Geostatistical 3D Density Modeling: Integrating Seismic Velocity and Well Logs

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Abstract

The paper presents the methodology used for the construction of a regional 3D density model in Campos Basin, Brazil. The approach uses Gardner relationship to compute the bulk density (RHOB) from the P-velocity (Vp). The specific objective of this work is to improve the density model by using local adjustments of Gardner parameters, and thus to obtain a better fit of the final model to the well data. The workflow involves geostatistical estimation for the interpolation of the Gardner parameters.

The methodology uses sonic and bulk density logs and the velocity model built for time-depth conversion as input data. The density 3D model is generated by Gardner's relation, using the coefficients of linear regression between the extracted RHOB and Vp profiles. A careful analysis of regression at wells was performed to obtain the most relevant coefficients at each well location. The spatial variability of the adjusted coefficients was assessed though variogram analysis. These parameters were then interpolated by kriging. The resulting density model from this methodology was finally compared to the density model obtained using the standard Gardner parameters.

The software used for the execution of the work was PETREL 2014 (Schlumberger).

Introduction

The density associated with compressional and shear velocities, is an important petrophysical property for lithology discrimination, as well as to estimation of economically important rock properties in the oil industry (porosity, presence of hydrocarbons and others). The robustness in modelling this property is particularly important for seismic acquisition, imaging and gravimetric studies.

Density information is sampled spatially through profiling and core samples of wells. In seismic and gravimetric data, there is a relative measure of this property because it does not provide information on low frequency. On the other hand, the seismic velocity cube P is densely sampled and includes low frequency information (to 0 – 6 Hz) that are measurements of macro trends.

From laboratory experiments, Gardner et al (1974) obtained an empirical law that expresses the relationship between density and P velocity (eq. 1). This relationship is suitable for the majority of sedimentary rocks, with the exception of halite and anhydrite (Castagna et al, 1993).

$$\rho = aV^b \quad (1)$$

with [ρ] = bulk density in g/cm³ and [V] = velocity in m/s. The standard values obtained by Gardner are a=0.3095 and b=0.25.

According to Castagna et al (1993) the best fit for the data set that he observed, separating by lithology, are shown in Figure 1.

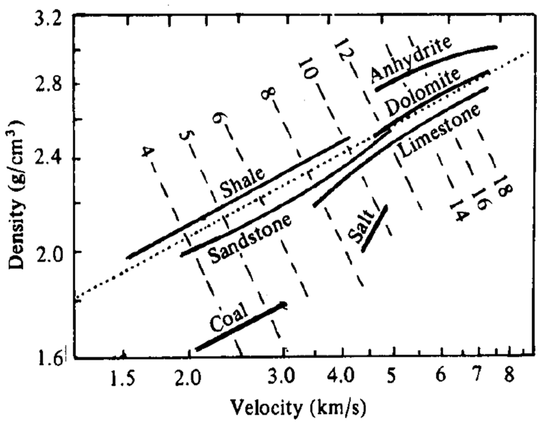

Figure 1 - Relationship between P velocity and density for several lithologies (Castagna, 1993). The dashed line represents the standard Gardner fit.

The methodology presented in this paper is not intended to be a determiner of lithology, because every rock has a tendency according to the burial, fluid saturation, pore pressure and others.

In the present work, instead of using the standard Gardner coefficients, the parameters "a" and "b" from equation (1) will be extracted from the data. As stated by Mavko et al (1998): "*These relations are empirical and thus strictly speaking they apply only to the set of rocks studied.*"

The studied region is located in the Campos Basin, comprising approximately 247,000 km², with a 515 km-width in north-south direction and 415 km east-west (Figure 2).

For this project, 173 wells were used with sonic, density and caliper profiles, 6 geological markers, 6 horizons and the regional velocity model built for the time-depth conversion (Bulhões et al, 2014).

Figure 2 - Modelling area - Campos Basin

The workflow followed in this work is presented in Figure 3.

