Application of forward stratigraphic-sedimentological simulations to model facies distribution and stacking pattern of an Aptian carbonate reservoir in the Santos Basin, Brazil.

Desiree Liechoscki de Paula Faria (PETROBRAS/UERJ)*; Antônio Tadeu dos Reis (Faculdade de Oceanografia /UERJ), Olinto Gomes de Souza Jr. (PETROBRAS)

Copyright 2017, SBGf - Sociedade Brasileira de Geofísica

This paper was prepared for presentation during the 15th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 31 July to 3 August, 2017.

Contents of this paper were reviewed by the Technical Committee of the 15th International Congress of the Brazilian Geophysical Society and do not necessarily represent any position of the SBGf, its officers or members. Electronic reproduction or storage of any part of this paper for commercial purposes without the written consent of the Brazilian Geophysical Society is prohibited.

Abstract

Forward stratigraphic-sedimentological is a valuable technique that may provide a better understanding of the environmental conditions in which sedimentary facies were deposited, as well as how sedimentological and stratigraphic parameters affect the geometry and facies distribution in a sedimentary layer. This method was applied in the Santos basin, Brazil, with the aid of the software DIONISOS (Granjeon, 1997; Granjean and Joseph, 1999), in the attempt to predict the major depositional parameters and environmental conditions that controlled the spatial facies distribution of an aptian section of a lacustrine carbonate platform (uppermost pre-salt section).Three main basin parameters were tested for a lacustrine environment: base level oscillations, variable depositional rates and distinct bathymetric intervals for carbonate facies deposition. Well facies analyses evidence that the studied carbonate platform is composed of four main carbonate facies: laminites, grainstones, stromatolites and spherulites. During simulations, we searched for the set of environmental parameters that could match the carbonates facies distribution revealed from well analyses. Two main models simulating the same initial lake bathymetry (60 m deep) were able to reproduce the stacking pattern described in the wells: Model 1 simulates grainstones and stromatolites facies to occur respectively as a proximal facies (from 5 to 20m deep) and as an intermediate facies (from 15 to 60m deep); Model 2 simulates different depths and positions for the occurrence of grainstones and stromatolites facies along the depositional profile. Grainstones occur from 1 to 10m deep and stromatolites occur from 10 to 30m deep. Model 1 fits better with the facies distribution revealed from well data of the studied carbonate platform at each time step, while Model 2 produces a thicker layer of spherulites and inexpressive deposition of laminites, differently from seen in the well data. The results of this study helped the prediction of carbonate platform architecture and facies distribution from the interaction between seismic, well data and geological interpretation resulting in a consistent numerical model. From the simulations it was observed that the environmental parameter which most affects the carbonate stacking pattern was the variation in the lake level curves compatible with the expected arid condition for the deposition of the aptian carbonates of Santos basin. However, to replicate the stacking pattern as described in the wells data, the lake level curve had to be applied in a sense to simulate a lower evaporation rate.

Introduction

The offshore of Santos basin, located in the Brazilian Southeastern continental margin accommodates a huge hydrocarbon province. In the early 2000's, oil discoveries in deep and ultra-deep waters, located in the Barremian-Aptian carbonate section of the rift and sag basin stages, brought a new massive economic interest to the area. Oil reserves are estimated at more than 45 billion barrels (Szatmari and Milani, 2016). In this study, we modelled the distribution of sedimentary facies that compose an aptian (sag phase context) lacustrine carbonate platform located in Santos basin (Figure 1) using the stratigraphic-sedimentological modelling technique. The study aims at the definition of a facies model that reproduces the sedimentary stacking pattern observed from well data analyses, based on the simulation and tests of three different parameters that act in the depositional process of carbonate rocks: base level oscillations, carbonate depositional rate and bathymetric intervals for facies deposition.

Data and Method

The available seismic data comprise a grid of 3D seismic data. The study also counts on the availability of side samples and cores, electric profiles and image log from 10 wells provided by PETROBRAS (Figure 1).

