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ARCHITECTURE AND STRATIGRAPHIC FRAMEWORK OF SHELF SEDIMENTARY SYSTEMS OFF RIO DE JANEIRO STATE, NORTHERN SANTOS BASIN-BRAZIL*,**

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ABSTRACT

Seismic analysis of sparker lines of GEOMAR cruises allowed us to address a first stratigraphic scenario for the shallow sedimentary record (~300 msec) of the continental shelf off Rio de Janeiro State, northern Santos basin. Two sets of seismic sequences were identified and interpreted as a succession of depositional sequences induced by repeated glacioeustatic cycles. Depositional sequences composing Set I (SqA-SqC) are dominantly sigmoidal, reflecting periods of increasing accommodation space that favoured the preservation of both aggradational and progradational units; sequences of Set II (Sq1-Sq5) are essentially seaward-thickening stacks of forced-regression wedges, implying periods of declining accommodation space. Comparison between seismic lines and chronostratigraphic data allowed the mapped sequences to be placed within the Plio-Quaternary. Correlations also suggest that most of Set I (SqA and lower portion of SqB) was deposited during the Pliocene (undifferentiated Pliocene), while the upper portion of sequence SqC and sequences of Set II (Sq1-Sq5) have been placed within the Quaternary. Correlation of chronostratigraphic data with $\delta^{18}O$ isotopic "sea level curves" also supports the hypothesis that sequences Sq1-Sq4 are fourth-order forced-regression sequences that record 100-120 kyr glacioeustatic cycles for the last 440-500 kyr, while sedimentary units labeled Sq5 would represent the transgressive and highstand deposition during the Holocene.

RESUMO

A análise sísmica de dados sparker das Operações GEOMAR permitiu a elaboração de um primeiro arcabouço estratigráfico da seção rasa (~300 msec) da plataforma continental do Estado do Rio de Janeiro, norte da bacia de Santos. Dois conjuntos de seqüências sísmicas foram interpretados como seqüências deposicionais induzidas por oscilações glacio-eustáticas. O Conjunto I (SqA-SqC), composto por seqüências dominantemente sigmoidais, reflete condições de geração de espaço de acomodação sedimentar capaz de preservar seus componentes agradacionais-progradacionais; o Conjunto II (Sq1-Sq5), composto principalmente por prismas de regressão forçada, indica diminuição relativa de espaço de acomodação. Dados cronoestratigráficos de poços permitiram posicionar a seção sísmica investigada na janela plio-quaternária: à maior parte do Conjunto I (SqA e parte inferior da SqB) foi atribuída uma idade Plioceno (indiferenciado); à seção estratigráfica que se estende da porção superior da SqC até o Conjunto II foi atribuída uma idade quaternária. A correlação entre a base de dados e curvas globais de variações isotópicas de $\delta^{18}O$ permitiu ainda sugerir que as seqüências Sq1-Sq4 registram sequências regressivas de quarta ordem (ciclos glacio-eustáticos de cerca de 100-120 ka) durante os últimos 440-500 ka. A sequência Sq5 representaria a deposição holocênica, constituída por depósitos transgressivos e de sistemas de mar alto.

Descriptors: Continental shelf, Forced regression, Quaternary, Pliocene, Glacioeustatic oscillations, Eastern Brazilian Margin.
Descritores: Plataforma continental, Regressão forçada, Quaternário, Plioceno, Oscilações glacio-eustáticas, Margem continental leste brasileira.

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INTRODUCTION

Studies from different geological settings around the world provide examples of sedimentary architecture of Plio-Quaternary continental shelf systems related to the interplay among several factors such as the amplitude and frequency of glacioeustatic oscillations, variable rates of sediment supply and prevailing tectonic regime (e. g. FOYLE; OERTEL, 1997; TRINCARDI; CORREGGIARI, 2000 TESSON et al., 2000; HERNANDEZ-MOLINA et al., 2000; RIDENTE; TRINCARDI, 2002; JIN et al., 2002; LOFI et al., 2003; RABINEAU et al., 2005; GROSSMAN et al., 2006; TEZCAN; OKYAR, 2006; LIQUETE et al., 2008; TRIPSANAS; PIPER, 2008). During the Plio-Quaternary, high-frequency and high-amplitude sea-level oscillations stand as one of the major elements inducing base level variations that control the morphological and stratigraphic evolution of prograding continental shelves. Concerning the middle-late Pleistocene, high-amplitude glacioeustatic signals (± 100-120 m) are characterized by slow sea-level falls and rapid sea-level rises, punctuated by short-lived intervals of sea-level highstand and stillstand conditions (SHACKLETON; OPDYKE, 1976; CHAPPEL; SHACKLETON, 1986; CLARK et al. 2006). Sea-level oscillations are, therefore, intense and dominated by the falling part of the glacioeustatic cycles (RABINEAU et al., 2006), which favours the deposition of forced-regression deposits (POSAMENTIER et al., 1992; POSAMENTIER; MORRIS, 2000). Forced-regression conditions reflect the process of seaward migration of the shoreline in direct response to falling relative sea-level, regardless of the rate of sediment supply (POSAMENTIER et al., 1992; HUNT; TUCKER, 1992; POSAMENTIER; MORRIS, 2000; PLINT; NUMMEDAL, 2000).

The occurrence of high rates of clastic influx into the Santos basin is known to have forced massive shelf progradation during the late Cretaceous and notably during the Paleogene (MOREIRA; CARMINATTI, 2004; MODICA; BRUSH, 2004). These depositional conditions prevailed until the Oligocene, when the Paraíba do Sul River, that discharged into the northern Santos basin, was captured and reorganized to its present-day coast-parallel orientation and diverted into the Campos basin (Fig. 1) (MODICA; BRUSH, 2004). As a consequence, the shelf environment was drowned and became relatively starved of clastic input; at the same time, the shelf edge backstepped more than 50 km landward from the Late Eocene shelf edge, close to its present-day position (Fig. 1).

However, very few studies have dealt with the stratigraphic and physiographic evolution of the Santos basin shelf sedimentary section during the Pliocene or the Quaternary. Most of the studies dealing with the Quaternary section have focused on the shelf morphology, superficial or subsurface sediment distribution or on the geomorphology and stratigraphic evolution of coastal features, like bays, coastal plains and the shallow shelf environments during the Holocene (e.g. KOWSMANN; COSTA, 1979; MAIA et al., 1984; MUEHE, 1989; MUEHE; CARVALHO, 1993; MUEHE; VALENTINI, 1998; TURCQ et al, 1999; MARTIN et al., 2003; ARTUSI; FIGUEIREDO, 2007; MAHIQUES et al., 2007; FLEMING et al., 2009). Therefore, the Plio-Quaternary stratigraphic window remains as an important gap in the attempt to reconstruct the sedimentary history of the Santos basin continental shelf and of the Brazilian continental margin, as a whole.

In this paper we investigate and discuss, based on seismic and exploratory well data, the stratigraphic architecture of continental shelf systems off Rio de Janeiro State, in order to address a first stratigraphic framework of the shallow section of the northern Santos basin.

MATERIAL AND METHODS

The stratigraphic analysis carried out in this study was based primarily on the interpretation of about 5,000 km of single-channel sparker seismic lines (500-1000 Joules, 100 to 1400 Hz), acquired on the continental shelf of the Santos and Campos basins during legs XVI and XX of GEOMAR Oceanographic Cruises[1] in the early 80’s (Fig. 1). Maximum signal penetration ranges from 300 to 400 msec, while the vertical resolution oscillates between circa 7 and 12 m, depending on the seismic line considered. Additionally, exploratory well information (wells P1 and P2) was provided by the Brazilian National Petroleum Agency - ANP, while regional bathymetric data were extracted from ETOPO2 (SMITH; SANDWELL, 1997) (Fig. 1).

