Comparing deterministic and stochastic seismic inversion for thin-bed reservoir characterization in a turbidite synthetic reference model of Campos Basin, Brazil

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The inversion of seismic data for acoustic impedance is a frequently used technique because it offers several advantages:

- It facilitates integrated interpretation.
- Stochastic inversion can improve the data's vertical resolution, allowing subseismic features to be more precisely mapped.
- It optimizes the correlation between seismic and petrophysical proprieties of the reservoir.

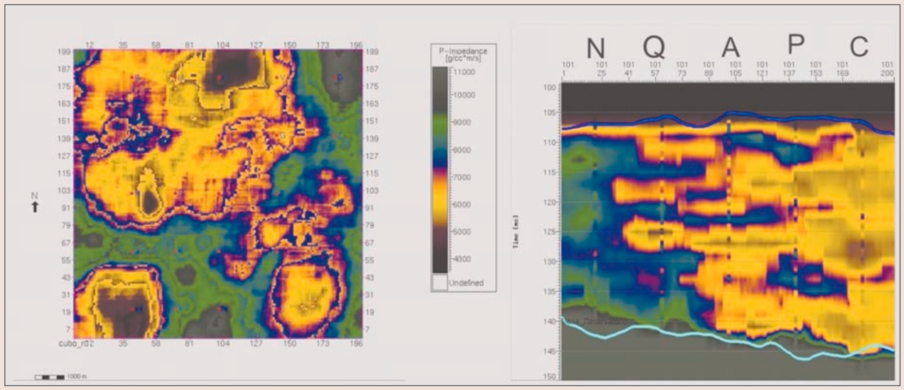

Figure 1. (left) Average acoustic map in the reservoir interval. (right) The section in the central portion of the impedance model between wells N, Q, A, P, and C.

Since acoustic impedance is obtained by multiplying density and the compressional velocity, it can be defined as a layer property and not as an interface property. This means that acoustic impedance can be easily related to porosity, lithology, net pay, and permeability and, as a result, can be the basis for models of reservoir properties. These models are very useful in estimating the volume of oil in place and can also be used during flow simulation, when the decisions about the location of the wells and the development of production strategies are made.

Seismic inversion techniques can be classified into two groups: deterministic methods that generate a single acoustic impedance model and stochastic methods that result in multiple equally probable models.

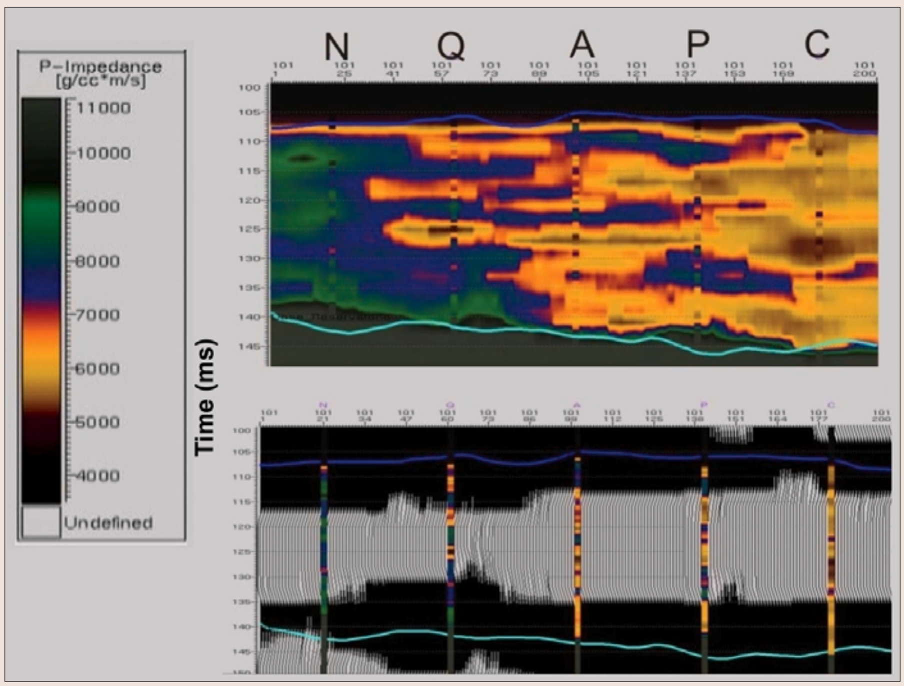

Figure 2. (top) The impedance section and (bottom) the seismic section between wells N, Q, A, P, and C.