Three basic methodological steps were applied for the stratigraphic-sedimentological model to be constructed: i) Review of rock description made internally at PETROBRAS with collaborators support, concerning the carbonate facies analysis from the available well data; ii) 2D structural restoration technique to obtain the paleo-topography from the beginning and the end of the sediment deposition time (Fossen, 2012; Gibbs, 1983; Nunns, 1991); iii) simulations to test and choose the main parameters to be used in the forward modelling (*e.g.,* subsidence rates, lake level oscillation, carbonate deposition rates and bathymetric interval for facies occurrence).

The software Dionisos (Granjeon, 1997; Granjeon and Joseph, 1999) was used to simulate the main depositional processes acting in a sequence of time intervals that allows sedimentary sequences architecture representation and facies proportions quantification. In the program, accommodation space for carbonate deposition can be controlled by lake level oscillation, subsidence and carbonate deposition rates (Figure 2).

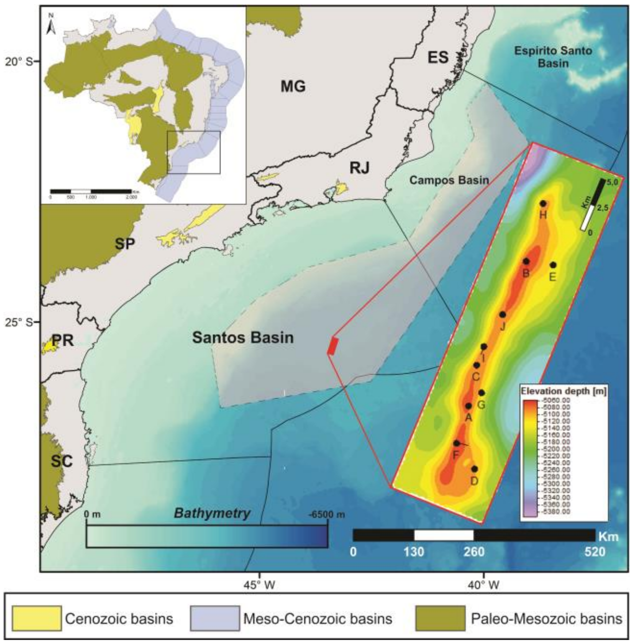

***Figure 1**: Location map of the study area. The dotted gray polygon marks the limit of the pre-salt field's occurrence at Santos and Campos basins. Outlined in red is the platform where this study was developed, with location of the 10 wells made available for it (wells A to J).*

After defining the main parameters to be considered, several simulations were performed, aiming the definition of suitable parameters capable of reproducing the same sedimentary stacking pattern and facies distribution observed in the available well data. Models calibration required numerous adjustments of the simulated parameters, i.e. the forward and backward of simulations parameters and the understanding of the interaction between them.

Lake level oscillation curves were used as a control parameter for the base-level variation in addition to subsidence. The dependence of carbonate accumulation on the lake depth allowed the relative lake level variations reconstruction: through facies characteristics, that is, cyclical fluctuations in the facies, lake level fluctuations could be interpreted. From these premises, supplemented by sequences cyclicity studies, the facies described in well were used to support the construction of the relative lake level oscillation curve applied to models. In order to reproduce the platform geometry and facies distribution, it was necessary to impose a downward tendency (regressive trend) to the lake level variation curve from base to top for the two models. For subsidence, we applied 0.05mm/a – a rate proposed by Contreras *et al*. (2010) to represent the subsidence rate for sag phase of Santos basin.

Carbonate deposition rate firstly tested were established in a relative way: from the ratio between thickness deposition observed in the wells (approximately 100 m) and a considered simulation time from 115.4-113Ma. However, the deposition rate had to be adjusted throughout the modelling phase in order to reproduce the facies distribution previously defined from well data.