Interpretation of seismic data was implemented according to the general principles of high resolution seismic and sequence stratigraphy, more adequate to address analyses of Quaternary high frequency glacioeustatic signals (fourth and fifth-orders, circa 100-120, 40 and 20 kyr depositional cycles, e.g. TESSON et al., 1990; HUNT; TUCKER, 1992; POSAMENTIER et al., 1992; EVANS et al., 1995; PLINT; NUMMEDAL, 2000; POSAMENTIER; MORRIS, 2000; CATUNEANU, 2002; CATUNEANU, 2006; CATUNEANU et al.,

[1] A total of 24 legs of GEOMAR oceanographic cruises were carried out between 1969 and 1986 in a joint scientific programme between Brazilian universities and governmental agencies, aiming at the acquisition of seismic data, sub-bottom profiling and sediment sampling throughout the Brazilian continental margin.

2009). To calculate the thickness of each seismic sequence, an estimated layer velocity of 1600 m/s was considered.

In the study area, no ages of paleoshorelines nor of measured or estimated sea-level curves from cores are available, either for the LGM (Last Glacial Maximum) or for earlier cycles and glacial maxima. For this reason, for a first approximation of high-frequency and amplitudes of Quaternary sea-level variations, we used a compilation of global sea-level curves based on $\delta^{18}O$ isotopic ratio calibrated by the dating of geological evidence, such as morphologic, diagenetic or organic features, on continental margins (RABINEAU et al., 2006).

Results

The study area comprises the east-west oriented continental shelf about 400 km long and between 70 and 120 km wide, off Rio de Janeiro State, northern Santos basin. It extends from Cabo Frio, on the east, to São Sebastião island, on the west, presenting a rather gentle seaward-dipping gradient of about 0.07° (Fig. 2). The shelf break is irregular, displaying large indentations between Cabo Frio and São Sebastião (Figs 1 and 2). The continental shelf is about 70 km wide and 170 m deep offshore of the Araruama lagoon (Figs 2 and 3); whereas it is wider (~120 km) and deeper (~200 m) off Sepetiba-São Sebastião on its western limits (Figs 2 and 4).

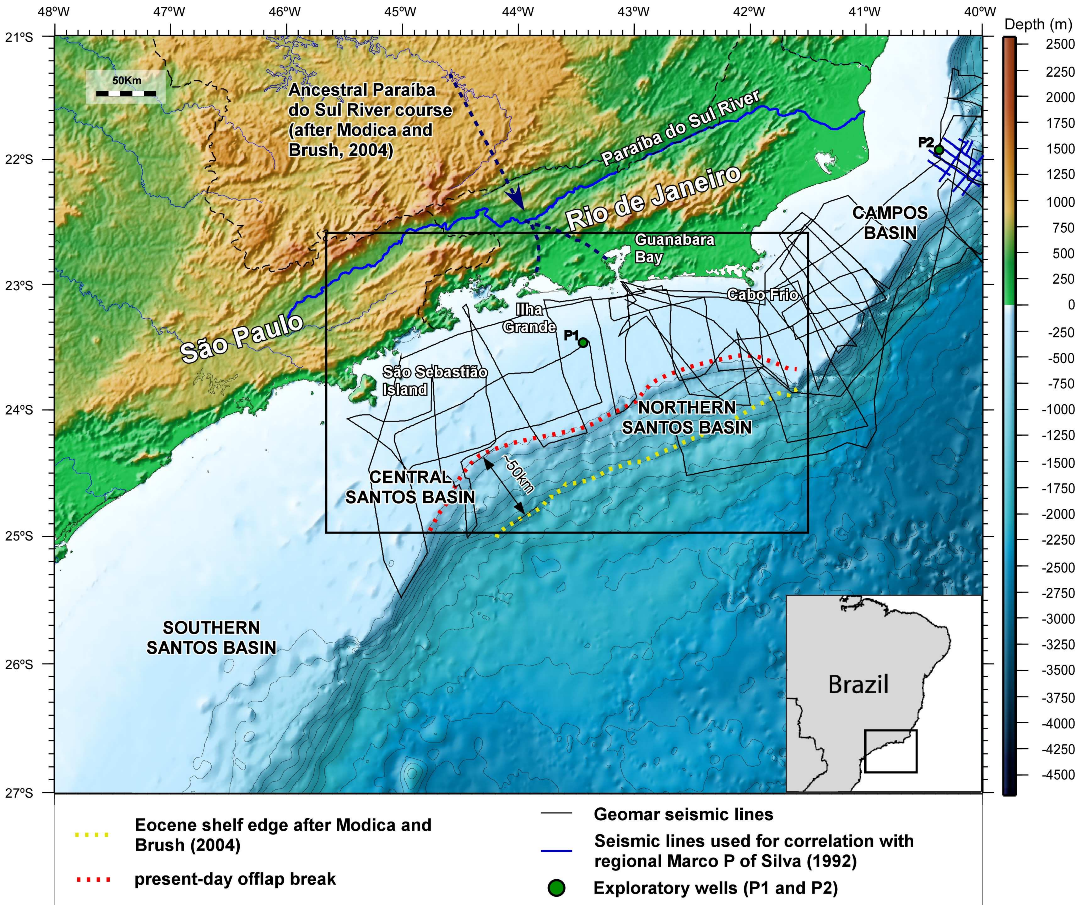

Fig. 1. Regional bathymetric map of the Santos basin with location of the study area and of the tracklines of the single-channel seismic data and exploratory wells used in this work. Regional bathymetry data are from ETOPO2 (SMITH; SANDWELL, 1997).

Seismic stratigraphic analysis shows a pattern of stacked seismic units that together constitute eight major seismic sequences bounded by angular unconformities. Mapped seismic sequences reveal depositional features of a mostly prograding shelf, defined by the continuous seaward displacement of successive offlap breaks of outer shelf sedimentary wedges (Figs 3 and 4). In accordance with the geometry of their clinoforms and internal architecture, the seismic sequences were grouped into two distinctive stratigraphic sets, identified as Sets I and II. Surface S1 distinguishes these two stratigraphic sets of sequences as a high amplitude reflector that portrays an erosive surface easily mappable on the shallow seismic lines and thus representing a key horizon to distinguish Set I from Set II (COSTA MAIA, 2009) (Fig. 3).

Sequences that compose the lower stratigraphic set (Set I shown in shades of gray and numbered SqA–SqC bottom-up in figure 3) are easily identifiable on the eastern sector of the shelf, but are relatively poorly-imaged on the western sector, either due to multiple reflections or because of weak acoustic return (Fig. 4). Nevertheless, seismic data show that, in the inner-mid shelf, sequences SqA, SqB and SqC are composed of plan-parallel seismic units (after MITCHUM et al., 1977; seismic facies *PP* in figure 5). In contrast, in the outer shelf, these sequences are composed of seismic units consisting of sigmoidal clinoforms (after MITCHUM et al., 1977; seismic facies *SC* in figure 5). On the eastern sector of the shelf, seismic units SqA to SqC can grade seaward into parallel-oblique clinoforms (after MITCHUM et al., 1977), composing prograding sedimentary wedges of relatively high angle of dipping foresets (~0.9-1.0°) (Fig. 3 and seismic facies *OC* in figure 5a). These seismic units form individual prograding sedimentary wedges that can reach a maximum thickness of up to 35-45 msec (i.e., ~25-35 m) on the mid-shelf and about 80-100 msec (i.e., ~65-80 m) at the level of their respective offlap breaks (Fig. 3).

