Improving pre-salt imaging through multi-layer horizon-constrained tomography – a case study in Brazil's Campos basin

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Summary

The Campos basin offshore Brazil is a challenging area for seismic imaging because of its complex geology and deep pre-salt targets. The presence of structurally complex and high-velocity carbonates above the salt, as well as the highly varying thickness of the salt throughout the basin, makes velocity-model building difficult. We show that a layer-stripping based single-layer tomography is not sufficient to provide the detail in the velocity model needed to accurately image the pre-salt sediments. The image of the pre-salt targets obtained using a velocity model built using a layer stripping approach, shows an imprint of the inaccuracies in the velocity model of the overburden on the image of the pre-salt sediments, while the image of the base of salt does not match known a-priori geological information. We show how multi-layer horizon-constrained tomography can be used to derive a velocity model that allows much improved imaging of both the pre-salt and post-salt sediments.

Introduction

The Campos basin is one of the Brazilian basins off-shore Brazil that is currently actively producing hydrocarbons. Several large oil-fields such as Albacora or Marlim have been discovered since production started back in the seventies. This 115.000 km^2 basin is situated 250 km East of Rio de Janeiro. In the North and South it borders, respectively, the Espirito Santo and Santos basins. Demand for seismic exploration in this basin has increased due to recent discoveries in both the post- and pre-salt areas, as well as the availability of blocks for new bidding rounds.

The complex geology in the Campos basin causes imaging to be a challenging task, in particular for the pre-salt targets. The presence of highly heterogeneous post-salt sediments, as well as potential volcanic intrusions, high-velocity carbonate layers and complex salt bodies of highly varying thickness, makes it difficult to determine an accurate velocity model using standard tomography. As a result an imprint of the inaccuracies in the velocity model of the overburden is often visible on the imaged structure of the pre-salt targets. This imprint can be identified using geological information. Therefore a horizon-constrained tomography that incorporates known a-priori information about the pre-salt target can be used to improve the velocity model in the post-salt, thus enabling the removal of the imprint of inaccurate post-salt velocities on the imaged structure of the pre-salt events.

In this paper we present a depth-processing case study that features the difficulties in imaging the pre-salt sediments in the Campos basin and shows how such difficulties can to a large extent be overcome using a multi-layer horizon-constrained tomographic approach that incorporates a-priori geological information about the base of salt (BoS).

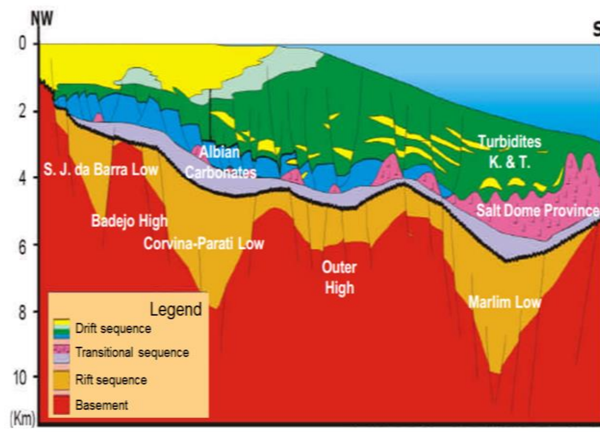

Figure 1: *Schematic geological section of Campos basin.*

Geological context and initial model

In order to understand better the nature of the geological complexities in the Campos basin, we define the main four tectono-stratigraphic units that together make up the majority of the geology in the Campos basin. We describe these units in a bottom-to-top fashion, i.e. the deepest unit first and the shallowest unit last (see also Figure 1).

Pre-salt: consists of Barremian siliclastics deposited on Neocomian basalt (120–130 Ma). In a pre-marine environment, the Barremian sequence (Lagoa Feia) is considered to be the principal source rock in the Campos basin.

Salt: transitional sequence mainly characterized by a thick sequence of evaporitic rocks that have undergone intense diapiric activity in the deep-water parts of the basin. The salt relief increases typically in a basinward direction (Figure 1). The thickness of the salt is highly varying, ranging from virtually zero to a few kilometers.

