Quaternary shelf sedimentary systems off Rio de Janeiro State, NE Santos Basin – Brazil

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Abstract

The combined analysis of *sparker* monochannel seismic reflection data acquired by GEOMAR missions in the early 80's and data from exploratory wells provides new insights into the shallow sedimentary record (~400 ms penetration) of the continental shelf systems along Rio de Janeiro state. The seismic data display a pattern of stacked prograding shelf wedges composing 8 major seismic sequences (SqC to SqA and Sq1 to Sq5), limited by unconformity surfaces (S0-S5) that suggest erosive processes indicative of prolonged subaerial exposure of the continental shelf. Sequences can be grouped into two distinct sets according to the geometry of their clinoforms, which are either dominantly sigmoidal (Set II) or dominantly oblique (Set II). Indirect correlation with seismic data from Silva (1992) points to an age of circa 0,5 My(Middle-Upper Pleistocene) for the erosive surface S1, whereas correlation with well data (by well projection) hints that S0 might be placed within the Pliocene stratigraphic window. Finally, interpretation of seismic and well data supports the hypothesis that the depositional pattern of sequences Sq1-Sq5 records a 100 kyr glacioeustatic cycle.

Introduction

The study area comprises the east-west oriented continental shelf off Rio de Janeiro State, SE Brazil, between Cabo Frio and São Sebastião Island (Figure 1). The present-day morphology and sedimentary environments of Santos Basin have evolved under the influence of successive migrations of the coastline (transgressions and regressions) linked to the Quaternary oscillations of relative sea-level (Muehe and Valentini, 1998; Turcq *et al.*, 1999; Moreira and Carminatti, 2006). Both the width of continental shelf and the depth of its shelfbreak increase westwards from Cabo Frio: immediately adjacent to Cabo Frio the continental shelf is about 100 km large and the depth of shelfbreak does not exceeds 150m, while a much broader continental shelf as large as about 160km large is present off São Sebastião Island, with its shelfbreak reaching 220m deep.

So far, very few studies have dealt with the Plio-Quaternary evolution of the shelf sedimentary section of Santos Basin offshore RJ State. Alves et al. (1980) were the first authors to point out the presence of progradational features at the shelf break within the upper sedimentary section (~ 400 ms) in the area, although the associated sedimentary architecture and depositional cyclicity were not discussed. The same scarcity of studies applies to seismostratigraphic or exploratory well data analyses of the inner-middle shelf environments (an exception is for example Artusi and Figueiredo, 2007). Actually, along RJ State, most of the studies dealing with the Quaternary stratigraphic window of Santos Basin's proximal sedimentary section have focused on the morphological and stratigraphic evolution of coastal plain features (e. g. Martin *et al*, 1979; Maia *et al.*, 1984; Turcq *et al*, 1999). The present-day coastal sedimentary environments vary considerably of along RJ State. Sandy coastal plains and a series of associated lagoons dominate the eastern coastal sector between Guaratiba and Cabo Frio (e.g. barrier-lagoon systems of Araruama and Maricá). On the other hand, drowned coastal environments dominate along the RJ's western sector. Sepetiba Bay is a shallow embayment enclosed by a barrier island about 45 km long, where estuarine conditions prevail (Borges, 1998), while Ilha Grande Bay is an embayment partially enclosed by Ilha Grande Island and mostly filled up by shelf waters (Borges, 1998; Muehe and Valentini, 1998).

The main objective of this work is to investigate the architecture of continental shelf sedimentary systems off Rio de Janeiro state in orden to understand how sedimentary sequences are developed, their associated depositional cyclity and finally how inner shelf sedimentary systems are linked to shelf edge systems.