Understanding the differences between these methods, their restrictions, and parameterizations is important to their correct application and interpretation. This article compares results obtained by a deterministic method and by a stochastic method to characterize heterogeneities and to calculate net pay in a synthetic reference reservoir model that is representative of Campos Basin turbiditic reservoirs.

The reference model. The reference model has three main parts: (1) geometry, (2) petrophysical proprieties, and (3) seismic data.

The geometric part of the model was generated by Boolean object simulation, a technique that inserts predefined geometric forms with desired characteristics. In this case, representative sand bodies were inserted into a shale background. The relative sizes and the shapes of the modeled bodies were obtained from an appropriate literature search and, as a result, the model is typical of turbiditic reservoirs (e.g., complex distribution and subseismic thickness of the sand bodies).

The next step was to fill the lithologies with petrophysical properties. The porosity, rock density, and compressional velocity were obtained by sequential Gaussian cosimulation. Wells were extracted from all generated models and a suite of well logs obtained that were similar to those available in actual reservoir characterization studies.

The synthetic seismic data were generated by convolving the reflection coefficients derived from the acoustic impedance model and a wavelet with a dominant frequency of 25 Hz, typical of a real seismic survey. These data do not contain low frequencies because they were generated from model data that did not contain low frequencies.

Figure 1, the average acoustic impedance map for the reservoir interval, shows the spatial distribution of the region with the most sand bodies (acoustic impedance between 4400 and 6750 g/cm^3∗m/s, shown in yellow) and the acoustic impedance section through wells N, Q, A, P, and C. Figure 2 shows a seismic section in the same spatial position.

Note that, with the seismic section, heterogeneity and sand bodies in the reference model could not be imaged. However, the acoustic impedance section distinctly characterizes three regions that are important for future analysis of seismic inversion results: the region between wells P and C with large sand bodies; the region between wells Q and A with sand bodies of little thickness but distributed in a more complex manner; and the region around well N, in which sand bodies are absent.

This situation, in which the conventional seismic data are unable to map heterogeneities in the reservoir, is normal for deepwater turbiditic reservoirs.

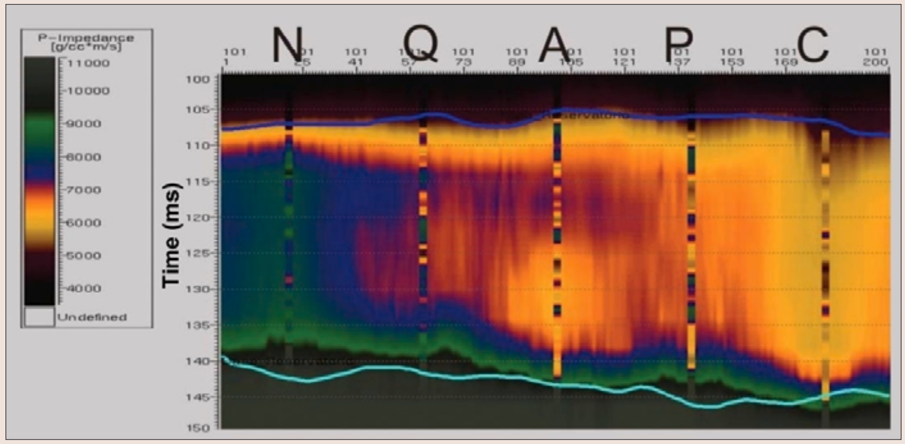

Figure 3. CSSI result between wells N, Q, A, P, and C.