Albian: lower part of the post-salt sequence dominated by shallow marine carbonates in the deepest parts. These carbonates are referred to as the Quissama sequence. The strong lateral velocity contrasts and high average velocity of 5500 m/s of these carbonates cause the imaging of the pre-salt targets to be challenging.

Upper Cretaceous / Tertiary: uppermost part of the post-salt sequence consisting of a large succession of fine-grained siliclastics deposited in marine environments.

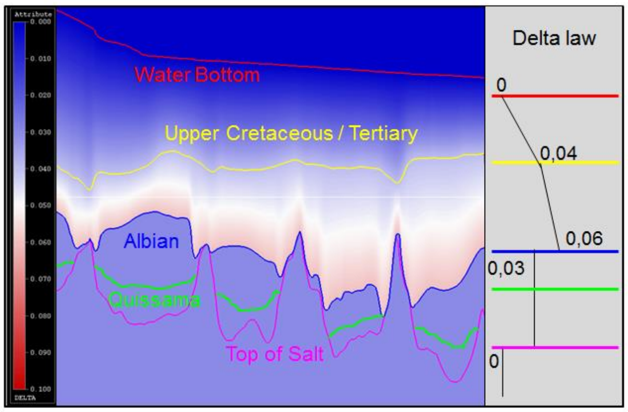

Figure 2: *The initial model for Thomsen parameter δ.*

Data acquisition and processing

The data used throughout this work was acquired in 2014 as part of a multi-client survey performed by CGG in the Campos basin off-shore Brazil. The data were recorded using twelve 8100 m long variable-depth streamers. The data processing sequence consisted of swell and linear noise removal, suppression of seismic interference, de-bubbling using the far-field source signature modelled from the recorded near-field hydrophone, ghost-wave elimination, water column static correction to correct for water-temperature variations, 3D surface-related multiple attenuation, and regularization onto a 25 m x 25 m grid. All the images shown throughout this work were calculated using a pre-stack Kirchhoff depth-migration algorithm.

Global and multi-layer tomography for a deep basin

The highly heterogeneous nature of the different sedimentary deposits described above is confirmed by the inherent anisotropic nature of many of the sediments. A tilted transverse isotropic (TTI) symmetry was assumed to be the most plausible symmetry for the post-salt sediments (e.g. Isaac *et al., 1999*), where the orientation of the symmetry axis is assumed to be orthogonal to the structural dip.

Fourteen well-logs and well-ties were available that facilitated the estimation of initial estimates of the Thomsen parameters δ and ε. An initial model for δ was constructed assuming different gradients between the water bottom (WB) and the top of the Albian, as well as between the top of Albian and the top of the carbonates (see Figure 2). For the carbonates in the lower part of the Albian unit, a constant value of δ was used. The initial model for ε was then obtained by finding a scalar that multiplies the initial model for δ that produces the best initial image. The salt was treated as isotropic, while for the pre-salt sediment we assumed values of 0.05 and 0.075 for *δ* and ε, respectively. These values were obtained through a priori knowledge about the region. Finally, a (very) smoothed version of a fast-track depth velocity model provided the initial estimate of the P-wave velocity along the symmetry axis direction, i.e. V_{P0} (Figure 3a-1). The three models for V_{P0}, *δ* and ε together with the tilted axis of symmetry provide the initial TTI model.

The tomography used was several iterations of a non-linear slope tomography, which allows updating the velocity, the anisotropy attributes and the horizons for one (global) or several layers (multi-layer) under various available constraints (e.g. Guillaume *et al*., 2008).

The sequence of tomographic updates was started with a global update of the initial V_{P0} model (Figure 3a-1) in a first attempt to determine the velocity in the Upper Cretaceous / Tertiary and Albian units. No a-priori information was used in order to let the seismic data alone drive the model updates. This first sediment update (Figure 3b-1) provided a model update that in turn was used as an initial model for a second pass of global tomographic updating, but this time using high-definition (HD) tomography (e.g. Sioni *et al.,* 2012) to provide more detail in the velocity model (Figure 3c-1). During the second HD tomography, V_{P0} was independently updated first, and *δ* and ε were subsequently jointly updated.