Method

Seismic data used in this paper are single-channel Sparker lines (500-1000 Joules, 100 to 1400 Hz) acquired during legs XVI and XX of GEOMAR Oceanographic Missions in the early 80's (Figure 1). Maximum signal penetration varied between 300 and 400 ms; the vertical resolution oscillated between circa 7 and 12 m, depending on the seismic line considered (pulse duration of about 10-15 ms). Interpretation of the seismic profiles was implemented using the general principles of seismic and sequence stratigraphy (Mitchum et al., 1977, Catuneanu, 2006). Chronostratigraphic correlations were based on exploratory wells (P1 and P2, Figure 1) from Petrobras, made available by the Brazilian National Agency of Petroleum-ANP, as well as on compilation of isotopic sea-level curves.

Depositional cyclicity of Quaternary sedimentary systems at the scale of the continental shelf

At the scale of the continental shelf off RJ State, the available seismic data (Figure 1) display a pattern of stacked prograding shelf wedges composing eight major seismic sequences limited by unconformity surfaces that suggest erosive processes indicative of prolonged sub aerial exposure (Figure 2). According to the geometry of their clinoforms, the seismic sequences can be grouped into two distinct sets, which are either dominantly sigmoidal (Set I, SqA-SqC) or dominantly oblique (Set II, Sq1-Sq4, Figures 2 and 3), separated by an important erosive surface, named S1 (Maia et al., submetido).

Crossing of seismic lines of our data base with those of Silva (1992) in the Campos Basin (Figure 1) allowed us to correlate an important erosive surface mapped in our seismic lines (surface ***S1*** that separates Set I from Set II) with a stratigraphic marker, named *Marco P*. *Marco P* is an unconformity regionally expressed on the Brazilian eastern marginal basins and was dated 0,5 My at the exploratory well P1 (Figure 1). Besides, correlation of seismic lines by projection with exploratory well P2 (Figure 1) indicates that erosive surface ***S0*** is laterally correlatable with an unconformity of Pliocene age (undifferentiated Pliocene dated at well P2). These stratigraphic correlations hint to a time span of circa 0,5 My (Middle-Late Pleistocene) for the deposition of the five mapped seismic sequences overlying erosive surface ***S1*** (sequences Sq1-Sq4), whereas sequences of Set 1 (SqA-SqC) are quite possibly Pliocene in age (the Plio-Quaternary limit must be placed along an undetermined horizon between surfaces ***S0*** and ***S1***) (Figure 3; Maia *et al. 2*008). Correlation of seismic interpretation, chronostratigraphic data from boreholes (wells P1 and P2) and "isotopic" sea level curves supports the hypothesis that clinoforms and shelf wedge prisms of sequences Sq1-Sq4 record 100 kyr glacioeustatic cycles for the last 0.5 My (Figure 3; Maia *et al*., 2008). Deposits labelled sequence Sq5 are represented by Holecene trangressive lags.

Sedimentary sequences in Set I and Set II also display distinct clinoform geometries that seem to reflect equally distinctive preservation rates of sequences. Sigmoidal clinoforms of Set I (example in gray scale in Figure 2A) are composed of shelfwedge prisms and tabular mid-inner shelf units indicating that both progradational and aggradational facies were partially preserved. On the other hand, oblique clinoforms of Set II are composed essentially by shelfwedge prisms, whereas no aggradational tabular units were preserved on the mid-inner continental shelf (except for sequence Sq4) (Figure 2A). Such disctinctive geometries and lateral extent of sequences may reflect a decreasing accommodation space and preservation rate through time. Lower preservation rates of Quaternary sequences (Sq1-Sq3) probably stem from slowing subsidence rates, associated to the thermically aging Santos Basin.

In addition, seismic analyses also evidence remarkable lateral variability of the internal geometry and preservation rates of sedimentary sequences composing Set II. On the eastern shelf of the study area, sequences Sq1-Sq3 are relatively poorly preserved in the form of regressive sequences (shelf edge sedimentary prisms). Their unconformities are also marked by rather irregular surfaces indicating strong erosional processes (Figure 2A). Contrastly, on the western shelf area, sequences Sq1-Sq3 are able to reach the mid-inner shelf domains and be also preserved as trangressive and/or high stand sedimentary systems (plan-parallel tabular units in Figure 2B). Such variability in the preservation rate of sequences Sq1-Sq3 sugests lateral availability of accommodation space between the east and west continental shelf of Santos Basin. Actually, sedimentary thickness of sequences Sq1-Sq4 also varies from east to west, pointing to differential subsidence rates (induced by differential sedimentary loading) in the study area though the Quaternary. Considering, for instance, depth to the Marco P (surface S1) at the contour line 110m water depth (~150ms), we observe that the total thickness of sequences Sq1-Sq4 is about 160m on the eastern shelf (adjacent to Cabo Frio), whereas on the western shelf area it is as thick as 200m .

