INTRODUCTION

Carbonate deposits result from the synergism between sediment production and accommodation creation. However, the intrinsic complexity of these rocks concerning the different modes of sediment precipitation and the extreme sensitivity to diagenetic processes makes mapping facies and interpreting sequences a challenging task.

For that reason, understanding the mechanisms of carbonate precipitation has been one of the keystones for building...
conceptual models to explain marine carbonate systems and their worldwide distribution. The first model was proposed by Chave (1967), who identified the occurrence of cool-water carbonates in modern oceans, and, along with Lees and Buller (1972) and Lees (1975), established the conceptual framework for cool-water carbonate deposition. These observations led to a major improvement in understanding depositional environments with regard to water temperature, energy and resulting facies associations (Wilson, 1975; Tucker, 1991).

Rao (1996), Betzler et al. (1997) and Pasley et al. (1998) suggested models for the geographic distribution of carbonate platforms based on climate and bathymetric data. Since then there have been many studies evaluating global trends for carbonate deposition (Halfar et al., 2004; Kiessling et al., 2007; Rasini, 2011) which suggest that marine carbonates are not randomly distributed, neither in the Modern nor in the past (Lees, 1975; Carannante et al., 1988; Schlager, 2005; Kiessling et al., 2007; Markello et al., 2008; Michel et al., 2019).

By observing modern carbonate systems, at a carbonate platform scale, Schlager (2000; 2003; 2005) defined and individualized three different marine precipitation modes based on stratigraphic and diagenetic principles, that is T/tropical, C/cool water and M/microbial or mud-mound factories, each factory with its own characteristics regarding mineral composition, depth range for sediment production and growth potential (Schlager, 2005).

Many subsequent efforts to discriminate different factories and establish specific settings further refined this concept (Pomar and Hallock, 2008; Michel et al., 2019) and provided sufficient foundation to identify global trends for factories occurring in modern oceans (Lokier et al., 2018; Michel et al., 2019) and in the geological record (Abadi et al., 2017; Brandano et al., 2017; Pohl et al., 2018; Wu et al., 2019).

Although the factory concept is a simplification, it can provide a better understanding of the marine carbonate systems and the relationship between stratigraphy and facies associations with ecosystem variables, such as water temperature, salinity and climate through time. The main objective of this paper is to discuss features indicative of different carbonate factories active during the Albian in the South Atlantic passive margin basins, and the tectonic-stratigraphic evolution of this succession, based on the analysis of the stratigraphic framework of the carbonates in the Campos Basin.

1.1 | Carbonate factory concept

A carbonate factory is a carbonate precipitation mode defined by an ecosystem (cf. James and Jones, 2015; Michel et al., 2019). Definitions of factories come from the Modern because they are characterized by functional traits, that is, ecological functions of biota and driven by universal physico-chemical rules (Michel et al., 2019). Although grain types have changed throughout the Phanerozoic, fundamental characteristics of factories such as oceanographic drivers, ecological systems and sedimentary behaviours remain valid (Michel et al., 2019), and therefore, the concept is applicable for the geological record.

Schlager (2000; 2003) generalized the marine precipitation modes defining three benthic carbonate factories (Pomar and Hallock, 2008): (a) A tropical or T-factory comprises warm water environments within the photic zone. In this factory, biologically controlled deposition is predominant and carbonate constructions are typical due to the intense biological activity associated with fast cementation (Schlager, 2005). (b) A cool water or C-factory spans photic or aphotic depths in cold-water regions (Schlager, 2005). The precipitated products consist of sand-sized skeletal fragments (Schlager, 2000; 2003; 2005). (c) A mud-mound or M-factory covers nutrient-rich waters with low oxygen levels at depths within the disphotic or aphotic zones (Schlager, 2000; 2003; 2005). Such a system has been called a benthic automictic factory (Pomar and Hallock, 2008) and, although not well-constrained in the modern oceans, it predominates through much of the Triassic (Pomar and Hallock, 2008).

Schlager (2005) also clarified the sediment characteristics, platform geometry and responses expected for each of the factories based on sea-level (SL) changes. Despite the improved understanding of these systems following their definition, their complexities remain a challenge. One of the persistent doubts concerns factory transitions, which are often arbitrarily delimited based on theoretical models (Schlager, 2000). Ancient deposits that show factory changes are infrequent (Albert-Villanueva et al., 2019; Wu et al., 2019) and such evidence in the geological record is therefore a topic of discussion.

1.2 | Sequence stratigraphy in carbonate systems

The sequence stratigraphy method applies to all types of deposits. However, there are fundamental disparities between carbonate and siliciclastic deposits (Tucker et al., 1993; Schlager, 2005; Catuneanu, 2006; Moore and Wade, 2013). These differences are related to the geometry of the deposits and, most importantly, to the origin of the sediments (Schlager, 2005; Moore and Wade, 2013). In carbonate systems, the sediments originate in the basin and undergo little or no transport. It means that the aggradation, in this case, is conditioned almost exclusively by precipitation (Schlager, 2005).

Besides that, the range of favourable environmental conditions for carbonate precipitation within factories is relatively...
narrow and directly controlled by base-level (BL) variations. It has decisive implications in the understanding of the stratigraphic arrangement.