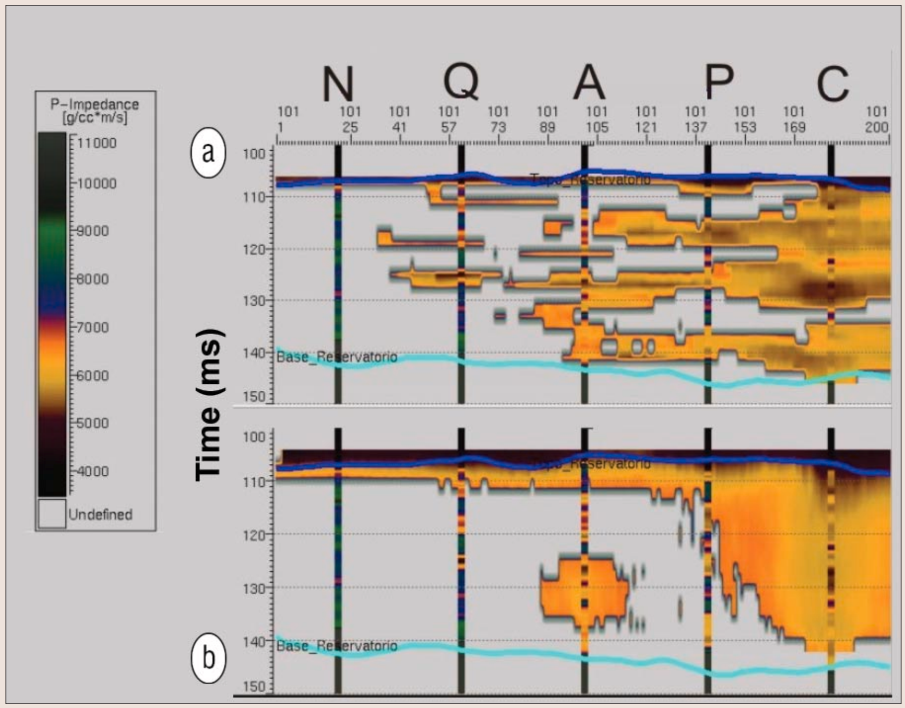

Figure 4. Comparison of reference model (a) and CSSI result (b) for impedance values between 4400 and 6750 g/cm^3∗m/s.

Seismic inversion. The limited vertical resolution in the conventional seismic data is because the frequency of the data is limited in both the low frequencies and the high frequencies. The inversion process can add low frequencies to the seismic spectrum through the constraint model.

The deterministic inversion approaches are normally cheaper in terms of computational time and storage. However, the vertical resolution remains constrained by the seismic bandwidth. Therefore, deterministic inversion mainly is useful for deriving general trends and highlighting large features in an exploratory stage. Stochastic inversion uses stochastic methods (i.e., random variation of parameters) to create data with vertical resolution that is superior to the conventional data. In this case, the higher resolution data were created using sequential Gaussian simulation which produces multiple, equally probable, models. Uniqueness problems are addressed by statistical analysis of the equally probable models.

These advantages of stochastic inversion in comparison with deterministic inversion will be evident when considering the following applications to the reference model.

Model	Range X (m)	Range Y (m)	Range Z (m)	Sill
spheric	1000	500	8	0.007
spheric	12 000	7000	250	0.007

Figure 5. Parameters used in the variographic modeling of geostatistical inversion.

CSSI. The deterministic method used in this study is constrained sparse-spike inversion, or CSSI, which creates a model of acoustic impedance from seismic amplitudes. This method is constrained by criteria based upon previous information (e.g., a geologic model or well data). These restrictions effectively limit the potential solutions, thus reducing nonuniqueness, and provide realistic geologic and geophysical results.

