle. Through a modelling and inversion scheme, LSM corrects these limitations, providing images with higher granularity in the presalt reservoir. This results in a higher definition of the fault patterns and enhanced resolution of the stratal geometries, particularly at the presalt reservoir section. The latter is significant for reservoir characterization, well placement and completion, while the high-resolution imaging allows detailed seismic stratigraphy (Figure 6). Recognizing, and accurately positioning fault populations reduces reservoir compartmentalization risk and has a significant impact on mitigating drilling hazards (Figure 7).

Conclusions

The Santos Vision project combined 13 different legacy surveys with variable acquisition parameters that provide a seamless broadband seismic volume over more than 50,000 km^2 of marine waters in the Santos Basin, Brazil. The use of modern modelling and inversion technologies and rigorous benchmarking of the earth model against geological subsurface constraints, assisted by interpretation, enabled a high-quality seismic image primarily focusing on the prolific presalt play. It demonstrates the value legacy seismic data may have for alleviating all forms of uncertainty, when reprocessed with new technologies. The model building workflow was optimized using FWI, resulting in a more accurate model and image of the presalt data. Least-squares migration was used to compensate for variable illumination and resolution, particularly with angle. The final data was accurately imaged with reliable amplitudes in both the prestack and poststack domains, which enables a new level of confidence in data interpretability and reservoir characterization.

Acknowledgements

The authors would like to thank PGS for permission to use Santos Basin data for this publication. The authors would also like to thank Tony Martin for his valuable assistance.

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