The resulting updated sediment velocity model allowed the ToS horizon to be interpreted. Once the ToS was obtained, a typical salt flood migration was used to interpret the BoS. Figures 3d-1 and 3d-2 show the resulting impact on the image of the BoS.

So far, the tomographic processing flow is mostly standard apart from the non-linear engine which allows performing internal iterations of tomography to get the most of the kinematic information used without remigrating the data. Typically this sequence of steps is then followed by an update of the pre-salt sediments, as in a standard layer-stripping approach (e.g. Jones *et al*., 2007). The presence, however, of structurally complex and high-velocity carbonates just above the salt, i.e. the Quissama formation, complicates the tomography. Their structural complexity makes it hard to get reliable residual-moveout (RMO) estimates for this sequence. This introduces inaccuracies in the velocity model that cause imperfect imaging of the layers below, in particular the pre-salt sediments.

To overcome this we adopt a multi-layer approach (e.g. Guillaume *et al*., 2012), where the RMO from both the Albian formation, which includes the Quissama sequence, as well as the RMO from the BoS and pre-salt reflections, are used simultaneously. In this way three distinct layers are jointly updated as well as their boundaries: the Albian formation including the Quissama sequence, and the salt

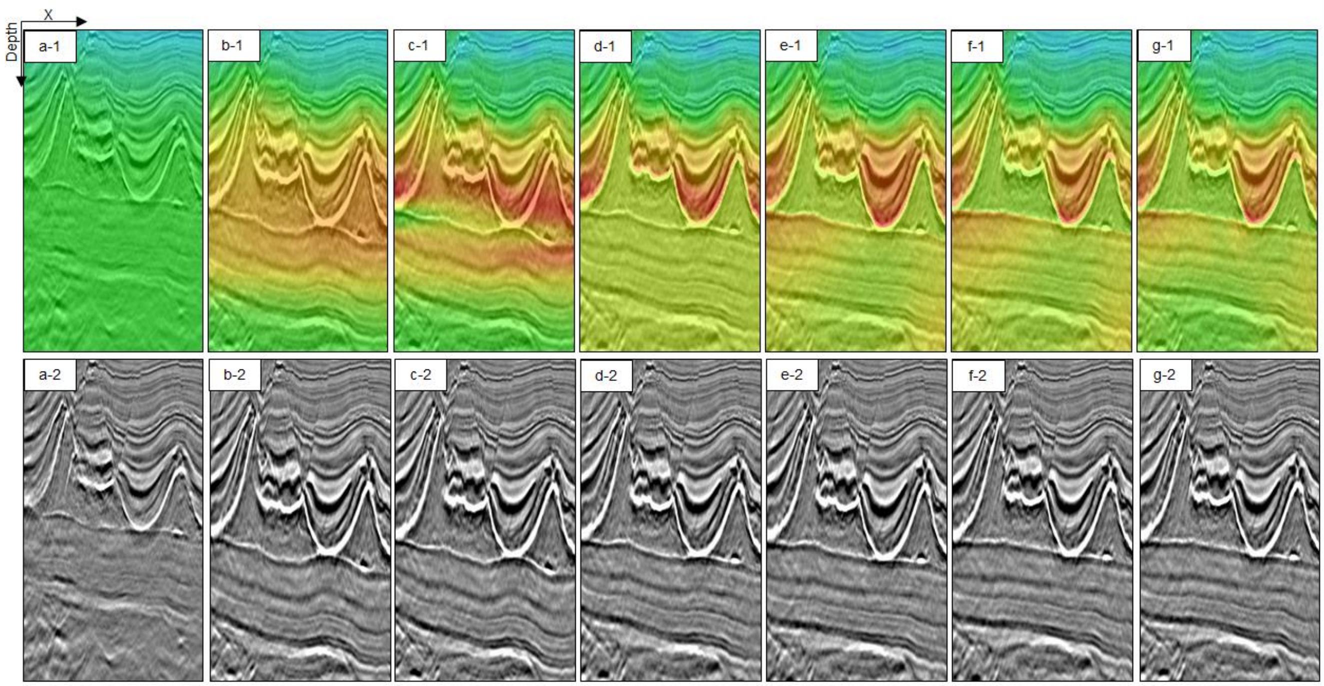

Figure 3: *Migrated stacked image (2) overlaid by its corresponding migration velocity model (1) after each step of the tomographic updating procedure: initial velocity model (a), 1st (b) and 2nd (c) post-salt sediment velocity updates, salt flood (d), multi-layer tomographic update (e), horizon-constrained update (f) and pre-salt single layer tomographic update (g).*

and pre-salt units. We thus attempt to improve the imaging in the Quissama layer by letting the tomography benefit from available and robust RMO information outside of this sequence. During this tomographic step we only update V_{P0} and leave δ and ε in the Albian unchanged. This multi-layer tomography resulted in updated horizons by zero offset map migration for the ToS and BoS. Figures 3e-1 and 3e-2 show the resulting velocity model and image. We observe a re-distribution of the high velocities in the Quissama formation, and a flatter BoS event as well as more continuous and better focused events in the pre-salt sediments. This result could not be achieved by updating each layer separately in a sequential fashion.