CSSI begins with the construction of an impedance model from a geologic model based on interpreted horizons, structural information, and well data. Low-frequency (0-10 Hz) information (using one of the commercially available methods) is interpolated into this "earth" model to produce a "constraint and tendency" model which is used in the seismic inversion. A wavelet is then estimated and the inversion performed.

In the case studied here, the geologic model was based on the horizons that define the top and the base of the reservoir. The well data in the model were then added. In this case, wavelet estimation was not necessary since the wavelet (with a dominant frequency of 25 Hz) that modeled the

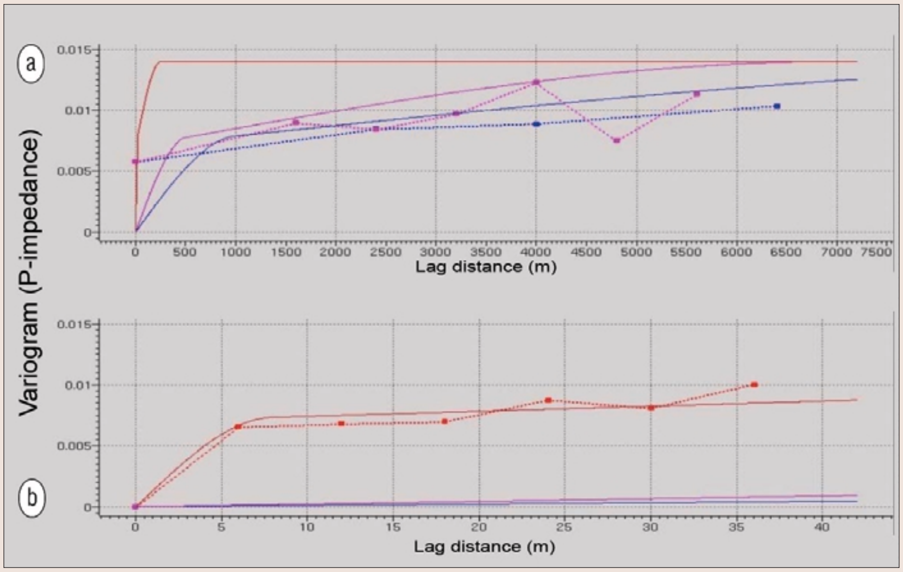

Figure 6. *Horizontal (a) and vertical (b) variograms used in the geostatistical inversion.*