Seismic sequences Sq1-Sq4, that compose the upper stratigraphic set (Set II, numbered Sq1–Sq5 bottom-up in Figs 3 and 4), are laterally correlatable at the regional scale of the study area between Cabo Frio and São Sebastião island (Fig. 2). These seismic sequences differ broadly from sequences that make up Set I: sequences Sq1, Sq2 and Sq3 are composed of seaward-thickening parallel-oblique clinoforms (after MITCHUM et al., 1977), are bounded above and below by internal truncation surfaces of local extent, and present toplap terminations of about 0.2-0.3° (Fig. 4 and seismic facies *OC* in Fig. 5). These seismic units form individual prograding sedimentary wedges that can reach a maximum thickness of up to 100-130 msec (i.e., 80-105 m) at the level of their respective offlap breaks (Figs 3 and 4). Distinct geometries and internal reflection patterns are exhibited by seismic sequences Sq4 and Sq5. Seismic data from several sectors of the study area evidence that on the inner shelf Sq4 consists mainly of plan-parallel tabular seismic units (~25-30 m thick) that grade into parallel-oblique clinoforms located farther seaward at the distal end of the shelf (Figs 3 and 4). On the other hand, the architectural style and overall thickness and distribution of the youngest top seismic sequence Sq5 are quite variable across the shelf and contrast markedly with the depositional styles of sequences Sq1-Sq4 (Figs 3 and 4). Sequence Sq5 is unevenly distributed throughout the study area: on the mid-outer shelf, it is represented either by local dune-like features (not exceeding circa 18 m thick, Figs 2 and 6b), or by a patchy sedimentary cover (up to about 15-30 m thick, Figs 2 and 6c, d) infilling erosive depressions carved on surface S5. On the inner shelf, Sq5 consists of a continuous along-strike wedge-like sedimentary prism, up to 15 m thick, that roughly follows the 50 m isobath from east to west (Figs 2 and 6a).

Seismic sequences are bounded by sub-horizontal or gently-inclined seaward-dipping reflectors, expressed by irregular surfaces identified as SA, SB and S1 to S5 (Figs 3 and 4). On the inner-mid shelf, the top of each sequence of Set I (surfaces SA, SB and S1) is usually a smooth erosive surface that grades seaward into enhanced erosional surfaces characterized by toplap terminations (Fig. 5A). In contrast, the top of each sequence of Set II (reflectors S2 to S5) is an erosive and frequently stepped-topped surface that truncates the underlying seismic sequences Sq1 to Sq4 in a toplap termination (examples in Fig. 5). Erosive surfaces S2, S3 and S4, though topping underlying sequences of limited updip extent, merge landward with the underlying surface S1 to become shelf-wide erosive surfaces (Figs 3 and 4).

As a general pattern, seismic sequences that compose Set I (SqA–SqC) stack on top of each other as composite shelf-wide sigmoidal and parallel-oblique prograding clinoforms, resulting in shelf wedges that prograded for about 25 km (Fig. 3). Contrastly, the seismic sequences that compose Set II (Sq1–Sq5) show highly variable thicknesses in the depositional dip. Seismic sequences Sq1-Sq3 stack on top of each other and have a more limited extent. They consistently pinch out in a progressively landward direction showing significant thickness variation over short distances on the outer shelf (Figs 2, 3 and 4). Sequence Sq4, on the other hand, is a laterally continuous shelf-wide sequence, constituted mainly of plan-parallel seismic units for most of its landward extent, though some contribution of the progradational component is observed at the shelf break (Figs 3 and 4). As a consequence, seismic sequences Sq1-Sq4 form a composite seaward-thickening shelf wedge, whose front prograded seawards for about 15-25 km in the study area (Figs 3 and 4). These sequences can reach a maximum thickness of about 180-220 m at the level of the present-day offlap break, forming clinofoms that dip at higher angles than those of Set I (examples in Figs 3 and 4).

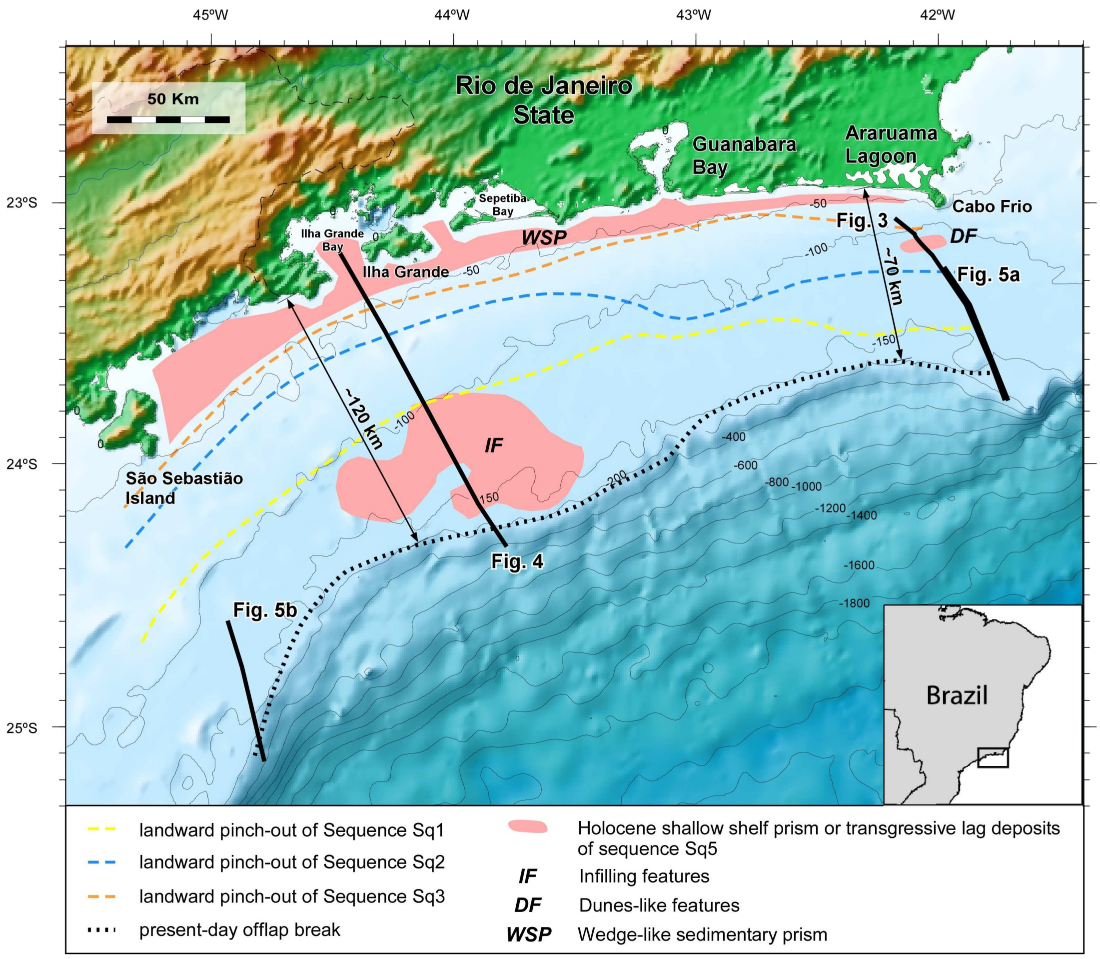

Fig. 2. Bathymetric map of the continental shelf off Rio de Janeiro State, northern Santos basin, illustrating features and stratigraphic elements concerning the shallow sedimentary record (~300 msec).