The considered value in the deposition per bathymetry is a non-dimensional coefficient that multiplies the deposition per time. Two relationships between carbonate deposition and the bathymetry were tested. The first establishes the occurrence of grainstones and stromatolites in deeper bathymetry, from 5 to 20m and from 15 to 60m, respectively (Model 1). The second test considers an occurrence of grainstones and stromatolites in a shallower bathymetry, from 1 to 10m and from 10 to 30m, respectively (Model 2). The hypothesis of shallow bathymetry values for grainstones occurrence and stromatolites present a better correlation with the depths in which Tanganyika stromatolites are estimated to have been deposited (Cohen et al., 1997).

The influx of clastic sediments in the studied platform was considered absent. Besides that, the simulated facies were considered as representative of primary depositional conditions, therefore, without any considered diagenetic factors.

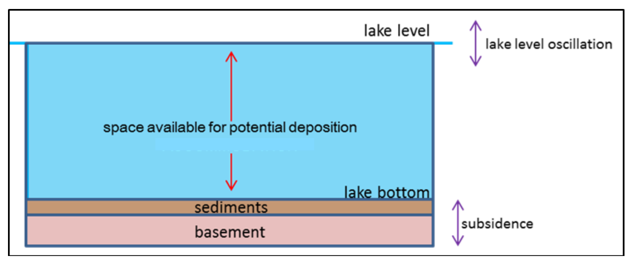

***Figure 2:** Schematic figure with the parameters that influence the available accommodation space variation: oscillation in lake level, subsidence and carbonate deposition*

Results

Facies Analyses

From well data analysis, four main facies were observed to occur in the studied carbonate platform: laminites (LMT), grainstones (GST), stromatolites (ETR) and spherulites (ESF). Facies analyses from wells also revealed the occurrence of: an intercalation of laminite and grainstone facies at the upper sedimentary succession; the predominance of stromatolite facies from the middle towards the basal sedimentary succession with a small intercalation with the spherulite and the presence of a thin layer of grainstone at the beginning of the stratigraphic interval deposition.

From the facies proportion distribution along the platform, facies characteristics and stratigraphic study based on previous work in carbonate environments (e.g. Salta basin, Argentina; Bento Freire, 2012; Pedrinha 2014), it was possible to estimate the position of each facies in relation to the bathymetric range of occurrence in the lake:

i) Laminites occur at the top of the shallow hemicycle (regressive phase), since they are characterized as shallow lake facies by the constant presence of exposure features and by a low accommodation space required for their development;

ii) The stromatolites stratigraphic position in the lake is attributed by the increase of the accommodation space, especially in the edge of the platform. An increase in accommodation space favors the vertical growth of the bush forms. Therefore, stromatolites appear in the transition between shallow the lake and the deeper lake;

iii) Grainstones are composed mainly of fragments. The absence of matrix allows their interpretation as components of a high energy environment. In the stratigraphic study, they record the moment when the lake level begins to rise and to rework previously consolidated facies.

iv) Spherulites, because of their common association with magnesium clays, are facies associated with a low energy environment. So they were positioned up on the top of the flood hemicycle (transgressive phase). Together with mudstones facies, they predominate in the platform basin where a thicker water column is interpreted for lake deposition. Mudstones were not observed in wells.

Seismic analysis and structural restoration

Seismic analysis showed that the carbonate platform of this study developed along a NE-SW structural high, limited by normal faults of same direction (Figure 3). The studied stratigraphic interval is approximately 100 m thick, with its upper limit located under the base of the thick regional basin's salt layer. Seismic reflectors are characterized by being sub-parallel, i.e., no progradation features were observed.

As a result of nine restored sections, we could obtain structural paleo-topography points of the base and top of the model. These paleo-topography points in each section were interpolated by convergent interpolation, in order to generate paleosurfaces. These paleosurfaces served as input data for the stratigraphic-sedimentological modelling phase (Figure 4). They are: topographic maps of the base and the top surfaces of the models; and initial bathymetric maps. The initial bathymetry map for both models was produced by the base model map normalization (0 to 60m).

