3D Velocity Model Building of Búzios oil field – improvements and updates

David Fraga Freitas[1], Raissa Siqueira[1], Marco Cetale[1], Maria González[2], Djalma Manoel Soares Filho. [3]
1-UFF/DOT/GISIS. 2-AspenTech. 3-Petrobras

Abstract

Improvements of migrated seismic images and more realistic seismic modeling from Brazilian pre-salt oil fields are still a challenge for industry and academy. Both quality of final seismic images and seismic modeling results are strongly dependent on the velocity model used as input in the migration process for the first case and for modeling wave propagation in the second one. In the Brazilian pre-salt oil fields, the reservoirs are commonly located in regions of thick and complex sedimentary packages which cause important scattering and severe attenuation of seismic signal. To improve seismic images, inversions and seismic modeling results from these areas, a more complex and detailed model of properties (e.g., V_p, V_s, ρ) is needed. This work exposes the updates and advances in the 3D velocity model building (V_p and V_s) of Búzios oil field carried out by Seismic Inversion and Imaging Group (GISIS) from Fluminense Federal University (UFF).

Introduction

The high geological complexity and significant sediment heterogeneities of the Brazilian pre-salt oil fields turn the task of producing high quality seismic images or performing realistic seismic modeling into remarkable challenges. In these oil fields, the reservoirs are commonly located in regions of thick and complex sedimentary packages which cause important scattering and severe attenuation of seismic signal (Freitas et al., 2021). In this sense, both quality of final seismic images and seismic modeling results are strongly dependent on the velocity model used as input.

The way how models are built can significantly affect the quality of the image migration, seismic simulations and their results. Improperly constructed models for the intended purposes, may fail to provide the expected results, simulate the seismic wave trajectory different from the real medium or even result in unnecessary effort. According to Fagin (1991), to avoid these problems, the following questions must be addressed to build velocity models:

• Should the model be two-dimensional (2D) or three-dimensional (3D)?

• What dimensions should the model have?

• Which and how many surfaces should the model contain?

• Where should the interval velocity be obtained? And the interval speeds, should they vary laterally or vertically between surfaces?

• What level of structural detail should be portrayed in the model?

The answers to these questions depend on how they affect the main objectives of seismic imaging or seismic modeling: wave path simulation, energy partitioning, attenuation, and resulting signal amplitudes. For imaging complex subsurface media, depth migration techniques are recommended as they honor the refraction caused by lateral velocity variations. However, to employ a depth migration to correctly deal with ray bending the velocity field of the subsurface must be estimated, so that the depth migration can deal appropriately with ray paths (Jones, 2010).

Interpreters must assess whether a particular structural problem can be studied more efficiently in two or three dimensions. The advantage of 2D studies is related to less effort to build the model and less computational cost, since 2D models demand significantly less memory and processing capacity. In this way, 2D models can be useful to evaluate simpler problems or even be used to make a preliminary study of more complex problems faster. While a 2D modeling project can be completed in a few days, a 3D modeling project can take several weeks (FAGIN, 1991) or even months to complete. However, 2D models must be used with caution and the evaluation of the results must be done in a qualitative way, especially in environments with high structural complexity. Skilled geologists know how to translate 3D to 2D and vice versa, but no matter how experienced someone can be, this mental translation is qualitative, therefore imprecise and sometimes incorrect (CAUMON et al., 2009). The seismic wave trajectory, the energy partition (e.g. transformation of P waves into S and S into P) and the amplitude of the recorded signal can present significant distortions compared to those obtained through real 3D geometry. For example, Karsou et al. (2019) built a 2D conceptual P-wave velocity model of Búzios field to be used for migration and inversion algorithms tests. Despite the model presents velocity ranges similar to what is observed in the real medium, due to the velocity values have been directly extrapolated from well logs in few interfaces (6 horizons), some features geometries are significantly different from that observed in the seismic data, mainly with respect the stratified salt and pre-salt layers and layers truncation caused by faults.

To overcome the 2D limitations described, it is necessary to use 3D models. In order to build more realistic 3D geological models, whose property volumes represent the various sedimentary layers that form a given exploratory field, it is necessary to understand the geotectonic and sedimentary context of the studied area, as well as to use geological and geophysical data from different available scales, such as composite profiles, well logs, seismic data and velocity models.