The highstand system tract (HST) in carbonate systems tends to favour deposition (Catuneanu, 2006) because it causes large-scale drowning of the coastal area so that the optimal conditions for sediment production are achieved in a vast area. There are three types of HSTs: Type-I HST is an initial system tract that leads to flooding and development of the carbonate platform; Type-II HST is a regular system tract implanted after transgressions; and Type-III, the final system tract, in which the accommodation generation is significantly higher than sediment production and results in drowning of the platform (Catuneanu, 2006).

Due to the high deposition rate, by the end of the HST, most of the available accommodation space is filled. It means that the falling stage system tract and the lowstand system tract occur under shallow-water conditions that prevail in most of the shelf. Hence, any BL drop leads to forced regression and subaerial exposure (Catuneanu, 2006).

In ramps, a base drop may lead to a generalized facies progradation, with subaerial exposure restricted to coastlines, carbonate banks or structural highs (Tucker et al., 1993). For that reason, T-factory carbonates usually do not form deposits of significant thickness during the BL drop stages (Schlager, 2005).

The transgressive system tract (TST) may favour sediment production depending on the rate of the BL rise. Commonly, BL rise is more substantial than the platform's aggradation rate, leading to a significant increase in the water depth and reduction in sediment production (Catuneanu, 2006). In the T-factory carbonates during the transgressive stage, the water depth increases, and the open sea conditions expand at the top of the platform, forming cycles with a deepening-upward pattern (Schlager, 2005).
1.3 | Geological Setting

The Campos Basin is a passive margin basin located in south-eastern Brazil (Figure 1A) formed during the break-up of Gondwana and the opening of the South Atlantic Ocean (Asmus and Porto, 1972). It extends for approximately 100,000 km² (Milani and Araújo, 2003). Structurally, it is limited to the north by the Vitória Arc and the south by the Cabo Frio Arc (Mohriak et al., 1990).

The extensional activity that led to the formation of the basin started in the Late Jurassic (Mohriak and Fainstein, 2012). At this stage, mechanical subsidence initiated through episodic events and reactivated the structures of the Proterozoic basement under regional extension in an E-W direction (Ponte and Asmus, 1976; Rabinowitz and Labrecque, 1979; Dias et al., 1990; Chang et al., 1992; Karner, 2000; Fetter, 2009).

In the syn-rift stage, the lithospheric stretching increased, and the basement was configured in a horst-graben geometry (Chang et al., 1992). Lacustrine sediments of Barremian age filled the low-relief zones, originating the syn-rift megasequence.

In the Aptian, during the transitional stage, an evaporitic succession was deposited under thermal subsidence (Fetter, 2009). In the Albian, the divergent margin stage started and the post-rift megasequence formed. This megasequence is characterized by marine sediments deposited under the influence of thermal subsidence and halokinesis (Winter et al., 2007).

1.4 | Stratigraphy of the Campos Basin

The Campos Basin has three sedimentary supersequences named rift, transitional and drift (Winter et al., 2007; Figure 2). The rift supersequence is composed of continental sediments deposited under the direct influence of the basement’s structural framework (Guardado et al., 1989).

The transitional supersequence includes sediments deposited in continental and marine environments (Guardado et al., 1989). It represents an intermediate phase of basin evolution when both thermal and mechanical subsidence occurred. In the offshore region, a massive salt layer was deposited during this period. In the Campos Basin, this unit is named the Retiro Formation (Winter et al., 2007), equivalent to the Ariri Formation in the Santos Basin (Chang et al., 1992; Cainelli

| (Ma) | PERIOD | EPOCH | AGE | DEPOSITIONAL ENVIRONMENT | LITHOSTRATIGRAPHY GROUP | FORMATION | MAIN TECTONIC EVENTS | GLOBAL SEA-LEVEL VARIATION |
|------|--------|-------|-----|---------------------------|------------------------|-----------|----------------------|---------------------------|
| 70   |        | LATE  |     | Deep Marine               | Campos                 |           |                      |                           |
| 80   |        |       |     |                           |                        |           |                      |                           |
| 90   |        |       |     |                           |                        |           |                      |                           |
| 100  | CRETACEOUS |       |     | Transgressive Marine      | Deep Marine            |           |                      |                           |
| 110  |        |       |     |                           |                        |           |                      |                           |
| 120  | EARLY  |       |     | Shallow Platform          | Restricted/ Lagoon     |           |                      |                           |
| 130  |        |       |     |                           |                        |           |                      |                           |
| 140  |        |       |     |                           |                        |           |                      |                           |
| 150  |        | LATE  |     | Continental               | Lacustrine             |           |                      |                           |
| 160  |        |       |     |                           |                        |           |                      |                           |
| 170  |        |       |     |                           |                        |           |                      |                           |
| 180  |        |       |     |                           |                        |           |                      |                           |
| 190  |        |       |     |                           |                        |           |                      |                           |

**Figure 2** Stratigraphic chart of the Campos Basin. Outlined in red is the studied interval. Modified from Winter et al. (2007)
FIGURE 3  Procedure for lithotypes definition by cluster analysis
and Mohriak, 1999; Moreira et al., 2007). In the African margin it is associated with the Loeme Salt in the Congo Basin (Pasley et al., 1998; Brownfield and Charpentier, 2006) and the Massive salt unit in the Kwanza Basin (Brognon and Verrier, 1966; Burwood, 1999; Brownfield and Charpentier, 2006).