Higher rates of sequence preservation and subsidence, and possibly a higher rates of sedimentary input, seem to be present on the western sector of the continental shelf off São Sebastião Island. This geological setting is finally reflected in the width of the continental shelf (as large as about 160km) and the depth of shelfbreak (as deep as 220m).

The inner-middle continental shelf: seismic sequences and variability of depositional environments

The morphology of the inner and middle continental shelf adjacent to RJ State is regionally smooth, except for the presence of wedge-like features that broadly follow the 50 m (*internal prism*) and 100 m (*external prism*) isobaths (Figure 1). While the *internal prism* (lying unconformably over sequence Sq4, Figure 4A) is the main expression of the Holocene Sq5 sequence (younger than ~11 kyr) along the continental shelf; the *external prism* represents, on the other hand, the uppermost units of the previous sequence Sq4 (Upper Pleistocene Sequence, Figure 4B). In the lack of both higher resolution seismic data and core samples, both prisms are here interpreted as marine sedimentary units deposited at sea-level highstands or stillstands during transgression cycles. Both prisms widens westwards, what may possibly be explained by the fact that drainage basins debouching directly into the coastline are presently found only along the western sector, like Macacú and Caceribú Rivers that flow into Guanabara Bay, and Guandú River that discharges into Sepetiba Bay (Borges, 1998; Catanzaro, 2002).

Seismic interpretation carried out across the inner-middle continental shelf allowed the mapping of four main seismic sequences, laterally correlatable with depositional sequences SqB and SqA (Set I) and sequences Sq4 and Sq5 (Set II). Sequence Sq4 (~123–20 kyr) lies unconformably over sequence SqA, which is older than 0.5 My (Figures 2A and 2B).

Seismic analysis also revealed remarkable lateral changes of seismic facies within both sequences SqA and Sq4 along the E-W direction of RJ's coast (Fleming et al., 2009):

(1) Along the eastern sector (between Guaratiba and Cabo Frio), both sequences SqA and Sq4 display fairly continuous and horizontal to sub-horizontal reflectors, with local cut and fill patterns (channel forms), while their lower boundaries are erosive smooth surfaces. These laterally persistent reflectors, coupled with their parallelism and local infilled channel, suggest a predominantly marine sequence cut by tidal inlets (?), compatible with sandy prisms/barriers that characterize the adjacent coastal plains composed of inner barrier systems of about 123 kyr BP (e.g. Martin et al, 1979; Maia et al., 1984; Turcq et al, 1999) (Figures 5A);

(2) Along the western sector (between Guaratiba and Paraty), both sequences SqA and Sq4 have their lower boundaries depicted by irregular erosion surfaces, expressing incision features formed during lowstand cycles. Their internal facies display a chaotic pattern of reflectors with superimposed cut and fill facies suggesting estuarine-fluviatile conditions (Figures 5B) that can be correlated to similar drowned coastal environments like those currently found along the adjacent coastal areas, such as Sepetiba and Ilha Grande Bays.

Differently from sequences SqA and Sq4 that exhibit rather distinct seismic facies between the eastern and western sectors offshore RJ State, sequence SqB (Pliocene in age) presents a very regular seismic facies that prevail at the inner-middle continental shelf all along RJ coast between Paraty and Cabo Frio. Sequence SqB displays high angle clinoforms forming inclined foresets that gradually become sub-parallel to parallel further offshore (Figure 2A and 5).

