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Carbonate dry rock modeling for time-lapse seismic integration with reservoir simulation models

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Abstract Summary

Integrating time-lapse data with reservoir simulation models is crucial for effective reservoir management and monitoring. 4D seismic aids model updates via history matching or data assimilation, while reservoir models enhance 4D seismic interpretation and feasibility studies. This integration often requires petro-elastic modeling. However, modeling dry rock properties (bulk and shear modulus) presents particular challenges in carbonate reservoirs due to their complex pore system. This study compares dry rock properties modeling approaches using a commonly used inclusion model versus a simplified data-driven proxy model. Both approaches yield satisfactory calibration with well-log data, and in this study, we demonstrate the impact of incorporating them into 3D/4D modeling using numerical reservoir models. The analysis is based on an ensemble of simulation models from the carbonate Tupi field focusing on Barra Velha Formation (BVE). We assess each approach's applicability and compare the errors between them. We also investigate the alignment between both approaches using acoustic impedance difference (∆IP) maps for the entire ensemble. The strong agreement between maps within a key zone of interest in the BVE formation supports the feasibility, simplicity, and practicality of the proxy approach for integrating time-lapse seismic data with reservoir engineering workflows.

Introduction

Time-lapse seismic (4D seismic) data can provide meaningful impact in reservoir management and monitoring. The possibility of tracking fluid and pressure changes related to 4D seismic signals may allow one to better understand the dynamic reservoir behavior. Reservoir simulation models and 4D seismic data are strongly interconnected. While 4D seismic provides valuable information for updating reservoir models through history matching or data assimilation, dynamic reservoir models, in turn, can support the interpretation of 4D seismic data and contribute to 4D feasibility studies. In all situations a petro-elastic model (PEM) is required to bridge the two domains, seismic and reservoir simulation. PEM can be divided into three key components: rock matrix model, dry rock model, and fluid model. Each of these components must be clearly defined within the modeling process. These components are integrated using the Gassmann fluid substitution equation, which enables the estimation of saturated moduli and density. Subsequently, seismic velocities and impedances can be estimated. Dry rock framework is responsible for a challenging part of this modeling. Defining the porous types and characteristics of the reservoir can be a complex task, especially for carbonate rocks (Danaei et al., 2025). In this regard, inclusion methods are commonly used to define this framework in carbonates. However, to attain the complexity of the problem these theoretical methods also present extensive and intricate formulations. Aiming to simplify this, data-driven proxy approaches were proposed. Emerick et al. (2007) and Danaei et al. (2025) are some examples. For practical uses, these proxy models can simplify the dry rock modeling in one equation where its coefficients must be calibrated.

This study aims to compare different dry rock modeling approaches, similar to the framework presented by Danaei et al. (2025). They compared inclusion and proxy models for 1D dry rock modeling using well-log data, both approaches yield satisfactory calibration with the measured well-log data. Here, we utilized reservoir simulation models for 3D/4D modeling and comparison. Applying the PEM in 3D models has limitations, mainly due to the lack of knowledge on properties such as porous aspect ratio, for instance. As an alternative, we used a proxy model based solely on porosity, which simplifies the process but may reduce accuracy by neglecting other relevant parameters. Moreover, since the results of these approaches are intended for use in data assimilation workflows, we also evaluated whether the final PEM products used for comparison, e.g., ΔIP maps, remain consistent or show significant differences depending on the dry rock modeling approach. The methodology was applied to a prior ensemble of 200 reservoir simulation models generated for the pilot area of the Tupi field. Our investigation was focused on the Barra Velha (BVE) formation (divided into BVE100, BVE200, and BVE300 zones), specifically in the BVE100 zone, where most of the 4D anomalies are identified.

Methodology

Building on the definition of petro-elastic modeling by Danaei et al. (2025) and their inclusion/proxy models for the dry rock framework, we conducted similar modeling with adjustments tailored to the application of PEM in reservoir simulation models. The key distinction in our approach lies in the incorporation of effective pressure for impedance estimations in dry rock modeling. However, the primary focus of this study is on the dry rock framework itself. Accordingly, we present a concise overview of the inclusion and proxy models employed in this study. The inclusion model consists in an approximation of Kuster-Toksöz equations for bulk and shear moduli. Two pore types were considered: stiff and compliant. Dry bulk and shear modulus (K_{dry} and μ_{dry}, respectively) were estimated from:

$$K_{dry}(\phi) = K_0(1-\phi)^P, \tag{1}$$
$$\mu_{dry}(\phi) = \mu_0(1-\phi)^Q. \tag{2}$$