The drift supersequence was deposited from the Albian to the Pleistocene under a thermal subsidence regime associated with halokinesis (Winter et al., 2007). The Macaé Group, which includes the formations investigated in this study, is part of this supersequence.

The basal formation of the Macaé Group, Quissamã, is characterized by calcilutites, shales, marlstones and oolitic/oncolitic calcarenites. This unit was deposited in a restricted epicontinental sea under hot and dry climate conditions (Spadini et al., 1988). The Outeiro Formation contains calcilutites, marlstones and shales intercalated with sandstone bodies, originated by gravitational flows (Castro and Picolini, 2014). It was deposited in a deep marine environment.

The final unit of the Macaé Group is the Imbetiba Formation, which contains marlstones and calcilutites from deep marine depositional environments (Winter et al., 2007).

The Macaé Group is equivalent to the Guarujá Formation in the Santos Basin (Chang et al., 1992; Cainelli and Mohriak, 1999; Moreira et al., 2007) and to the Pinda-Catumbela Formation in the Congo Basin (Pasley et al., 1998; Brownfield and Charpentier, 2006).

2 STUDY AREA, DATASET AND METHODS

2.1 Seismic and Well Data

The present study employed 21 2D seismic lines, one 3D seismic volume of 150 km² in area and eight wells (Figure 1B). All data were provided by the ANP (National Agency of Petroleum, Natural Gas and Biofuels) through the public data policy. The seismic data were obtained post-stack and time-migrated and interpreted in Petrel Software using the normal display polarity according to the SGE convention. The well data contained basic logs: gamma-ray (GR), density (RHOB), neutron (NPHI), sonic (DT) and caliper (CAL), in addition to the description reports and composite profiles.

The lithological interpretation was carried out with the sample description reports, along with a multivariate analysis based on the spatial association of density (RHOB), neutron (NPHI), gamma ray (GR) and sonic (DT) logs. Caliper logs assured the data reliability, indicating zones of well wall collapses.

The petrophysical analysis differentiated seven electrofacies for the full thickness of the eight wells. As follows:

(a) Sandstones, (b) Mud-dominated carbonates, (c) Grain-dominated carbonates, (d) Carbonate mud, (e) Shale, (f) Anhydrite and (g) Halite (Figure 3). Once the electrofacies were defined, the description reports allowed the main classes to be differentiated into 15 facies. The results obtained were represented in stratigraphic columns designed in the software SedLog and edited in CorelDraw on a scale of 1:5,000.

The well-seismic tie was accomplished between the 3D seismic volume and wells 2, 3 and 6. The procedure was achieved through a synthetic seismogram generated over a reflectivity series obtained with sonic (DT) and density (RHOB) logs. The time–depth relationship was estimated from the sonic profile and calibrated with the check-shot data. Finally, a wavelet extraction was performed using a statistical approach to obtain a pulse in the seismic window of interest.

Although the data are publicly accessible, not many wells drilled in the study area reached the depth of the Albian carbonates because the target was principally the Marlim complex oilfields, well-known giant fields in the Upper Cretaceous turbidite reservoirs. Historically, most of the data were acquired from these rocks which are above the zone of interest for this study. Direct rock data are limited and difficult to access, so indirect approaches were employed using petrophysics and statistics.

2.2 Facies Analysis

Facies analysis was carried out using the results obtained via petrophysical analysis, correlated with the description reports. This procedure followed Miall’s (1996) methodology, which considers that similar depositional environments generate similar depositional products. The facies nomenclature is in alphabetical order, from coarse-grained to fine-grained facies. Genetically related facies were grouped in facies associations.

By way of comparison and to confirm well descriptions, facies identified in the studied wells were verified in the literature. These included studies that employed samples from the Macaé Group where this unit is a reservoir in the Campos Basin (Favoreto, 2014; Okubo, 2014; Okubo et al., 2015).

