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RESEARCH PAPER

SEISMIC STRATIGRAPHY OF THE EOCENE–LOWER OLIGOCENE IN THE URUGUAYAN CONTINENTAL MARGIN

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Abstract

The Uruguayan continental margin was generated following the fragmentation of the Gondwana supercontinent and the subsequent opening of South Atlantic Ocean. It constitutes an extensive sedimentation area in which three sedimentary basins can be found: the Punta del Este Basin, the southernmost portion of the Pelotas Basin, and the poorly defined Oriental del Plata Basin. The aim of this work was the identification and characterization of the different seismic units (seismic facies, systems tracts, depositional sequences) for the sedimentary interval assigned to the Eocene in the Uruguayan continental margin. Sequence stratigraphy was used as a basin analysis method for this purpose, using a database that consisted of approximately 10,000 kilometers of 2D seismic sections, acquired in exploratory surveys in 2007 and 2008. The workflow included the recognition of stacking patterns and/or stratal terminations, the definition of genetically significant stratigraphic surfaces and, based on these, the identification of systems tracts and depositional sequences. Three depositional sequences were identified in the studied sedimentary interval. The basal sequence is composed of four depositional systems tracts, including falling stage, normal regression (lowstand and highstand) and transgressive deposits. The intermediate sequence only preserves lowstand normal regression deposits. The third sequence is composed by three depositional systems tracts, including lowstand, transgressive and falling stage deposits.

Keywords: Eocene. Sedimentary Basins of Uruguay. Sequence Stratigraphy. Stratal Stacking Patterns.

1. Introduction

The Uruguayan continental margin (UCM) constitutes a typical divergent margin, of a volcanic and segmented type (Soto et al., 2011), characterized by the presence of wedges of seaward-dipping reflectors (SDRs) and a high-velocity lower crust (HVLC) (Franke et al., 2007; Soto et al., 2011; Morales et al., 2017). The UCM appears segmented by the Río de la Plata Transfer System (RPTS; Soto et al., 2011), which sinistrally displaces geophysical anomalies and depocentres and interrupts the occurrence of the SDRs wedges. This region represents an extensive sedimentation area in which three sedimentary basins can be found: the Punta del Este Basin, the southernmost portion of the Pelotas Basin, and the poorly defined Oriental del Plata Basin (Stoakes et al., 1991; Ucha et al., 2004; Soto et al., 2011; Conti et al., 2017; Morales et al., 2017) (Fig. 1).

In shallow waters, the Polonio High divides the Punta del Este Basin, to the southwest, and the Pelotas Basin, to the northeast (Fig. 1). However, in deep waters, the morphological expression of this structural high cannot be observed; therefore, in ultra-deep waters sedimentation shows continuity between the two basins (Morales et al., 2017).

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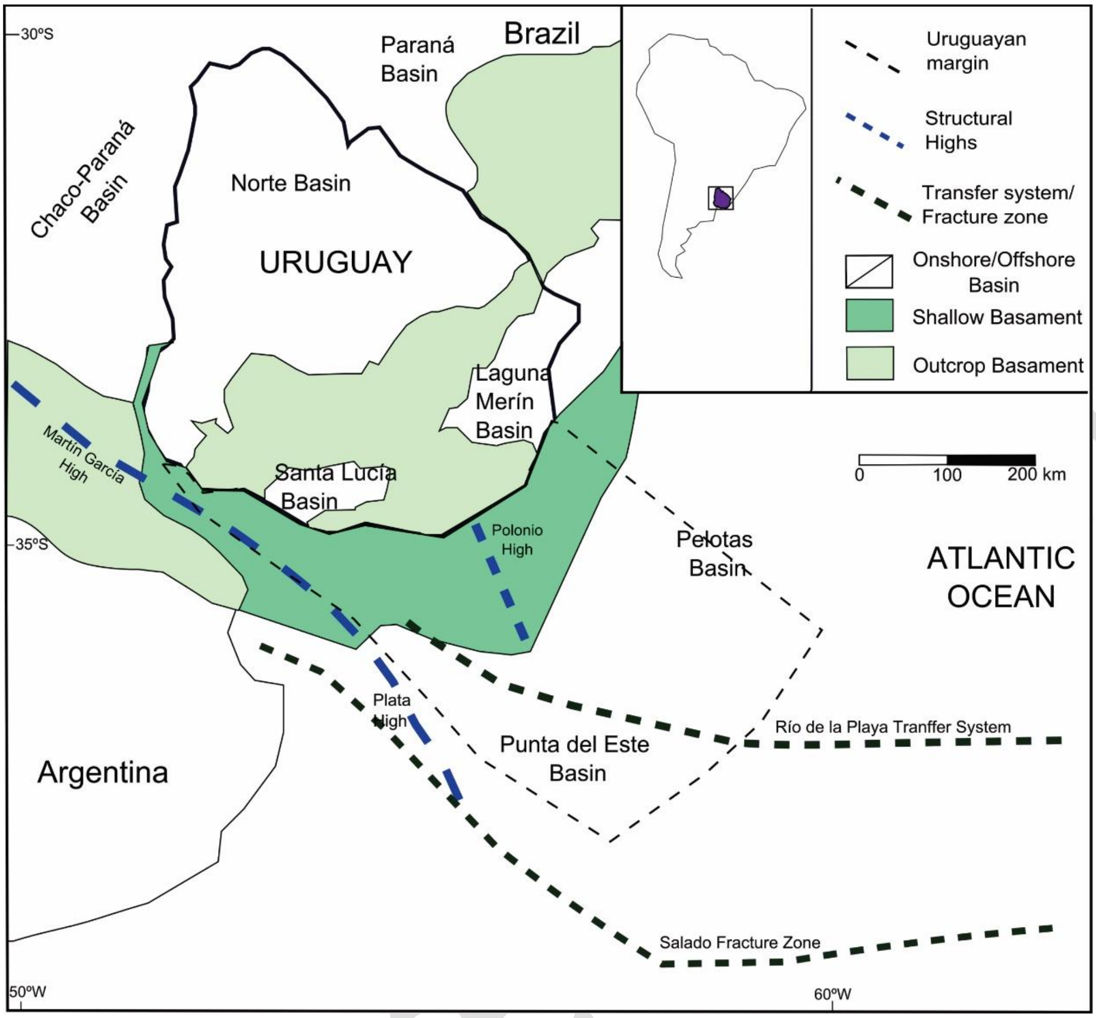

Fig. 1. Geological map depicting transfer systems, fracture zones, structural highs, and Uruguayan onshore and offshore basins. Modified from Soto et al. (2011).

The UCM has an extension of approximately 130,000 km^2 (up to the 200- nautical mile limit) and water depths ranging from 20 m to over 4,000 m. In the UCM 3 exploratory wells were collected, Lobo, Gaviotín and Raya (Fig. 2). The Lobo and Gaviotín wells were drilled in 1976, in a very proximal sector of the Punta del Este Basin, reaching the base rift-related basalts and pre-rift sediments, respectively. The Raya well was drilled in 2016, in ultra-deep waters of the Pelotas Basin, ending in an Oligocene turbidite.

Although historically the UCM may be regarded as scarcely explored, over the past decade it has sparked the interest of researchers, professionals and oil companies, especially after significant reserves of hydrocarbon were discovered in the 'pre-salt' of the Brazilian continental margin. This situation has contributed to an increase in the amount and quality of data available for the research of the basins located in the UCM, leading to a greater understanding of their origin, evolution, and their tectonic and stratigraphic configuration.

Most of the previous research work focused on the recognition of the depositional sequences that make up the different phases of basins evolution, in shallow as well as in deep and ultra-deep waters, since the opening of the South Atlantic Ocean (e.g. Raggio et al., 2011; Morales et al., 2017; Conti et al., 2017), as well as the interpretation of depositional and erosive features related to contour currents in sedimentary intervals with well-defined ages (e.g. Hernández Molina et al., 2010, 2016; Creaser et al., 2017). In this work, the aim was the identification and characterization of the different seismic units (seismic facies, system tracts, deposition sequences) for the sedimentary interval assigned to the Eocene in the Uruguayan continental margin.

2. Geological Framework

The Gondwana supercontinent fragmentation processes, which started in the Jurassic, and the subsequent opening of the South Atlantic Ocean, resulted in the development of a set of passive margin basins along the South American and African continental margins (e.g. Almeida, 1967; Rabinowitz and LeBrecque, 1979; Gladczenko et al., 1997; Franke et al., 2007; Heine et al., 2013).

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Based on gravimetric data, the Atlantic Ocean can be divided into four major segments separated by large fracture zones, known as, from south to north: Falkland (Malvinas), South, Central and Equatorial segments (Moulin et al., 2005). The South Atlantic Ocean opening occurred from south to north; therefore, the different phases of the basin evolution and unconformities in the study area become progressively younger towards the north (Jackson et al., 2000; Milani and Thomaz Filho, 2000).