Where dry bulk and shear modulus are in function of the porosity (ϕ), K_0 and μ_0 are rock matrix bulk and shear modulus, and P and Q are defined based on pore aspect ratio functions ($T_{iijj}$and F) and fractions of compliant and stiff pores. The extensive formulation of this approach comes from the estimation of T_{iijj} and F, where many parameters should be calculated previously for each pore type. For more details of these formulations see Keys and Xu (2002). Conversely, the proxy model used consists in the equation:

$$M_{dry} = a\exp(b\,\phi). \tag{3}$$

Where M stands for K (bulk) or μ (shear). The coefficients *a* and *b* should be calibrated for each reservoir zone based on well-log data, according to Danaei et al. (2025) steps. Thus, by performing the modeling using both approaches, we compared the results for dry moduli based on the errors between inclusion and proxy models. The errors were defined separately for each BVE zone. After that we evaluated the errors for the ΔIP in the two methods used. This was performed for one simulation model of the ensemble. Lastly, we assessed the feasibility of using the map approach of impedance difference for proxy in data assimilation procedures. We compared the similarity of both approaches using different metrics. This last investigation was performed to the entire ensemble of models.

Results

This section presents the key results from the dry rock modeling analysis. Figure 1 shows the distribution of error for K_{dry} and μ_{dry} for each BVE zone. These plots are for one model of the ensemble. The highest deviation is observed at BVE200. This is coherent with the observation of Danaei et al. (2025), as they noted that due to the high heterogeneity in this zone, when compared to the others, the proxy tends to present more significant deviations. For BVE100 and BVE300 the results present smaller errors (mean errors of 3.16% and 4.94% for bulk; mean errors of 9.17% and 11.52% for shear) than BVE200 (mean errors of 23.19% for bulk and 20.16% for shear). Therefore, the results for shear presented higher errors than bulk at BVE100 and BVE300; and smaller errors than bulk at BVE200. BVE100, the region of most interest due to 4D signatures related to dynamic changes, displays the best agreements in all contexts. It is noteworthy that the spikes at BVE200 data are related to very small porosities that were defined in the simulation models at this region.

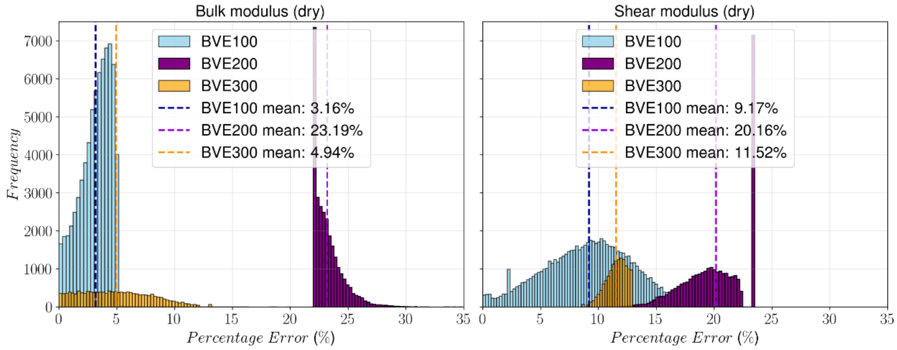

Figure 1: K_{dry} and μ_{dry} distribution of percentage errors across each BVE zone.

Figure 2 shows the average ΔIP map of the Upper BVE100 zone for each method of dry rock model applied. Using absolute errors (in $kPa.s/m$), we note that the mean error is 0.58, with maximum around 7~10 in few places. The actual data for ΔIP maps vary from -200 to 200. Qualitatively, we observe a high similarity between the average ΔIP maps for both approaches. This indicates that even though there are errors, its impact is not significant in the result to be used in data assimilation, for example.

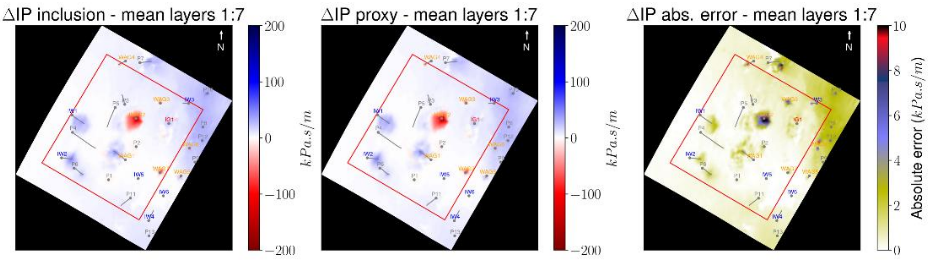

Figure 2: Average ΔIP ($kPa.s/m$) maps generated using inclusion model (left) and proxy (middle). On the right, the absolute error between them. All maps refer to the upper BVE100 interval. The red rectangles indicate Tupi pilot area.