The interpretation of sedimentary processes, energy levels and depositional setting of each facies was based on the characteristics of its constituents: the amount of matrix, type and nature of grains, absence/presence of skeletal particles and character of the bioclastic components. For example, the matrix percentage was indicative of the energy level (Wilson, 1975; Tucker and Wright, 1990; Hanken et al., 2010; More and Wade, 2013). Ooids indicate settings with wave or tidal agitation so that the nuclei are continuously moved and precipitation occurs regularly on the grain surface (Wilson, 1975; Tucker and Wright, 1990; Scholle and Ulmer-Scholle, 2003;
| Code | Facies                          | Description                                                                 | Bioclastic components                      | Interpretation                                                                 |
|------|--------------------------------|-----------------------------------------------------------------------------|---------------------------------------------|--------------------------------------------------------------------------------|
| A    | Oolitic/oncolitic grainstone   | Brownish, medium to coarse. Well-sorted rounded grains. Partial micritization and dolomitized matrix | Echinoids, foraminifera and mollusc fragments | Shallow water conditions and moderate to high energy associated with oscillatory subaqueous flow |
| B    | Bioclastic grainstone          | Brownish, medium to coarse. Subrounded grains and moderately to poorly sorted | Foraminifera, mollusc fragments              | Shallow water conditions with high hydrodynamic conditions                      |
| FC   | Peloidal grainstone            | Whitish, medium to coarse                                                   | Echinoids and foraminifera                  | Shallow water conditions and moderate to high energy associated with oscillatory subaqueous flow in protected environment |
| D    | Oolitic/oncolitic packstone    | Greyish, fine to medium, Well-sorted rounded grains                          | Echinoids and foraminifera                  | Relatively shallow water conditions and moderate to high energy associated with oscillatory subaqueous flow |
| E    | Bioclastic packstone           | Greyish, fine, irregular grains, poorly sorted                              | Echinoids and foraminifera                  | Shallow water conditions and moderate to high energy                           |
| F    | Peloidal packstone             | Greyish, fine to medium                                                      | Echinoids and foraminifera                  | Shallow water conditions and moderate to high energy associated with oscillatory subaqueous flow |
| G    | Bioclastic wackestone          | Brown, fine to medium, laminated, poorly sorted                              | Echinoids and calcispheres                  | Shallow to medium water laminae with subaqueous decantation                    |
| H    | Peloidal wackestone            | Light brown, fine, poorly sorted                                             | Radiolarians, echinoids and red algae       | Medium to deep water laminae, in a low energy setting                           |
| I    | Oolitic/oncolitic wackestone   | Light brown, fine to medium, well-sorted grains                              | Echinoids and foraminifera                  | Shallow to medium water laminae and moderate energy associated with oscillatory subaqueous flow |
| J    | Mudstone                       | Whitish, fine                                                                | Foraminifera, red algae                     | Subaqueous decantation                                                         |
| K    | Marlstone                      | Light grey to off-white, laminated                                           | Foraminifera, red algae                     | Subaqueous decantation                                                         |
| L    | Dolostone                      | Brownish, fine, saccharoidal with homogeneous aspect                         | Not identified                              | Diagenetic origin                                                              |
| M    | Anhydrite                      | White, semi-hard                                                             | None                                        | Subaqueous decantation                                                         |
| N    | Shale                          | Dark grey, laminated                                                         | Foraminifera                                | Subaqueous decantation                                                         |
| O    | Siltstone                      | Brownish, laminated                                                          | Not identified                              | Subaqueous decantation                                                         |
Hanken et al., 2010). Oncoids are formed by a less uniform process (Wilson, 1975; Tucker and Wright, 1990) and occur in shallow settings with low to moderate turbulence (Hanken et al., 2010). Peloids form by extensive micritization of pre-existing carbonate grains, in settings with lower agitation (Tucker and Wright, 1990) and in areas subjected to occasional storms that move grains from active areas of formation to quiet sites (back-barrier, back-bar grass flats, lagoons and protected deeper shelf settings (Scholle and Ulmer-Scholle, 2003).

The interpretation of the bioclastic components was used carefully since none of them occur strictly in one environment. Red algae and foraminifers are more common in shallow-water and high luminosity settings (Scholle and Ulmer-Scholle, 2003; Armstrong and Brasier, 2005) but both have a wide range of occurrence (Scholle and Ulmer-Scholle, 2003). The same situation occurs with calcispheres and mollusc fragments which need to be classified to give environmental information, since they can be transported far from their site of formation (Scholle and Ulmer-Scholle, 2003). Fossil forms of echinoids are most common in normal marine, open shelf or platform deposits (Scholle and Ulmer-Scholle, 2003). Radiolarians are found at all depths in modern oceans and are common constituents of pelagic deposits throughout the Phanerozoic (Scholle and Ulmer-Scholle, 2003).

2.3 Seismic Stratigraphy Analysis

The interpretation of seismic data followed four main stages. Initially, the structural domains were identified in the area by interpreting faults. Then followed the interpretation of the primary reflectors: base and top of the salt layer, the top of Albian carbonates and the ‘blue marker’, a negative, high amplitude reflector of regional occurrence (Winter et al., 2007).

Subsequently the analysis of reflection terminations within the units provided information on the accommodation conditions at the time of deposition and assisted in the identification of key surfaces. The final procedure was the interpretation of stratigraphic units and their boundaries guided by the well data. At this stage, sequence boundaries were interpreted based on the geometry of the reflectors, stratal terminations and the information provided by the wells.

3 RESULTS

3.1 Lithofacies analysis

Based on the petrophysical analysis and description reports, 15 lithofacies were identified (Table 1).

3.1.1 Facies associations

The facies were grouped into seven facies associations based on depositional characteristics and occurrence (Table 2).

### Table 2

| Sequence | Facies association                          | Facies set | Palaeoenvironmental interpretation                        |
|----------|--------------------------------------------|------------|----------------------------------------------------------|
| S1       | Lagoon Facies Association (FA1)            | D, G, A, L and M | Lagoon, high salinity water, hot and dry weather   |
| S2       | Shoals Facies Association (FA2)            | A, C, D, L, B, I | Carbonate ramp, shallow waters, direct wave action      |
|          | Inter Shoals Facies Association (FA3)      | A, D, F, G, H, J, L | Carbonate ramp, shallow waters, moderately protected from wave action |
|          | Outer Ramp Facies Association (FA4)        | A, D, E, G, I, J | Carbonate ramp, distal context, shallow to medium water depth |
| S3       | Drowning Facies Association (FA5)          | A, D, E, G, H, I, J, N | Partial drowning of the carbonate ramp, shifting from shallow to deeper water environment |
| S4       | High Sea-Level Facies Association (FA6)    | K, N, J | Ramp under neritic water depths                         |
| S5       | Mixed Sedimentation Facies Association (FA7)| N, K, O, J | Basinal setting, basinal water depths                   |
association shows repeated coarsening-upward cycles that vary from 15 to 20 m thick, starting with fine-grained facies and ending with grainstones and packstones. Fossils are rare in this association, sparse foraminifers occur in the upper layers.