The UCM is located in the South segment, of South Atlantic Ocean. In this segment, the seafloor spreading started in the southern part in the Early Hauterivian (134 to 132 Ma; Moulin et al., 2010) and continued to the north in the Late Hauterivian (132 and 130 Ma; Gradstein et al., 2004).

From a tectonostratigraphic point of view, the South Atlantic evolution may be summarized in a general model that includes four stages, each of them characterized by specific tectonic and sedimentary patterns: a) pre-rift, b) rift, c) transition, and d) post-rift (Chang et al., 1992; Cesero and Ponte, 1997; Cainelli and Mohriak, 1999; Karner and Discoll, 1999; Karner et al., 2003).

The pre-rift stage was characterized by deposition in the Western Gondwana intracratonic basins, related to the subsidence and stretching processes that lead to the rift stage (Chang et al., 1992; Garcia, 1999). These sedimentary rocks are part of two supersequences, of Palaeozoic and Jurassic age, separated by a Triassic unconformity (Chang et al., 1992; Cainelli and Mohriak, 1999).

According to Cainelli and Mohriak (1999), the rift stage was characterized by intense faulting, which leads to the generation of a series of half-grabens with internal highs. Sedimentation ranges was from continental sediments to shallow marine sediments.

The transition phase or sag (Aptian) is the most diverse stage in lithological terms, ranging from clastic and evaporitic to carbonate deposits according to the different regional tectonic and environmental conditions. At north of the Walvis-Río Grande Ridge, the main sequences are evaporitic, whereas the southern region is characterized by predominantly clastic deposits (Payton et al., 1977; Fontana 1987, 1996).

The post-rift stage was developed from Aptian/Albian times to the present. The origin of these sequences is the result of lithospheric cooling and an increase in sedimentary loading, which cause thermal and flexural subsidence, giving way to oceanic crust formation in the distal sector. The Aptian/Albian sequences are made up of two supersequences, according to Cainelli and Mohriak (1999) (a) a restricted marine sequence, typical of shallow and anoxic environments, and (b) an open marine sequence bearing mixed platforms (carbonate, clastic) with turbidites and mass flows in marine environments. The latter sequence varies along the Atlantic continental margin, since conditions were different in each basin, thus generating areas of sedimentary input, subsidence and positive tectonic features (Morales, 2013).

Within this context, the UCM was characterized by significant volcanism during its genesis. This volcanism affected both margins of the Atlantic (South American and African margins) (Hinz, 1999; Franke et al., 2007; Soto et al., 2011).

Moreover, on the Argentinean and Uruguayan margins develop a group of basins, perpendicular to the continental margin with NW-SE oriented, of which Punta del Este, located in the Uruguayan margin, is the northernmost basin of this group.

From the perspective of tectonic and stratigraphic evolution, several proposals for the Punta del Este Basin are found in the literature. An example of this, is the work performed by Stoakes et al. (1991), the first seismostratigraphic study, which recognizes four stages: a) pre-rift; b) rift (late Jurassic-Cretaceous); c) sag-thermal subsidence (middle Cretaceous-Palaeocene); and d) passive margin (Eocene to date).

Ucha et al. (2004) carried out an interpretation of the basin sedimentary infill based on sedimentological, geochemical and palynological data from Lobo and Gaviotín wells, identifying five evolutionary stages: a) pre-rift (Palaeozoic); b) rift I (Jurassic-Early Cretaceous); c) rift II (late Early Cretaceous); d) sag (early and late; late Cretaceous); and e) passive margin (late Cretaceous - Palaeocene to date).

Meanwhile, Raggio et al. (2011) identified three main tectonic phases: a) rift (alluvial-fluvial and lacustrine deposits prior to the Barremian); b) sag (predominantly regressive sequences from the Barremian to the Maastrichtian); c) passive margin (transgressive sequences at the base giving way to several transgressive-regressive cycles deposited from the Early Palaeocene to present).

Whereas, Morales (2013) and Morales et al. (2017) recognized regional stratigraphic unconformities, identifying fifteen depositional sequences that make up the stratigraphy of the Pelotas and Punta del Este basins in the Uruguayan continental margin. The sequences were grouped into four main evolutionary phases: pre-rift (Palaeozoic), rift (Jurassic-Early Cretaceous) with continental sedimentary and volcanic infill, transition (Barremian-Aptian) and post-rift (from Aptian to present), the latter including a regressive Cretaceous megasequence and a transgressive Cenozoic megasequence.

Morales (2013), Conti (2015), Conti et al. (2017) and Morales et al. (2017) described the evolution of Uruguayan portion of the Pelotas Basin in three phases: pre-rift (Palaeozoic), rift (Early Cretaceous), and post-rift (from Aptian/Albian to present). As for the post-rift phase, Morales et al. (2017) characterized the migration of sedimentary depocenters from the Punta del Este Basin to the Pelotas Basin, identifying, in the latter, the greatest sedimentary thickness found in the Uruguayan margin.

3. Material and Methods

A seismostratigraphic analysis of the Eocene-Lower Oligocene sedimentary interval is carried out in this work. The recognition of the top and base horizons, the intervals H.9 and H.12, respectively, after Morales et al. (2017), was based on age assignment made by Conti et al. (2017), Creaser et al. (2017) and Morales et al. (2017).

The used database comprises 55 2D multichannel seismic reflection lines (Fig. 2), acquired in 2007-2008, totalizing 10,000 linear km approximately.

In the seismostratigraphic analysis, stratigraphic units of lower hierarchy than a depositional sequence were identified and characterized in order to contribute to the understanding of the UCM stratigraphic architecture, as well as to the generation of predictive models for energetic resources exploration.

Sequence Stratigraphy was the selected analysis method, which applies key concepts of basic stratigraphy on the analysis of seismic data, combining them with different variables controlling the sedimentary regime in a basin (tectonics, eustasy, accommodation space, etc.) (Catuneanu, 2006; Catuneanu et al., 2009).

In this work, stratal terminations, stacking patterns and internal and external configurations of the sedimentary selected interval for this study were recognized, which led to the identification of different seismic units, including seismic facies, depositional systems tracts, and stratigraphic sequences. The characterization of the different sedimentary tracts was based on the nomenclature described by Catuneanu (2006), Catuneanu et al. (2009, 2011), Holz (2012), and which follows a quadripartite model in which a full base-level rise and fall cycle is defined by four tracts of deposit systems (low- and high-stand regression, transgressive and forced regression).

Based on the identification of depositional systems tracts a local base level variation curve was constructed.

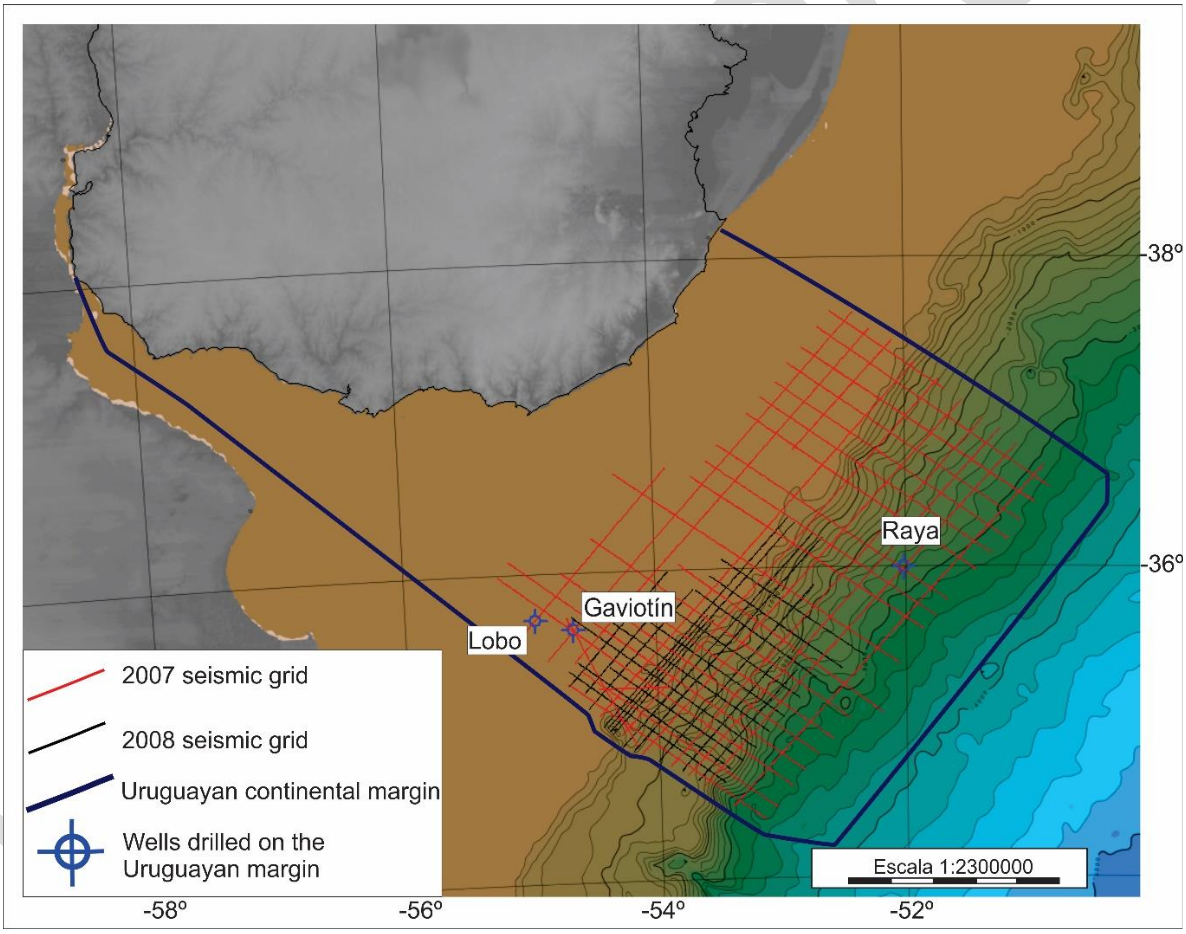

Fig. 2. Location of exploratory wells and seismic lines acquired in 2007-2008 on the Uruguayan offshore.