Initially, it is relevant to study the main geotectonic and sedimentary processes that formed the sedimentary basin where the exploratory field is located, to understand the regional structural framework of the basin, as well as the composition, arrangement and geometry of sedimentary layers and underlying basement. This knowledge is very useful for the correct interpretation of the tops and bases of the formations observed in the seismic data and well logs, better understanding of the petroleum system and better characterization of the reservoir, besides helping to eliminate possible ambiguities of interpretation.

The use of data at different scales, in turn, helps to reduce the limitations that each data type presents separately. For example, although seismic data cover large lateral distribution in three dimensions, reach great depths in the subsurface, and provide structural imaging of the area of interest, it presents vertical resolution relatively low and, consequently, uncertainties in the depth of the layers represented by the seismic horizons. Well logs, in turn, provide data related to petrophysical properties of rocks with very high vertical resolution and accurate depth record, but these data are restricted to the location of the well, that is, to one dimension (1D)

In this way, the present work uses the most advantageous characteristics of each data type described above to build more accurate and representative V_p and V_s models of Búzios oil field, which could be used for both seismic modeling and image migration. From the seismic data, the 3D structural model and initial property cubes with low resolution are obtained. Well data are used to mitigate uncertainties in the position of formations by correlating seismic events to geological markers (top and base of formations) identified in the wells, using synthetic seismograms and time-depth tables obtained from checkshots (or VSP data). Additionally, well log data are used to populate the structural model created by the seismic interpretation, composed of several horizons and faults, with an average of measured velocity values for each layer. So, the properties of well logs can be criteriously extrapolated, guided by horizons and faults, in the 3D structural model. Finally, a more finely stratified model is obtained by introducing velocity variations related to seismic amplitude values through a mathematical approximation.

Búzios oil field

The Búzios field is located in the central part of Santos Basin and was discovered in 2010. It is the largest deep water oil field in the world and today is the second most productive oil field of the Brazilian Pre-Salt play. The field is located approximately 200 km far from the coast of the Rio de Janeiro State, covers an area of 852.2 km² and lays under approximately 2000 m of water column.

The Santos Basin is located at the southeastern Brazilian margin and is one of the basins that were created during the breakup of the paleocontinent Gondwana. It is bounded by the Campos Basin at the North, and the Pelotas Basin at the South. This basin is one of the most extensive offshore Brazilian basins, with an area of 352,000 km², and a current water depth of up to 3,000 m, with sediment thicknesses greater than 10 km in the main depocenters (Chang et al., 2008). It is limited by the Cabo Frio High to the Northeast, the Florianópolis Platform to the Southwest, and by the Santos hinge line to the west, which restrains the limit of the salt - Ariri Formation (Fm.).

The most used tectonostratigraphic division in the Santos Basin is threefold: Rift, Post-rift and Drift (Moreira et al, 2007). The Rift phase shows extension efforts of separation between the South American and African plates and subsequent opening of the South Atlantic Ocean (White and Mckenzie, 1989).

The rift mega-sequence is composed by the Camboriú, Piçarras and Itapema Formations (Fm.), in the initial stage of rifting the basin was affected by an intense period of volcanism, growth faulting and subsequent sedimentary infill of the newly formed sedimentary basin. This first volcanism corresponds to the Camboriú Fm. (Valanginian-Hauterivian) which is the economic basement of the basin (Buckley et al., 2015). In order, the Piçarras Fm. (Barremian) corresponds to the source rock of Pre-Salt play (Moreira et al., 2007).

The reservoirs of the Pre-Salt play were formed during the rift and post-rift stages, respectively, and are characterized by carbonate deposits of two main types: Coquinas from Itapema Fm. (Barremian-Aptian) and microbial limestones from Barra Velha Fm. (Aptian) (Moreira et al. 2007). In the Búzios field these reservoirs reach depths between 5500-6000 m. Above the reservoirs a thick salt layer was deposited during the final stage of the post-rift phase. It was the Ariri Fm (Aptian), which was deformed as domes of complex geometries that can reach more than 2000 m of thickness (Freitas et al., 2021). This sequence is mainly composed of halite, and intercalations of anhydrite, tachyhydrite and carnallite can be found and turns more present in regions where the salt is more stratified.

After the sedimentation of the salt layer finishes, the drift phase starts, which is a typical marine sequence varying from coastal, shelf, slope and deep sedimentation. In the Albian, there is a mixed sedimentation from siliciclastics rocks to marine carbonates. Along the drift mega-sequence there is an intercalation between sandstones, shales, marls and carbonates.

