Iterative approach to imaging beneath volacanics: a case study in Brazil’s Santos Basin
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Summary
Brazil’s Santos and Campos basins remain areas of interest after a series of impressive pre-salt discoveries. However, the regions’ complex geology and deep pre-salt targets can create difficulties in seismic imaging. One of the largest challenges faced is imaging beneath igneous intrusives found primarily in the post-salt section. We introduce an iterative approach to updating the velocities beneath these volcanic intrusions and other shallow, post-salt structural anomalies that limit the imaging beneath the salt. We focus on the challenges of identifying the post-salt structural anomalies, and then discuss a workflow for updating the velocity model that assists us in further improving the images of pre-salt targets.

Introduction
Recent pre-salt discoveries in the Santos Basin have driven the advancement of new acquisition and processing technologies to better understand the basin and its potential fields. We have found the need for improvements to the velocity model building workflow to be a key to imaging some of the more challenging pre-salt targets. A top-down strategy to model building in the Santos Basin introduced by Huang et al. (2010) incorporates several layer-based tomography iterations, interpreting key horizons such as the Albian layer. By incorporating the layer-based tomographic approach, we see an improvement in reflections of the top of salt (TOS) and base of salt (BOS) and an improved pre-salt image in many areas. However, imaging challenges associated with volcanic intrusions limit the effectiveness of a top-down approach in more complex regions.

The survey used for this study is situated between the Santos and Campos basins in offshore Brazil. A traverse line through the survey demonstrates the difference in salt character between the two basins (Figure 1). On the left, there is a consistently flat BOS and a thick, layered salt similar to the structures found in the recent pre-salt discoveries at the Libra field in the Santos Basin. On the right side, we see a more complicated salt structure with a BOS that rapidly changes depth. In the center, at the Cabo Frio high, the most notable igneous intrusions are seen as high-amplitude reflections above salt. A more detailed example of some of the volcanic intrusions can be seen in Figure 2, indicated by the yellow arrows.

Figure 1: A traverse line through the Santos (left) and Campos (right) basins. The blue line indicates the positioning of the Cabo Frio high. There is an increase in high amplitude volcanic reflections above the top of salt (TOS) near the Cabo Frio high. Volcanic intrusions are highlighted with arrows.

Figure 2: A zoomed in image of the volcanic level highlighted with arrows. The BOS can be seen in red, with the salt model overlaid in yellow.
Volcanic intrusions can be identified by a strong change in impedance, related to the relatively fast velocity of volcanic material. In this survey, most of the volcanic intrusions have a thickness less than 50m, which adds additional challenges to velocity updates. Due to the strong change in impedance, we often see little reflectivityon the gathers between the top of volcanic material and the TOS. This lack of reflectivity limits the effectiveness of traditional tomographic solutions in this area. Our approach builds on the work of Huang et al. while incorporating a new iterative workflow for updating the post-salt volcanic model, resulting in further improvement of the pre-salt image.

**Motivation**

An initial tilted transversely isotropic (TTI) model is built using a top-down approach incorporating high-resolution tomography in the post-salt sediment area, providing additional detail to the overburden model (Guillaume et al., 2012). With this flow, we are able to accurately image the full post-salt column in most regions. By analyzing the data further, we find the velocity update above the top of volcanic intrusions to be sufficient; however, updates in regions beneath the volcanic level tend to be inconclusive. We subsequently attempt velocity scans and tomography below the volcanic intrusions, hoping to identify a clear TOS reflection and more accurately estimate the post-salt velocity. Due to the limited reflectivity below the volcanic intrusions, tomographic solutions do not work well. Initial velocity scans also give little insight into the true model (Figure 3). The lack of events below the volcanic intrusions in the post-salt region makes it extremely difficult to evaluate the scan results. Unable to accurately update the velocity using tomography and scans, we look to a new method.

**Methods**

**Iterative volcanic velocity updates**

Understanding the importance of an accurate post-salt velocity model to imaging pre-salt targets we begin searching for a new methodology in order to further understand the basin. Because the post-salt tomography and velocity scans beneath the volcanic intrusions are ineffective, we deploy an iterative approach to updating the volcanic velocities. This time, we incorporate the salt geometry interpretations into the post-salt velocity update. The first step is to build a complete salt-body velocity based on the current, most accurate post-salt velocity, knowing some regions may require further modifications. From the migrated image, areas in the pre-salt that are not well imaged can be identified. Then, a series of velocity updates are performed iteratively in these areas. With each iteration, the sediment velocity is updated in the region between the volcanic intrusion and the interpreted TOS. The salt geometry is then modified to reflect the new overburden velocity, and a migration is performed using the updated model. Finally, the images are compared against the previous iteration, focusing on the pre-salt level for evaluation. If the pre-salt image improves, the post-salt update is kept; otherwise, it is discarded, moving on to another iteration. This iterative flow requires significant interpretation effort, including iterative interpretations of the top of volcanic, TOS, and BOS. It is possible for each of the three surfaces to require some level of modification after each update. The workflow is depicted in Figure 4.

The focus of this new workflow is the iterative use of deep pre-salt images to evaluate and update shallow post-salt velocity anomalies beneath complex volcanic intrusions. Agnihotri (2013) used a similar approach focused on salt overhang interpretations in the Gulf of Mexico. In his method, approximations of the salt geometries are defined early on, and sub-salt images are used to identify areas that may require salt modification. Our method for volcanic intrusions builds on Agnihotri’s technique to include not only the salt geometry iteration, but also the velocity anomalies above salt. Also, where Agnihotri’s technique uses sub-salt focusing as a way to evaluate the impact of the update, we attempt to use the image beneath salt to help

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**Figure 3**: Velocity scans with (a) slower and (b) faster velocities beneath the volcanic layer (red). Notice the limited focusing beneath the top of volcanic intrusion down to the TOS.