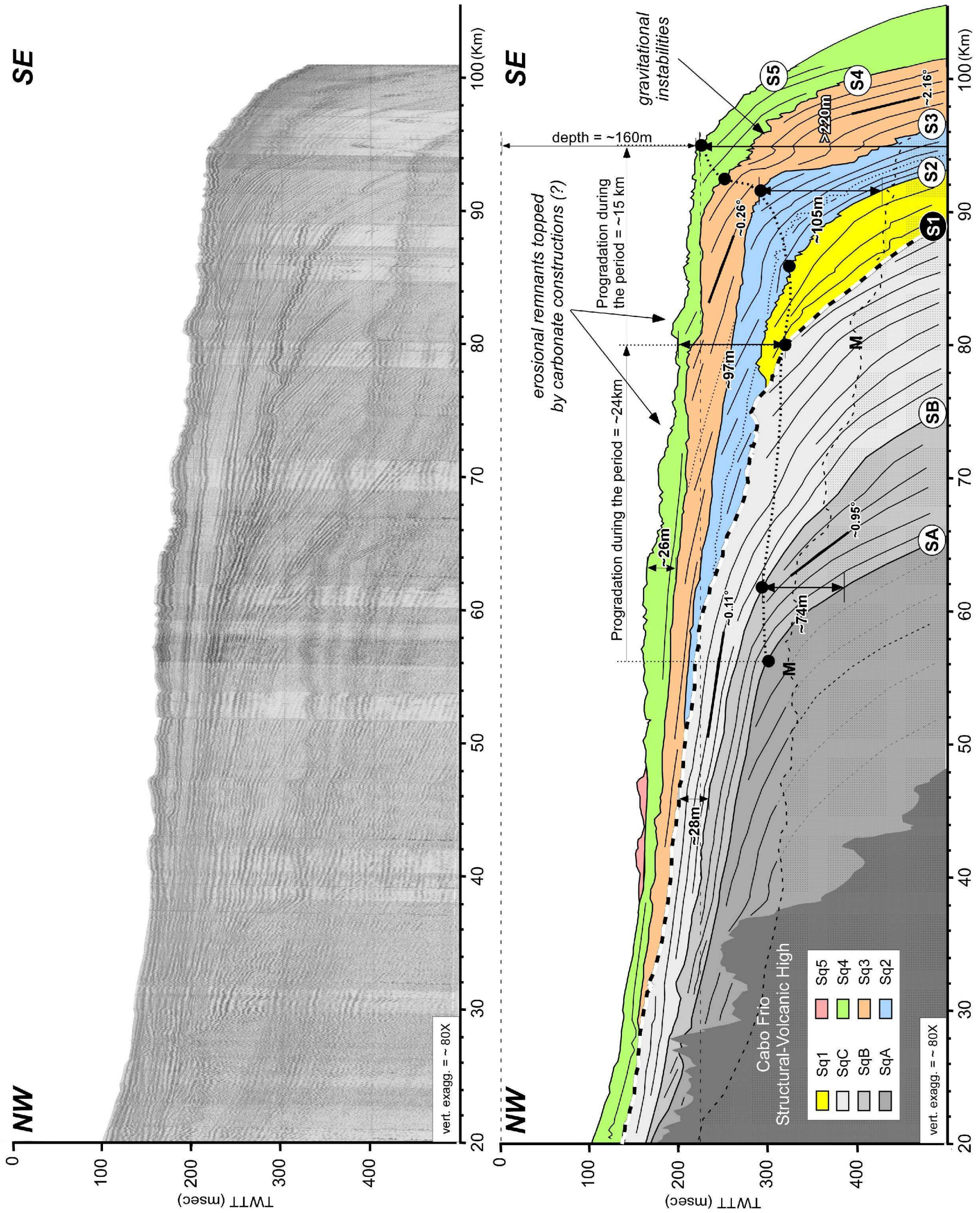

Fig. 3. Top-Uninterpreted dip single-channel seismic line across the eastern shelf sector off Rio de Janeiro (close do Cabo Frio). Bottom- Linedrawing illustrating a lower set of aggradational-progradational sigmoidal clinoforms (SqA-SqC) topped by a stacking of five seismic sequences (Sq1-Sq5), composed of shelf-edge clinoform wedges (Sq1-Sq4) and dune-like features (Sq5). Dotted line = offlap break trajectory of the prograding continental shelf. See Figure 2 for location.

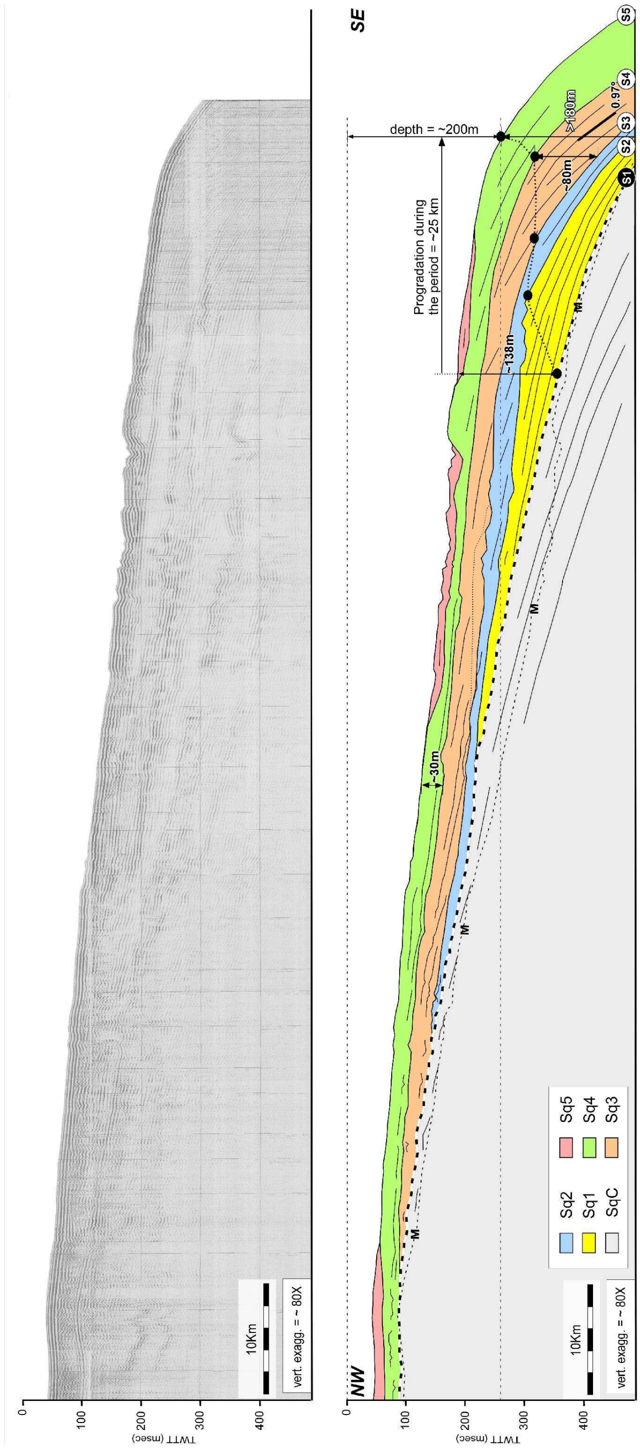

Fig. 4. Top-Uninterpreted dip single-channel seismic across the western shelf sector off Rio de Janeiro (offshore Ilha Grande Bay). Bottom- Linedrawing illustrating a stacking of five seismic sequences (Sq1-Sq5), composed of shelf-edge clinoform wedges (Sq1-Sq4) and localized infilling sedimentary units (Sq5) on the outer shelf. Dotted line = offlap break trajectory of the prograding continental shelf. See Figure 2 for location.

