Maximizing the value of seismic data for a better regional understanding and exploration assessment in the Santos Basin, Brazil

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Abstract

Based on integrating 3D and 2D seismic data with well information, this study provides a regional overview of the petroleum geology of the Santos Basin, offshore Brazil. Regional-scale seismic composite sections through the major pre-salt oil discoveries give a valuable insight into how the petroleum system elements work in the pre-salt play and unveil new exploration opportunities in the area.

These seismic sequences are distinguished within the pre-salt section: lower rift, upper rift, and sag sequence. The microbialite carbonates in the sag sequence (Barra Velha Fm.) are the main reservoirs of the pre-salt play and are overlain by the Ariri Fm. evaporite seal.

Major pre-salt structural highs of the basin are recognized in the base salt map constructed from the 3D and 2D seismic interpretation. The Outer High, where most of the giant pre-salt oil discoveries are located, is the main structural feature in the Santos Basin and had a strong influence on the deposition of the prolific lacustrine carbonate reservoirs.

In the Outer High fault interpretation, supported by 3D seismic attributes, highlights rift-related fault orientation variations from NE-SW to N-S. This structural trend variation could be due to the presence of active transfer zones during Early Cretaceous times.

Additional to the known Peroba and Pau-Brasil prospects identified in the base salt map herein, exploration opportunities were defined east of the Santos Outer High within Block Cruzeiro do Sul. 3D seismic interpretation shows pre-salt structural closures south of the Jupiter oil/gas discovery within the same trend.

Introduction

Globally speaking, the Santos Basin in Brazil is one of the most attractive places for hydrocarbon exploration. The basin has an area of approximately 350,000 km^2 and is located in the southeastern sector of the Brazilian continental margin. It is bordered to the west by the Brazilian mainland, to the north by the Cabo Frio High and the Campos Basin, to the south by the Florianopolis High and Pelotas Basin, and to the east by the basinward boundary of the Sao Paulo Plateau (Figure 1).

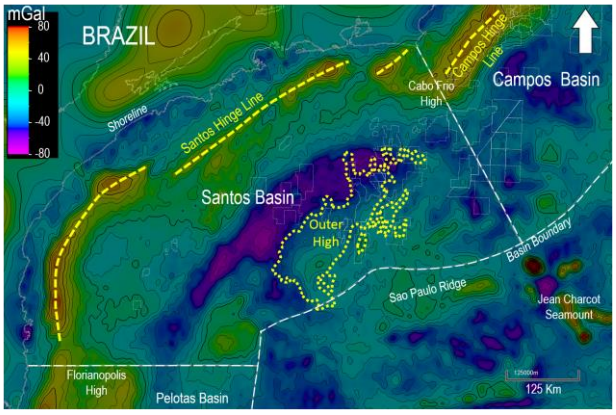

Figure 1 – *Free-air gravity anomaly map of the Southeastern Brazilian Margin (Sandwell et al., 2014). Yellow dashed and dotted lines are the major structural features; i.e., basin hinge lines and Outer High. Thin white dashed polygons indicate awarded blocks.*

Exploration success in the Santos Basin did not come easily and was the result of not giving up after multiple dry holes during early exploration. 59 dry wells, mainly focused on post-salt plays, were drilled during the initial exploration drilling campaign from 1970 to 1987. The Merluza field with 0.07 TCF of gas in place in Santonian turbidites was the only discovery made as early as 1979 (Juarez, 2013). Exploration evolved with better results as small and medium-sized discoveries took place between 1988 and 2005, e.g., the Tubarao field, a 30-MMbbl oil-in-place accumulation in the Early Albian carbonate (Chang et al., 2008) was discovered in 1988. The Mexilhao field, a 3.2-TCF gas-in-place discovery (Vieira, 2007) in the Santonian sandstone reservoir was drilled in 2001.