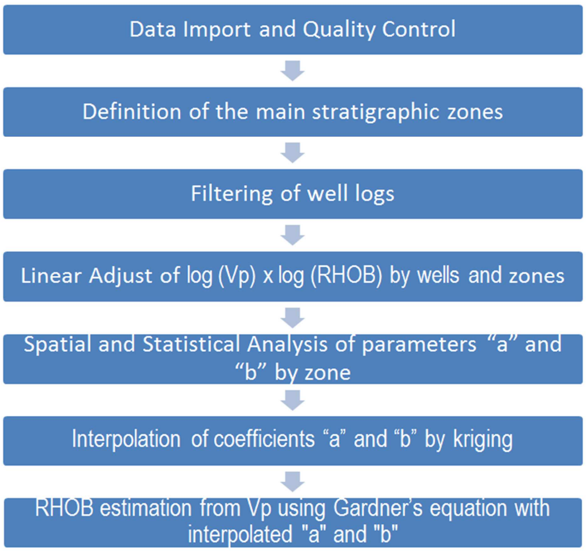

Figure 3 - Workflow for the construction of the density model

Method

1. Data mining and filtering

In the first stage of the work, the survey and analysis of well data were performed.

Gardner equation (eq. 1) can be rewritten as a linear relation between log (ρ) and log (Vp) (eq. 2):

$$\log(\rho) = \log(a) + b.\log(Vp) \quad (2)$$

In each zone of each well, the linear regression between log(Vp) and the log(RHOB) was computed to determine the coefficients "a" and "b" of Gardner equation (Figure 4).

The crossplot log(RHOB) x log(Vp) for all the available well data is displayed in Fig. 4. It shows a high dispersion of the data, with no clear general relationship. Obviously, a proper quality control must be performed on the input profiles to identify outliers and only retain relevant data.

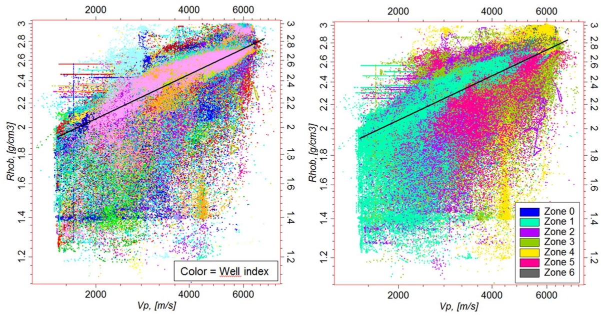

Figure 4 - Crossplot of log(Vp) x log(RHOB) of all wells. The color on the left represents the wells and the color on the right represents the stratigraphic zones.

The proposal of a workflow that optimizes the process of filtering and linear regression wells is an important tool for analyzing large volumes of data. At each step of the process, the participation of the interpreter is of primary importance, as he has a full knowledge of the geological and geophysical characteristics of the area.

Geophysical and statistical criteria were used for the elimination of noise and to identify outliers of Vp and RHOB values. Among the geophysical criteria, the caliper was used as a measure of the reliability of the other profiles.

Measurements with caliper values above 17 ½ inches were flagged as unreliable Vp and RHOB values. This is illustrated in Figure 5.

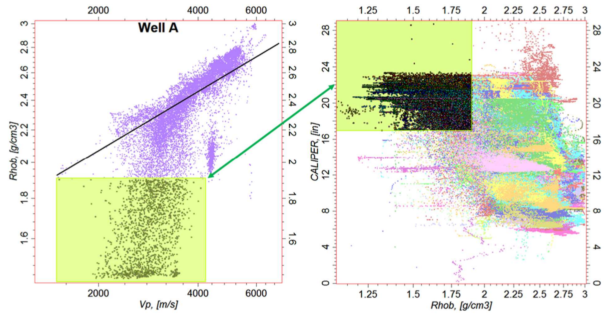

Figure 5 – On the left, crossplot of log(Vp) x log(RHOB) of well A with anomalous values of density. On the right, crossplot of RHOB x caliper of all wells (highlighted area with anomalous low values of RHOB and high caliper to be removed)

For homogeneity and consistency purposes, the well data were divided into 6 stratigraphic zones, and the data analysis was performed on each zone independently.

For each stratigraphic zone, the values of log(Vp) x log(RHOB) were plotted, as shown in Figure 6.