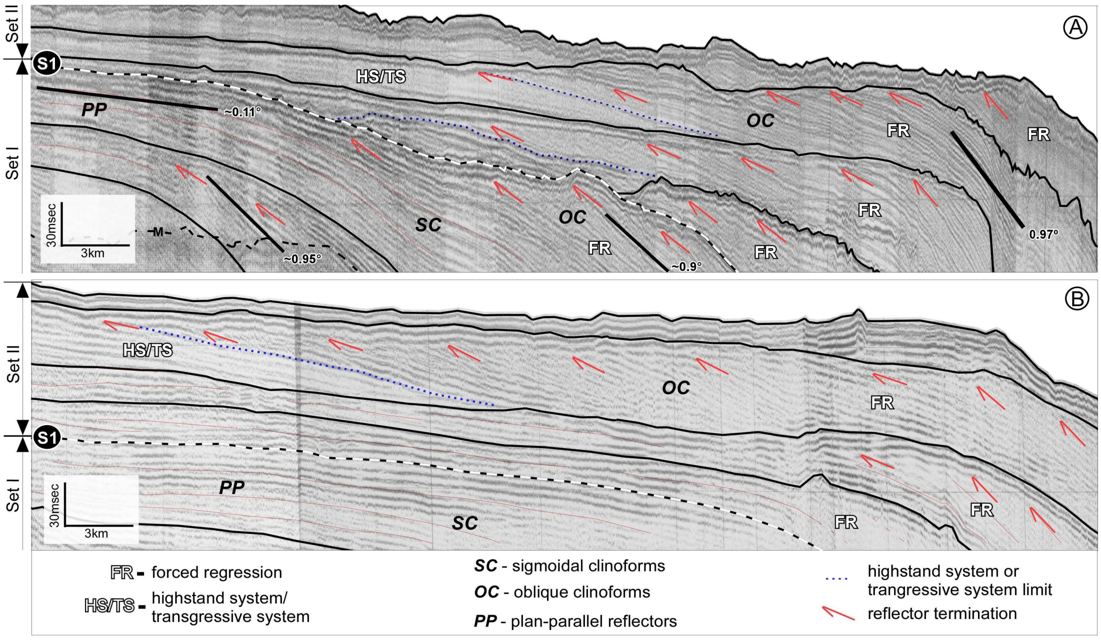

Fig. 5. Zoom-in of dip single-channel seismic lines across the outer shelf off Rio de Janeiro State. A and B illustrate distinct geometrical relationships displayed by seismic reflections, as well as various reflection patterns and external geometries that characterise the prograding continental shelf systems in the study area. See Figure 2 for location.

Discussion

Seismic stratigraphic analysis of GEOMAR XVI and XX data sets carried out in this study made it possible to subdivide the upper stratigraphic section of the northern Santos basin into definable depositional packages bounded by laterally continuous surfaces.

Seismic sequences of Set I (SqA–SqC, Figs 3 and 4) and Set II (Sq1–Sq5, Figs 3 and 4) are bounded by rather irregular bottom and top surfaces, suggesting the occurrence of erosive processes related to long-lasting subaerial exposure of the continental shelf (surfaces SA, SB and S1 to S5, Figs 3 and 4). Sets I and II were thus interpreted as a succession of depositional sequences induced by repeated glacioeustatic cycles of alternating sea-level lowering and rising. In this context, the upper and/or lower bounding surfaces of each sequence (surfaces SA, SB and S1 to S5) were interpreted as master sequence boundaries (*sensu* HUNT; TUCKER, 1992; PLINT; NUMMEDAL, 2000), since their unconformable expression is the most easily identifiable shelf-wide surface on the seismic lines. Each surface represents a diachronous horizon originated at times of maximum sea-level lowstands and most extensive subaerial exposure of the continental shelf (Fig. 7c), that was subsequently reworked during sea level rises.

Seismic stratigraphic analysis also evidenced highly variable along-dip depositional styles of sequences that compose Set I and Set II. Set I (SqA-SqC) is a dominantly sigmoidal set of sequences displaying aggradational and progradational components that record both enhanced regional subsidence and/or longer-term relative sea-level rise and higher rates of sediment supply, conditions that are required for the development and subsequent preservation of aggradational depositional units (e.g. seismic facies *PP* and *SC* in Fig. 5) (CATUNEANU, 2002; TRINCARDI; CORREGGIARI, 2000).

Subsidence conditions seem to have changed throughout the basin during the deposition of the sequences that make up Set II. For instance, sequences Sq1–Sq4 are characterized by a seaward downstepping succession of prograding clinoforms located on the outer shelf (e.g. seismic facies *OC* in Fig. 5); these sequences are apparently detached from any preserved inner shelf sedimentary system and are topped by seaward-dipping erosional surfaces that merge landward and form shelf-wide diachronous horizons (Figs 3 and 4). This configuration implies that the generation of accommodation space was less important than during the build-up of Set I. As a consequence, sequences Sq1–Sq4 stack on top of each other and form a composite seaward-thickening progradational wedge that reaches a maximum thickness of about 180-220 m at the level of the present-day offlap break (Figs 3 and 4). According to this stratigraphic architecture, each depositional sequence was interpreted as representing a repetition of transgressive-regressive cycles, being essentially composed of thicker regressive deposits and reduced, or even absent, transgressive and highstand units. These prograding elements are indicative of depositional sequences formed under forced-regression conditions (Fig. 7, *sensu* POSAMENTIER et al., 1992; POSAMENTIER; MORRIS, 2000), whereas the plane-parallel or seaward gently-dipping reflectors, like those observed in sequence Sq4 (Figs 3 and 4), are clearly not part of progradational wedges and have thus been interpreted as indicative of deposition during phases of sea-level rise, preserved either as transgressive and/or highstand sedimentary systems (TRINCARDI; CORREGGIARI, 2000; RIDENTE; TRINCARDI, 2002; CATTANEO; STEEL, 2003; CATUNEANU, 2006; CATUNEANU, 2009). Nevertheless, preservation of forced-regression deposits within stacks of regressive-prograding units requires a subsidence regime capable of inducing the seaward tilting of the margin by, for example, differential compaction and/or overloading subsidence (POSAMENTIER; MORRIS, 2000). In comparison with the sequences of Set I, sequences Sq1-Sq4 (from Set II) exhibit more limited landward extent and show both a progressive seaward progradation and reduced or absent transgressive and/or highstand deposits; their landward pinch-out gradually shifts landwards (Figs 2, 3 and 4), which suggests the generation of accommodation space during deposition of Set II, regardless of the low subsidence rates expected for the thermally old Santos basin (CHANG et al., 1992; MODICA; BRUSH, 2004). Still in the context of the forced-regressive shelf-edge wedges of sequences of Set II, the high-angle dipping foresets (~0.8-1.0º) that characterize these clinoforms are prone to gravitational instabilities inducive of sediment layer disruption and sediment sliding or slumping (Fig. 3).