In 2006, the giant Lula pre-salt discovery in the Santos Basin was a play opener and exploration game changer. Recoverable reserves for the Lula field are estimated in the order of 7.3 BBOE (IHS, 2019). This discovery opened a new exploration frontier in Brazilian deep and ultra-deep water and led to multiple pre-salt discoveries, the majority of which were located in the Santos Basin. There has been a significant increase of the pre-salt production over the last ten years in Brazil. At the end of 2018, pre-salt production reached 1.82 MMBOE/d representing 55.5% of Brazil production (ANP, 2018). 85% of the pre-salt production was from the Santos Basin and the remainder from the Campos Basin.

The huge reserve volumes and high productivity rate of the pre-salt reservoirs have attracted the economic interest of the major international oil companies. However, this prolific pre-salt play has significant

subsurface and imaging challenges that require a systematic approach to fully improve its exploration assessment.

This study presents a regional integration of geological and geophysical data in the Santos Basin to obtain a better understanding of the pre-salt play at basin scale. Stratigraphic and structural interpretation with improved quality 2D and 3D seismic data was carried out in the pre-salt succession. The main objective of this exploration work is to analyze the tectonostratigraphic relationship amongst the major discoveries in the Santos Basin and search for potential analog prospects.

Geological Setting

The Santos Basin was formed by Early Cretaceous rifting and subsequent drifting that separated the South American and African tectonic plates (Moreira et al., 2007; Chang et al., 2008). The Santos hinge line and the Outer High are the main structural elements (Figure 1). The Santos hinge line is a NE-trending structural feature subparallel to the coastline and defines the basin's western margin. The Outer High is a prominent intrabasinal high (Gomes et al., 2002, 2009). It forms a NE-SW structural closure at the Aptian level (base salt) that covers approximately 300 km in length by 100 km in width (Figure 2). This mega-structure includes a number of minor highs; Sugar Loaf, Tupi, and Buzios stand out. Libra, Jupiter, and Peroba highs are located in the nearby area (Figure 2).

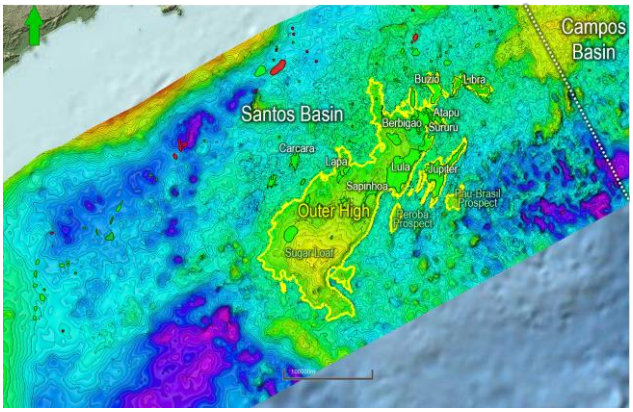

Figure 2 - *Depth structural map of the base salt or near top of pre-salt reservoirs in the Santos Basin. Outer High, the major structural feature in the basin, is highlighted in yellow.*

The Santos Basin tectono-stratigraphic evolution is traditionally divided into three major mega-sequences that are associated with the early rifting and subsequent drifting between the the South American and African plates (Mohriak and Fainstein, 2012).

- A Hauterivian to Early Aptian rift phase that was preceded and accompanied at the beginning by the extrusion of the basaltic lavas that overlie an igneous metamorphic basement and constitute the Camboriu Formation (Moreira et al., 2007). This rift sequence is characterized by half-graben structures filled in the lowermost part by the basalts of the Camboriu Formation (Chang et al., 2008) and then followed by fluvial and lacustrine sediments of the Guaratiba Group (Meisling et al., 2001; Modica and Brush, 2004; Moreira et al., 2007; Rodriguez et al., 2017). Lacustrine shale source rock with total organic content values from 2 to 6% was deposited during the final stage of this rift phase (De Oliveira, 2017). Coquina facies was deposited in the uppermost rift fill and is part of the main reservoirs of the pre-salt play.