4. Results

In the studied sedimentary interval, nine seismic horizons, corresponding to three third-order depositional sequences, *sensu* Catuneanu et al. (2009), were mapped. These sequences, called A, B and C from the base to top, are bounded by four unconformities and their respective correlative conformity surfaces, totalizing a thickness of approximately 2,100 m. Table 1 summarizes the stratigraphic surfaces, the genetic meaning assigned, the criteria adopted for their definition, and the attributed age.

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Tab. 1. Mapped horizons, interpretation criteria and age attribution *sensu* Daners and Guerstein (2004), Morales (2013), Conti (2015) and Daners et al. (2017). Legend: PB= Pelotas Basin; U1, U2, U3, U4= unconformity; MRS= maximum regressive surface; MRS= maximum flooding surface; BSFR= Basal surface of forced regression; CC= correlative conformity surface; Tr=truncations; Dl= downlap; Ol= onlap; Off= offlap; Tp= toplap.

Sequence	Nº	Meaning	Age	Criteria
C	S9	U4+CC	Lower Oligocene	Above: Dl Below: Tr in central and distal sectors
	S8	BSFR	Eocene	Above: Dl Below: Off
	S7	MRS	Eocene	Above: Ol
	S6	U3+CC	Eocene	Above: Ol central sector, Dl in distal sector of PB Below: Tr in distal sector
B	S5	U2+CC	Middle Eocene	Above: coastal Ol, Double Dl in distal sector Below: Off/Tr in distal sector
A	S4	BSFR	Eocene	Above: Double Dl/Dl in distal sector Below: Tr in distal sector
	S3	MFS	Eocene	Above: Dl in continental shelf Below: Tr in distal sector
	S2	MRS	Eocene	Above: Ol
	S1	U1+CC	Top of the Palaeocene	Below: Tr

In the studied sedimentary interval, nine seismic horizons, corresponding to three third-order depositional sequences, *sensu* Catuneanu et al. (2009), were mapped. These sequences, called A, B and C from base to top, are bounded by four unconformities and their respective correlative conformity surfaces, totaling a thickness of approximately 2,100 m. Table 1 shows the stratigraphic surfaces interpreted, the genetic meaning assigned, the criteria adopted for their definition, and the attributed age.

The analyzed sedimentary package includes three depositional sequences that represent sedimentary cycles associated with base-level rises and falls, resulting in transgressive-regressive shoreline movements (Fig. 3), which allow the characterization of an aggradational to retrogradational margin.

3.1. Sequence A

Sequence A (Figs. 4 and 5) is bounded at the base by a surface made up by the unconformity S1 and its correlative conformity surface, and by unconformity S5 and its correlative conformity surface at the top. It is preserved at the shelf, slope and abyssal plain margin sectors, being partially eroded at the top due to the overlying unconformity resulting from a base-level fall.

This sequence comprises four depositional systems tracts corresponding, from base to top, to the following sedimentary depositional systems: lowstand normal regression, transgression, highstand normal regression, and falling-stage. Below, a description of each sedimentary depositional systems is provided.

3.1.2 Lowstand Systems Tract

This tract is bounded at the base by the surface represented by unconformity S1 and its correlative conformity surface (shown as lower red horizon in Fig. 6), and by the maximum regressive surface S2 (shown as green horizon in Fig. 6) at the top. The basal surface is defined by truncations below and double downlaps above. Also, onlaps are arranged on the maximum regressive surface, characterizing a base-level rise. This tract is mainly developed in the most distal sectors of the margin, corresponding to the slope base and the abyssal plain.

The seismic facies found in this tract (Fig. 6) correspond to continuous to discontinuous parallel reflectors, from the slope base to the abyssal plain, with acoustic impedance contrast and medium to low amplitude, laterally changing to low amplitude mound-shaped bodies, with downlap and/or double downlap terminations towards the abyssal plain, thus infilling the palaeo-relief.

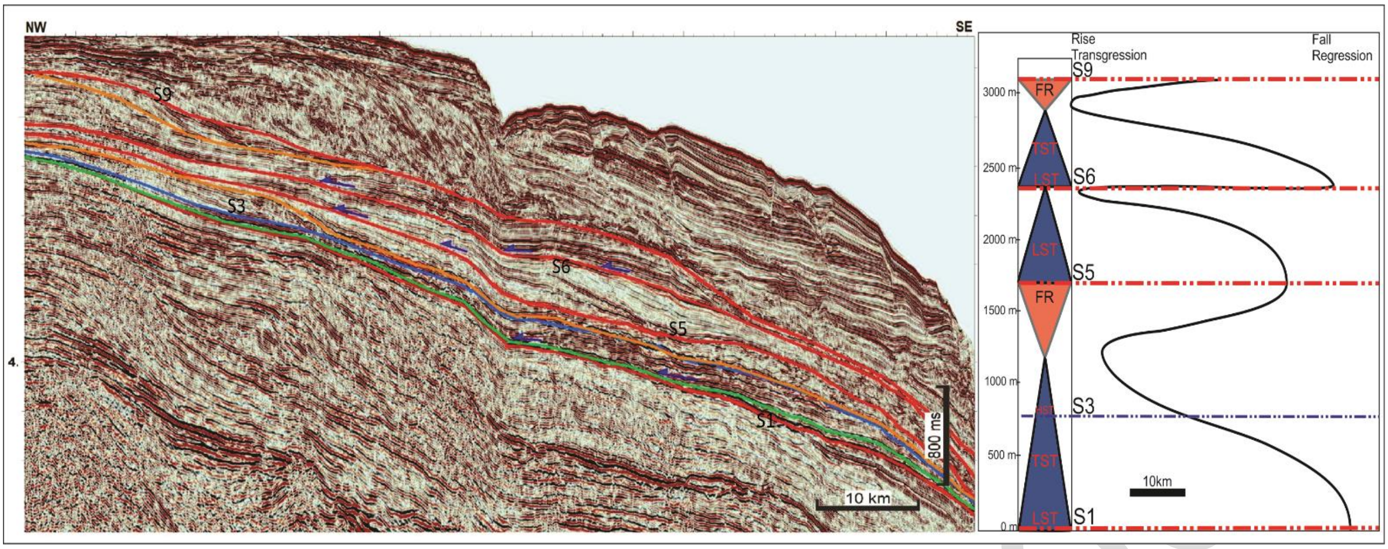

Fig. 3. (a) Dip seismic section of the Punta del Este Basin, depicting the position of the onlaps used in the construction of the local base level variation curve (b). S1, S5, S6 y S9 represent unconformities; S3 represent maximum flooding surface.