Conclusions

- Analysis of *sparker* monochannel seismic reflection data allowed us to map 8 major seismic sequences on the continental shelf off RJ State, between Cabo Frio and São Sebastião Island (Figure 1). Sequences were grouped into two geometrical sets: Set I (SqC to SqA) and Set II (Sq1 to Sq5), each sequence being limited by unconformity surfaces (S0-S5). Correlation of seismic interpretation, chronostratigraphic data from boreholes (wells P1 and P2) and isotopic sea level curves supports the hypothesis that sequences Sq1-Sq4 record 100 kyr glacioeustatic cycles for the last 0.5 My, whereas sequences of Set I (SqA-SqC) are quite possibly Pliocene in age (Figure 3). Sequence Sq5 is related to Holocene deposits in the inner (internal prism) and middle shelf (transgressive lag deposits) that are hence parts of a sequence still under development.
- Sequences SqC to SqA (Set I) display aggradational and progradational features, while sequences Sq1 to Sq3 (Set II) display only progradational features (shelfwedge prisms located at the shelf edge). Such disctinctive geometries of sequences may result from decreasing accommodation space and preservation rate of sequences from the Pliocene to the Quaternary, probably because of decreasing subsidence rates (associated to sedimentary loading) through time.
- Geographical extent of sequences Sq1 to Sq3 (Set II) also varies from east to west along the continental shelf off RJ State. Sequences are relatively poorly preserved as shelfwedge prisms and their unconformities are also strongly erosional on the eastern sector of the continental shelf (offshore Cabo Frio area). On the western shelf area, sequences are able to reach the mid-inner shelf domains and be also preserved as high sea-level stands agradational units (Figure 2B). Lateral variability in the preservation rate of sequences from east to west may quite possibly reflect a differential subsidence rates between the east and west continental shelf of Santos Basin.
- Concerning the coastal and inner shelf sedimentary environments of RJ State, distinct seismic facies found nowadays in the inner-middle continental shelf can be correlated with equally distinct modern coastal environments, dominated westwards by drowned coastal features (bays/estuaries) and eastwards by barrier-lagoon systems. Sequences SqA and Sq4 present the same east-west environmental variability showing that a similar partitioning of coastal environments as observed today may have been present since before 0,5 My (age of top of sequence Sq A). The regular seismic pattern of sequence SqB (possibly Pliocene in age) composed of prismatic foresets at the scale of the whole shallow shelf (up to depths of ~60-70 m) indicate the regional prevalence of more energetic conditions (sandy shorefaces?) between Paraty and Cabo Frio during the Pliocene (Figure 6A e 6B).

Acknowledgments

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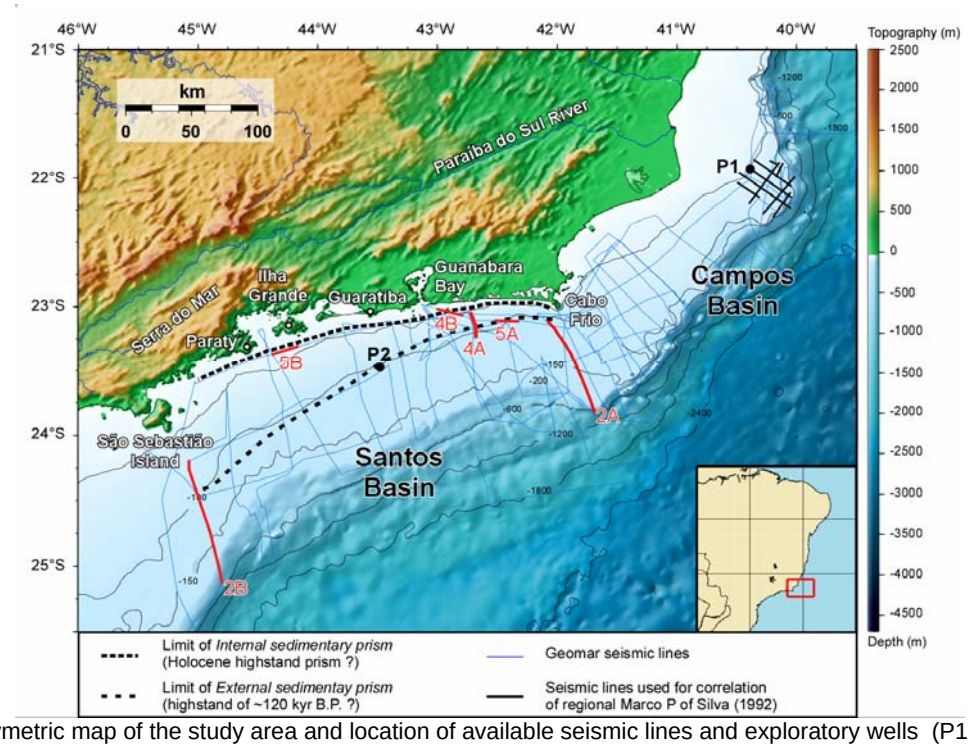