- An Aptian to Early Albian post-rift phase comprises the Barra Velha and the Ariri Formations, deposited in a transitional environment ranging from continental to shallow marine (Moreira et al., 2007). The Barra Velha Formation consists of microbial carbonates in proximal depositional settings and carbonate shales in more distal settings. The Ariri Formation is an evaporite-rich succession characterized by multiple marine incursions and basin desiccation (Jackson et al., 2014; Rodriguez et al., 2017). The non-marine carbonate of the Barra Velha Formation is the main pre-salt reservoir and the overlying evaporites of the Ariri Formation is the main seal.

- The Albian to present drift phase, characterized by thermal subsidence and open marine conditions, resulted in the salt deposition cessation during the Albian time. The marine drift mega-sequence may be subdivided into two sequences: shallow marine platform carbonate deposits during the Albian (Guaruja Formation) and deep-marine clastic-dominated deposits from Cenomanian to present (i.e., Itanhaem to Marambaia Formation) (Modica and Brush, 2004; Moreira et al., 2007; Rodriguez et al., 2017). A rapid eustatic sea-level rise during the Cenomanian-Turonian drowned the Albian carbonate system and led to a fine-grained, clastic-dominated sucession (Jackson et al., 2015). The large Santos post-salt discoveries occur in deep-marine turbidite reservoirs.

Database and Methodology

This regional study of the Santos Basin integrates 2D and 3D seismic data with well information. The 2D seismic data are part of a large prestack depth migration database that covers all the main Brazil offshore basins from Para Maranhao in the north to the Pelotas Basin in the south. In the Santos Basin, the available 2D seismic data totals ~ 76,000 line km. 3D seismic data used in the interpretation comprise a 3D regional seismic merge of 35,200 km^2 and three high-density (HD) surveys: Guara-Carioca 3D (3,150 km^2), Jupiter 3D (4,270 km^2), and Iara 3D (3,180 km^2). All these 3D surveys are in the depth domain.

Figure 3 shows the extent of the available seismic database in the Santos Basin. Public well data offered by the Brazilian Agência Nacional do Petróleo (ANP) was incorporated into the study. Markers and composite logs from more than 50 wells shown in Figure 3 were available to constrain the seismic interpretation. The well data integration allows calibration of the interpreted near-top of pre-salt reservoir horizon displayed in Figure 2.

To improve the structural framework interpretation, seismic attribute extraction was performed. Amplitude-based attributes from the 3D seismic surveys were used to enhance the delineation of the structural features in the

area. Horizon probes were created near the top of the pre-salt reservoirs. An example of these horizon probes, in which three different types of amplitude contrast seismic attributes are integrated, is shown in Figure 4.

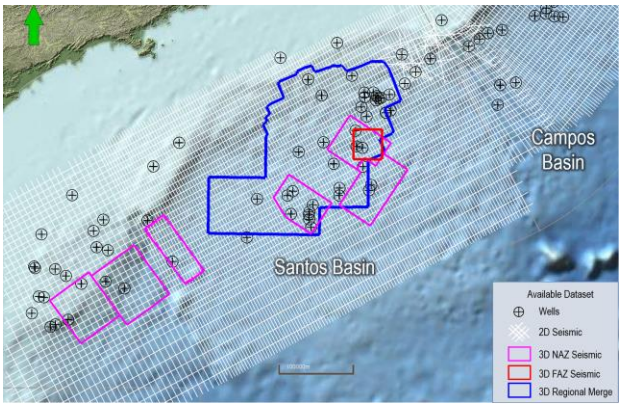

Figure 3 - *Available data set used in this study. (NAZ = narrow azimuth; FAZ = full azimuth)*