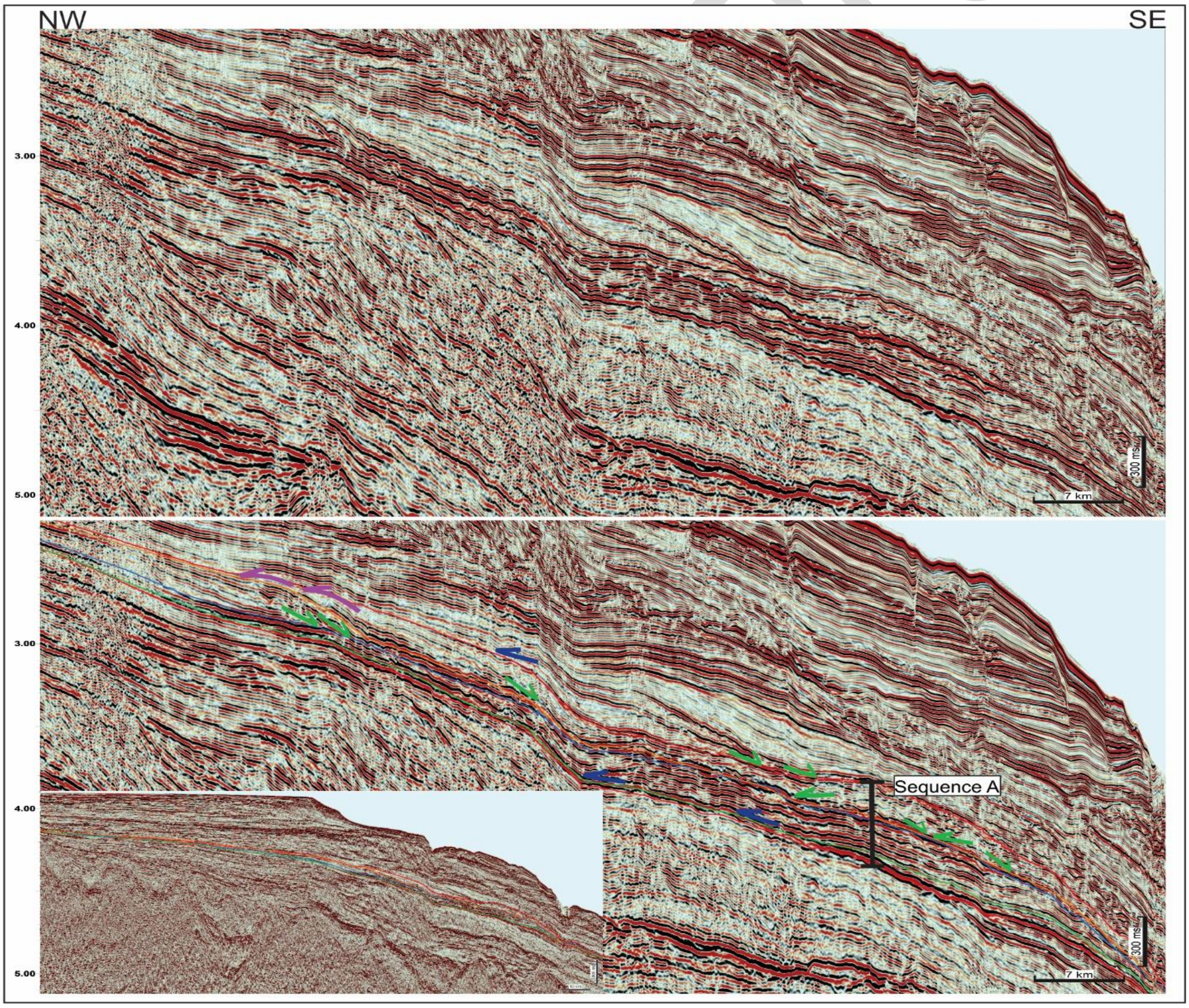

Fig. 4. Stratal terminations and bounding surfaces of Sequence A depositional systems tracts in the Punta del Este Basin. Legend: Blue arrow =onlap; green arrow=downlap; purple arrow = Off= offlaps; red line: U1+CC; green line: MRS; blue line: MFS; orange line: BSFR.

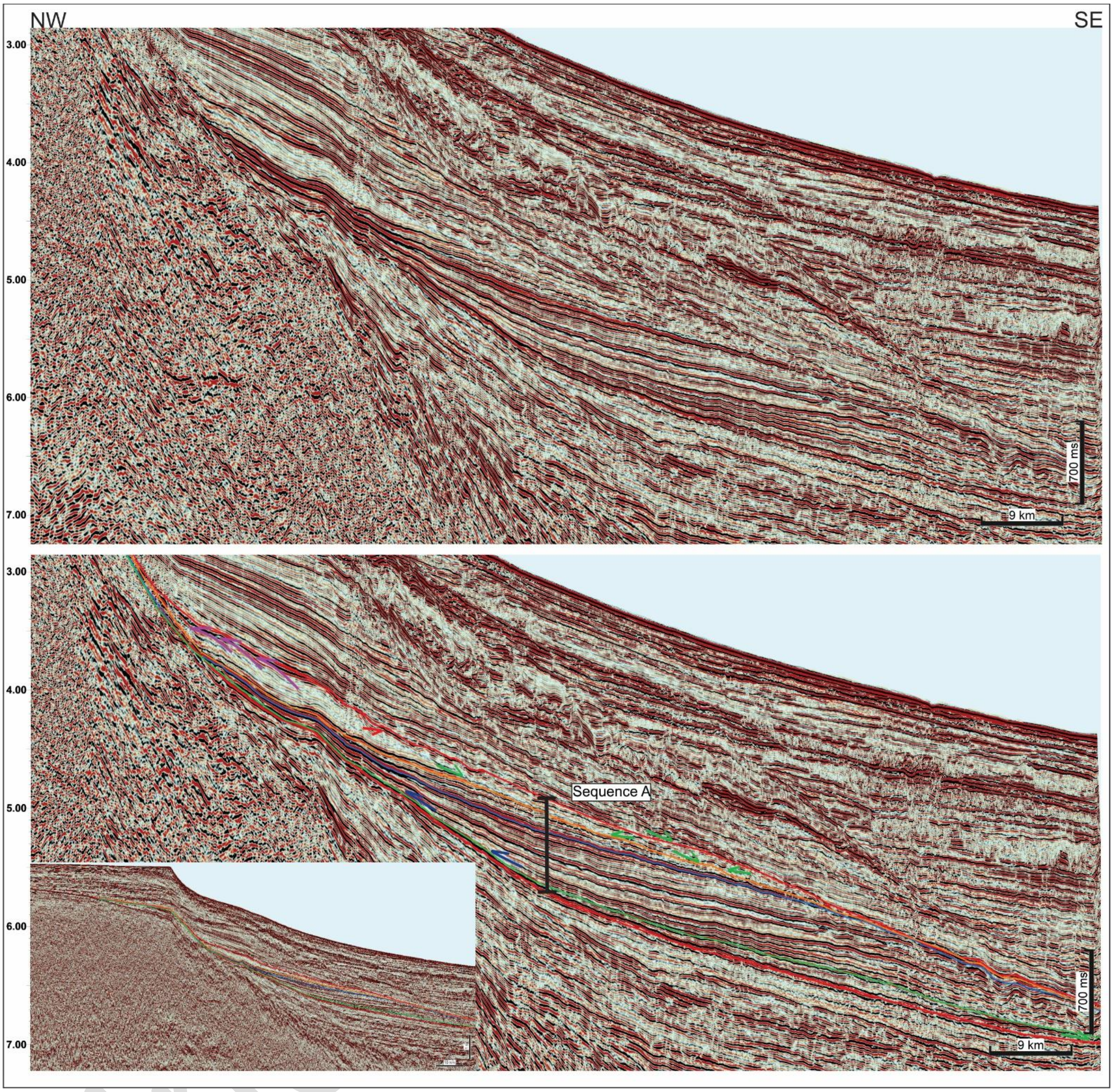

Fig. 5. Stratal terminations and bounding surfaces of Sequence A depositional systems tracts in the Pelotas Basin. Legend: Blue arrow = onlap; green arrow= downlap; red arrow = truncations; purple arrow =offlaps; red line: U1+CC and U5+CC; green line: MRS; blue line: MFS; orange line: BSFR

3.1.3 Transgressive Systems Tract

The transgressive tract is bounded by the maximum regressive surface S2 (shown as green horizon in Figs. 4 and 5) at the base, and by the maximum flooding surface S3 (shown as blue horizon in Figs. 4 and 5) at the top. The latter is defined by clinoforms with downlap terminations, mainly in the shelf sector. This tract appears eroded in the abyssal plain of the Punta del Este Basin due to the sequence upper unconformity. The tract seismic facies correspond to slightly divergent parallel to subparallel reflectors, of medium amplitude contrast and continuity, laterally changing to subparallel reflectors in the palaeoslope sector (Fig. 4).

3.1.4 Highstand Systems Tract

This highstand tract is bounded by maximum flooding surface S3 (shown as blue horizon in Figs. 4 and 5) at the base, and by the basal surface of forced regression S4 (shown as orange horizon in Fig. 4) at the top. The basal surface of forced regression was defined as the surface on which the first clinoform is deposited exhibiting an offlapping pattern.

The tract stacking pattern is progradational in the Punta del Este Basin shelf area. The seismic facies identified in the shelf region are clinoforms that downlap over the maximum flooding surface, characterized by sigmoidal to oblique tangential clinoforms of medium amplitude.

3.1.5 Falling-Stage Systems Tract

This tract is bounded by the basal surface of forced regression S4 (shown as orange horizon in Figs. 4 and 5) at the base, and by the surface comprised by the sequence upper unconformity S5 and its correlative conformity surface (shown as upper red horizon in Figs. 4 and 5) at the top. The upper unconformity S5 is defined in the shelf region by truncations below, and coastal onlaps above. This tract exhibits a progradational stacking pattern.