Regarding the top seismic sequence Sq5, its stratigraphic architecture supports the interpretation of deposition that occurred under transgressive and highstand conditions. The patchy sedimentary cover that makes up Sq5 on the outer shelf has been interpreted as transgressive units (in the sense of CATTANEO; STEEL, 2003), deposited by reworking during transgression, and whose preservation has probably been favoured by the occurrence of pre-existing erosive depressions imprinted on surface S5 (Figs 2 and 6c, d); these features can be topped by a highly irregular sea-bottom morphology (Fig. 6D), which may correspond to carbonate bioconstructions, already identified in the outer shelf of the study area (SIMÕES, 2007). The dune-like seismic features mapped on the mid-shelf were equally interpreted as having been formed under transgressive conditions, possibly as transgressive lags developed during sea-level stillstands (Figs 2 and 6B); similar sedimentary motifs were observed by RABINEAU et al. (2005) across the continental shelf of the Gulf of Lions, western Mediterranean sea, and have been interpreted as transgressive sedimentary prisms constructed under stillstand conditions**.** As for the inner shelf laterally-continuous sedimentary prism, it probably represents sedimentary elements of Sq5 that developed under sea-level highstand conditions, resulting in a wedge-like feature whose external limit roughly coincides with the -50 m isobath (Figs 2 and 6A).

As discussed above, the seismic stratigraphic analysis carried out in this study led to the identification of eight shallow seismic sequences based on their bounding surfaces and on their respective internal architectural elements. However, their age definition based on chronostratigraphic data remains elusive due to the lack of core data. Thus, the only option left was to rely on chronostratigraphic correlations based on the oil industry's exploratory wells that usually neglect the Plio-Quaternary section because of its economic irrelevance for oil. Nonetheless, our chronostratigraphic reconstruction can be partially supported by stratigraphic data from exploratory well P1 (well 1-SPS-0003-SP, located at 110 m depth) and well P2 (well RJS-001-RJ, located at 49 m depth, figure 8a), which exceptionally offer biostratigraphic dating within the Plio-Quaternary stratigraphic window.

Sediment intervals from well P1 sampled between 245 and 423 m below the seafloor were dated as Pliocene deposits (undifferentiated Pliocene age, Fig. 8B). Correlation by lateral projection with seismic lines located 2 km away from well P1 shows that the seismic section extending from sequence SqA up to the upper portion of sequence SqB corresponds to the Pliocene interval sampled at well P1 (Fig. 8B). For this reason, sequences SqA and most of sequence SqB that compose Set I may be placed within the Pliocene window. Moreover, correlation of GEOMAR seismic lines with chronostratigraphic data from well P2 (Figs 8c, d) also offers additional data for tentative age constraint. By crossing seismic lines of our data base with those of Silva (1992), surface S1 has been correlated with a regional erosive surface, the so-called "Marco P". This horizon lies unconformably over sediments of SqC that were sampled 150 m below the seafloor and dated by biostratigraphic proxies (Figs 8c, d). According to SHIMABUKURO (1989, *apud* SILVA, 1992), sediments recovered at the level of "Marco P" lay at the top of biozone N710 (international biozone NN19 of MARTINI, 1971) indicated by the presence of *Pseudoemiliania lacunosa*, whose occurrence corresponds to a large time span between 910-440 kyr (early-middle Pleistocene). So, if the dated interval in fact corresponds to the top of biozone N710 (actually subzone D at the top of biozone N710 of ANTUNES, 1994), surface S1 could then be placed at around 440-500 kyr, as stated by SILVA (1992). However, this age would be fully credible only if species younger than 440 kyr, like for instance *Gephyrocapsa oceanica* (ANTUNES, 1994), were found within sediments overlying “Marco P”; unfortunately this is not mentioned by SHIMABUKURO (1989, *apud* SILVA, 1992). Besides that, in all likelihood, erosive surface “Marco P” shows substantial spatial and temporal variability related to distinct degrees of shelf erosion across the southern Campos and the northern Santos basins.

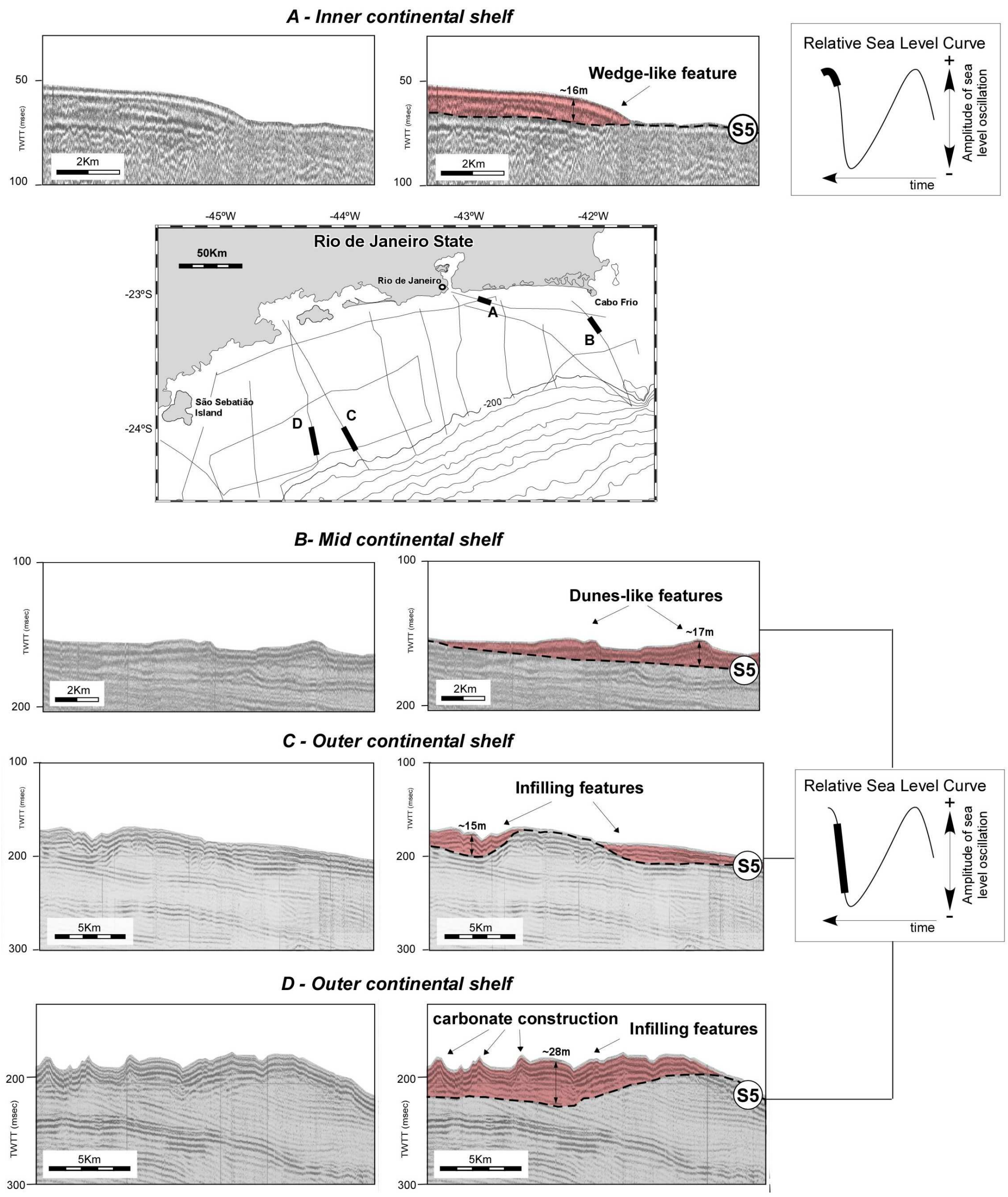

Fig. 6. Zoom-in of single-channel seismic lines to illustrate the varying architectural style of sequence Sq5 across the continental shelf of the study area.