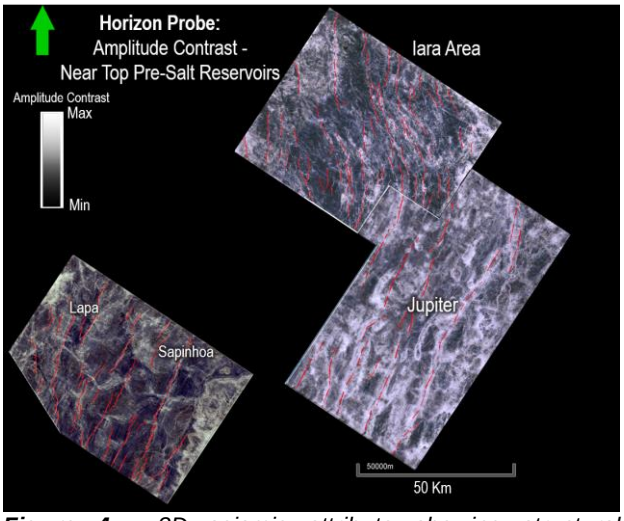

Figure 4 - *3D seismic attribute showing structural discontinuities in red (rift faults). Variation in the structural trend is observed between the Jupiter and Iara areas, changing from NE-SW to N-S.*

Regional interpreted composite sections, combining different seismic surveys and connecting key wells in the major pre-salt oil discoveries, were made. These sections enable a better understanding of the results of the pre-salt proven structures as they show the stratigraphic and structural variation below the salt. This subsurface evaluation can provide a valuable insight into how the petroleum system elements work in the Santos pre-salt play, and can help reveal new exploration opportunities in the area.

Results and Discussion

Three main stratigraphic sequences were identified on seismic data and calibrated with well information in the pre-salt interval: the lower rift, the upper rift, and the sag sequence (Figures 5 and 6).

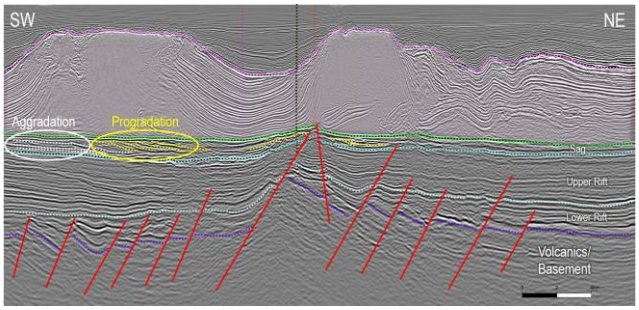

Figure 5 - *3D seismic data showing the three main stratigraphic sequences, i.e., Lower Rift, Upper Rift, and Sag, below the evaporites of the Ariri Formation (pink color).*

The volcanics of the Camboriu Fm. are at the base of the lower rift sequence and they were part of the beginning of the synrift phase (e.g., Moreira et al., 2007). The lower rift is marked by a higher extensional tectonic activity compared to the upper rift as shown in Figure 5. The divergent seismic reflection toward the downthrown sides of the normal faults denotes the syntectonic sedimentation during that sequence. The sediments of the lower rift sequence are the non-marine clastic-dominated strata of the Picarras Fm.

In the upper rift, the extensional deformation is still active, but with relatively less intensity. Parallel to sub-parallel reflections are the dominant seismic facies (Figure 5) with divergent reflections in some areas. The top of the upper rift in most of the structural high (e.g., Lula structure) constitutes an erosional unconformity (Figure 6). The upper rift sequence is composed of the lacustrine deposits of the Itapema Fm., which comprises the coquina facies.

Above the upper rift unconformity and below the Ariri evaporite Fm., the sag sequence was deposited. This sequence corresponds to the Barra Velha Fm. Seismic reflections within the sag sequence show a good amplitude contrast and the interval is mostly unfaulted. Parallel reflectors of aggradational build-ups and low-angle dip reflectors of progradational clinoforms can be observed in the sag sequence (Figure 5). Figure 6 shows the sag sequence thickness variation thinning out over paleo-highs, such as over the Lula structure and over some of the rotated fault blocks in the Jupiter area.

In the composite section in Figure 6, we notice that the western-dipping normal faults dominate in the western part of the basin and the eastern-dipping faults in the eastern part. This rift system of rotated fault blocks led to the formation of the Outer High (Gomes et al., 2009). On the eastern border of the Outer High is the Lula field, a giant oil discovery on a pre-salt rift high with significant microbialite carbonate reservoirs (Pedrinha et al., 2018) in the sag sequence (Barra Velha Fm).