These deposits are best preserved in the Punta del Este Basin slope and shelf area, where the most representative seismic facies are low-amplitude clinoforms with low continuity (Fig. 4). Towards the distal sector, facies shift laterally to mound-shaped with low acoustic impedance contrast and double downlap terminations. Whereas in the Pelotas Basin the tract is mainly developed in the slope, slope base and abyssal plain sector, showing very gentle clinoforms with an offlapping pattern, displaying continuity and medium to low amplitude contrast, changing laterally to irregular forms with low amplitude and continuity (Fig. 5).

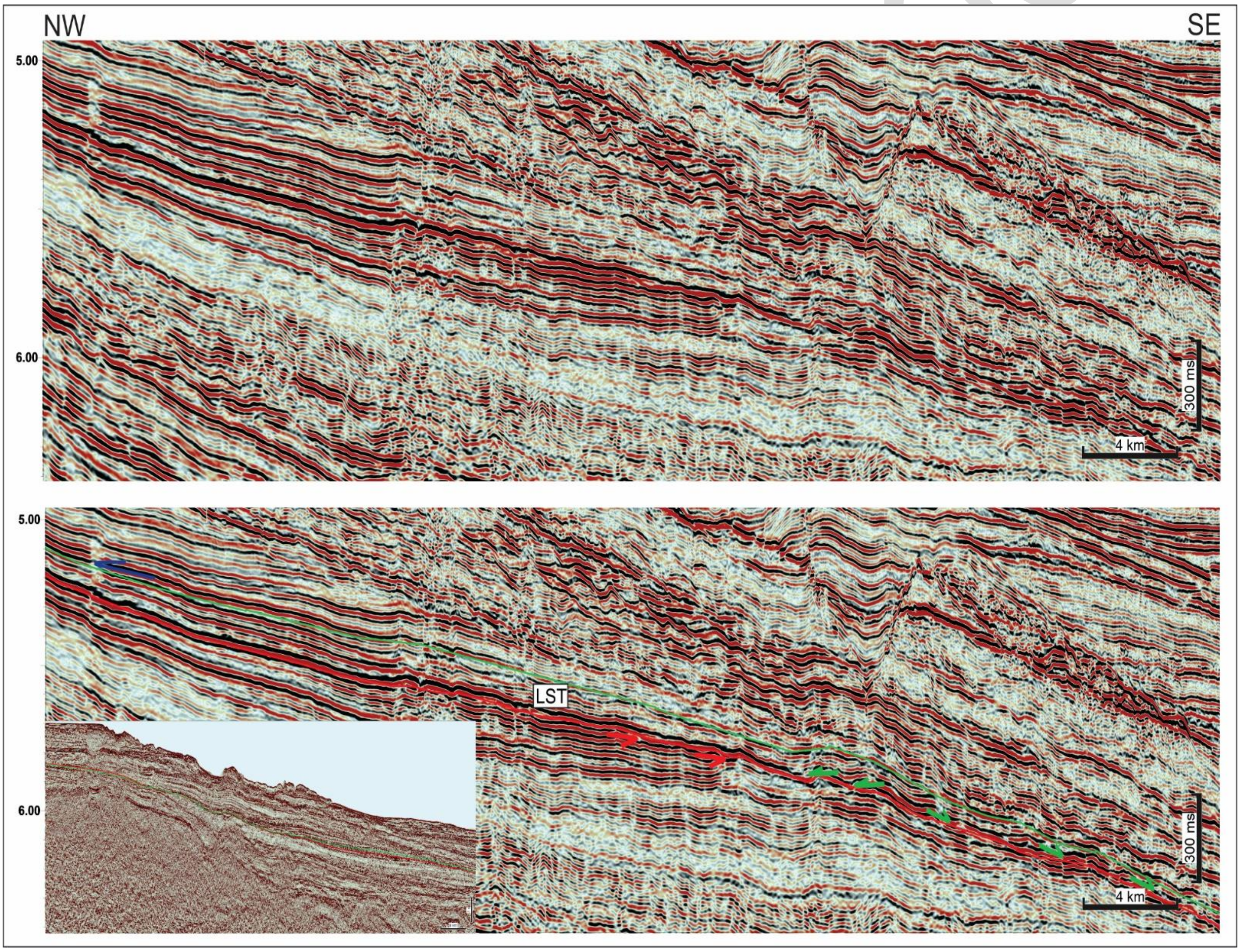

Fig. 6. Dip seismic section of the Punta del Este Basin depicting stratal terminations characterizing the bounding surfaces of the lowstand systems tract. Legend: Blue arrows = onlap; green arrow= downlap; red arrow = truncations; LST= Lowstand System Tract; green line= MRS; red line=U1+CC.

3.2. Sequence B

This sequence is bounded at the base and top by the unconformities S5 and S6 (lower and upper red horizons in Fig. 7) respectively, and their correlative conformity surfaces. The top unconformity is characterized by toplaps and truncations below, and onlaps above. This sequence is eroded in the distal sector of the margin.

Only the lowstand systems tract is preserved in this sequence, characterized by the development of clinoforms, with a stacking pattern ranging from progradational at the base to slightly progradational towards the top, showing a concave-up shoreline basinward trajectory, which according to Catuneanu et al. (2009), is typical of lowstand systems.

Within this tract, it is possible to characterize two sets of clinoforms with slightly different seismic attributes that allow to distinguish two separate seismic facies associations. The clinoforms at the base exhibit a sigmoidal geometry, with medium to low amplitudes and frequencies.Towards the top, the clinoforms range from sigmoidal to oblique tangential geometries, with a decrease in amplitude. Towards the distal area, seismic facies with mounded internal configuration low-amplitude are developed in both sectors.

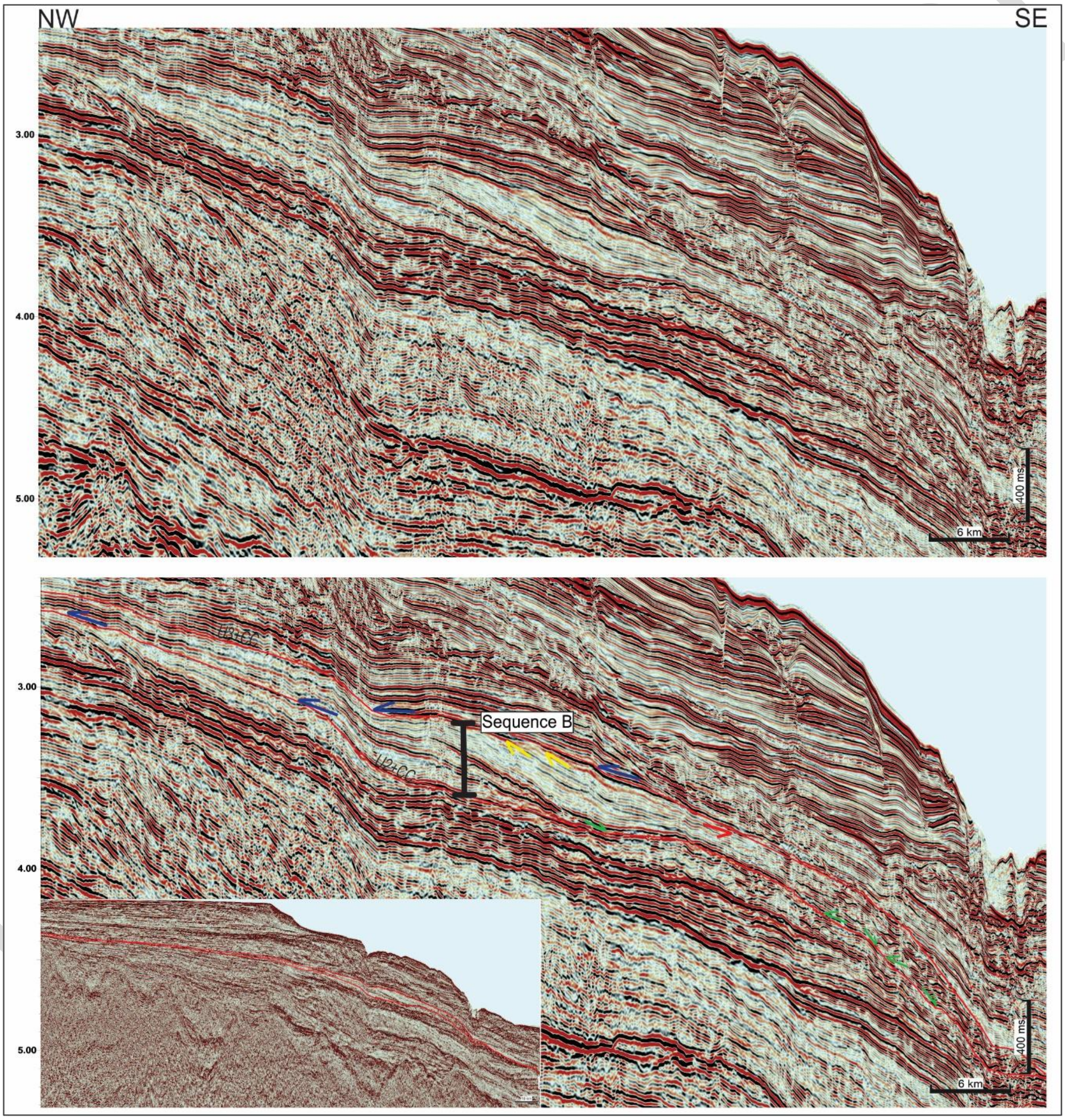

Fig. 7. Stratal terminations, bounding surfaces, and depositional systems tract identified in Sequence B. Legend: Blue arrows= onlap; green arrows= downlap; red arrows= truncations; yellow arrows= toplaps; red line= U2+CC and U3+CC.