After the multi-layer tomographic update, in principle all the available RMO information has been used to update the velocity and the boundaries between layers. At the same time, we observe that the BoS event as well as the pre-salt reflectors contain several small scale undulations that are more likely related to remaining inaccuracies in the velocity model than to the actual geological structure (Figure 3e-2). Since all the kinematic information in the seismic data has already been used, we are left with trying to incorporate a-priori geological information into the tomography. In this way we attempt to remove the small scale variations in the image of the pre-salt sediments, caused by the inaccuracies in the velocity model of the overburden.

Horizon-constrained tomography

A deeper understanding of the Campos basin has been developed since the first well was drilled in the seventies. For instance, it is known that the BoS horizon typically has a smooth appearance without many small scale variations. This information can be used to constrain the BoS horizon to further improve the image of the pre-salt sediments.

Figure 4 shows a larger and more zoomed-in version of the image shown in Figure 3e-2 with the interpreted BoS indicated by the blue line. The smaller scale variations in the BoS can be observed. We note that such variations are typically present on the edge of the salt domes where the above-lying carbonates layers are rather thick. Removing smaller scale variations from the interpreted BoS horizon can be done by applying a local median filter to the interpreted horizon. The width of the median filter is chosen to be smaller in places closer to the margin areas and larger when on the abyssal plain. The red line in Figure 4 shows the result of applying such a median filter

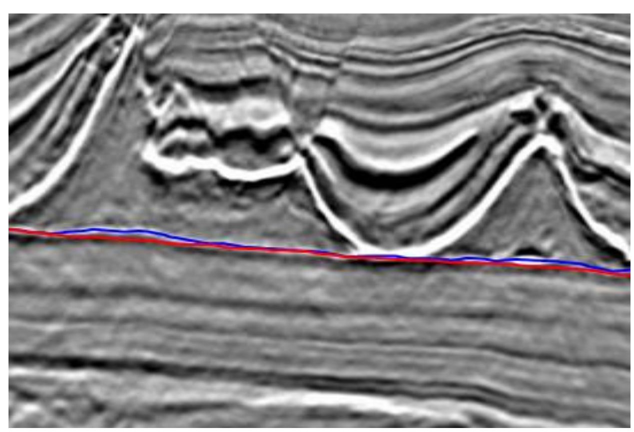

Figure 4: *Migrated and stacked image with interpreted base of salt horizon (blue) and filtered target base of salt horizon (red).*