Half-graben blocks of the Jupiter area form the eastern extension of the Outer High before basement deepens on the east (Figure 6). Deep-seated faults of the Jupiter structure could explain the occurrence of the high CO_2 content found in this oil/gas discovery.

Further fault interpretation was carried out over a horizon probe at the level of the near top of pre-salt reservoirs. This structural interpretation, supported by seismic attribute, shows the rotation of the normal fault systems in the basin. As can be seen in Figure 4, NE-SW trending normal faults change orientation towards the north to a N-S trend. Rotation in the structural trend could be ascribed to the interaction of the Early Cretaceous transfer zones (Meisling et al., 2001) with an oblique rift system.

Mapping the base salt was carried out for the whole Santos Basin, combining 3D and 2D seismic interpretation (Figure 2). Priority was given to the interpretation from the HD surveys for the base salt merged horizon and, secondary, to the regional 3D merge. This depth structural map reflects the near top of the pre-salt reservoirs. The major structural feature recognized in that map is the Santos Outer High, where most of the giant pre-salt discoveries have been found. It could indicate that this basement high was key in the pre-salt reservoir distribution, controlling the deposition of lacustrine carbonates (Carlotto et al., 2017).

A 3D view of part of the base salt map in Figure 7 shows major pre-salt fields and exploration opportunities in the Santos Basin. Based on the Jupiter 3D, exploration opportunities were identified and delineated within the Block Cruzeiro do Sul where structural closures seem to extend from the Jupiter discovery. Pre-salt prospects that were identified in the basin are also recognized in the 3D view; e.g., Peroba and Pau-Brasil. Peroba is south of the Lula field and on the same structural trend. To the east of the Jupiter discovery, the 3D structural view displays the Pau-Brazil pre-salt opportunity.

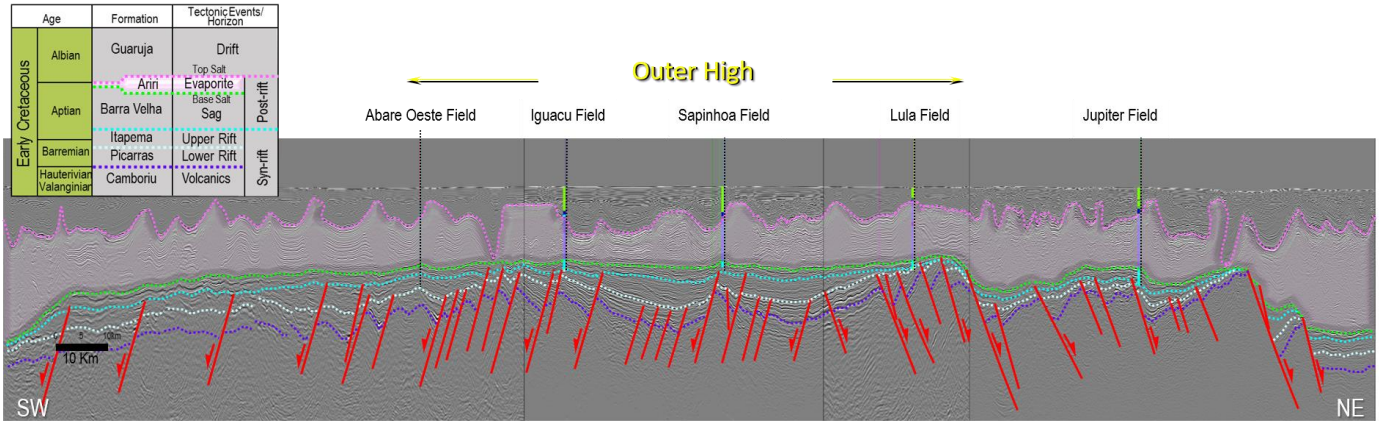

Figure 6 - *3D seismic composite section in depth through some of the major pre-salt oil discoveries in Santos Basin.*