Methodology

The methodology used in this work for 3D velocity model building is composed by the following steps:

1. Well logs QC and well-seismic tie
2. Seismic interpretation
3. 3D Structural Model Building
4. 3D Velocity Model Building

The dataset used to build the Búzios field 3D velocity model includes: one Pre-Stack Depth Migrated (PSDM) seismic volume, one interval velocity model and nine wells. The data set was provided by the National Petroleum Agency Database (BDEP – ANP). The PSDM volume was migrated by Kirchhoff technique using the interval velocity volume mentioned above (Figure 1). A more detailed description of each method step is described below. All the process of QC, interpretation and building of the models were made on Emerson/Paradigm software.

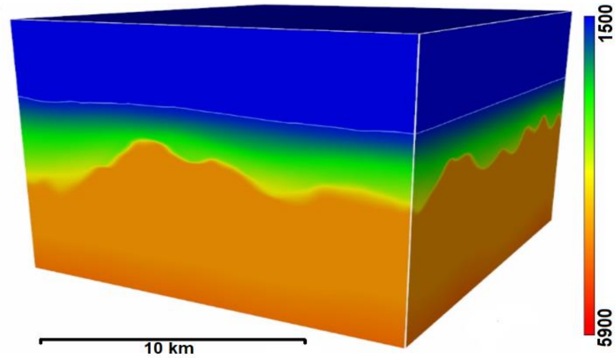

Figure 1: Interval velocity model used to depth-migrate the PSDM seismic data provided by ANP.

Well logs QC and well-seismic tie

The technique widely known as well-seismic tie is used to reduce possible errors in the position of the events in the seismic image - which lead to errors in the velocity model values - and to establish the link between seismic events and the lithologies which generated them. To achieve that, it performs the correlation of these seismic events to the corresponding geological markers (top and bottom of the formations) identified in the wells using synthetic seismograms obtained from well logs (commonly slowness and density logs) and time-depth tables obtained from checkshots (or VSP data) (Figure 2).

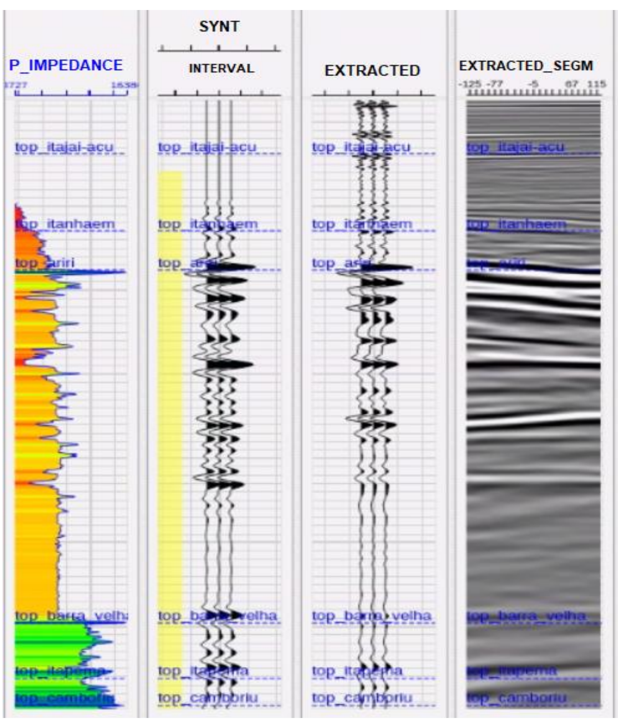

Figure 2: Example of well-seismic tie window. Note as the position of seismic events in the synthetic seismogram (SYNT) match with the events found in the extracted seismic trace.

As well logs and seismic data show significant differences in terms of scale, recording method, type of information recorded and data sampling rate, the synthetic seismogram acts as a link between the high frequency well data and the low frequency seismic data.

Seismic interpretation

After the correct identification and positioning of seismic events using the well-seismic tie technique, the seismic interpretation is performed. The interpreted horizons and faults are used to form the compartments of the structural model that will be filled with different physical properties (e.g., P-wave velocity V_p, S-wave velocity V_s, density ρ). In this work was interpreted eight horizons (Figure 3):

• Five horizons at the post-salt, including the seabed;

• Two horizons as top and bottom of the salt;

• One horizon at the pre-salt.