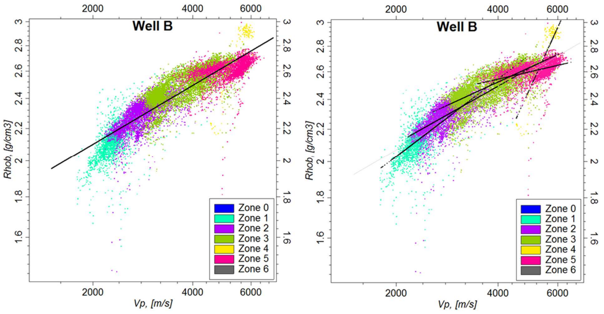

Figure 6 - Crossplot log(Vp) x log(RHOB) of the well B. On the left, global linear adjustment. On the right, the adjustments made by zone.

The data density per RHOB and Vp interval (also called 2D histogram or pdf) was used as a statistical criterion, to identify isolated data. It was computed and superimposed to the crossplot in Figure 7. A 1% cut-off was applied to this data density in order to remove the outliers.

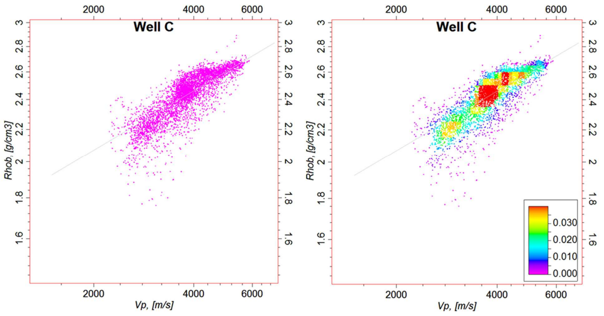

Figure 7 – Crossplot of log(Vp) x log(RHOB) of the well C in zone 5. In the plot on the right the points that are more densely sampled are represented with yellow to red color. The samples out of this criterion will be removed.

The correlation coefficient was used as a criterion of linear adjust. For each zone, wells were classified into 3 categories according to their correlation coefficient:

i) R > 0,80 – High correlation

ii) 0,60 < R < 0,80 – Moderate correlation

iii) R < 0,60 – Low correlation (wells / discarded zones "quarantine")

2. Spatial analysis of Gardner local coefficients

Analyses of spatial variations were performed on the coefficient "log(a)" and exponent "b", by zone, considering only wells with correlation above 0.6. Figure 8 shows the value of the exponent "b" at well locations for zone 5.

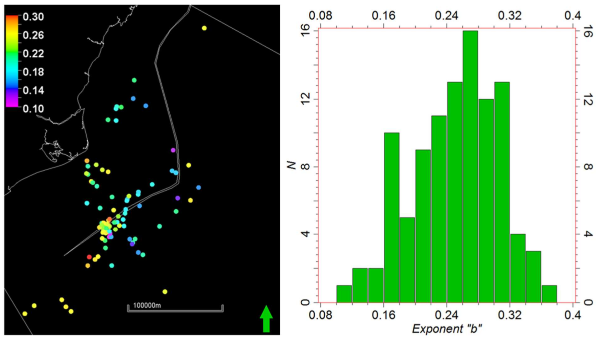

Figure 8 - Distribution of parameter "b" of the stratigraphic zone 5 in the map (left) and the corresponding histogram (right).

A strong anti-correlation was observed (-0.999264) between the "log (a)" and the exponent "b" of Gardner equation (Figure 9). Therefore, they should not be treated independently. It was decided to model the coefficient "b" in the first step, and then "log(a)" conditioned to "b".

The variogram map of the exponent "b" shows a clear NE-SW anisotropy (Figure 10 left). Its variogram was modeled by a spherical structure, with a range of aproximately 30 km in the main direction (N40º) and 20 km in the minor direction (Figure 11 left). To ensure a better continuity, the nugget value was forced to zero, even if a nugget up to 0.3 can be observed in the experimental variogram.

The residuals of "log(a)" in relation to exponent "b" were then computed, in order to model the non-correlated part of the coefficient "log(a)". The corresponding variogram map (Figure 10 right) shows a NNW-SSE anisotropy. The variogram of the residuals was modeled as a spherical structure, with a 14 km-range in the main direction (N130º), and 10 km-range in the minor direction (Figure 11 right).