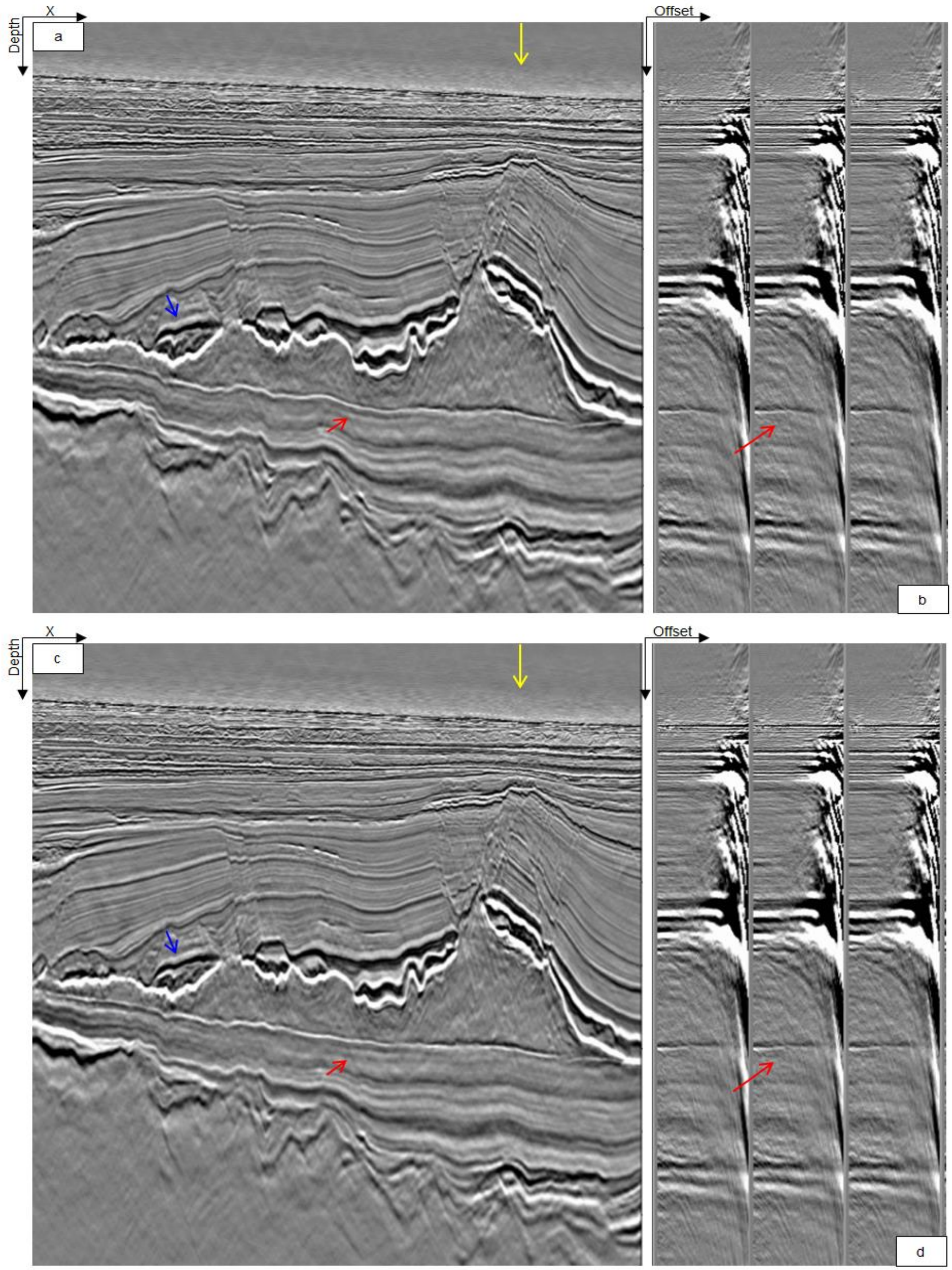

Figure 5: *Migrated stacked image and CDP gathers before (a,b) and after (c,d) horizon-constrained tomography. The yellow arrow indicates the location of the central CDP gather.*

to the original BoS event. The smaller scale variations are removed, while maintaining the global structure of the horizons defined and constrained by the previous only RMO-driven tomographic updates.