Figure 3 extends this analysis for the 200 models of the ensemble indicated by different metrics, the Pearson Correlation, R^2, RMSE (root mean square error) and MAE (mean absolute error) between the two PEM formulations (inclusion and proxy models). From boxplots for Pearson correlation and R^2 we note the distribution entirely above 0.95, indicating almost perfect match. The RMSE and MAE boxplots reveal low values, and the variability across models is small, meaning the predictions are stable and reliable. A small number of models exhibit slightly higher error values. However, deviations are not substantial. To enhance confidence in the results, Figure 4 presents one of the worst-performing models from the ensemble metrics analysis (R^2=0.960). The same considerations discussed for Figure 2 apply here. Moreover, only an area in the northeast shows a broader region with higher errors (errors around 5 to 6 $kPa.s/m$), but these do not significantly affect the overall similarity of the maps.

Conclusions

This study evaluated the applicability in reservoir simulation models of a proxy model for dry rock modeling within PEM, comparing it to an inclusion model. In the zone of major interest (BVE100), the proxy approach demonstrated mean percentage error values of 3.16% for K_{dry} and 9.17% for μ_{dry}, i.e., excellent to good agreements with the inclusion model. From ΔIP maps comparison of one reservoir model, we observed that the impact between dry rock approaches is minimal, as the mean absolute error between the two results is around 0.58 $kPa.s/m$. This is significantly small considering a data range where anomalies vary from approximately -200 to 200 $kPa.s/m$, reinforcing the reliability of each approach. Additionally, we assessed the consistency between the two methods in generating impedance results, specifically ∆IP maps of upper BVE100 interval for the entire ensemble. Pearson correlation and R^2 displays a boxplot distribution entirely above 0.95, revealing a high degree of similarity between the maps generated by both approaches. Given the inherent uncertainties in reservoir characterization and modeling, using a proxy represents a simpler and more practical approach, particularly in comparison to estimating aspect ratios of porous types across the reservoir. Moreover, this strategy facilitates integration with reservoir engineering, supporting a more cohesive interdisciplinary analysis.

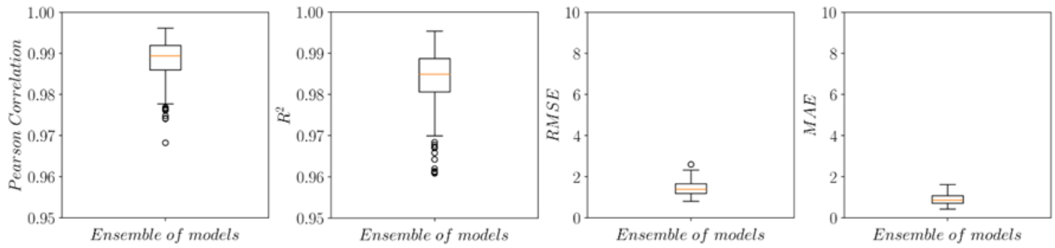

Figure 3: Boxplots for Pearson correlation, R^2, RMSE, and MAE. Consider average ∆IP maps between both approaches for dry rock model. The entire ensemble of models was used.

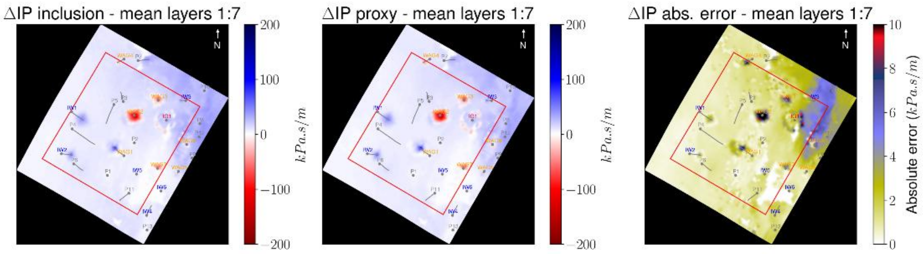

Figure 4: Average ∆IP ($kPa.s/m$) maps generated using inclusion model (left) and proxy (middle) for one of the worst models based on the metrics of Figure 3. On the right, the absolute error between them. All maps refer to the upper BVE100 interval. The red rectangles indicate Tupi pilot area.

Acknowledgments

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