Environmental Interpretation: The coarse-to-medium oolitic and oncolitic facies associated with the fine-grained facies are indicative of a moderate-energy depositional environment with shallow and clean waters. The presence of anhydrite indicates a marine environment with periods of negative water balance that favoured the accumulation and precipitation of salts. Facies Association 1 is interpreted as being formed in a high-salinity restricted marine environment, described as a lagoon by Spadini et al. (1988).

**Shoals Facies Association (FA2)**

Facies Association 2 is composed of thick layers of ooidal, bioclastic and peloidal grainstones and packstones, interbedded with wackestones and mudstones (Table 2, Figure 4B). Dolostones with recrystallization textures occur at the base. The coarsening-upward cycles initiate with wackestones and
Foraminifers are very common towards the top of the unit and an increasing occurrence of grainstones and packstones. There is a grain size decrease upwards and the units and the concomitant occurrence with FA2 and FA3 indicate that deposition occurred in slightly deeper waters, above storm wave base and seaward of FA3. Although more distal, FA4 is located before the foreslope. In this depositional setting, lower energy periods depositing fine-grained sediments are eventually disturbed by periods of wave action, when oolites and oncites are formed.

**Drowning Facies Association (FA5)**

Facies Association 5 is characterized by grainstones, packstones, wackestones, mudstones, marlstones and shales (Table 2, Figure 5A). An interbedding of carbonate and siliciclastic facies occurs, and there is an increase in carbonate mud and terrigenous sediments towards the top. At the base of FA5, coarsening-upward cycles start with mudstones or wackestones, in 5–20 m thick layers, and terminate with grainstones and packstones, 5–15 m thick. Towards the top of FA5, these cycles are progressively replaced by fining-upward cycles that start with packstones, overlain by mudstones, marlstones and shales. Facies Association 5 presents very high GR values, which stand out from the other units.

Environmental Interpretation: The significant decrease in coarse-grained facies towards the top, where mudstones, marlstones and shales are dominant, suggests an increase in water depth. The occurrence of coarse oolitic facies at the base indicates that the shoal’s accretion initially kept pace with BL rise, until it was finally replaced by deeper water facies.

**High SL Facies Association (FA6)**

Facies Association 6 is characterized by mudstones, marlstones, shales and siltstones (Table 2, Figure 5B). The siliciclastic and carbonate deposits which make up this facies association commonly show bioturbation and parallel laminations. Foraminifers frequently occur throughout.

Environmental Interpretation: The fine-grained facies, along with the abundant foraminifera, suggest that deposition occurred in a deep-water marine environment. The small siliciclastic component indicates limited terrigenous input.

**Mixed Sedimentation Facies Association (FA7)**

Facies Association 7 is characterized by mudstones, marlstones, shales and siltstones (Table 2, Figure 5C) and, unlike FA6, in this unit the siliciclastic facies are predominant. In addition, GR values show a significant increase over the previous sequence supporting a larger continental input. Foraminifers occur throughout.

Environmental Interpretation: The fine-grained facies suggest that, as with FA6, deposition occurred in a deep marine environment subject to significant terrigenous input. At the top of FA7, the carbonate facies are sparse, indicating that sediment input suppressed carbonate precipitation.
The definition of carbonate sequence adopted in the present work refers to a facies set arranged in a shallowing-upward cycle (Vail et al., 1977). A mixed-composition sequence is a conformable succession of genetically related strata bounded by unconformities and their correlative conformities (Vail et al., 1977). The same authors defined sequence boundaries as “observable discordances… that show evidence of erosion or non-deposition with obvious stratal terminations, but in places, they may be traced into less obvious paraconformities recognized by biostratigraphy or other methods.”

Vail’s definition is appropriate for carbonate systems because it does not add a genetic connotation to the term. It makes the concept less restrictive, since evidence of subaerial exposure is difficult to identify in seismic data and may not be noticeable even in outcrops (Schlager, 2005). The identification of the sequences in this study was based on the recognition of unconformities along with erosional or non-depositional surfaces representing either exposure periods or drowning events, and their correlative condensed sections. These boundaries were recognized and mapped in the seismic data with the support of the well data.

According to the stratigraphic chart of the Campos Basin proposed by Winter et al. (2007), the entire Albian succession was deposited over a period of approximately 16 Myr. Therefore, the five sequences defined are being interpreted as third-order sequences, ranging between 0.5 and 3 Myr (Vail et al., 1991; Table 2).

3.3 | Sequence 1

Sequence 1 (S1) is the first Albian carbonate sequence of the Campos Basin. It lies upon the unconformity at the top of...
a salt layer (Retiro Formation), corresponding to the basal part of the Quissamã Formation (Búzios Member) defined by Winter et al. (2007), and to Sequence I of Esteves et al. (1987). This limit is recognizable in the wells due to an abrupt change in the log readings (Figure 6A). In the seismic sections, this surface is identified by a high-amplitude reflector with irregular geometry forming pillows and diapirs (Figure 6C). Sequence 1 occurs in the basal portion of nearly all wells in the study area. The facies distribution is constant along the study area; therefore, it contains only one facies association that corresponds to FA1.