Once the BoS horizon has been filtered to satisfy the known a-priori geological information, we perform a simultaneous tomographic inversion of the RMO and the horizon mismatch to update V_{P0}. We define this step as a horizon-constrained non-linear slope tomography. Considering that the main source of inaccuracies in the velocity model is likely caused by the complex structure of the carbonates overlying the salt (i.e. the Quissama sequence), a single layer horizon-constrained tomography, where only the velocities in the Quissama sequence are updated, would be most desirable. However, the thickness of this sequence is highly varying throughout the area, ranging from one kilometer to almost zero in some areas. This could cause a tomographic update to become unstable. In order to stabilize the tomographic inversion, we therefore chose a multi-layer tomographic update where the velocities in both the Albian unit (containing the Quissama sequence) and the salt unit were simultaneously updated. Figures 3f-1 and 3f-2 show the result in the velocity model and the image, respectively. Note how the smaller scale variations in the BoS have now been removed, as expected.

Figures 5a and c show a different migrated stack from Figure 3, both before (a) and after (c) horizon-constrained tomography. Clearly this tomographic update has removed the imprint of the inaccuracies in the velocity model for the carbonates on the top BoS horizon. When looking at some CDP gathers (at the location indicated by

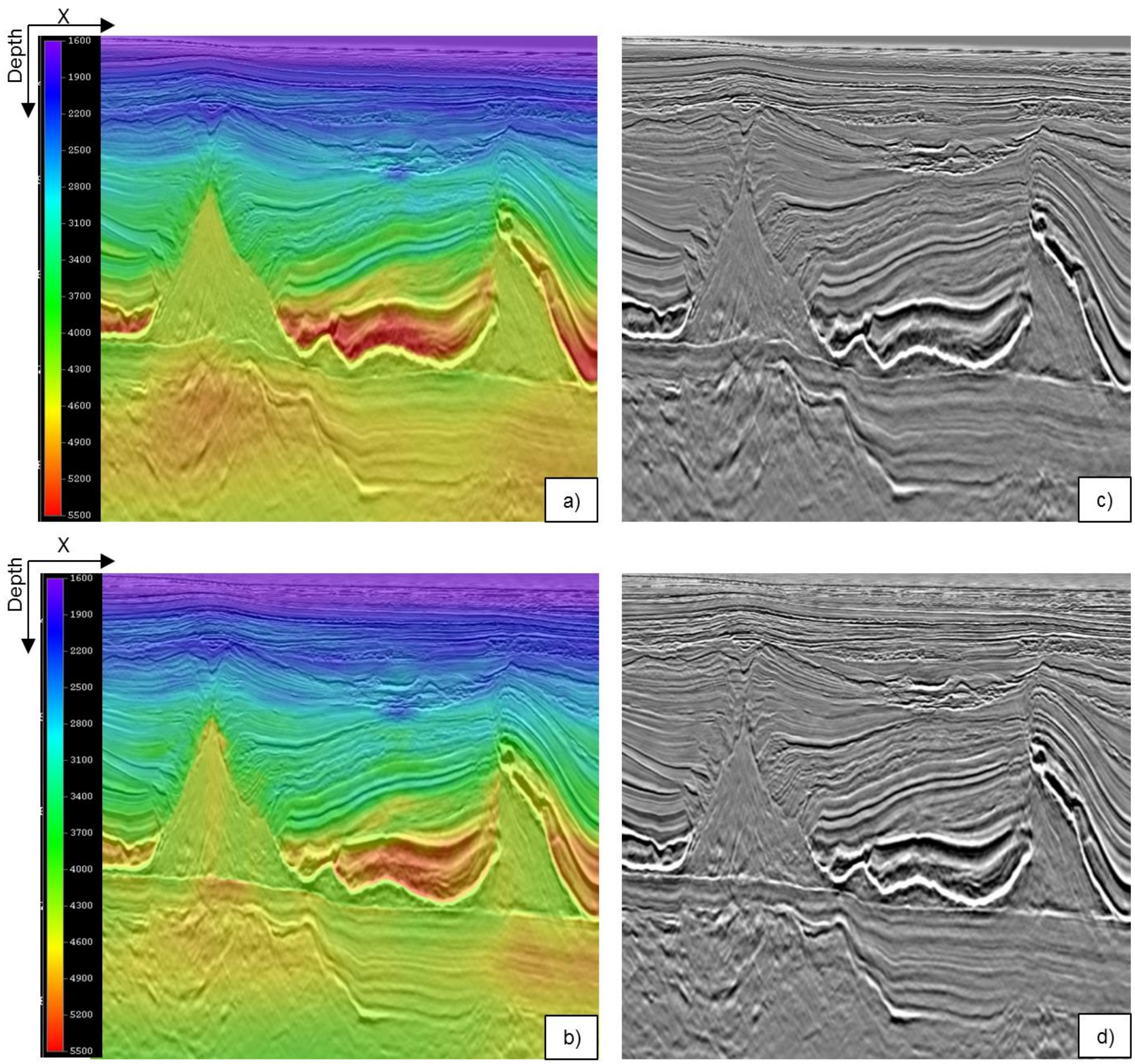

Figure 6: *Top: migrated stacked image using final TTI velocity model obtained using the reference tomographic updating sequence (a, c). Bottom: migrated stacked image using final TTI velocity model obtained using multi-layer horizon-constrained tomography (b, d).*

the yellow arrow in Figures 5a and c), we note that the horizon-constrained tomography has substantially improved the flatness of both the ToS and the BoS (indicated by the red arrow) events in the CDP gathers. Furthermore, we note that the image of the carbonates above the salt (indicated by the blue arrow) has also improved.

Finally, a single-layer tomographic update was performed for the pre-salt sediments to further refine the pre-salt velocity model and to obtain improved focusing in the deeper parts of the image (see Figures 3g-1 and 3g-2). No further attempt was made to update the anisotropic parameters δ and ε after the HD tomographic update of the sediments above the salt. It remains to be seen if a further improvement in the image quality can be obtained when the anisotropy parameters are updated once more in the Albian as well as in the pre-salt.