Figure 1: Bathymetric map of the study area and location of available seismic lines and exploratory wells (P1 and P2). Bathymetric data from Smith and Sandwell (1997).

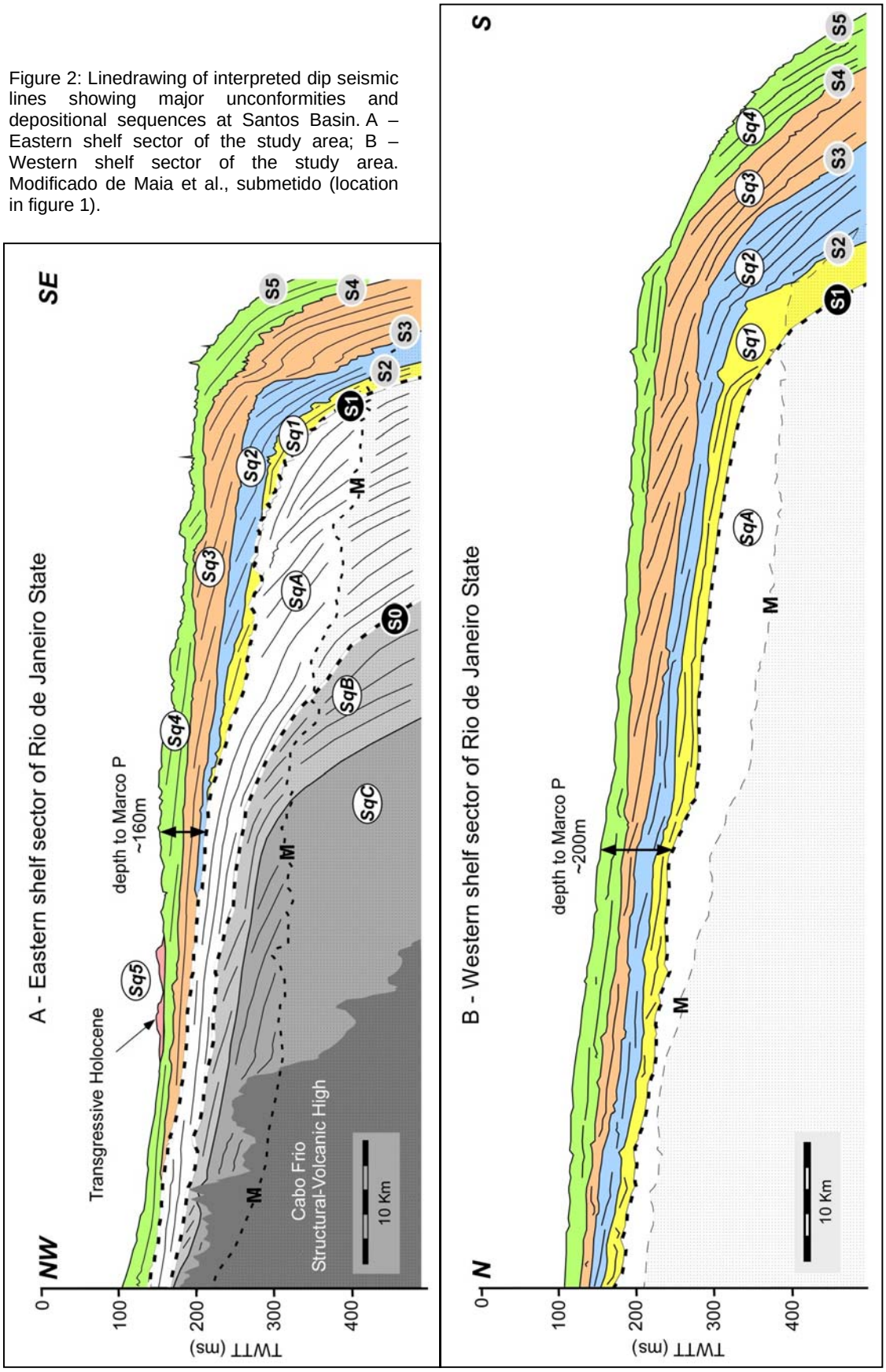

Figure 2: Linedrawing of interpreted dip seismic lines showing major unconformities and depositional sequences at Santos Basin. A – Eastern shelf sector of the study area; B – Western shelf sector of the study area. Modificado de Maia et al., submetido (location in figure 1).