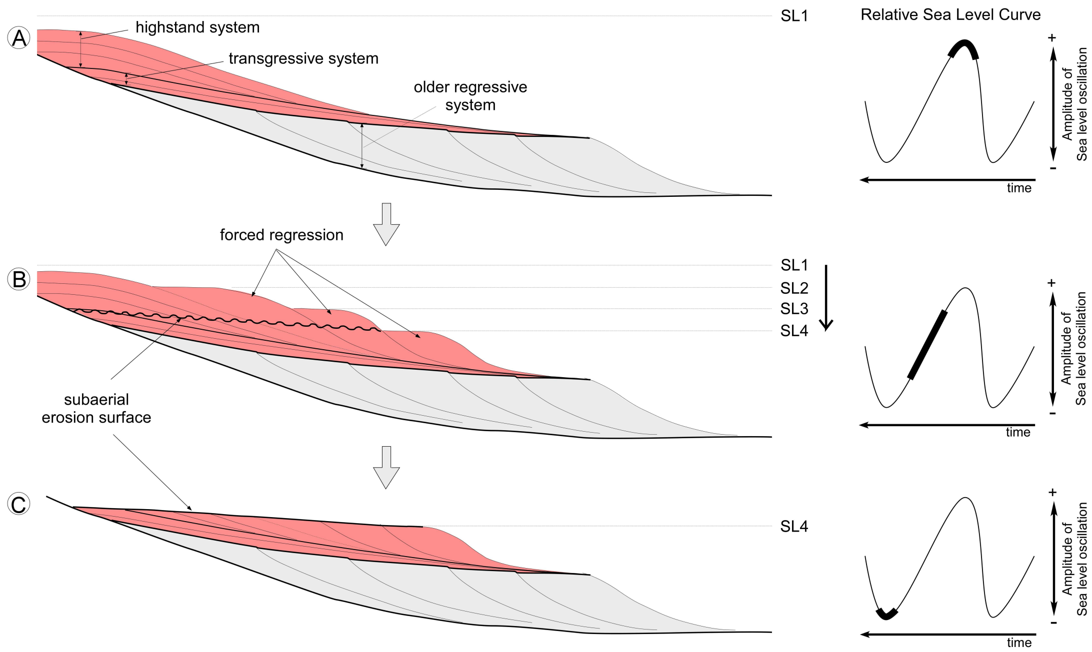

Fig. 7. Simplified conceptual model of regressive sequences based on seismic evidences and depositional geometries observed in the upper set of depositional sequences (Sq1-Sq4) of the sedimentary record of the continental shelf off Rio de Janeiro State. SL = sealevel (modified from RIDENTE; TRINCARDI, 2002).

Nonetheless, despite the scant amount of available chronostratigraphic data, it was possible: (1) to place the shallow seismic section (~300 msec) depicted by the mapped sequences of Set I (SqA–SqC) and Set II (Sq1–Sq5) within the Pliocene-Quaternary interval; and (2) to estimate a Quaternary age for the exposure surface S1 (lower-middle Pleistocene, between 910-440 kyr) (Fig. 9a). Therefore, even if time intervals involving deposition of all sequences cannot be fully constrained in the study area, the larger part of the seismic sequences that compose Set I (SqA and part of SqB) are of Pliocene age, while the upper part of SqC is Quaternary in age (Figs 8A, 9A and 10). On the other hand, concerning the age of surface S1, seismic stratigraphic analysis has shown that it is overlain by five depositional sequences (sequences Sq1–Sq5, Figs 3 and 4). Considering that since the Middle Pleistocene (~last 800 kyr; SHACKLETON; OPDYKE, 1976), there is a global prevalence of high frequency fourth-order depositional cycles of circa 100-120 kyr, stratigraphic correlations discussed above hint at a time span of circa 440-500 kyr for the deposition of sequences Sq1 through Sq5 (Fig. 9a). Thus, as the four regressive sequences Sq1-Sq4 exhibit similar internal geometry, as well as a similar relation to their bounding surfaces, it is suggested that they record fourth-order depositional cycles for the last 440-500 kyr. The Pliocene-Quaternary limit would then be placed at an undetermined horizon between the upper portion of sequence SqB and the upper portion of sequence SqC (Figs 9 and 10).

In this scenario, the first four sequences of Set II would encompass the succession of oxygen marine isotope stages (MIS) 12 to 2 (RABINEAU, 2006, Fig. 9B): Sq1 would be the record of deposition between MIS 12 and 10 (ca. 430-450 to 330-350 kyr BP); Sq2 would be correlated to deposition that took place between MIS 10 and 8 (ca. 330-350 to 230-250 kyr BP); Sq3 would be related to MIS 8 and 6 (ca. 230-250 to 130-140 kyr BP); and Sq4 would be the testimony of deposition from MIS 6 to 2 (ca. 130-140 to 30-20 kyr BP). The fact that MIS 5 is represented by the highest sea-level position (up to ~15-20 m above current sea-level, figure 9b), and that the low sea-level of the subsequent LGM (135-145 m, MIS 2) was at a higher position than the preceding glacial maximum (150-160 m, MIS 6), can possibly explain why sequence Sq4 is characterized by preserved transgressive and/or highstand units (Figs 3 and 9b). Last but not least, sequence Sq5 is represented by transgressive lags (dune-like features and infilling deposits developed during the Holocene transgression, Figs 2 and 6B, C, D) and the continuous inner-shelf sedimentary prisms deposited under highstand sea-level conditions (Figs 2 and 6A) being thus interpreted as a sequence still under construction.

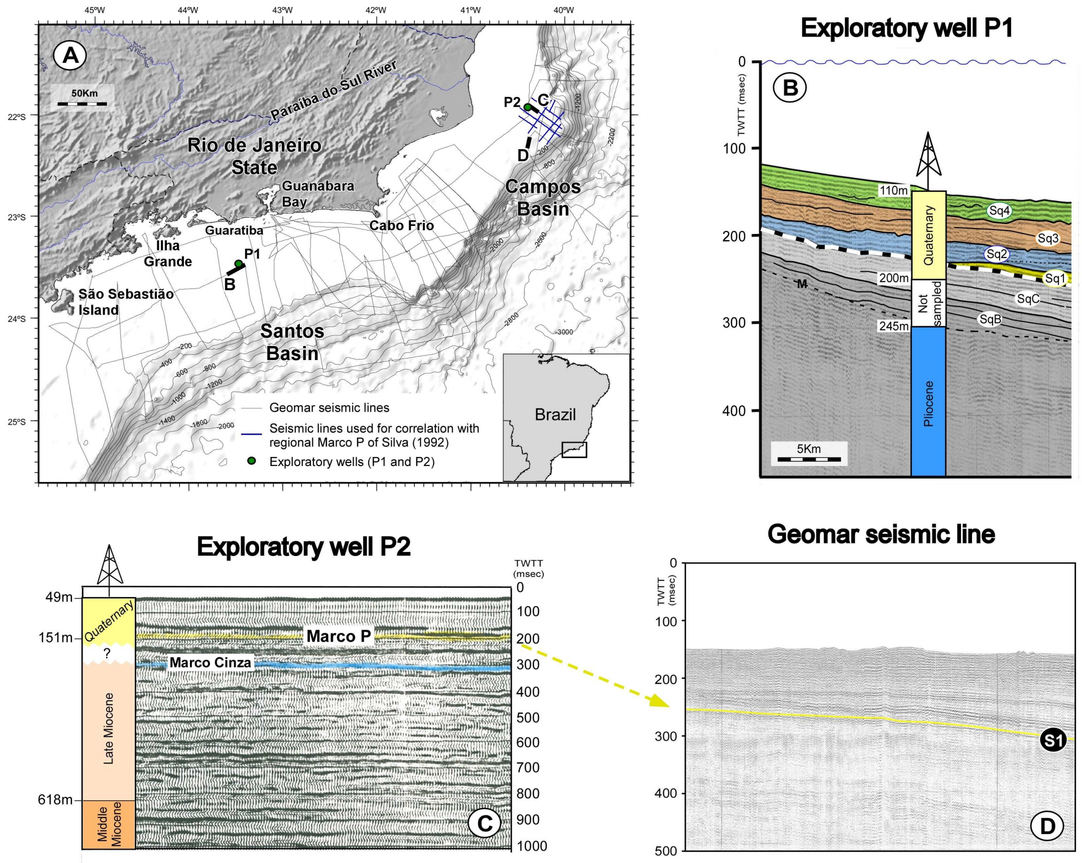

Fig. 8. Well log information of wells P1 and P2 used in this study, as well as their calibration on the respective seismic lines.