These horizons were interpreted in an interval of 32 x 32 inlines/crosslines. The interpreted horizons (Figure 3), are identified from the top to the bottom as: 1) Sea bottom (top of Marambaia Fm.), 2) Post-salt1 (Fm. still not identified), 3) Post-salt2 (Fm. still not identified), 4) top of Itajaí-Açu Fm., 5) Top of Itanhaem Fm. 6) Salt top, 7) Salt base and 8) Top of Itapema Fm. All the horizons were interpreted over strong reflectors, what is an indication of interfaces which separate important properties contrasts.

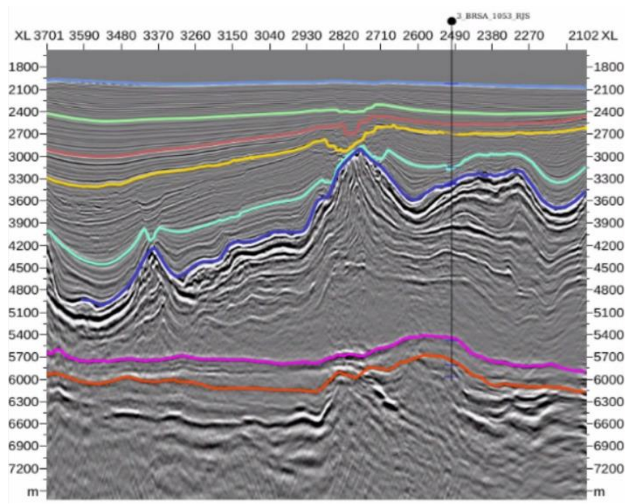

Figure 3: PSDM seismic cross section with the eight interpreted horizons used to obtain the surfaces of the 3D structural model.

Due to the immense number of faults identified in the seismic data, it was necessary to create some criteria to select the first faults to be interpreted. In this phase, only post-salt faults that present heaves large enough to impact in the layer truncation were interpreted. 53 faults have been interpreted with a spacing of 32 lines between each fault segment (Figure 4). These fault segments are triangulated posteriorly to create fault planes.

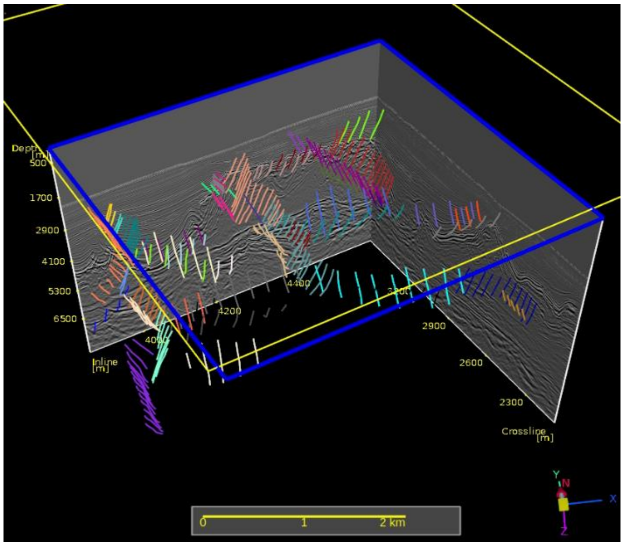

Figure 4: Interpreted fault segments used to build the fault planes. Segments with the same color corresponds to the same fault plane.

3D Structural Model Building

The 3D structural model was built in the software Skua-Gocad, using 8 horizons and 53 fault planes interpreted in the PSDM seismic data. The horizons are grided and the fault segments are triangulated to obtain continuous surfaces which will form the model compartment interfaces. A stratigraphic column is defined and works as a constraint to establish the relationships among the different geological units (conformable, baselap or eroded). The geological markers identified in the wells are used to make a QC of interfaces positioning.

It is important to observe that we find large changes in layers thickness in this area, sometimes varying from about 2000 m to zero. Truncations of horizons due to unconformities are often observed. These characteristics, added to the large number of faults, turn the structural model building a difficult procedure. For example, horizons may cross each other after gridding in the areas where the layer separating these horizons are very thin. Horizons-fault boundaries may present grid artifacts if the correct grid sample size is not well defined. These issues are solved by software tools or by manual interpreters editions.

Thus, additional edition of horizons surfaces and fault planes are needed in this step to perform the correct compartmentalization of the 3D geological model and allow the filling of the compartments with physical properties without errors.