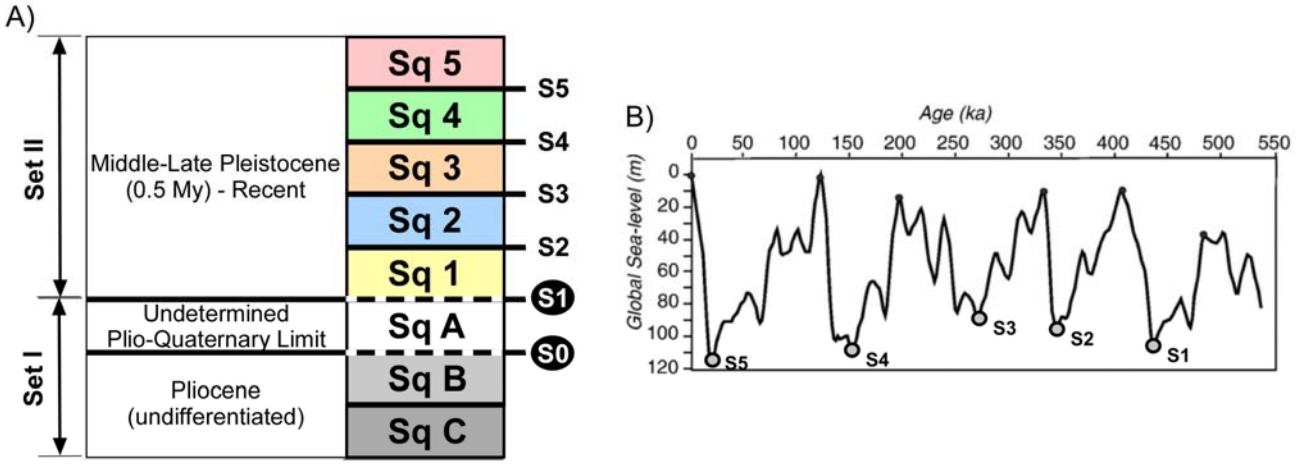

Figure 3: A- Correlation of mapped sequences constrained by chronostratigraphic data from exploratory wells: ***S1*** (0.5 My) and ***S0*** (Pliocene, undifferentiated); B- Proposition of depositional cyclicity of mapped sequences based on correlation with isotopic curves of sealevel changes (modified from Jouet *et al*., 2006)

