Seismic stratigraphy and structural analysis of the pre-salt of Santos Basin and its implications on basin evolution

Introduction

The Santos Basin has attracted great attention from both the petroleum industry and academia during the last decade due to several oil and gas discoveries in the pre-salt province, culminating in the production of over 1 million oil barrels per day (Abelha and Petersohn, 2018). The presence of syn-rift structures and the thick salt layer overlying the lacustrine carbonate reservoirs comprise effective seals. Investigating the geometry of those structures is paramount to highlight areas that might constitute prospective reservoirs and understand the evolution of the continental margins.

The area of interest is located 250 km (160 mi) offshore Rio de Janeiro, at ultradeep waters (>2000 m). The simplified tectonostratigraphic evolution of the Santos Basin (Moreira et al. 2007; Karner and Gambôa 2007) at the study interval includes a Neocomian rift phase, characterized by the occurrence of basalts (Camboriú Formation) that marks the opening of the South Atlantic Ocean. The overlying lacustrine calcarenite and marls from the Itapema Formation were deposited during the Barremian, coinciding with the transition from the rift to the post-rift stage. During the Aptian, the post-rift sequence was characterized by the deposition of lacustrine carbonates from the Barra Velha Formation, which comprises the main reservoir interval of the Santos Basin. Overlying the carbonates, there is a salt domain (Ariri Formation), which dates from the Aptian-Albian boundary. The salt layer geometry is distinguished by the presence of pinnacles and diapirs, as well as thin salt layers from a restricted shallow lacustrine depositional setting.

The main objective of this study is to assess the geometry of the faults offsetting the pre-salt carbonate reservoirs of the Santos Basin. We also aim at constraining the basin configuration to provide a revised tectonostratigraphic evolutionary model of Santos Basin.

Data and Methods

The dataset for this study comprises a high-quality 3-D pre-stack seismic data previously processed and migrated using Kirchhoff pre-stack migration. It resulted in a 3-D post-stack volume with a 12.5 x 12.5 m grid line spacing from which a smaller volume was cropped based on a superficial area of 2180 km². The vertical extent of the seismic survey is limited to 6.5 s Two-way travel time (TWTT). Seismic interpretation for Santos Basin is displayed in the standard SEG polarity convention for a zero-phase wavelet, with peaks of acoustic impedance shown as red reflections on seismic profiles and decreases in acoustic impedance as blue seismic reflections. 4 wells drilled at depths around 4000 m below the seafloor were also used for the seismic well-tie calibrations and to correlate petrophysical parameters with seismic attributes and the lithology described from cores for wells B and C.

One hundred and fifteen (115) faults were mapped every inline (12.5 m), and every five crosslines (62.5 m). Structural seismic attributes algorithms were applied to image the faults in the study area (Chopra and Marfurt, 2008; Torabi et al., 2017). Variance provided a delineation of the structural information of the study area (Figure 1a). To eliminate the noise in the input seismic data and further highlight the fault geometry, the 3D Edge Enhancement and Median Filtering attribute volumes were generated and used in the fault imaging (Figure 1b). The fault geometry was assessed through the creation of a structural framework that allowed the classification of the faults into three families related to their strike. Displacement analysis including displacement-length (D-x) and throw-depth (T-z) plots were undertaken to ten faults to depict the onset of faulting and investigate the mechanisms of fault growth and propagation (Baudon and Cartwright, 2008).

Six (6) key horizons, including the sea floor, were mapped at a spacing of five (5) seismic lines. In areas around igneous intrusions, smaller intervals of 1-3 lines (12.5 to 37.5 m) were used to map the horizons corresponding to the reservoir intervals to provide more reliable isochron thickness maps. Seismic attributes, directly correlated with the lithological core descriptions, show the lithological variation between inline and crossline intervals to identify three-dimensional variations of stratigraphic and
structural features of the carbonate lithologies (Hart, 2008). These include Instantaneous Phase using a window of 198°, Relative Acoustic Impedance at a low-cut frequency of 5 Hz, Generalized Spectral Decomposition with two cycles in the wavelet and frequency of 5 Hz at a phase of 90° and filter length of 5, and Sweetness using a window of 33°.

Figure 1 Seismic attributes time-slice at -5000 ms. a) Variance time-slice showing a delineation of the structures despite exhibiting seismic noise. b) The same time-slice after applying 3D Edge Enhancement and Median Filtering algorithms to highlight the discontinuities representative of faults and reduce the seismic noise.

Seismic stratigraphy of the Santos Basin

Based on the character and geometry of the interpreted seismic sections and the lithostratigraphic data from the well logs, three main units were defined in the study area (Figure 2): Valanginian-Hauterivian (Unit 1), Barremian-Aptian (Unit 2), and Albian-Pleistocene (Unit 3).