Forward stratigraphic-sedimentological modelling

The simulated area of the carbonate platform is 9km wide versus 34km long.

During modeling, the deposition rate had to be adjusted in order to reproduce the facies distribution previously defined from well data. To reach this goal, the carbonate deposition rate had to be increased from 0.04 (for an estimation of a 100m-thick layer deposited in 2.4Ma) to 0.08mm/a in both models.

It is important to point that Model 1 and Model 2 were both simulated considering a same initial lake bathymetry (60m deep).

MODEL1

Stratigraphic-sedimentological Model 1 simulated grainstones and stromatolites facies to occur respectively as a proximal facies (from 5 to 20m deep) and as an intermediate facies (from 15 to 60m deep).

The fence diagram of Model 1 (Figure 5) reveals: a predominance of laminites and grainstones in the shallower central portion of the platform; the predominance of stromatolites at the edge of the platform; and the spherulites predominating at the platform bottom, in deeper portion of lake together with mudstones occurrence. Therefore, Model 1 reproduces the carbonate stacking pattern shown in well data.

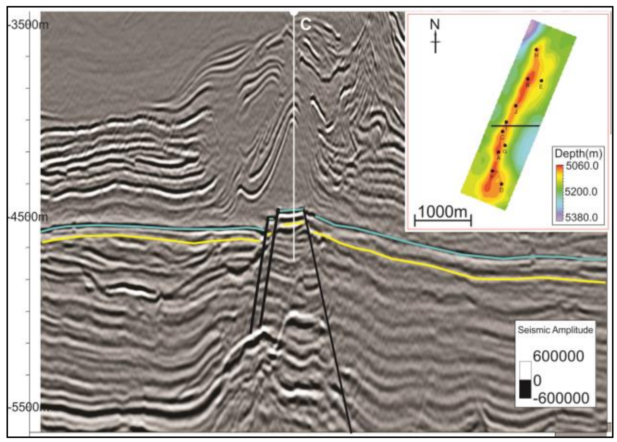

***Figure 3**: 2D seismic profile. In green, the seismic top horizon of the studied section. In yellow, the seismic base horizon of the studied section. In black, the two major flaws that cut the platform. Vertical Exaggeration: 3x*

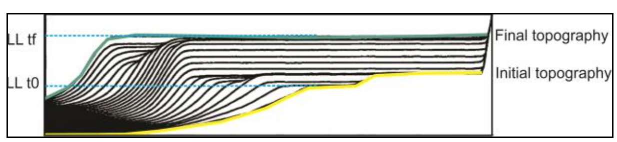

Figure 4: Schematic figure from modelling inputs. LL=lake level. (Adapted from Waltham,1992)

MODEL2

Model 2 was conceived for simulating the occurrence of grainstones and stromatolites facies in different depths and positions along the depositional profile. Grainstones occur from 1 to 10m deep and stromatolites occur from 10 to 30m deep.