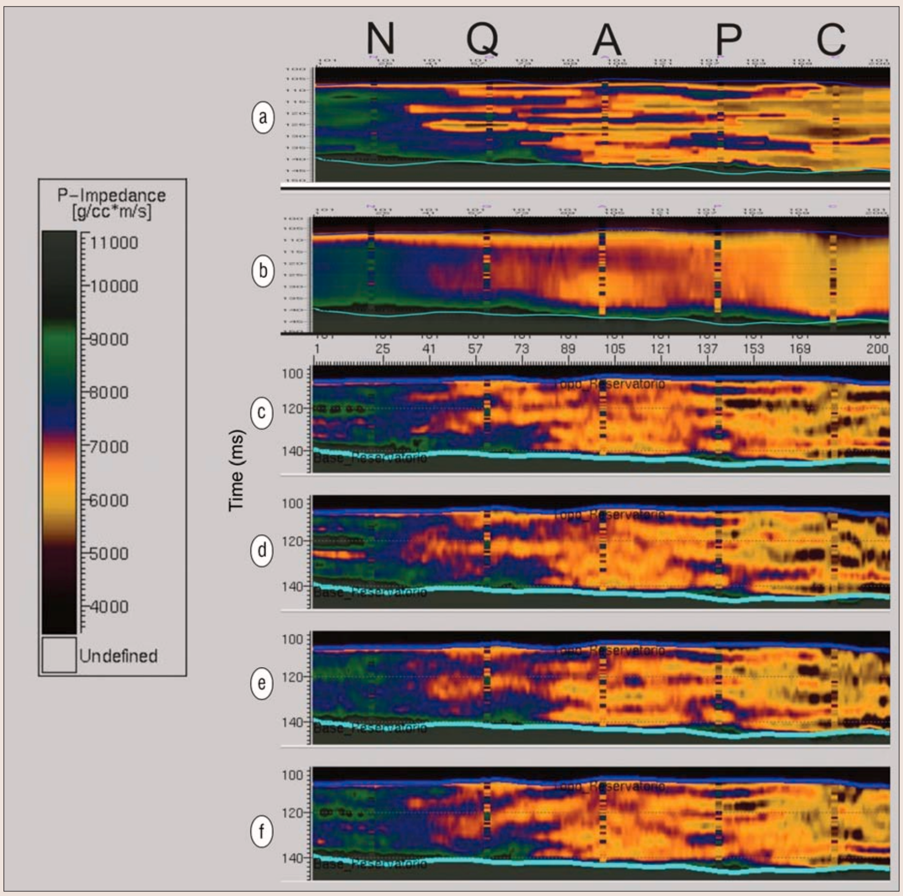

Figure 7. *Comparison of reference model (b), CSSI (b), and (c)-(f) four of the 20 results of the geostatistical inversion.*

complete data for the original project was available. Hence the wells and the seismic data were already tied.

Figure 3 shows the CSSI result between wells N, Q, A, P, and C.

In some portions of the section, the heterogeneities in the model are characterized in a satisfactory manner. This occurs mainly in the region of well C, which includes the largest bodies.

In order to evaluate the seismic inversion result more conclusively, we compared the reference model and the CCSI result by considering only the acoustic impedance values that characterized the sand bodies (4400-6750 g/cm^3*m/s).

The comparison (Figure 4) shows that, in the region around well C, the inversion presents a satisfactory reproduction of a sand body. Another region in which CSSI shows reliable results is the lower part of well A. However, in the other regions of this section, CSSI was not able to characterize the complexity of the sand bodies in the model.

Note also how CSSI exaggerates the connectivity of the sand bodies. This occurred because the deterministic inversion produces an average estimate of acoustic impedance values, a critical limitation of the method.

The geostastistical inversion. Geostatistical inversion results are multiple 3D volumes with the same horizontal resolution as the seismic and with the vertical resolution of the well data. Since the geostatistical inversion is not solely controlled by the acoustic impedance features, but also by other information, the number of possible solutions is reduced and nonuniqueness decreased.

The algorithm used in this project (implemented in the Jason Geoscience Workbench package) makes and adjustment between the synthetic trace and the original seismic trace by means of an optimization process, called simulated annealing, where some solutions considered degraded are also accepted within preselected criteria. The algorithm for geostatistical inversion used in this article is composed of the following stages:

- The vertical and horizontal variograms are generated and modeled.
- Initially a sequential Gaussian simulation is performed using the acoustic impedance well logs, aiming at filling the volume to be inverted.
- Each cell of the grid is revisited randomly and resimulated.
- For each cell, a synthetic trace is calculated, and for this, once again, knowledge of the wavelet is needed.
- The synthetic trace is generated and compared with the original trace where the residuals are calculated based upon the squares-sum of the difference between the original trace and the synthetic trace.
- These residuals are then submitted to an acceptance/rejection test. The optimization uses simulation annealing. The residuals are accepted if they satisfy the criteria that measure the correlation of the synthetic trace and the original trace. Some traces, even if they do not meet the criteria, are accepted in order to achieve a bet-