Impact of multi-layer and horizon constrained

To show the impact of the extra care taken to obtain an improved image for the pre-salt sediments using the multi-layer horizon-constrained tomographic updating sequence we outlined in the above, we compare our final image with an image obtained from a reference tomographic updating sequence (Figure 6) involving several iterations of a non-linear slope tomography. This sequence consists in a global tomographic update followed by a HD global tomographic update. Subsequently the ToS horizon is picked, a salt flood migration is done, and the BoS horizon is picked. Finally a single-layer tomography then updates the pre-salt sediments.

When comparing the images obtained using the reference tomographic processing sequence (Figure 6c) with that obtained using the multi-layer horizon-constrained tomographic updating procedure (Figure 6d), it is obvious that the image of the pre-salt sediments is much improved as a result of the extra effort spent in the velocity-model building. The velocity model obtained using multi-layer horizon-constrained tomography shows improved lateral velocity variations in the carbonate layer (compare figure 6a and 6b), and provides more details as well as more continuous seismic events in the image of the carbonates just above the salt. Furthermore, the image of the BoS and the pre-salt sediments strongly benefits from the improved velocity model. The BoS and the pre-salt sediment reflectors are more continuous and better focused, and overall the image of the pre-salt sediments shows more detail.

Conclusions

The complex and challenging geology of the deep water Campos's basin, and in particular the presence of structurally complex and high-velocity carbonates above the salt, make imaging of the pre-salt sediments challenging. Inaccuracies in the velocity model of these carbonates often leave an imprint on the imaged structure of the pre-salt sediments. We showed that a layer-stripping and single-layer tomographic approach to building the velocity model is not sufficient to deal with the complex geology of the post-salt sediments. Instead, a careful multi-layer and horizon-constrained tomography that incorporates a priori known geological information about the BoS, can provide an improved velocity model, in particular for the structurally complex carbonates above the salt, that provides a significant uplift in the image quality of the pre-salt sediments.

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