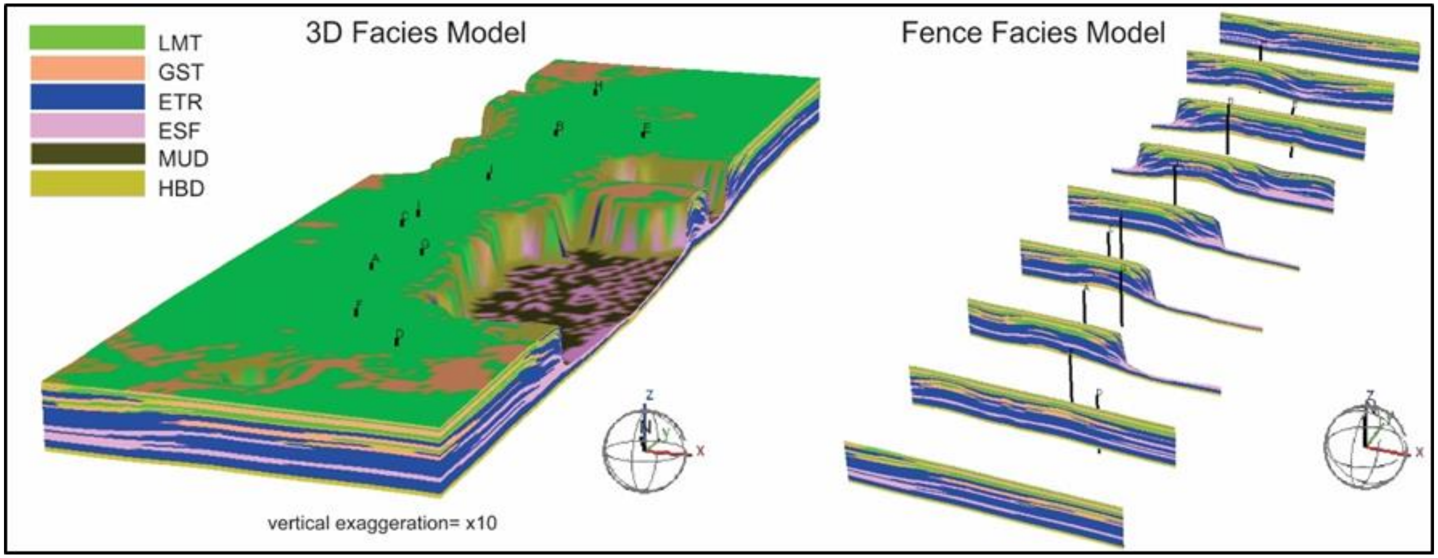

Figure 5*: Facies model from Model 1. LMT = laminites; GST = grainstones; ETR = stromatolites; ESF = spherulites; MUD=mudstones; HBD=hybrid facies. It is worth noting that hybrid facies have no geological significance, it only represents equal proportions of facies.*