The lower boundary of Unit 1 is not clearly distinguished in the seismic cube. The top of this unit is marked by horizon H1, which is a moderate to high-amplitude positive reflection. This unit is characterised by low amplitude to transparent seismic reflections that are chaotic to the south and somewhat continuous to the north of the study area. It corresponds to the rift phase basalts of Camboriú Formation and consists of the basement where the reservoir units overlie. Most of the mapped faults initiate at this unit and propagate to the base of the salt deposits at the top of Unit 2.

The Unit 2 is the primary unit of interest in this study and represents the Barremian-Aptian, which is bounded at the base by horizon H1, and at the top by horizon H5. This unit is divided into sub-units 2a, 2b, and 2c. Sub-unit 2a is bounded at the base by horizon H1 and at the top by horizon H2 and comprises medium to high amplitude sub-parallel seismic reflections offset by faults. This sub-unit corresponds to the shales and siltstones from Piçarras Formation at the base and the coquinas of Itapema Formation towards the top. Sub-unit 2b is bounded at the base by horizon H2 and to the top by horizon H3 comprising low to moderate internal reflections in the centre and moderate to high amplitude sub-parallel internal reflections near the lower and upper boundaries. Well log and core data indicate this interval corresponds to the lacustrine deposits of the Barra Velha Formation, consisting of spherulites, shrubs and minor laminites and calcarenites and comprises the main reservoir interval of the pre-salt of the Santos Basin. Fewer faults offset this sub-unit in comparison to the previous sub-unit. Sub-unit 2c consists of Aptian salt deposits overlying the carbonates from the Barra Velha Formation. The diapir domain of this sub-unit is limited by the unconformity defined by horizon H3 at the base and by horizon...
H4 at the top and is characterised by chaotic to transparent seismic reflections. Most of the interpreted faults do not reach the salt interval (Sub-unit 2c). The upper part of this sub-unit is delimited by horizons H4 and H5 and is characterised by continuous moderate to high amplitude folded reflections representing stratified evaporite deposits of the Ariri Formation.

Unit 3 is bounded by the horizon H5 at the base and the sea floor at the top corresponding to the Albian-Pleistocene interval and the drift phase of the basin evolution, characterised by low to moderate amplitude seismic reflections faulted at the crest of salt diapirs.

Figure 2 Interpreted seismic line of the Santos Basin highlighting the seismic-stratigraphic units and the faults in the study area.

Fault distribution in the study area

The structural interpretation of the seismic lines and the seismic attribute volumes resulted in the establishment of fault framework for the study area that allowed to identify three fault families in terms of their strike (Figure 3a): a) to the north the faults trend to NW, b) to the west the faults are nearly N-S and c) to the southeast the faults strike NE-SW. The spacing between the NW-SE and the N-S-striking faults to the north is small with most faults offsetting the interval spanning from Unit 1 to the top of sub-unit 2b, whereas in the central portion of the study area there is more space between faults. To the southeast, the NE-SW-striking faults form half-grabens and reach mostly the interval corresponding to the basalts from Camboriú Formation, as the sedimentary cover is thin due to the predominance of igneous intrusions in this area (Figure 1). Interestingly, the faults to the southeast part of the study area have the largest lengths and dips ranging between 20 and 30°, while to the north the dips vary between 40 and 60° (Figure 3b). Throw-depth measurements for the representative faults indicate that the maximum throws occur at the horizon H1 and displacement analysis indicate the nucleation of segments comprising the faults to southeast, pointing to the occurrence of reactivation episodes related to the uplift of the basement during the opening of the South-Atlantic.

Conclusions

The interpreted seismic dataset allowed to identify the controls the basement exert in the fault geometry and evolution of the Santos Basin following the onset of the basin opening. Three stratigraphic units limited by six key-horizons were identified in the study area. Unit 1 encompasses the rift-phase basalts from Camboriú Formation. Unit 2 comprises de post-rift deposits and is subdivided into three sub-units represented by (2a) shales and coquinas from Piçarras and Itapema Formation, (2b) lacustrine carbonates from Barra Velha Formation, and (2c) salt deposits from Ariri Formation, respectively. Lastly, Unit 3 contains carbonate and siliciclastic drift-phase deposits dating from Albian up to Pleistocene. Three main fault families were recognized: a) NW-trending faults occur at the north of the study area and reach Unit 1 until the top of sub-unit 2b; b) N-S faults are situated in the western region also
offsetting Unit 1 and sub-unit 2b and c) faults with strike NE-SW that have the largest lengths and occur in the southeast of the study area reaching mainly Unit 1. The opening of the South Atlantic and the consequent development of accommodation space that now comprises the Santos Basin was subject to extension and uplift episodes during the Early Cretaceous, with the southeastern part of the study area more active than its northern counterpart.

**Figure 3** Structural framework for the interpreted faults in the Santos Basin. a) Faults were subdivided into three families in terms of strike, with the southeast area characterised by faults striking to NE-SW. b) Fault dip ranges between 40 to 60º to the north of the study area, and between 20 to 30º to the southeast.

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**References**

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