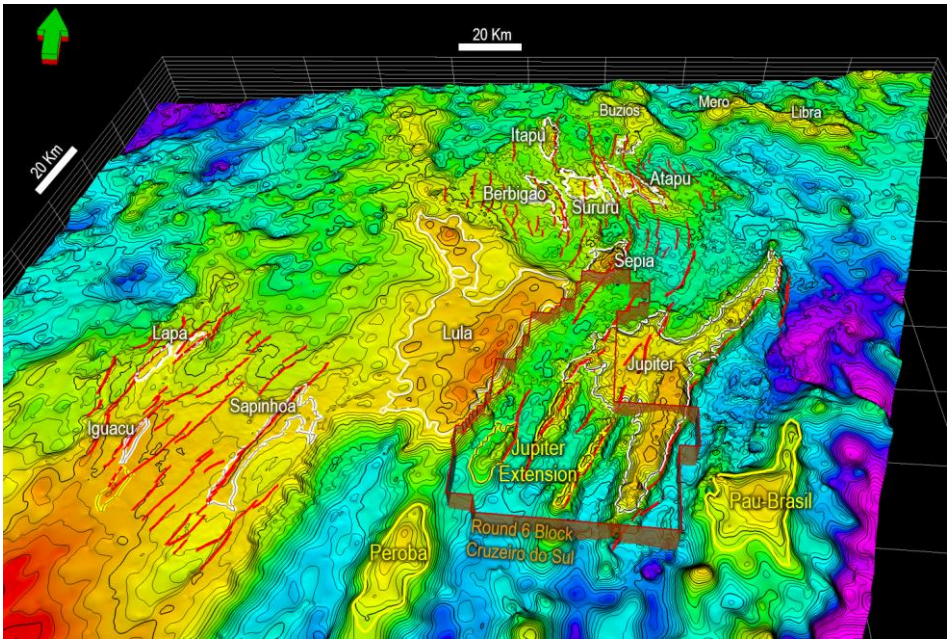

Figure 7 - *3D structural view in depth of the near top of the pre-salt reservoirs showing the major oil discoveries (white polygons) in the Santos Basin. Exploration opportunities are indicated by yellow polygons.*

Conclusions

- This study provides a regional overview of the Santos Basin based on the integration of 3D and 2D seismic data with well information. This work helps to improve the understanding of the petroleum system elements from basin scale to prospect level.
- Three main seismic sequences were recognized in the pre-salt interval: the lower rift, the upper rift, and the sag sequence. The microbialite carbonates, that are the primary reservoirs of the pre-salt play, were deposited within the sag sequence.
- The major structural feature identified in the base salt map of the Santos Basin is the Outer High that seems to play a key role in the deposition of the lacustrine carbonate reservoirs.
- Fault interpretation based on 3D seismic attributes reveals rotation in the structural trend changing from NE-SW to N-S. This change in the rift fault systems orientation could be due to the presence of transfer zones during the Early Cretaceous.
- Pre-salt exploration opportunities were identified in the Block Cruzeiro do Sul based on 3D seismic interpretation. They are proposed to be lateral extensions of the Jupiter discovery.

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References

ANP, AGÊNCIA NACIONAL DO PETRÓLEO, GÁS NATURAL E BIOCOMBUSTÍVEIS. Boletim da Produção de Petróleo e Gás Natural, November 2018. No. 99, 32p., 2018.

CARLOTTO, M.A., BAPTISTA DA SILVA, R.C., YAMATO, A.A., TRINDADE, W.L., PINHEIRO MOREIRA, J.L., ROSA FERNANDES, R.A., SOARES RIBEIRO, O.J., PERES GOUVEIA JR., W., CARMINATI, J.P., QICAI, D., JUNFENG, Z., DA SILVA-TELLES JR, A.C. Libra: A newborn giant in the Brazilian Presalt Province. In: R. K. Merrill and C. A. Sternbach, eds., Giant fields of the decade 2000–2010, AAPG Memoir 113, p. 165-176, 2017.