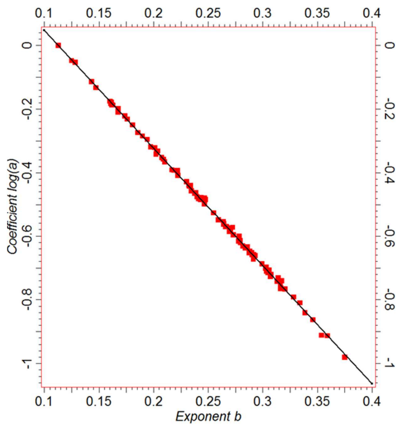

Figure 9 - Relation between the coefficient "log(a)" and exponent "b" obtained from the regressions in zone 5.

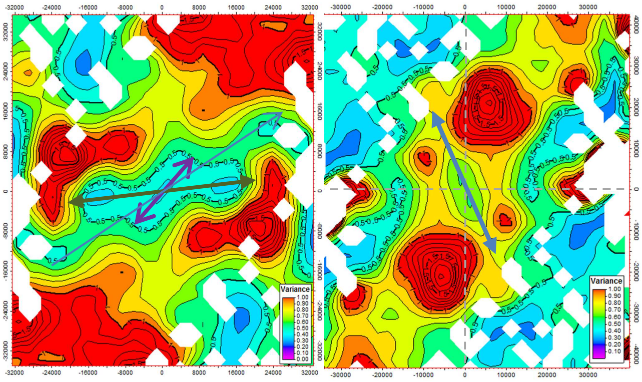

Figure 10 - On the left: variogram map of exponent "b" in zone 5. On the right: variogram map of the "log(a)" residuals.

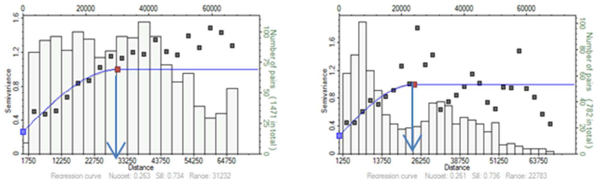

Figure 11 – Sample variograms related to exponent "b" and "log(a)" coefficient in Zone 5. On the left: variogram in the direction of major continuity N40° for exponent "b". On the right: variogram in the direction of major continuity N130° for coefficient "log(a)".

3. 3D density model construction

The 3D modeling was performed by zone on a stratigraphic grid.

The exponent "b" was first estimated by ordinary kriging, then the coefficient "log(a)" was estimated by kriging using exponent "b" as trend (Figure 15).

At last, the density model was calculated by applying the Gardner formula on the regional velocity model, using the estimated coefficients "a" and "b". For comparative purposes, the density was also calculated using Gardner standard coefficients a = 0.3095 and b = 0.25.

Results

Maps of interval velocity and its estimated density map for the zone 5 are displayed in Figure 16.

The estimated density field was compared to the measured RHOB profile. The relative error at wells was calculated as the difference between the density obtained from the regression and the value measured in the profile (eq. 3).

$$\varepsilon_{perc} = 100\% \cdot \frac{\rho_{estimated} - \rho_{measured}}{\rho_{measured}} \quad (3)$$

The same was done for the density estimated by the standard Gardner parameters.

In the histogram of Figure 12, all wells show similar results on a global scale, with a global average error of about 0% for the local and Gardner parameters.

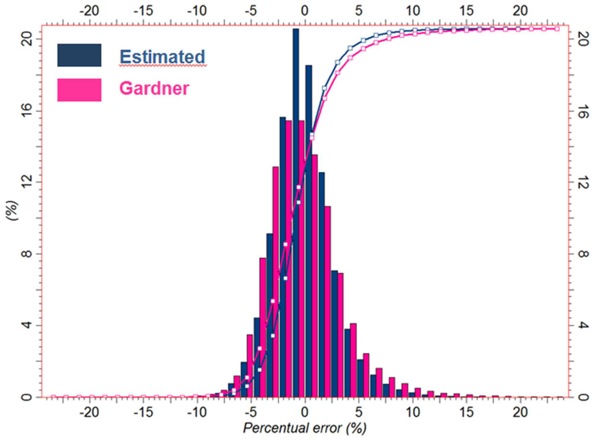

Figure 12 - Histogram of errors in zone 5 in all wells, for the locally estimated model (blue) and the reference model using Gardner standard parameters (pink).

On the other hand, the density estimated in each well by the standard Gardner model presents discrepancy more accentuated than the density calculated by the model with local adjustment, as shown in Figure 13.