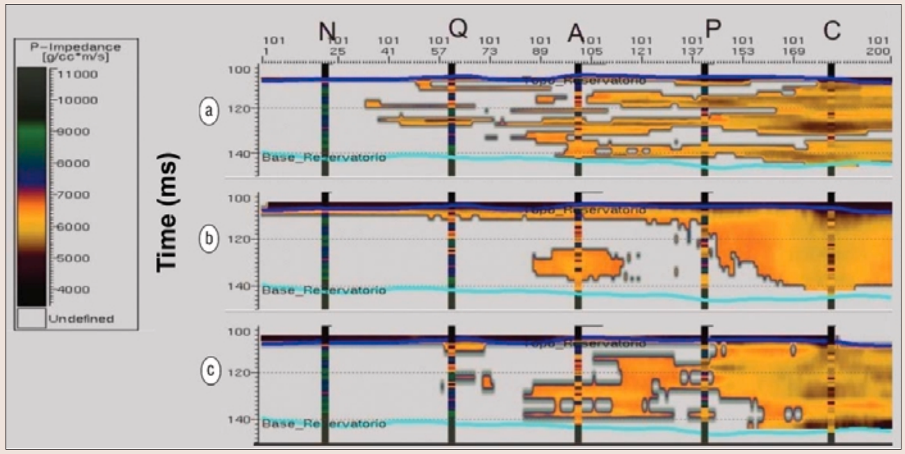

Figure 8. Comparison of the reference model (a), CSSI (b) and the mean of the 20 geostatistical results between impedance values of 4400 and 6750 g/cm³∗m/s.

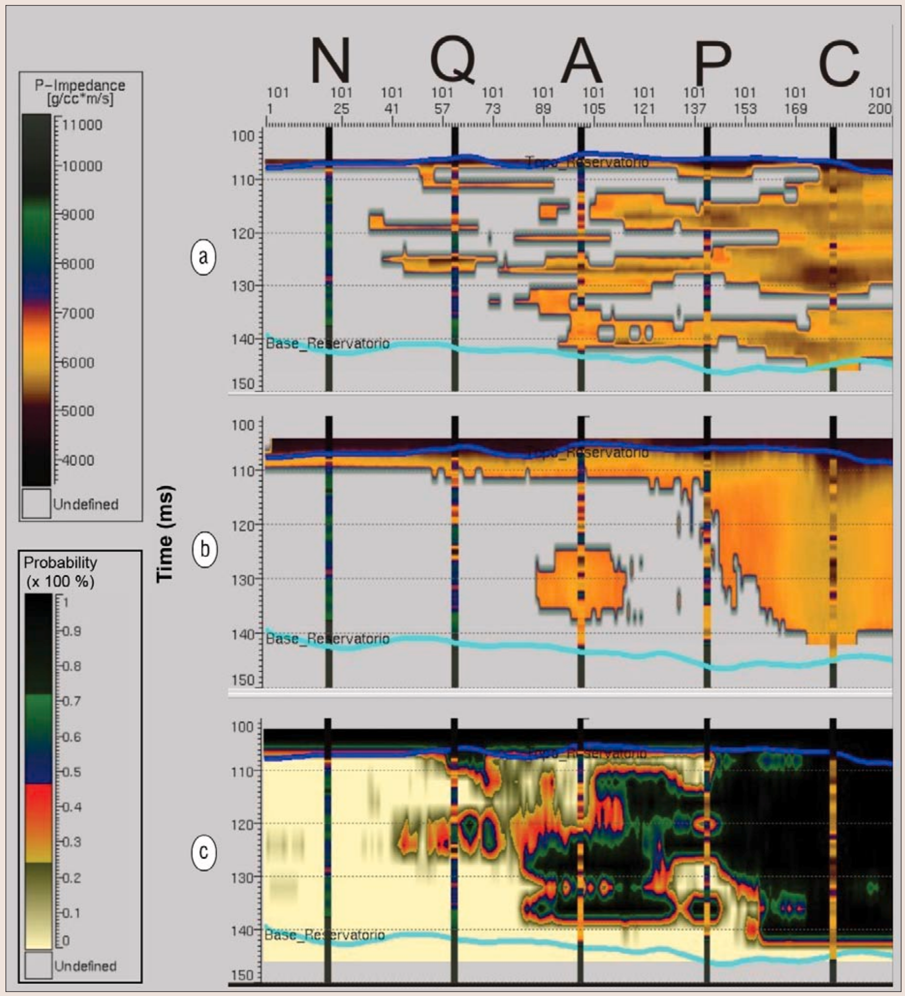

Figure 9. Comparison of reference model (a), CSSI (b) and the section of calculated probability from the 20 geostatistical results.

ter final solution. If accepted, the trace is considered as the solution of the inversion, and is incorporated into data and a new trace is visited/ simulated.