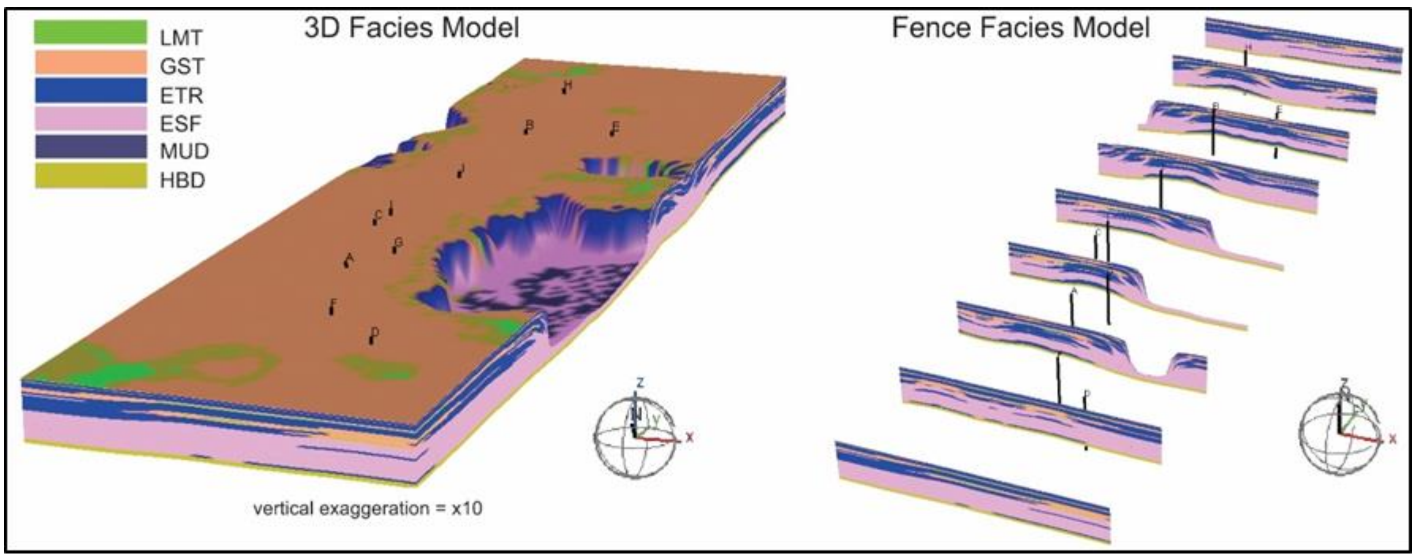

Figure 6*: Facies model from Model 2. LMT = laminites; GST = grainstones; ETR = stromatolites; ESF = spherulites; MUD=mudstones; HBD=hybrid facies. It is worth noting that hybrid facies have no geological significance, it only represents equal proportions of facies.*

As such, there was a need to enhance the lake level downward trend capable of reproducing a stronger evaporation conditions. Otherwise, the deposition of stromatolites dominates throughout the entire thickness of the simulated wells. Considering this lake level downward trend, we obtained the deposition of laminites and reworked sediments in the upper sedimentary succession of the wells. We reached the described facies stacking pattern as well. However, laminites production was very incipient and a thick spherulites layer was produced (Figure 6).

Discussion and Conclusions

According to Walker (1984), a simulation of facies model must be usable in different ways: it must incorporate a large volume of data (many of them unknown to the studied platform) capable of summarizing the sedimentary processes involved; it should stimulate future investigations; it should act as a predictor; and, finally, it should help in the understanding of dynamic interpretations of sedimentary units.

Besides that, proportions and frequencies of facies occurrences are difficult to be perfectly respected during forward stratigraphic-sedimentological modelling (as they appear exactly in well data), due to a question of difference in resolutions levels.

Nonetheless, an approximate reproduction of facies distribution and stacking pattern (as shown on well data) was successfully achieved through our modelling. The integration of all results lead to the following main points of discussion:

(1) The results of the seismic interpretation show that the seismic reflectors corresponding to the base and top of the aptian carbonate interval are cut by NE-SW normal faults. These main normal faults intercept both the carbonate interval focused in this study, and the base of the salt layer. These relationships, together with the results of the structural restoration, show that the faults represent a syn-depositional deformation phase. According to Karner and Gambôa (2007), due to the lack of significant faulting, many researchers have suggested that the sag phase is necessarily a post-rift unit deposited in a thinned continental crust or oceanic crust (*e.g.,* Marton *et al*. 2000; Jackson *et al*. 2000). However, within the Santos basin, extensional failure in the sag pre-salt basin occurs until the base of the evaporites, i.e., the extension continued clearly until the end of the Aptian;

(2) During the stratigraphic simulations, variations of the lake level allowed to control the variation of the water depth of the lake and, therefore, the accommodation space for carbonate deposition. On models, variations in the lake level proved to control the deposition of the facies in each simulated time step, due to the dependence of facies deposition on the lake depth. In order to reproduce the platform geometry and its facies distribution, it was necessary to impose a downward tendency (regressive trend) to the lake level variation curve from 115.4Ma to 113Ma. This level downward trend corroborates to the expected climatic condition for the modelled time (arid condition; Chaboureau *et al*., 2012; Brownfield & Charpentier, 2006; Petri; 1987), since the presence of the thick salt layer above the studied carbonate stratigraphic interval evidences the occurrence of a higher ratio between evaporation and precipitation, which would, in fact, lead to a shallower lake level at the end of the carbonate deposition;

(3) It is worth noting that the changes in the bathymetric lake level in the models which provide the occurrence of grainstones and stromatolites significantly modify the model result. As revealed in Model 2, this change led to the deposition of an over-thickened layer of spherulites at the base of the modelled stratigraphic succession, and to an inexpressive deposition of laminites at the uppermost carbonate deposition. The inexpressive occurrence of laminites deposition does not evidence the expected arid climate conditions;