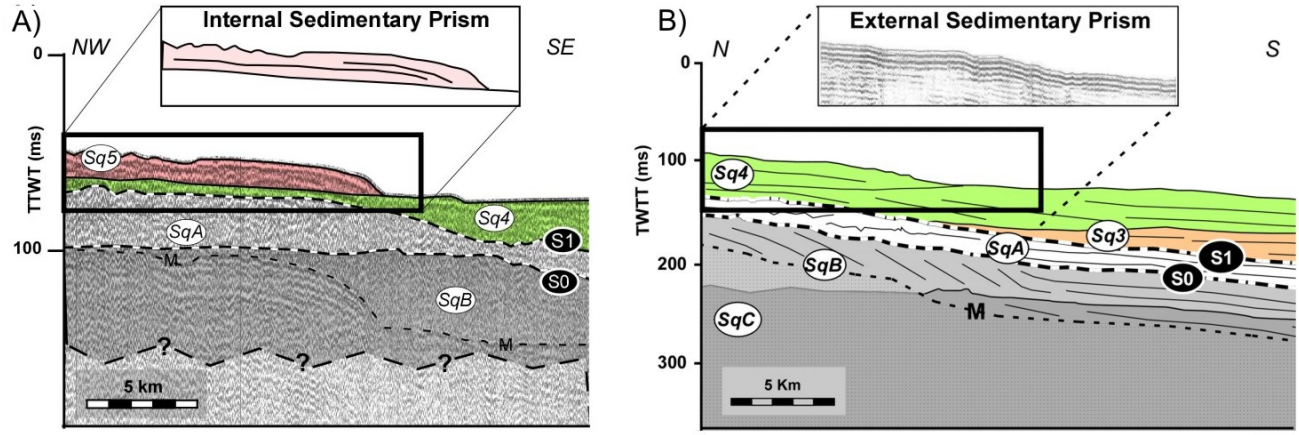

Figure 4: A - Extract of dip seismic line illustrating the *internal sedimentary prism* at the inner-middle continental shelf off Rio de Janeiro State; B – Linedrawing illustrating the *external sedimentary prism* at the inner-middle continental shelf off Rio de Janeiro State (location in figure 1).

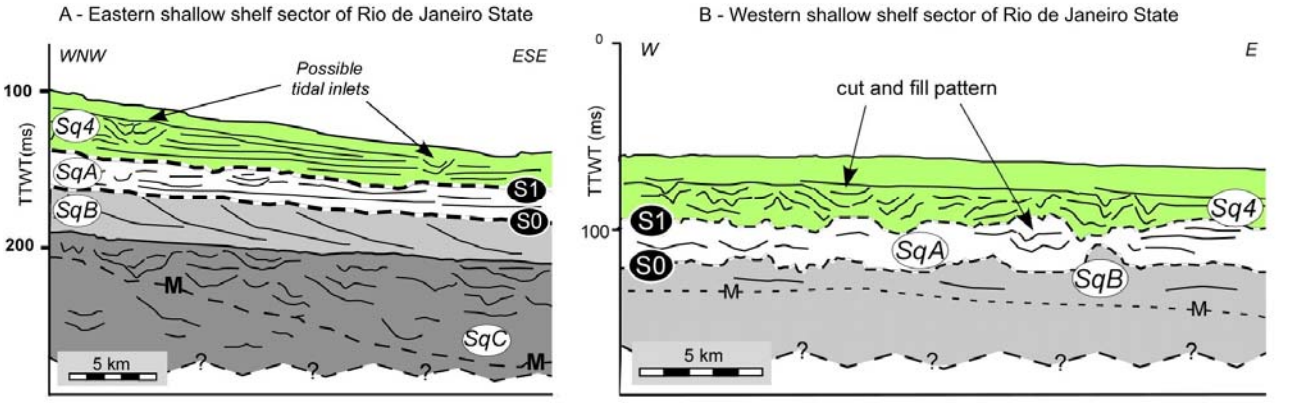

Figure 5: A – Linedrawing of the shallow shelf adjacent to the eastern sector of RJ State. B – Linedrawing of the shallow shelf adjacent to the western sector of Rio de Janeiro State (location in figure 1).