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3.3. Sequence C

Sequence C is bounded by the unconformity S6 and its correlative conformity surface at the base (lower red horizon in Fig. 8) and by the unconformity S9 with its correlative conformity surface at the top (upper red horizon in Fig. 8). The basal unconformity was defined by truncations below and onlaps above. The upper unconformity is also characterized by truncations below and downlaps above.

In this sequence, three depositional systems tracts, lowstand, transgressive and falling-stage systems, were identified.

3.3.1. Lowstand Systems Tract

The lowstand tract is bounded by unconformity S6 and its correlative conformity surface at the base, and by the maximum regressive surface S7 at the top. The maximum regressive surface was defined in relation to the last clinoform, exhibiting marine onlaps above (Fig. 9). This tract is restricted to the central area of the Uruguayan continental margin, showing very poor development.

It exhibits a progradational stacking pattern with development of seismic facies corresponding to medium-amplitude, continuous and sigmoidal clinoforms in the slope sector (Fig. 9), while in the abyssal plain sector, attributes vary to partially eroded irregular shapes.

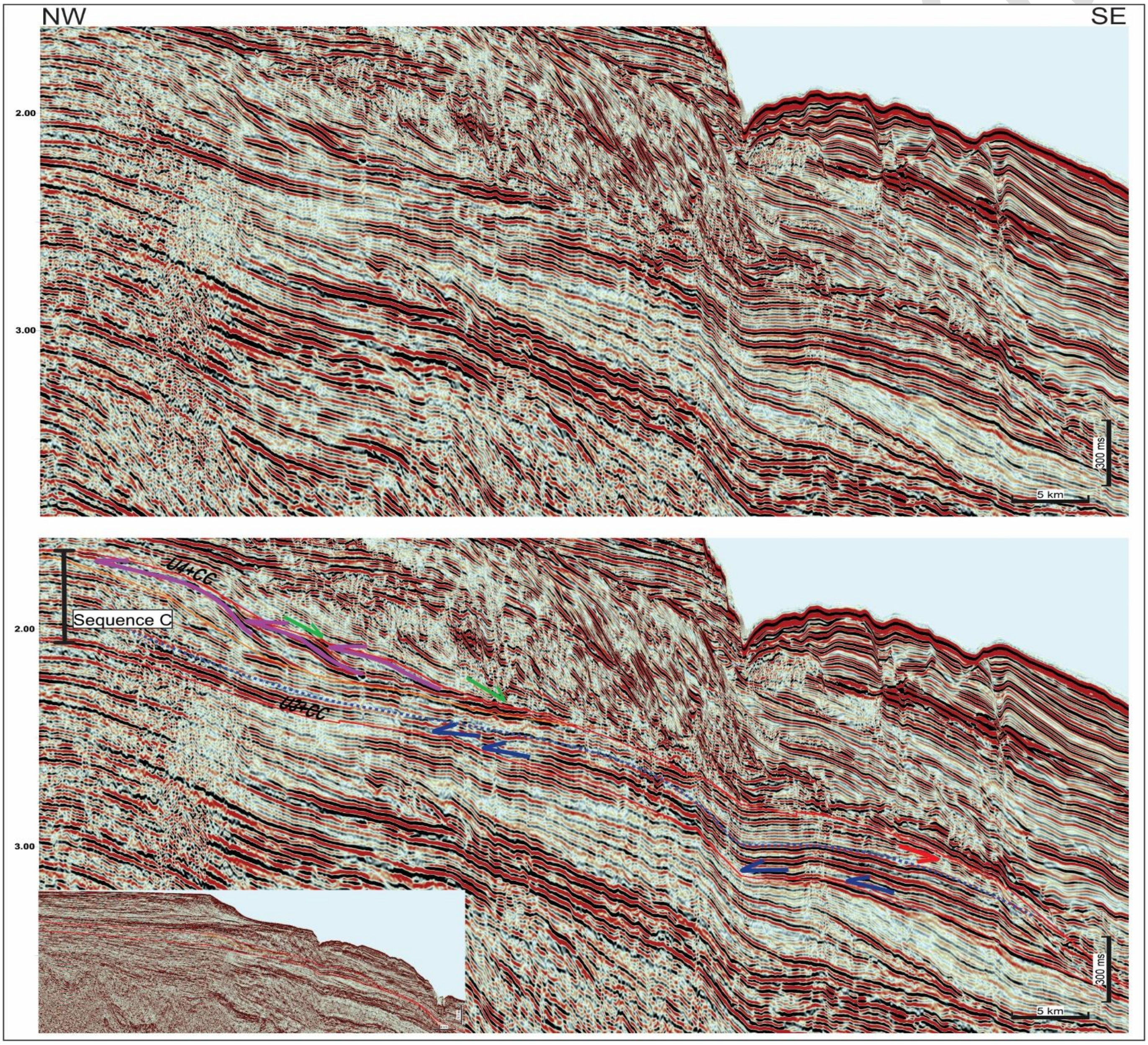

Fig. 8. Stratal terminations, bounding surfaces, and systems tracts identified in Sequence C. Legend: (Line blue= auxuiliary line; Onlap= blue arrows; Downlap= green arrows; Truncation= red arrows; Offlap= purple arrows; red lines= U3+CC and U4+CC).

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3.3.2 Transgressive Systems Tract

This tract is bounded by the surface comprised by unconformity S6 (shown as lower red horizon in Fig. 9) and the maximum regressive surface S7 (shown as green horizon in Fig. 9) at the base, and by the basal surface of forced regression S8 (shown as orange horizon in Fig. 8) at the top. It exhibits a retrogradational stacking pattern, with development of marine onlaps and high continuity in the Uruguayan offshore

Seismic attributes allowed the identification of two different groups of seismic facies within the same tract (Fig. 8). At the base, reflectors are parallel and continuous, with medium to high acoustic impedance contrast. Towards the top, attributes vary, and the seismic facies identified are associated with parallel reflectors, of medium to low continuity and medium to low acoustic impedance contrast.

3.3.3 Falling-Stage Systems Tract

This tract is bounded by the basal surface of forced regression S8 (shown as orange horizon in Fig. 8) at the base, and by the surface comprised by unconformity S9 and its correlative conformity surface (shown as red horizon in Fig. 8) at the top.

The basal surface of forced regression corresponds to the base of the first clinoform exhibiting an offlap pattern; therefore, downlaps can be observed over this surface. The top surface was mapped above the reflectors exhibiting an offlapping pattern, while downlaps can be observed above this surface. The development of this is restricted to the shelf sector.

The seismic facies, typical of this tract, are represented by gentle clinoforms with an offlapping pattern, of medium to low amplitude.