3D Velocity Model Building

The building of the 3D velocity model starts with the filling of each 3D structural model compartment with the respective interval P-wave velocity. To obtain velocity values for each layer we first calculate the average interval velocity of each layer using P-wave slowness logs available in the wells. Then, the interval velocity volume obtained is used as reference to calculate velocity variations based on the amplitude values variations observed in the PSDM seismic volume, through the following relations:

$$V_p = V_p^0 + V_p^0(b.A) \qquad A \geq cutoff^+$$

$$V_p = V_p^0 + V_p^0(-b.A) \qquad A \leq cutoff^-$$

$$V_p = V_p^0 \qquad cutoff^- \leq A \leq cutoff^+$$

Where V_p is the final interval P-wave velocity, V_p^0 is the initial interval P-wave velocity built with the average interval velocity of each layer using P-wave slowness logs, A is the seismic amplitude and b is a multiplier factor that controls the magnitude of velocity variations and present different values for each layer. $cutoff^+$ and $cutoff^-$ are, respectively, the positive and negative amplitude cutoffs from which the conditions are valid.

The S-wave velocity model, in turn, was built using an approximation assuming that $V_s = 0{,}45V_p$.

Results

The structural model used to construct the velocity models is composed by 8 horizons and 53 fault plans (Figure 5). Observe how the interpretations satisfactorily represents the very structured and complex framework of the studied area. The compartments of this structural model have been filled with velocity values calculated as described in the previous section.

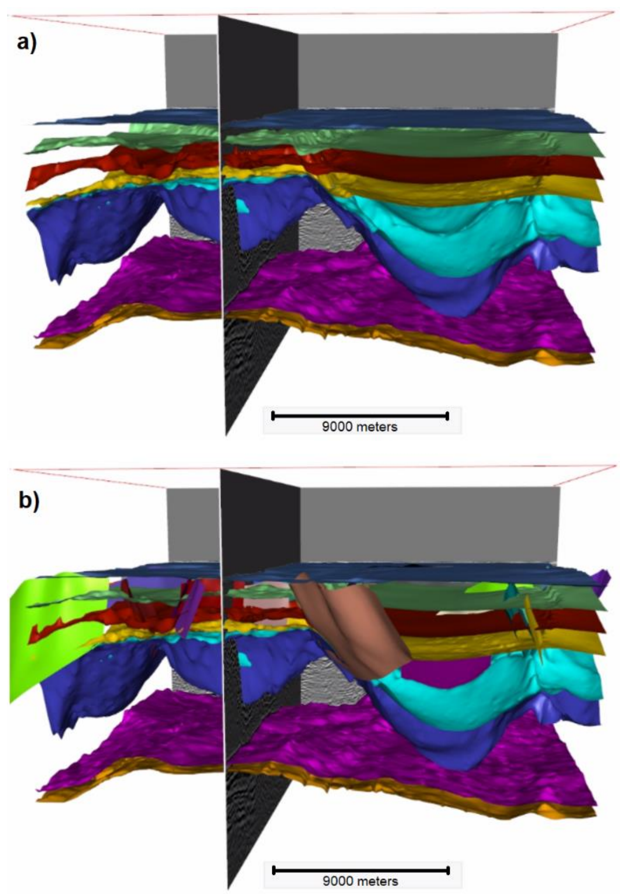

Figure 5: 3D structural model used to build the velocity models: a) Structural model with horizons only and b) Structural model with horizons and faults.

The 3D P-wave interval velocity model built following the methodology described above is illustrated in the Figure 6b. In the specific case of the models presented in the results of this work, the mathematical relations described above were used to calculate maximum and minimum interval P-velocities for each layer related, respectively, to maximum and minimum amplitude values observed in each layer. This was made to avoid velocity gradients and obtain interfaces with abrupt velocity variations for seismic modeling proposes. Note as the final model presents a larger number of layers if compared with the initial model (Figure 6a). Also, these additional thinner layers show a complex geometry that follows the seismic stratigraphy observed in the PSDM seismic data (Figure 6c). The velocity variation range observed in each layer match with the velocity values commonly measured by well logs for the respective formations.