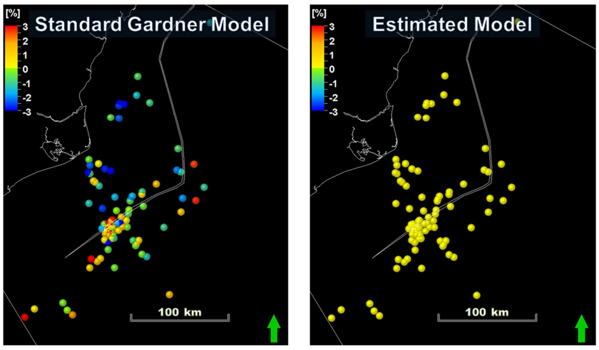

Figure 13 - Average error by well between the calculated density and well measures: On the left by Gardner reference values; on the right calculated by local adjustment.

Conclusions

In this study it was observed on the global scale that the Gardner standards coefficients a = 0.3095 and b = 0.25, setting in a reasonable way. However, observing locally in each zone of the well, these parameters in some zones are overestimated and other underestimated the amounts recorded in the profiles (Fig. 14).

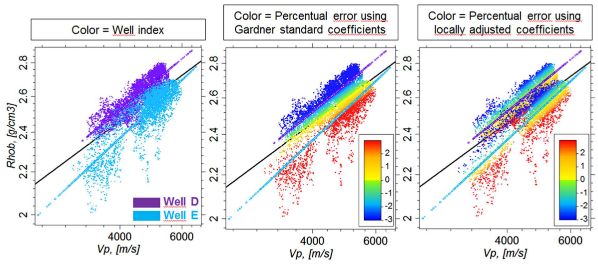

Figure 14 - Crossplot of log(Vp) x log(RHOB) of the wells D and E for zone 5. The color represents the well index (left), the percentage error at well for the standard Gardner model (middle) and the percentage error for the locally adjusted model (right).

The methodology presented obtained a better result locally, minimizing relative errors in the density estimates with measured profiles.

In the future works, wells will be added in this modelling to make it more robust, with better assessment and impacts of result. Following this line the next challenges are:

1) The answer to the density model of the gravimetric in comparison with the date collected in the field.

2) The building of a shear velocity model associated with velocity model (P) and density may be used to the illumination study.

3) Development of empirical laws which presents correlation with the P seismic velocity.

Acknowledgments

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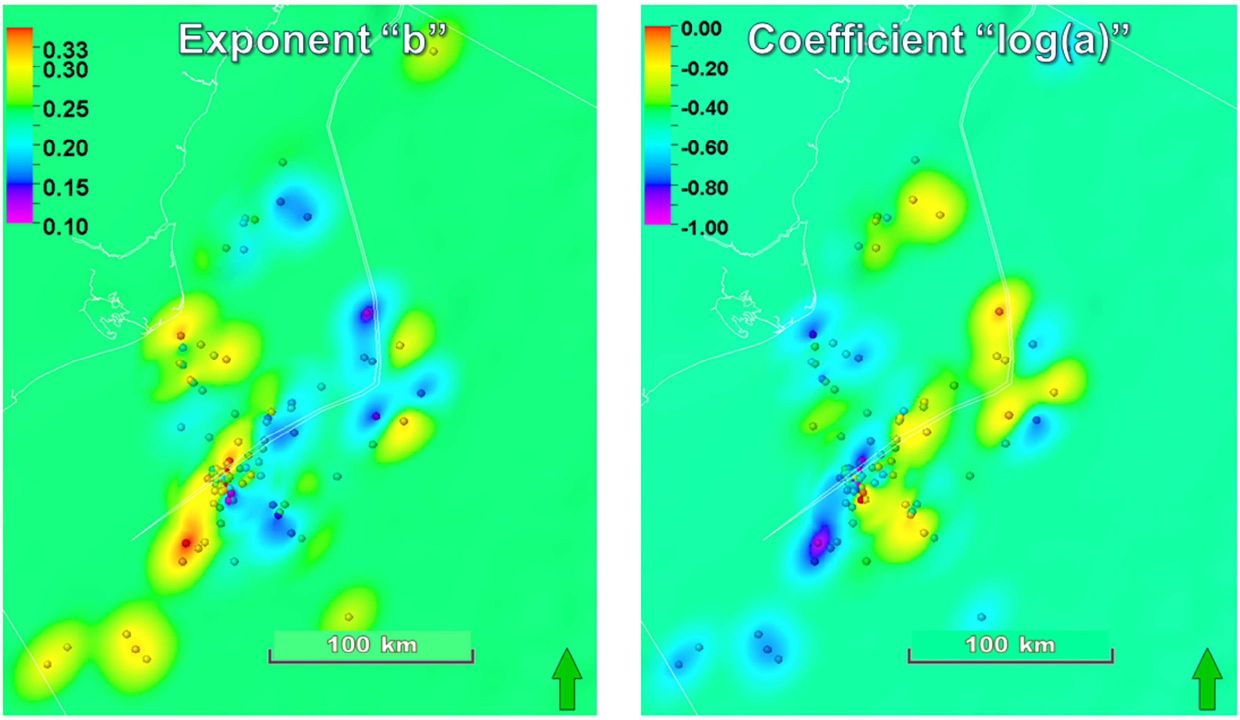