(4) The original and exact sediment thickness of a layer will hardly be exactly reproduced the same way as observed in all wells. One or another well will inevitably not be fully respected. During this work, we searched to reach the exact sediments thickness as shown in each well. However, although the resulting modelled layer thickness may be surpassed in a few wells, this configuration may be geologically justified by a subsequent decrease in sediment thickness as a result of erosion and/or compaction. As an example, in Model 2, lake accommodation space is smaller due to the application of a strong regressive tendency of the lake bathymetry. Thus, the sediment thickness reproduced by simulation in well (e.g. well A) becomes smaller than the sediment thickness observed in the well (Figure 7). Model 1 better reproduced the original thickness of the carbonate layer as observed in well data.

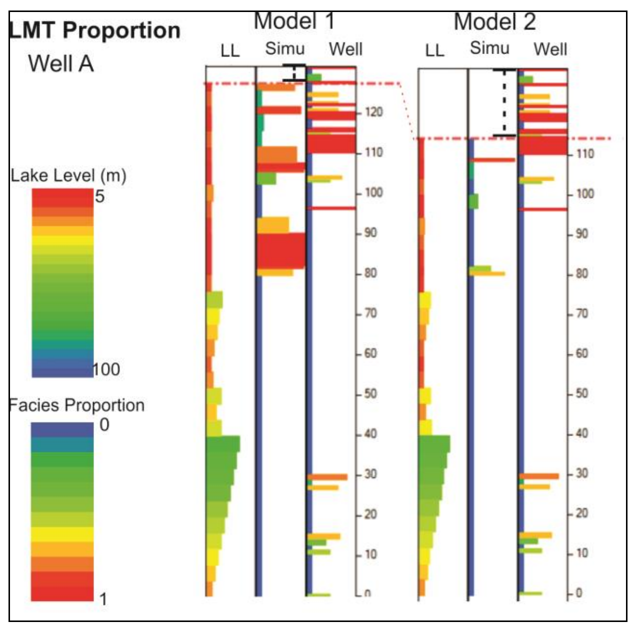

***Figure 7**: Correlation, in well A, between the sediment thicknesses obtained in Mode 1 and Model 2. The black dotted line shows the difference between the sediment thickness produced by the simulation (Simu) and the sediment thickness observed in the well (Well). LL=lake level.*

As the main conclusion, considering the integration of all data, we propose that:

A. the environmental conditions simulated in Model 1 were more satisfactory to reproduce the carbonate facies stacking pattern and the sediment thicknesses observed in wells (Figure 5; Figure 7). In addition to that, the facies distribution along the platform simulated in Model 1 corroborates with the conceptual model for carbonate lacustrine deposition already proposed for Salta basin, Argentina (Bento Freire, 2012; Pedrinha 2014) which has been up to now adopted and adapted by PETROBRAS for the aptian carbonates in the Santos basin. This conceptual model proposes the distribution of laminite and grainstones in the shallower central portion of the lake, the occurrence of stromatolites at the edge of the platform, with the predominance of spherulites in the deeper portion of the lake;

B. the results of the forward stratigraphic modeling achieved in the present study may be applicable to reduce uncertainties in the prediction of reservoir facies distribution of the aptian carbonate platform of the Santos basin. The modelling results may also serve as a basis for testing several other conceptual models of this carbonate platform and other platforms inserted in similar depositional settings, as well as for future studies of diagenetic models.

Acknowledgments

The authors greatly acknowledge the Brazilian National Agency of Petroleum-ANP and Petrobras for the data release. We also thank BEICIP-FRANLAB, Brazil, for providing Faculdade de Oceanografia (UERJ) with the Educational License of the software DIONISOS.