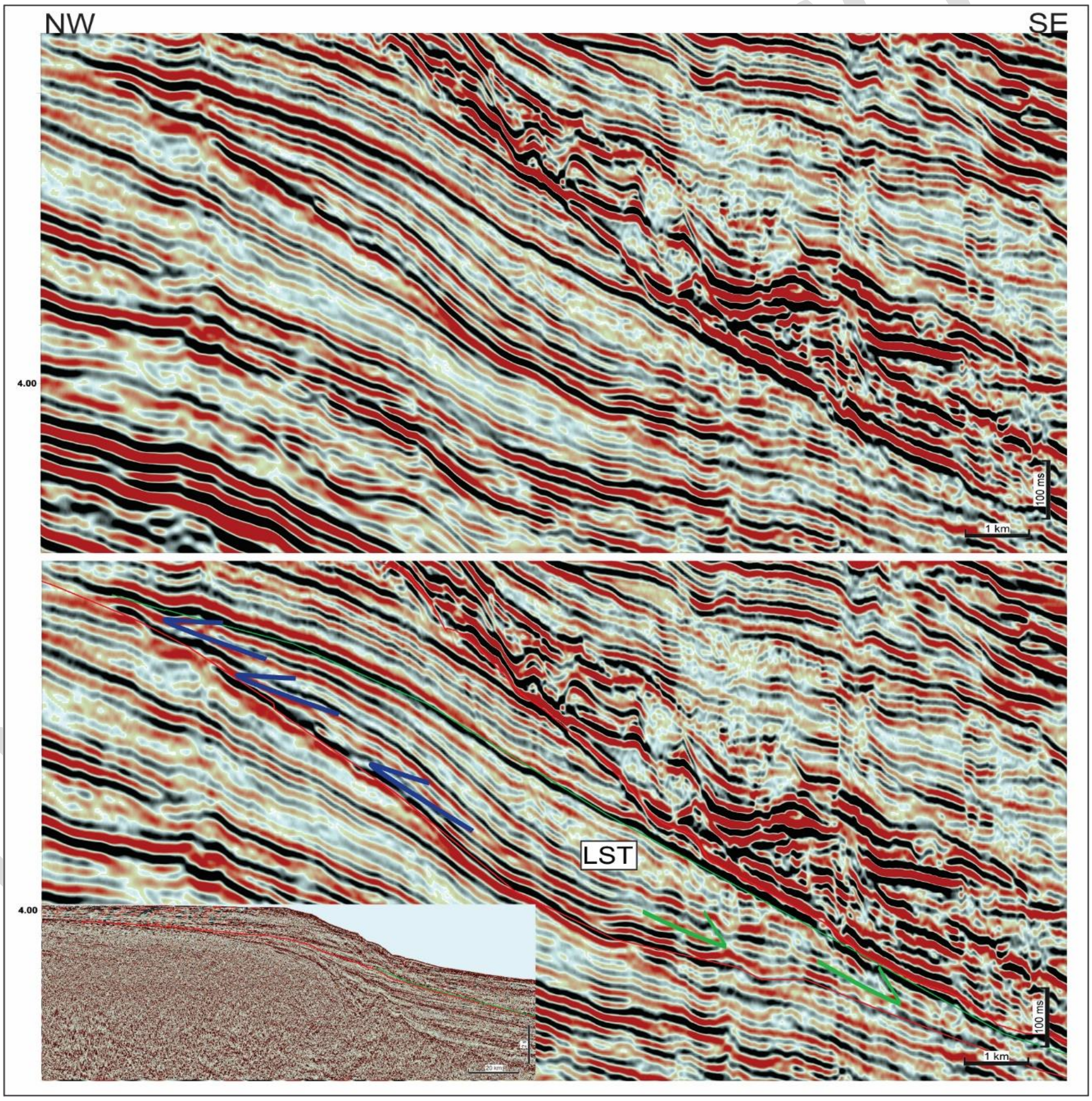

Fig. 9. Dip seismic section of the Pelotas Basin depicting the seismic facies typical of lowstand tracts Legend: Onlap= blue arrows; Downlap= green arrows; red line= U3+CC; green line= MRS.

4. Discussion

The depositional sequences analyzed in this work exhibit more thickness in the Pelotas Basin, which, according to Morales (2013), corresponds to the depocentre of the Uruguayan continental margin for the Cenozoic. The significant sediment accumulation in this basin is, probably, the result of the generation of greater accommodation space due to flexural subsidence, and of a considerable sedimentary input associated with different pulses of the Andean orogeny (Morales et al., 2017).

Sequence A represents a full base-level rise and fall cycle. Above the basal unconformity, and mainly in the basin distal sectors, a sedimentary package is developed, interpreted as a lowstand systems tract, associated with the beginning of the base-level rise. The mounded seismic facies of this tract may be interpreted as turbidite deposits, linked to basin-floor fan complexes, which evolve from high to low density with a decrease in the sand/clay ratio (Mitchum et al., 1977; Posamentier and Kolla, 2003; Catuneanu, 2006).

The development of the transgressive systems tract, overlying the above-mentioned tract, corresponds to landward shoreline migration and to the identification of a retrogradational stacking pattern, in a base-level rise context. This base-level rise could be associated with the Palaeocene-Eocene Thermal Maximum (Miller et al., 1987; Kennett and Stott, 1991), which was responsible for a 5°C rise in global average temperature. Kennett and Stott (1991) have attributed this event to intense oceanic volcanic activity and to the massive carbon dioxide emission. The continuity and homogeneity of the seismic facies that make up this tract may be related to the extensive geographical distribution of the marine depositional environment and to the steadiness of the acting sedimentary processes (Mitchum et al., 1977; Catuneanu, 2006).

The lowstand and transgressive tracts identified in this work are coincident with the object of study of Turrini et al. (2017) for the Pelotas Basin. These authors identified a Polygonal Fault System (PFS) affecting the sedimentary package that includes both tracts (Fig. 10). Based on how faults are transmitted, according to different rock grain sizes, these authors suggest that the interval holding the PFS is dominated by very fine-grained deposits in the slope and basin floor, with the occurrence of coarser-grained deposits in the proximal sectors and at the sedimentary interval base. The seismic facies interpreted by these authors as sand-rich fans at the base of the PFS coincide with the lowstand systems tract defined in this work.

The stacking pattern shift, from retrogradational to progradational, and the development of clinoforms above the maximum flooding surface allow the definition of the occurrence of a highstand tract, overlying the transgressive one. This tract is characterized in the shelf sector by seismic facies represented by clinoforms ranging from slightly sigmoidal to oblique. Sangree and Widmier (1979) associate the first type to low depositional energies and the second one, to higher depositional energies. This might be an indicator of progradation in relatively shallow waters, associated with a rising to relatively stationary base level and an increase in the sediment supply, which translates into an increase in depositional energy. According to Roksandić (1978), these facies are related to the delta front in a deltaic depositional environment. Laterally, towards the basin distal sector, thickness of deposits decreases, and the parallel seismic facies indicate a relatively uniform depositional energy that Roksandić (1978) attributes to a prodelta system.

Over the highstand tract, the falling-stage systems tract deposition is interpreted associated with a base-level fall, which leads to the generation of the unconformity in the basin proximal sectors. These deposits exhibit clinoforms with offlap stratal terminations, which, according to Catuneanu et al. (2009, 2011) and Holz (2012) is a diagnostic attribute of this type of sedimentary tract. The occurrence of oblique tangential clinoforms (more markedly in the Punta del Este Basin), is an indicator of high-energy depositional environments, which can be expected in the more proximal sectors of this type of sedimentary tracts (Mitchum et al., 1977; Severiano Ribeiro, 2000). The differences in the configuration of clinoforms between the Punta del Este and Pelotas basins probably result from the difference in basin type. While the Punta del Este Basin exhibits a lower gradient and a continental crust floor, the Pelotas Basin features a higher gradient and an oceanic to transitional crust floor.

Towards the slope base area, the falling-stage tract seismic facies shift to mound-shaped or migrating macro undulations that may be associated with high-density turbidite deposits (Mitchum et al., 1977; Catuneanu, 2006; Holz, 2012) (Fig. 11). Hernández Molina et al. (2016) identified these mounded facies as a dune field generated by marine contour currents, in a context of high sediment supply. High sediment supply is expected in falling-stage systems tracts, given that a significant base-level fall occurs during their formation, with considerable seaward shoreline migration, thus leaving extensive continental areas exposed and subject to erosion (Hunt and Tucker, 1992; Catuneanu, 2006; Holz, 2012).

The verification of coastal onlaps above clinoforms with offlap terminations and, therefore, above the unconformity (S6), allows to identify the development of a lowstand tract, in a base-level rise context, which marks the beginning of a new sedimentary cycle, represented by the Sequence B. This sequence only preserves deposits related to this tract, mainly in the slope and slope base sectors.

The shoreline trajectory of this sequence leads to the identification of a first stage where the depositional trend is dominated by a progradational pattern and, secondly, a stage where the aggradation rate increases over time. This allows the characterization of the shoreline trajectory as concave-up (Fig. 12), which can be associated with normal regression systems in a lowstand context (Catuneanu et al., 2011).