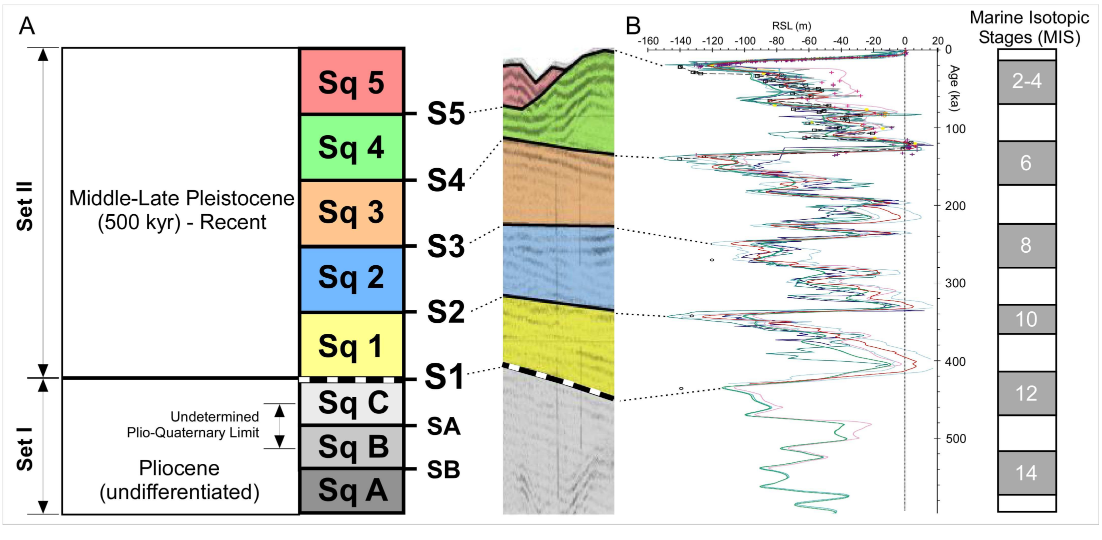

Fig. 9. A- Stratigraphic column showing the correlation of the mapped sequences constrained by chronostratigraphic data from exploratory wells. B- Proposed depositional cyclicity of mapped sequences based on correlation with $\delta^{18}O$ isotopic "global sea-level curves" compiled by RABINEAU et al. (2006).

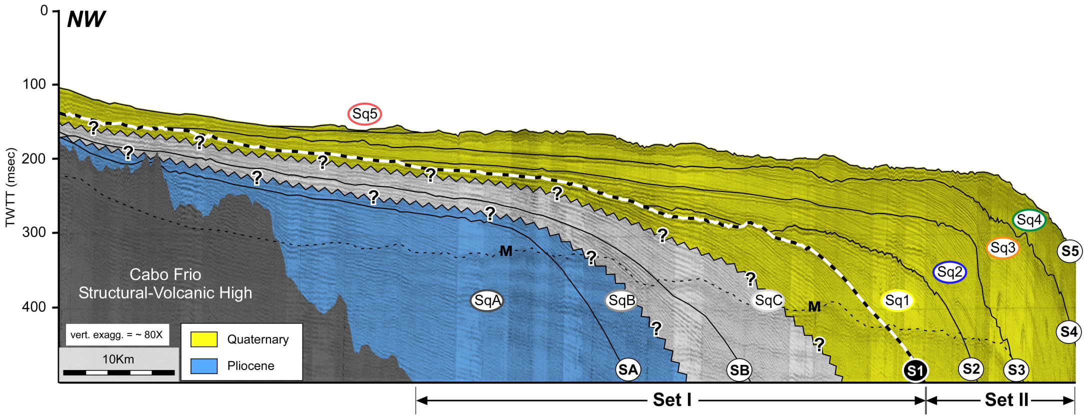

Fig. 10. Interpreted dip single-channel seismic line across the eastern shelf sector off Rio de Janeiro, illustrating ages of the stratigraphic Sets I and II.

The above proposed interpretation of sedimentary architecture of the study area is consistent with many evidences coming from other Quaternary margins worldwide, where the depositional cyclicity is dominated by the falling part of high-frequency, fourth-order glacioeustatic cycles resulting in a sedimentary pattern of stacked forced-regression wedges (e.g. PIPER; AKSU, 1992; SYDOW; ROBERTS, 1994; TRINCARDI; CORREGGIARI, 2000; EVANS et al., 1995; HERNANDEZ-MOLINA et al., 2000; RIDENTE; TRINCARDI, 2002; JIN et al., 2002; LOFI et al., 2003; BERNÉ et al., 2004; OKYAR et al., 2005; RABINEAU et al., 2005; TEZCAN; OKYAR, 2006; GROSSMAN et al., 2006; LIQUETE et al., 2008; TRIPSANAS; PIPER, 2008).

Conclusion

The seismic analysis of GEOMAR data sets allowed the recognition and mapping of identifiable seismic sequences in the shallow sediment record (~300 msec) of the prograding continental shelf of the northern Santos basin for the first time. Two distinctive sets of stratigraphic sequences, Set I and Set II, were defined and described, constituted by eight mapped seismic sequences (SqA, SqB, SqC, Sq1 to Sq5) (Figs 3 and 4).

Seismic stratigraphic analysis also evidenced major differences between the depositional styles of Set I and Set II indicating distinctive interplays between base-level variations and sequence preservation. Set I (SqA-SqC) is a dominantly sigmoidal set of sequences that illustrates an aggradational-progradational shelf, reflecting relatively enhanced regional subsidence and/or a longer-term relative sea-level rise, which favoured deposition and preservation of aggrading sedimentary units, as well as the shelf progradation for about 25 km in the study area (Fig. 4). In contrast, the first four seismic sequences of Set II (Sq1-Sq4) stack on top of each other to form a composite regressive wedge developed under dominant forced-regression conditions; stacked regressive seismic sequences still imply a prevailing subsidence regime, able to induce the seaward tilting of the margin, but also decreasing accommodation space when compared to conditions that seem to have prevailed during the deposition of Set I; under these circumstances, the shelf prograded between circa 15-25 km in the northern Santos basin (Fig. 3).

Correlation among seismic interpretation, chronostratigraphic data from boreholes (wells P1 and P2, Fig. 8) and isotopic sea level curves (Fig. 9B) supports the hypothesis that sequences Sq1-Sq4 record 100-120 kyr glacioeustatic cycles for the last 440-500 kyr, whereas most sequences of Set I (SqA and part of SqB) are Pliocene in age (Fig. 9a). Sequence Sq5 is related to Holocene deposits found in the inner (internal prism) and mid-shelf (transgressive lag deposits) that are hence part of a sequence still under development (Figs 2, 3, 4, 6 and 9).

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