- The inversion continues until all points are simulated, and all resulting realizations are consistent with seismic and with well data.

The vertical and horizontal variograms used in our study were calculated from the well data and the parameters used in the geostatistical modeling are presented in Figure 5. Figure 6 shows the variograms used in the inversion.

The geostatistical inversion generated 20 realizations of acoustic impedance, from which other volumes were obtained; the mean of the realizations; the maximum and the minimum of these realizations; the standard deviation; and a volume related to the probability of finding acoustic impedance values less than 6750 g/cm³∗m/s.

Figure 7 compares four geostatistical inversion realizations with the reference model and the CSSI result. The four geostatistical realizations (Figures 7c-f) have improved vertical resolution—particularly in region of well Q and which was not seen on the CSSI. This makes the inverted models much closer to the reference model.

When working with multiple realizations, selecting the model which best characterizes the reservoir is difficult, since all are equally probable. One way to solve this problem is by calculating the mean of the realizations because, although it is an averaged result and does contain the high resolution present in some realizations, it retains important features which are in all realizations. Figure 8 compares the mean of the 20 geostatistical realizations (panel c) with the reference model (panel a) and the CSSI (panel b). Only the information highlighting sand bodies is shown.

Note that the region between wells P and C with thick bodies is well characterized in both inversions. But "thin" areas can only be characterized by the geostatistical inversion. This can be observed between wells A and P. Furthermore, even thin sand bodies can be identified (for example, around well Q) and there is less exaggeration of connectivity between the bodies.

Another advantage of working with stochastic simulations, such as the case of geostatistical inversion, is the ability to access the probability fields and study the uncertainties involved in the characterization process. Thus, we performed, on the 20 geostatistical realizations, the probability calculations to find acoustic impedance values as low as 6750 g/cm³∗m/s. This result can be interpreted as a probability of finding sand bodies which are present in the reference model. Figure 9 repeats the comparison made in Figure 4 but adds a calculated probability section from the geostatistical inversion realizations.

Net-pay calculation. As previously noted, one advantage of working with acoustic impedance data is the existing relation between these data and fundamental properties of the

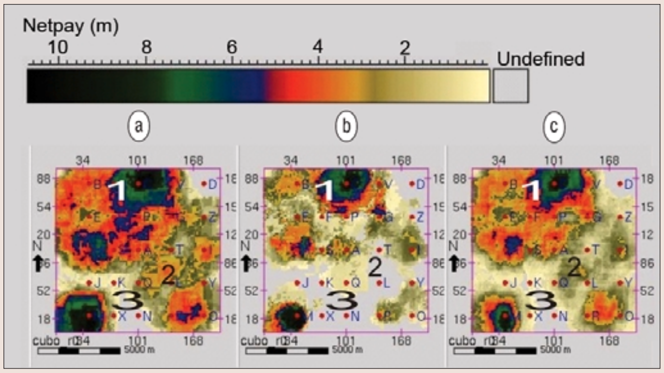

Figure 10. Comparison of reference model (a) and CSSI (b) net pay with average of net pays obtained from geostatistical inversion.

reservoir. Among the most important properties for planning a development strategy is net pay, which is related to the thickness of the reservoir and is a fundamental input in calculating the volume of oil in the reservoir.