Its upper limit, separating S1 from Sequence 2 (S2), corresponds to a cemented surface, which is perceptible as an abrupt change in the DT log readings (SB1). This

**FIGURE 6**  (A) Correlation between the wells representing S1 and S2. The unconformity at the top of the salt layer (Retiro F.) was used as datum. (B) Map of wells and seismic line location, the red line on the map indicates the direction of the correlation between the wells. (C) Interpreted seismic line, the red horizon represents the sequence boundary SB1 and SB2
unconformity also coincides with a facies shift in which coarse-grained facies are overlapped by fine-grained facies. The coarse-grained facies are extremely well-cemented and dolomitized and exhibit the lowest values of the GR logs (Figure 6A).

Sequence 1 was deposited in a relatively restricted environment with high salinity, evidenced by the presence of anhydrite levels and the absence of fossils at the base of this unit. Towards the top, mollusc fragments and foraminifera are occasionally found. In the seismic sections, this sequence shows parallel reflectors with downlap and onlap terminations against the salt diapirs (Figure 6C) and salt welds and reactive structures associated with extensional fault footwalls, which contribute to the overall lateral discontinuity.

### 3.4 | Sequence 2

Sequence 2 is equivalent to the intermediate portion of the Quissamá Formation. It comprises a number of facies associations (FA2, FA3, FA4) across the study area, which suggests the simultaneous development of different depositional environments. The sequence represents a stage in which the shelf developed in a discontinuous ramp geometry. Similar facies associations supporting the ramp geometry in the Macaé Group were described by Okubo et al. (2015).

Sequence 2 is a cemented interval with frequent oolites, oncites and bioclasts, including mollusc fragments, echinoids, foraminifera and rare calcispheres. It shows the lowest GR values of all the studied sequences. The upper boundary (SB2), separating S2 from Sequence 3 (S3), is a cemented surface, which also coincides with a change from coarse-grained to fine-grained facies (Figure 6A).

Sequence 2 was deposited during the middle Albian, when halokinesis began to affect the basin. The effects of mechanical subsidence became progressively smaller, while thermal subsidence became prominent (Winter et al., 2007). In contrast with the previous sequence (S1), the abundant fossils indicate that deposition occurred in an environment with normal salinity.

In the seismic sections, S2 is characterized by curved reflectors that follow the geometry imposed by the salt layer (Figure 6C). The strata undergo thinning in the regions of saline domes, where they form a condensed section. This deformation usually makes the interpretation of the reflectors difficult and, in some cases, it is impossible to identify and define the original geometry of the reflectors.

### 3.5 | Sequence 3

Sequence 3 corresponds to the upper portion of the Quissamá Formation. It represents a period of SL rise on the shelf evidenced by the progressive shift from oolitic/oncolitic grainstones to mudstones and wackestones towards the top of the sequence. The bioclastic components are foraminifera and echinoids. Sequence 3 shows little lateral facies variation, consisting of a single facies association (FA5). This interval is recognized in the well data as an interval with extremely high GR values (Figure 7A).

The thickness of this sequence decreases to the west in the study area. The upper limit of S3 is a cemented horizon characterized by a peak in GR and DT logs (SB3; Figure 7A).

Sequence 3 was deposited in the middle to upper Albian, a period when the basin was dominated by thermal rather than mechanical subsidence and when halokinesis was significant. Sequence 3 represents deposition in open marine conditions. In the seismic sections, S3 occurs as a series of plane-parallel reflectors (Figure 7C). The geometry and character of the reflectors are not always trackable, since they formed when halokinesis was operating. Sequence 3 is vastly affected by faults and deformations imposed by the salt layer (Figure 7C).

### 3.6 | Sequence 4

Sequence 4 (S4), corresponding to the Outeiro Formation, was deposited in an open marine context. The FA6 facies are predominantly fine-grained and show little lateral variation. This sequence includes the first siliciclastic facies of the Albian succession, indicating the onset of terrigenous input to the basin. Fragments of foraminifera and red algae are common.

The succession characterised by relatively high GR values that decrease significantly towards the top (Figure 8A), although values are lower than in the preceding S3. The upper boundary is a cemented surface, recognized in the well data by an abrupt change in the GR logs, with the lowest values of the sequence, as well as a peak in the resistivity and DT logs due to carbonate cementation.

Sequence 4 was deposited in the upper Albian, a period of thermal subsidence and intense halokinesis in the basin. In the seismic sections, S4 appears as plane-parallel reflectors with relatively high lateral continuity despite being affected by listric faults and salt relief. Due to the salt movements, the reflectors may be locally chaotic when associated with salt welds (Figure 8C).

### 3.7 | Sequence 5

Sequence 5 (S5) was deposited in an open marine setting and corresponds to the Imbetiba Formation, the uppermost unit of the Macaé Group. Previous work attributes this unit to an
upper bathyal setting (water depths >200 m; Koutsoukos and Dias-Brito, 1987; Spadini et al., 1988). The fine-grained facies (shales, marlstones, mudstones and siltstones) of FA7 (mixed sedimentation) comprise this unit. In this sequence, siliciclastic and mixed facies are prevalent (Figure 8A). Foraminifers are very common and red algae fragments occasionally occur.
FIGURE 8  (A) Correlation between the wells representing Sequence 4 (S4) and sequence 5 (S5). The surface that marks the top of S3 (yellow line) was used as datum. (B) Map of wells and seismic line location, the red line on the map indicates the direction of the correlation between the wells. (C) Interpreted seismic line
The DT and GR logs show a significant increase at the base of unit (SB4), and remain practically constant throughout the sequence, indicating a considerably higher organic matter component when compared to the previous sequence.