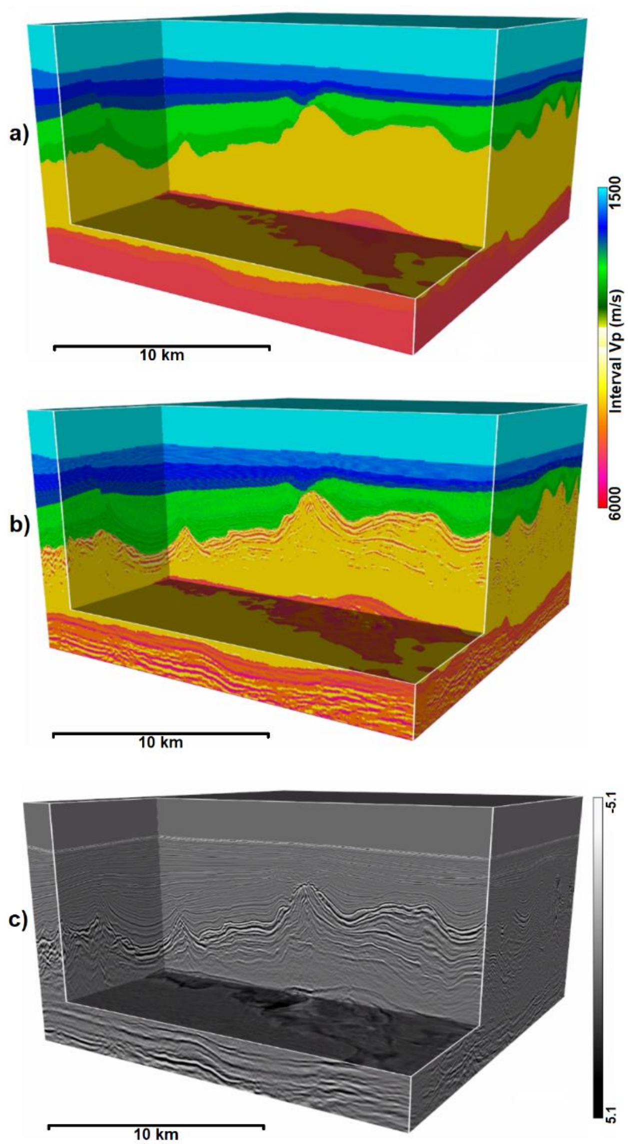

Figure 6: Interval V_p models compared with the PSDM seismic volume: a) intermediate interval $\mathbf{V_p}$ model obtained with the 3D structural model filled with average interval V_p calculated from well logs; b) final interval V_p model and; c) PSDM seismic data.

For example, V_p > 5000 m/s in the salt layer represents anhydrite layers and V_p close to 3500 m/s corresponds to tachyhydrite and carnallite layers.

In a similar way, the 3D interval S-wave velocity model (Figure 7) obtained from the P-wave velocity model shows velocity stratifications of complex geometry that follows the seismic stratigraphy observed in the seismic data.

In general, the thinner velocity stratifications of the V_p and V_s final models (Figure 6b and 7) demonstrates excellent correlation with the seismic reflections observed in the PSDM seismic volume (Figure 6c). The results shows that the mathematical relations used to approximate high frequency velocity variations based on amplitude values recorded in the PSDM seismic volume provides representative velocity values.

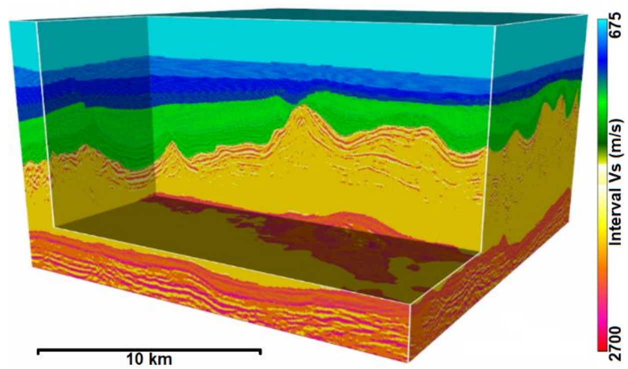

Figure 7: Final 3D interval V_s model obtained from the 3D Interval V_p model using the approximation $V_s = 0{,}45V_p$.

Conclusion

The results indicate that the mathematical relations used to approximate high frequency P-wave velocity variations, based on amplitude values recorded in the PSDM seismic volume, provides representative velocity values compared with that measured in the real medium. However, to improve the fidelity of the velocity models, cutoff values need to be refined. Moreover, additional horizons and faults may be interpreted to increase the model detail and improve the compartmentalization.

The stratified velocity models can be efficiently used to perform both depth migration and seismic modeling. In the case of seismic velocity modeling, it is expected that the resultant synthetic seismograms show similar reflections if compared to the real data, what is impossible to achieve with the smoothed interval V_p model used for migrating the seismic data (Figure 1), as the last does not present defined velocity stratifications.

The 3D structural model constructed in this work is also being used to build models of other physical properties as ρ, Q_p and Q_s to feed viscoelastic seismic modeling programs.

Acknowledgments

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