In this project, net pay was obtained with the following procedure:

- The acoustic impedance model was converted from the time domain to the depth domain so that we could measure the thickness of interest.
- A relationship between porosity and acoustic impedance was generated. For this relationship, we applied a cutoff value in both the acoustic impedance and in the porosity model to guarantee the identification of sand bodies.
- On each trace, the values identifying sand bodies were integrated with regard to thickness. Ultimately, a map was obtained that represents the net pay value in the whole reservoir.

Figure 10 compares the net-pay maps obtained with the reference model (a), with CSSI (b), and with geostatistical inversion (c). We obtained the net-pay geostatistical inversion results by calculating a net-pay map for each realization and then deriving the mean of the 20 net-pay maps.

We see in Figure 10 that, although there is an exaggeration in the connectivity of the sand bodies as previously shown with the CSSI result, the porosity thickness and, consequently, the final volume of the reservoir have been underestimated. (Because of scale differences, the data are averaged.)

This occurs because CSSI does not correctly reproduce acoustic impedance values, since it uses an average of the inverted values. The porosity thickness resulting from the geostatistical inversion has proven more reliable for the entire extent of the reservoir under study.

We selected three regions to be qualitatively and quantitatively analyzed in detail. The first analyzed region (1) corresponds to larger body thickness. CSSI only identifies those areas with thicknesses larger than 7 m. Geostatistical inversion produces a reliable result in this region. Region 2 has bodies of intermediate thickness. The limitation of CSSI is evident since this methodology is unable to reproduce values of interest. Geostatistical methods underestimate the thickness in this region, but are able to identify the important heterogeneities. Finally, Region 3 has bodies with little thickness and both inversion methods did not identify heterogeneities, thus establishing a limit for the inversion methods.

In the reference model, the net-pay varies between 0 and 12 m. In the CSSI, only the net-pay values between 7 and 12 m are successfully reproduced. However, geostatistical inversion identifies net-pay values between 2 and 12 m. This 5-m difference in net-pay characterization is important, mainly for the volume calculation in the reservoir, since this will define exploration and development targets.

Conclusions. The research presented in this article shows the importance of seismic inversion in the reservoir characterization process, mainly in thin and heterogeneous reservoirs such as found in Campos Basin. The reference model used in this article represents a deepwater turbiditic reservoir.

Comparison of the two seismic inversion methods studied revealed the advantages in using geostatistical inversion and limitations which are present in the use of CSSI which exaggerated the connectivity of the sand bodies.

In this study, CSSI only reproduced thick bodies and, thus, we feel it is not a viable technique for reservoirs where more detailed heterogeneity is needed. On the other hand, when using geostatistical inversion, the small-scale heterogeneities are satisfactorily characterized because of improved vertical seismic resolution. Although the geostatistical inversion produces multiple models, it does allow the uncertainty to be quantified.

The methods studied in this research were also used to calculate the net pay for the reservoir.

Suggested reading. "Constraining stochastic imagines to seismic data" by Bortoli et al. (in *Geostatistics Tróia'92*, Kluwer, 1993). "Using geophysical, geological, and petrophysical data to characterize reservoirs in the North Sea" by Buiting and Bacon (5th Conference on Petroleum Geology of NW Europe, 1997). "Lp-norm deconvolution" by Debeye and van Riel (*Geophysical Prospecting*, 1990). "Limitations of deterministic and advantages of stochastic inversion" by Francis (*CSEG Recorder*, 2005). "Geostatistical inversion—A sequential method of stochastic reservoir modeling constrained by seismic data" by Haas and Dubrule (*First Break*, 1994). "An interpreter's guide to understanding and working with seismic-derived acoustic impedance data" by Latimer et al. (*TLE*, 2000). "Geostatistical inversion: A new methodology for thin beds reservoir characterization" by Mundim et al. (8th International Congress of The Brazilian Geophysical Society, 2003). "Multidisciplinary stochastical impedance inversion: Integrating geological understanding and capturing reservoir uncertainty" by Rowbatham et al. (*Petroleum Geoscience*, 2003).

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