The upper boundary corresponds to a cemented surface that shows an abrupt change in the GR, ILD and DT logs (SB5). This unconformity is evident in the seismic sections because it marks a shift in the reflection pattern. Below this surface, chaotic reflectors or geometries in the form of banks are common (Figure 8C), whereas above it, plane-parallel reflectors and clinoforms predominate. Upwards from SB5, the mixed facies are punctuated, and carbonates no longer occur.

Sequence 5 was formed in a period of thermal subsidence and intense halokinesis in the Campos Basin, therefore, the sequence interpretation in the seismic lines is complex due to the occurrence of rollers, welds and faults related to reactive structures.

4 | DISCUSSION

4.1 | Stratigraphic framework

The facies characteristics of S1 indicate deposition in a shallow hypersaline lagoon (Figure 9), implying that the shelf flooded at the beginning of the Albian but that the restricted marine conditions operating during evaporite deposition (Retiro Formation) remained. Restriction was probably due to the existence of structural highs (e.g. Rio Grande-Walvis system) that acted as barriers between the North and South Atlantic oceans (Tissot et al., 1980; Spadini et al., 1988) and also between the Brazilian and Argentinian offshore basins (Pérez-Días and Eagles, 2017). To the south, the Falkland Plateau regulated the marine incursion through the Cape Basin until the late Albian (Pérez-Días and Eagles, 2017).

The initial SL rise that led to flooding in the early Albian corresponds to a Type-I or initial HST, which leads to the
FIGURE 10  Stratigraphic column for well 3, representing the study area and depicting the local SL variation curve (based on interpreted shallowing-upward and deepening-upward cycles) compared to the global eustatic variation curve from Haq et al. (1988)
development of the carbonate deposits (Catuneanu, 2006). The SL increase does not coincide with the global eustatic variation curve (Haq et al., 1988; Figure 10), suggesting that it is related to the tectonic configuration of the newly rifted basin, still undergoing mechanical subsidence (Spadini et al., 1988; Winter et al., 2007), rather than a global event.

Sequence 2 represents a shallow marine setting with concomitant depositional environments of: (a) high-energy (FA2); (b) partially protected, with lower energy areas (FA3) and (c) relatively deeper waters, seaward from the previous two settings (FA4). The distribution of facies associations indicates that, during S2 deposition, the shelf comprised a disconnected ramp, where shoals act as barriers, with no abrupt break towards the basin (Figure 9). This is standard geometry for slightly evolved carbonate platforms (Wilson, 1975; Tucker, 1991).

Sequence 2 shows a series of shallowing-upward cycles, and both global and local data indicate relatively low SL (Figure 10). For carbonate constructions to form, the sediment production must be higher than the accommodation creation (Schlager, 2005; Catuneanu, 2006; Moore and Wade, 2013). Under ideal conditions, the high rate of sediment production causes high rates of accumulation and vertical accretion (Schlager, 2005), leading to a gradual decrease in accommodation and consequently water depth, resulting in shallowing-upward cycles (Figure 10).

The occurrence of carbonate shoals in the Quissamã Formation is long known (Falkenhein, 1981; Koutsoukos and Dias-Brito 1987; Guardado et al., 1989; Okubo et al., 2015). However, they are referred to as elongated banks in a NE-SW direction, which is opposite to the alignment in the study area (NW), indicating some structural control, oriented parallel to a fault zone (Figure 11).

Sequence 3 includes the drowning facies association (FA5). The unit presents shallowing-upward cycles overlain by deepening-upward cycles towards the top of the sequence (Figure 10). This pattern indicates that carbonate production kept pace with SL rise until accommodation creation surpassed sediment production, leading to the partial drowning of the shelf (Figure 9). The cycles, the facies characteristics and the extremely high GR values are very characteristic of this sequence. This interval is part of a higher order (possibly second-order) TST that resulted in a maximum flooding surface which coincides with the upper boundary of S3.

Sequence 4 is composed of FA6 (high SL) deposited in the neritic zone established after the SL rise registered in the previous unit (Figure 9). Sequence 5 includes FA7 (mixed sediment) deposited in a deep marine setting, under high terrigenous input (Figure 9). Both sequences are part of a possibly second-order HST (Figure 10). However, while most of S4 comprises biogenic deposits, particularly those attributable to benthic foraminifera and red algae, S5 consists of mostly siliciclastic sediments. Local and global SL variation curves indicate a high SL period. Sequence 5 correlates with a final HST or Type III, which results in the drowning of the platform (Catuneanu, 2006). Therefore, S5 marks the final stages of the carbonate shelf in the Campos Basin, evidenced by the surface that limits this sequence,
which equates to a drowning unconformity (Schlager, 1989; 2005).

### 4.2 Carbonate Factories

Based on the facies associations, S1 was interpreted as deposited in a shallow marine environment. The climate was probably similar to that of the Aptian, with the salt layer deposited under a hot and arid climate, as reported by Brownfield and Charpentier (2006) and Chaboureau et al. (2016).