References

Bento Freire, E., 2012. Caracterização estratigráfica em alta resolução das sequências calcárias de origem microbiana do intervalo paleocênico da Formação Yacoraite (Sequência Balbuena IV) na região de Salta - Argentina. 2012. 243 f. Dissertação (Mestrado) - Curso de Geologia, Instituto de Geociências, Universidade Federal do Rio de Janeiro, Rio de Janeiro.

Brownfield, M. E., Charpentier, R. R., 2006. Geology and total petroleum systems of the west-central coastal province (7203), west Africa (No. 2207-B).

Chaboureau, A. C., Donnadieu, Y., Sepulchre, P., Robin, C., Guillocheau, F., Rohais, S., 2012. The Aptian evaporites of the South Atlantic: a climatic paradox?. Climate of the Past, 8(3), 1047-1058.

Cohen, A. S., Talbot, M. R., Awramik, S. M., Dettman, D. L., Abell, P.,1997. Lake level and paleoenvironmental history of Lake Tanganyika, Africa as inferred from late Holocene and modern stromatolites. Bulletin Geological Society of America, 109, 444–460.

Contreras, J., Zühlke, R., Bowman, S., Bechstädt, T., 2010. Seismic stratigraphy and subsidence analysis of the southern Brazilian margin (Campos, Santos and Pelotas basins). Marine and Petroleum Geology, 27(9), 1952-1980.

Fossen, H., 2012. Geologia Estrutural. Editora Oficina de Textos. São Paulo.

Gibbs, A.D., 1983. Balanced cross-section construction from seismic sections in areas of extensional tectonics. Journal of Structural Geology, v.5, p. 153-160.

Granjeon, D., Joseph, P., 1999. Concepts and applications of a 3D multiple lithology, diffusive model in stratigraphic modeling. Numerical Experiments in Stratigraphy: Recent Advances in Stratigraphic and Sedimentologic Computer Simulations. SEPM Special Publications 62.

Granjeon, D., 1997. Modelisation stratigraphique deterministe: conception et applications d'un modele diffusif 3 D multilithologique (Doctoral dissertation).

Jackson, M. P. A., Cramez, C., Fonck, J. M., 2000. Role of subaerial volcanic rocks and mantle plumes in creation of South Atlantic margins: implications for salt tectonics and source rocks. Marine and Petroleum Geology, 17, 477–498.

Karner, G.D., Gambôa, L.A.P., 2007. Timing and origin of the South Atlantic pre-salt sag basins and their capping evaporates. In: Schreiber, B.C., Lugli, S., Babel, M. (Eds.), Evaporites Through Space and Time. Geological Society, London, Special Publication, vol. 285, pp. 15–35.

Marton, L. G., Tari, G. C., Lehmann, C. T., 2000. Evolution of the Angolan passive margin, West Africa, with emphasis on post-salt structural styles. In: Mohriak, W. & Talwani, M. (eds) Atlantic Rfts and Continental Margins. Geophysical Monographs,115, 129–149.

Nunns, A., 1991. Structural restoration of seismic and geologic sections in extensional regimes. American Association of Petroleum Geologists Bulletin, v. 75, p. 278-297.

Pedrinha, S., 2014. Análise estratigráfica em depósitos lacustres maastrichtianos da Formação Yacoraite (Bacia de Salta-Argentina): definição e rastreabilidade de sequências de alta resolução. Dissertação (Mestrado) - Curso de Geologia, Instituto de Geociências e Ciências Exatas, Universidade Estadual Paulista “Júlio de Mesquita Filho”, Rio Claro-São Paulo.

Petri, S., 1987. Cretaceous paleogeographic maps of Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology, 59, 117-168.

Szatmari, P., Milani, E. J., 2016. Tectonic control of the oil-rich large igneous-carbonate-salt province of the South Atlantic rift. Marine and Petroleum Geology.

Walker, R. G. (Ed.), 1984, Facies Models (2nd Edition). Geoscience Canada Reprint Series, 1.

Waltham, D., 1992. Mathematical modelling of sedimentary basin processes. Marine and Petroleum Geology, 9(3), 265-273.