CHANG, H.K., ASSINE, M.L., CORRÊA, F.S., TINEN, J.L., VIDAL, A.C. AND KOIKE, L. Sistemas petrolíferos e modelos de acumulação de hidrocarbonetos na Bacia de Santos. Revista Brasileira de Geociências, 38: 29-46, 2008.

DE OLIVEIRA FERNANDEZ, R. Bacia de Santos Sumário Geológico e Setores em Oferta. Brazil, Round 15, ANP, 19 p., 2017.

GOMES, P.O., PARRY, J., AND MARTINS, W. The outer high of the Santos Basin, southern São Paulo Plateau, Brazil: Tectonic setting, relation to volcanic events and some comments on hydrocarbon potential. AAPG, Search and Discovery Article # 90022, 2002.

GOMES, P.O., KILSDONK, B., MINKEN, J., GROW, T., AND BARRAGAN, R. The outer high of the Santos Basin, Southern São Paulo Plateau, Brazil: Pre-salt exploration outbreak, paleogeographic setting, and evolution of the syn-rift structures. AAPG, Search and Discovery Article #10193, 2009.

JACKSON, C.A.L., RODRIGUEZ, C.R., ROTEVATN, A., AND BELL, R.E. Geological and geophysical expression of a primary salt weld: An example from the Santos Basin, Brazil. Interpretation, v. 2, p. SM77–SM89, 2014.

JACKSON, C.A.L., JACKSON, M.P., AND HUDEC, M.R. Understanding the kinematics of salt-bearing passive margins: A critical test of competing hypotheses for the origin of the Albian Gap, Santos Basin, offshore Brazil. Geological Society of America Bulletin, v. 127, p. 1730-1751, 2015.

JUAREZ FEIJO, F. Santos Basin: 40 years from shallow to deep to ultra-deep water. AAPG, Search and Discovery Article #10553, 2013.

IHS. Lula Field Summary Report. 64p., 2019.

MEISLING, K.E., COBBOLD, P.R., AND MOUNT, V.S. Segmentation of an obliquely rifted margin, Campos and Santos Basins, southeastern Brazil. AAPG Bulletin, v. 85, p. 1903-1924, 2001.

MODICA, C.J., AND BRUSH, E.R. Postrift sequence stratigraphy, paleogeography, and fill history of the deep-water Santos Basin, offshore southeast Brazil. AAPG Bulletin, v. 88, p. 923-945, 2004.

MOREIRA, J.L.P., MADEIRA, C., GIL, J.A., AND MACHADO, M.A.P. Bacia de Santos. Bulletin Geociencias Petrobras, v. 15, p. 531-549, 2007.

MOHRIAK, W.U., AND FAINSTEIN, R. Phanerozoic regional geology of the eastern Brazilian margin. In: D.G. Roberts and A.W. Bally, editors: Geology and tectonics: phanerozoic passive margins, cratonic basins and global tectonic maps, Vol. 1c, Elsevier, The Netherlands, p. 222-283, 2012.

PEDRINHA, S., ARTAGÃO, V., MOREIRA, T.P., FREITAS, L.C.S., RICHTER, E., AND SANTOS, B.T. Reservoir geology aspects of Lula supergiant field, Santos Basin - Brazilian pre-salt province. AAPG ACE Abstract, Search and Discovery, 2018.

RODRIGUEZ, C.R., JACKSON, C.A.L., ROTEVATN, A., BELL, R.E., AND FRANCIS, M. Dual tectonic-climatic controls on salt giant deposition in the Santos Basin, offshore Brazil. Geosphere, v. 14, no. 1, p. 1-28, 2017.

SANDWELL, D.T., MÜLLER, R.D., SMITH, W.H., GARCIA, E. AND FRANCIS, R. New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. Science, 346(6205), p. 65-67, 2014.

VIEIRA, J. Brazil Round 9 - Santos Basin. ANP, 73p., Accessed 2017-09-04, 2007.