**Figure 4**: A diagram of the iterative volcanic model building workflow. The majority of the velocity model building is done through a traditional top-down approach; however, problematic areas go through an iterative volcanic velocity update workflow after each update. The workflow is depicted in Figure 4.
determine the update. This change provides additional control to the updates, and allows for convergence of the velocity updates.

**Application**

*Model updates*

From a top-down flow, sediment velocity is updated by tomography and salt geometries are interpreted to generate a complete velocity model. A migration is performed and referred to as the salt body migration. By thoroughly evaluating the salt body migration, regions with poor pre-salt focusing become the focal point for future updates. Areas for potential updates are determined by pre-salt focusing, structural fidelity, and gather flatness when possible. Regions requiring modification are updated through an iterative combination of velocity scans and tomography.

After identifying the poorly focused pre-salt sections related to the volcanic intrusions, velocity scans are run to estimate the velocity error between the volcanic intrusion and the TOS. Upon determining a reasonable estimate, a subsequent migration is run to evaluate the result. After only the first iteration of velocity update significant improvements are seen in both the gathers and stacks (Figure 5). Where the previous post-salt velocity scans failed to show any significant benefit, we see that by incorporating the salt geometry, evaluation of the sediment velocity impact can be seen at the BOS and pre-salt levels. Furthermore, pre-salt focusing is improved on the gathers allowing for additional model evaluations using tomography. As the gather and stack focusing improves, additional insight into the model can be derived from the data. Previously unseen events become clear, and often times lead to modifications of previous salt body and possibly even volcanic interpretations.

With the improved understanding of the pre-salt geology provided by the first iteration of volcanic velocity updates, we find additional areas requiring more attention. These areas are identified individually for further testing and evaluation. Following the scans, a combination of structurally guided tomography and residual curvature analysis are run on the pre-salt regions in order to more accurately determine the local velocity. Structurally-guided tomography incorporates the regional geological interpretation of the BOS and the pre-salt structure to anticipate velocity errors in the post-salt. This methodology further refines the model from the previous velocity scan updates, and provides additional insight into the pre-salt resolution.

Prior to the velocity scans and structurally-guided tomography, limited gather curvature prevented any tomographic solution from fully updating below volcanic intrusions. With a model more accurately imaging the post-salt, areas that were previously incapable of updating are now able to be evaluated with tomography. Iterative tomographic updates are subsequently performed in these local regions, incorporating gather curvature from the pre-salt and re-picking the salt geometry with each update. By implementing an iterative process, including re-evaluation of the TOS, BOS, and post-salt velocities, we are able to converge to an accurate velocity model. An example of the local updates is shown in Figure 6.

**Horizon modification**

Interpretation plays a significant role in this iterative flow. Being able to effectively modify the TOS and BOS horizons for each iteration makes the iterative flow possible. Accurate salt interpretation in complicated areas normally requires a significant amount of time. In order to speed up the interpretation while preserving sufficient accuracy, two types of interpretation modifications are used.

![Figure 5](https://example.com/fig5.png)

Figure 5: Stacks and gathers are shown (a, b) before and (c, d) after the first velocity update. Notice the improved focusing on the gathers (d) after the update.

![Figure 6](https://example.com/fig6.png)

Figure 6: A stacked image with velocity overlaid (a) before and (c) after update. Notice the velocity change highlighted in red. The stack sections without velocity overlay are seen in figures b and d.

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in the flow: three-dimensional (3D) ray tracing and manual interpretations. The 3D ray tracing methodology performs a de-migration of the surface using the previous velocity model, and subsequently re-migrates the surface with the new model. This method is fast and works well for overall regional velocity changes. When the updated model has a larger velocity variation or if the updated sediment velocity provides a new understanding to the geologic structure, significant change of the previous interpretations is needed. In these cases, manual salt interpretation is required. It is slower than the 3D ray tracing, but it provides well-needed improvement and detail to the updated model. Also, the significant change of the salt interpretation itself can reflect the improvement of the updated velocity model.

With the added benefit of the iterative post-salt velocity updates, we see improvements in the latest model. Figure 6 compares Kirchhoff migrations with the initial model and the latest TTI velocity model. A more geologically consistent structure can be seen at the BOS and pre-salt levels, marked by a simpler structure and better-focused image. This new approach to post-salt velocity updates provides an improved understanding of the regional geology in the Santos Basin and more focused images in a complex environment.

Conclusions

Conventional top-down approaches to model building may not be sufficient in regions with shallow complex velocity anomalies when searching for such deep pre-salt targets. With this improved method, we are able to create a geologically-constrained velocity model that provides an enhanced migrated image and better-focused gathers.

By incorporating the salt geometry along with deep pre-salt reflections, it is possible to generate a more accurate post-salt velocity model beneath velocity anomalies related to volcanic intrusions. With this new iterative approach to sub-volcanic velocity updates we see the potential for more accurate TOS and BOS interpretation, as well as improved pre-salt imaging.

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![Figure 6: An image of the (a) stack line and (b) depth slice of the original model compared against the update TTI velocity model (c,d). The red line in the depth slice shows the location of the corresponding stack line. From the stack image it is clear to see the improvement in the pre-salt focusing. The depth slice shows an increase in continuity at the pre-salt targets highlighted in yellow.](image-url)
EDITED REFERENCES
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