The low-latitude, hot climate and shallow-water setting allowed a T-factory to develop in the Albian (Figure 9). Sequence 1 is the thinnest of all sequences, which is consistent with its depositional context, since carbonate production in recently flooded environments starts at a slow pace, following the ‘law of sigmoidal growth’ (Neumann and Macintyre, 1985; Moore and Wade, 2013; Figure 12A). Accordingly, there is a time lag between the first shelf flooding and the onset of sediment production, as the carbonate-secreting organisms are gradually established on the shelf (Moore and Wade, 2013). Although the T-factory was active during S1 deposition, it was a period of low sediment production, with the lowest accumulation rate of the entire succession (Figure 12B). Which resembles the ‘start-up phase’ of deposition (Neumann and Macintyre, 1985; Moore and Wade, 2013; Figure 12).

During S2 deposition, the shallow water conditions remained, and the same production system was active. At this time, the T-factory was well-established on the shelf, and sediment production reached its optimum point. Sequence 2 showed the highest depositional rate of all the sequences, resembling the ‘catch-up phase’ (Figure 12). Which is the phase when the available accommodation is rapidly filled, due to the high accumulation rate associated with rapid cementation, favouring the development of carbonate constructions.

Sequence 3 was deposited in a similar setting as S2, but it displays a gradual dominance of fine-grained facies. The observed succession indicates that accommodation creation became significantly higher than sediment production. The basal portion of Sequence 3 resembles the ‘keep-up phase’, in which the space remains filled with sediments, regardless of accommodation creation (Moore and Wade, 2013; Figure 12A).
The top units are indicative of a distinct depositional setting, characterized by deeper waters and milder climate during the Mid Cretaceous (Scotese, 2014). The substantial accommodation creation led to the end of the keep-up phase, since the new depositional conditions were no longer ideal for the T-factory phototrophic biota, for example, rudists and corals (Michel et al., 2019). Therefore, from this moment on, carbonate constructions and shallow-water deposits cease to occur. The same pattern is noted on the upper part of the ramp section in the Kwanza Basin, on the African margin (Eichenseer et al., 1999).

Sequence 4 records the onset of silicilastic input into the basin, under deep-water and mild weather. The presence of red algae and benthic foraminifera is indicative of a C-factory, equivalent to the Photo-C-factory (Michel et al., 2019), which shows smaller carbonate accumulations compared to the T-Factory (Figure 12B).

Depositional environments of S5 experienced increasing sediment input and turbid waters, possibly linked to the erosion of the uplifted Brazilian continental margin (Mohriak et al., 2008). Besides this, it is probably that the basin went through progressive deepening during S5 deposition. Which was due to increasing SL (Figure 10) along with the opening of the equatorial Atlantic gateway ca 100 Ma (Pérez-Díaz and Eagles, 2017). Although deep water exchange with the Central Atlantic was still restricted by the Rio Grande-Walvis system, this opening led to less salty and deeper waters from the Albian-Cenomanian boundary, changing the circulation patterns from very restricted conditions in the early Cretaceous to more productive environments by the end of the period (Pérez-Díaz and Eagles, 2017).

Since light is the steering environmental factor controlling the Photo-C-factory, the highest rates of production will develop in well-illuminated settings (Michel et al., 2019). The inefficiency of the production system in a setting experiencing significant sedimentary input and increasingly deep waters led to the termination of carbonate sedimentation in the Campos Basin. After the deposition of S5, silicilastic deposits predominate in both the Campos and Santos basins alike (Mohriak, 2003; Moreira et al., 2007).

The demise of the C-factory is a result of three main factors: (a) the rift evolution of the area that today lies between the South American and African plates; (b) the Cretaceous SL rise (Miller et al., 2005) and, (c) sediment input. The first two contributed to a particularly significant increase in accommodation space, while the latter, presumably the most important, influenced the turbidity of the water and the chemical equilibrium of the system (Pohl et al., 2018; Michel et al., 2019).

5 | CONCLUSIONS

Five third-order sequences constitute the Albian succession in the Campos Basin. They register the slow onset of carbonate deposition, the establishment of a discontinuous ramp setting and the complete drowning of the depositional system. The first sequence (S1) represents the installation of a T-factory production system and its deposition is associated with a Type I HST. The depositional environment was a shallow lagoon formed by shelf flooding. This initial stage corresponds to the start-up phase of the carbonate shelf.

The following sequence (S2) records the period of definitive implementation of the carbonate shelf, it represents the catch-up phase of the factory, characterized by an intense sediment yield. During this period, the shelf configured a ramp formed of discontinuous oolitic shoals associated with intershoal and outer-ramp deposits.

The third sequence (S3) was deposited in the context of relative SL rise. The basal portion of this unit is related to the keep-up phase of the carbonate shelf, but towards the top, accommodation creation at rates higher than the growth potential of carbonate shoals led to partial drowning of the shelf. This sequence also registers the gradual transition from a T-factory to C-factory (Schlager, 2005) or Photo-C-factory (Michel et al., 2019).

Sequences 4 and 5 were deposited in the deep marine setting associated with a C-factory production system. Sequence 5 records a significant increase in terrigenous sediment input and corresponds to the last sequence of the studied succession. Its upper limit corresponds to a drowning unconformity that marks the end of carbonate sedimentation in the Campos Basin.

The replacement of a T-factory for a C-factory took place due to the combination of three main factors: SL rise, increased terrigenous sediment input and accommodation creation due to the opening of the South Atlantic.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.
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