Figure 15 - Maps of the coefficients "log(a)" and exponent "b" in zone 5

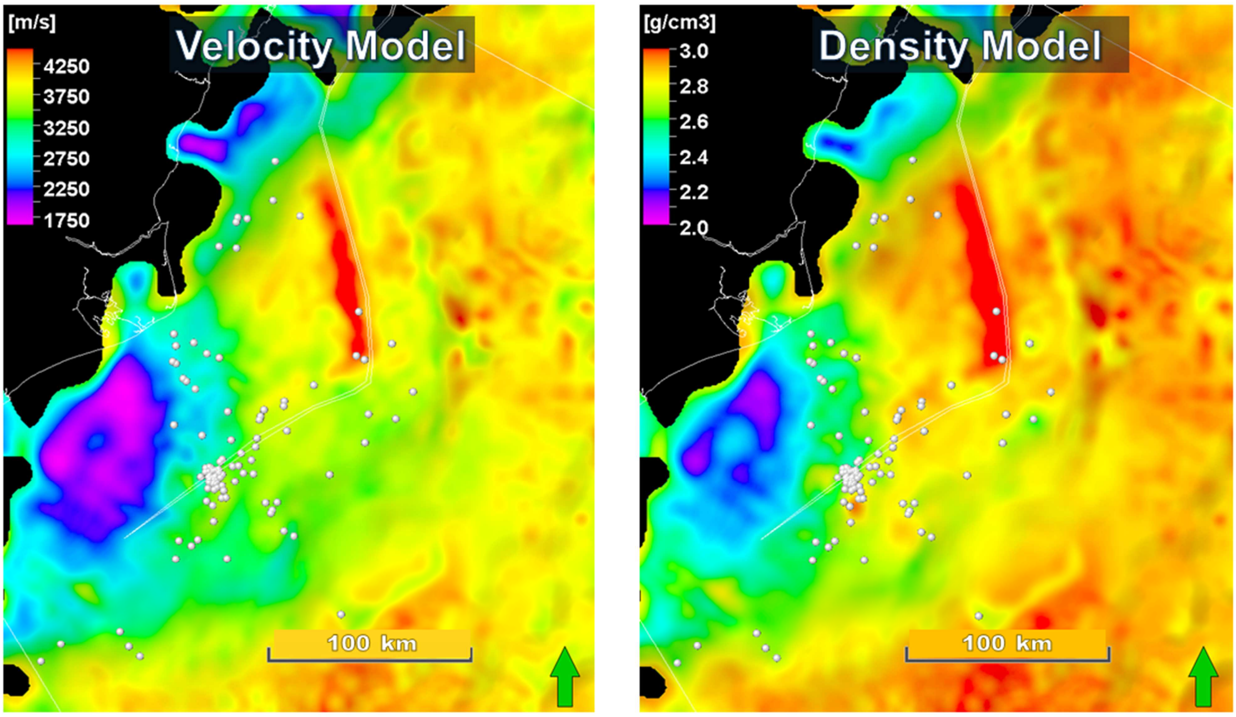

Figure 16 - Velocity map in zone 5 (on the left) and the corresponding density map obtained by the estimated parameters (on the right).