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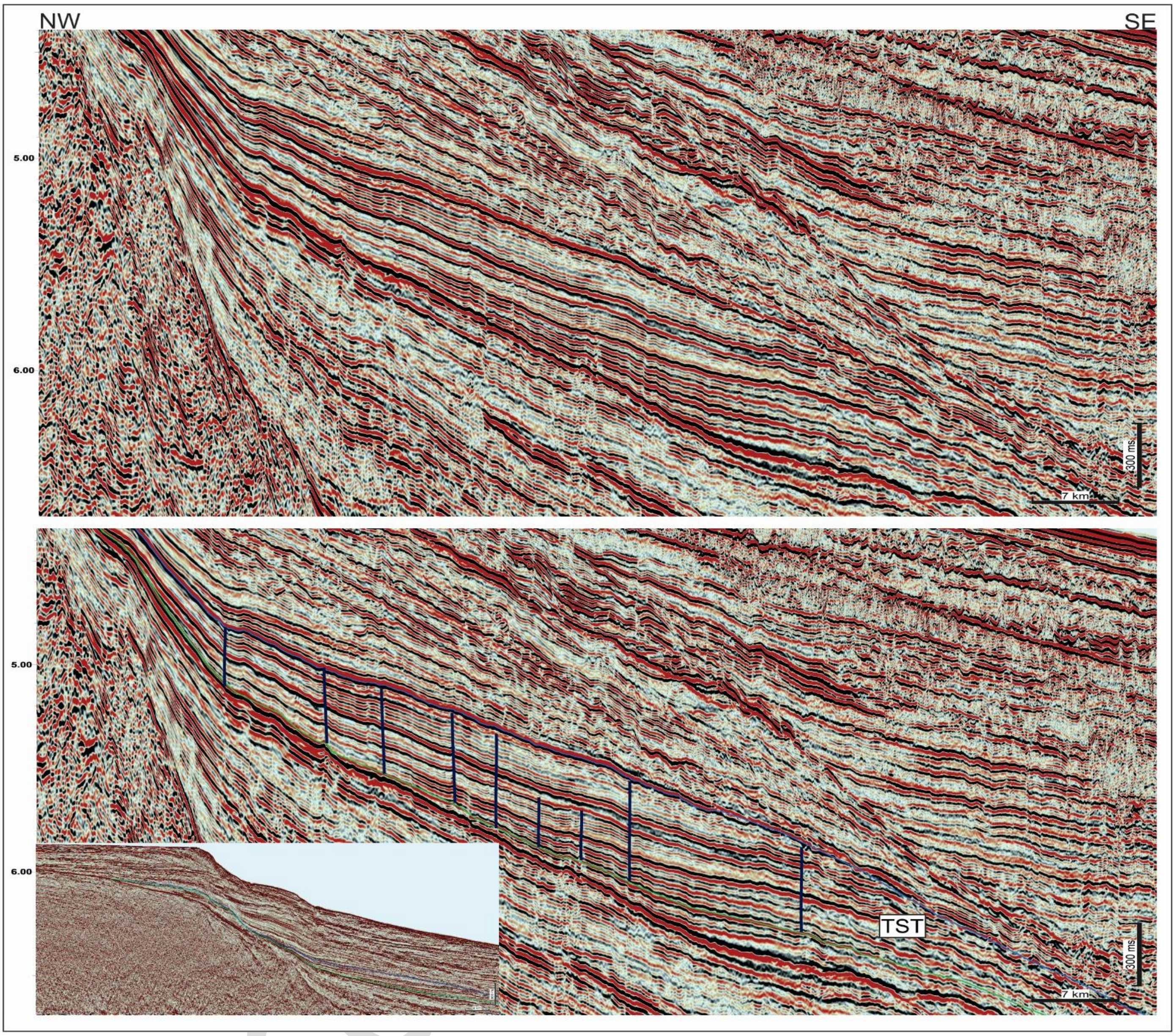

Fig. 10. Dip seismic section of the Pelotas Basin depicting Sequence A transgressive tract with faulting. Legend: Dark blue line= fault; blue line= MFS; green line_ MRS

The clinoforms present at the base of this tract are gentle and sigmoidal, which, according to Roksandić (1978), indicates a depositional environment exhibiting low energy and low sediment supply. Towards the basin, laterally, associated mounded facies can be observed, which, according to Mitchum et al. (1977), are the result of turbidite sedimentary processes related to basin-floor fan complexes.

Towards the top, clinoforms shift from sigmoidal to oblique geometries, indicating an increase in depositional energy, probably associated with an increase in sediment supply (Roksandić, 1978; Severiano Ribeiro, 2000). In the distal sector of the Punta del Este Basin, mound-shaped bodies and migrating macro undulations can be recognized again, which, according to Hernández Molina et al. (2016), correspond to a second dune field generated by marine contour currents.

In this sequence, transgressive, highstand or falling-stage systems tracts were not observed; which may be due to the fact that accommodation, base level and sediment supply conditions did not allow their formation, or to later erosion (Catuneanu et al., 2009).

The base of Sequence C is characterized, in the Uruguayan margin central sector, by the occurrence of a downdip dislocated lobe (Fig. 9), which indicates a new base-level fall and, therefore, the recording of a new sedimentary cycle. This sequence first deposits are assigned to lowstand systems tract since onlaps can be observed on the palaeoslope, indicating a base-level rise (Catuneanu, 2006).

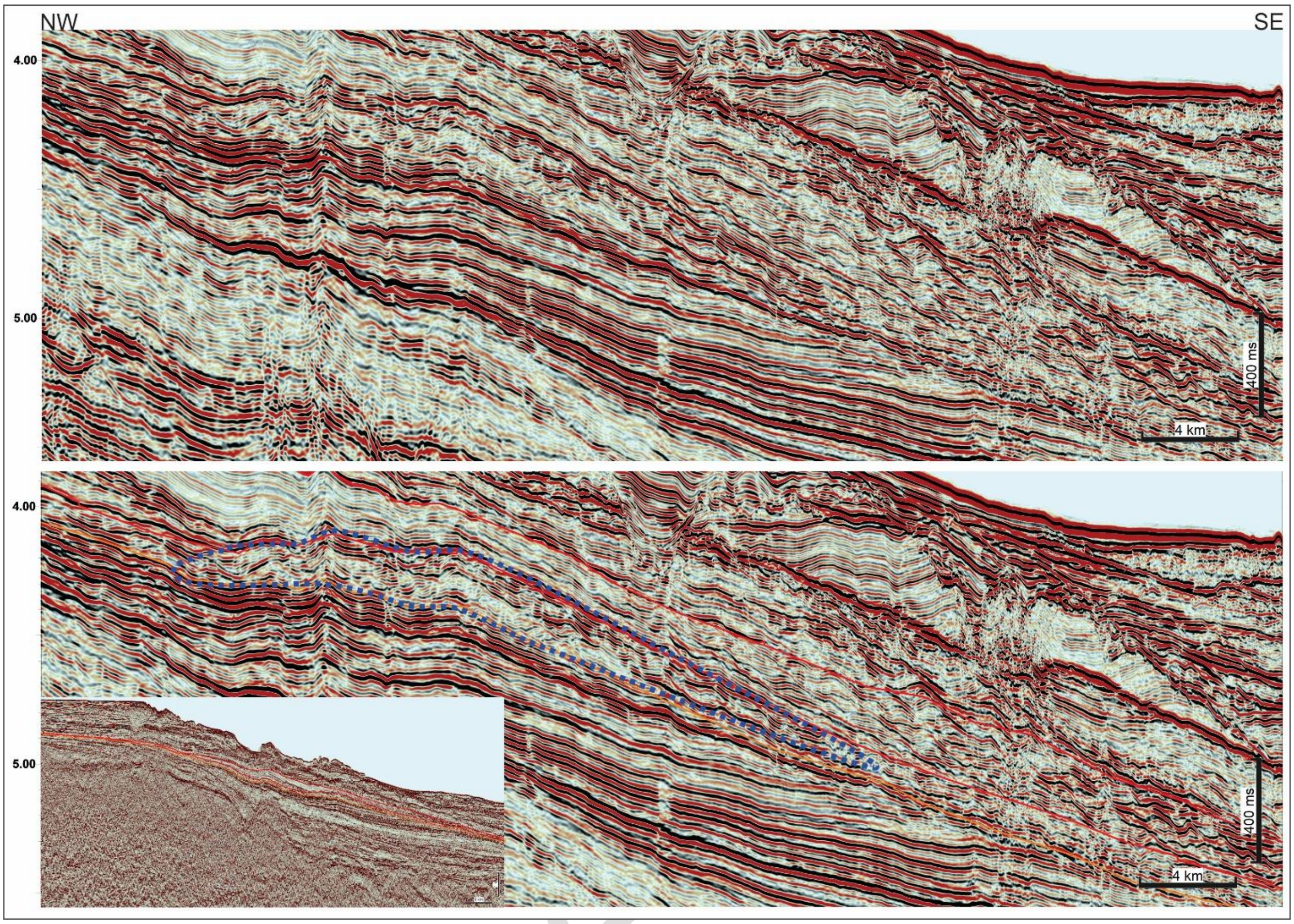

Fig. 11. Dip seismic section of the Punta del Este Basin depicting migrating macro undulations (dark blue line) *sensu* Mitchum et al. (1977a), interpreted as a sand dune field by Hernández Molina et al. (2016).

This tract is characterized by poorly developed sigmoidal clinoforms, exhibiting low depositional energy and small sediment supply (Roksandić, 1978).

The stacking pattern shift, from progradational to retrogradational, with the occurrence of marine onlaps, allows characterizing the development of transgressive systems tract overlying the lowstand systems tract. The seismic facies at the transgressive tract base exhibit high reflector continuity, probably resulting from greater homogeneity of conditions in the sedimentary environment, which may have a similar interpretation to that of Sequence A transgressive tract. Towards the top, the reflectors continuity reduces and the amplitude decreases; and prevalence of a certain lithology and stability in an environment of relatively higher depositional energy (Mitchum et al., 1977) may be inferred, especially for the shelf break and slope sector.

The identification of clinoforms with offlap terminations overlying the transgressive tract makes it possible to characterize the development of a falling-stage tract, indicating a new shoreline migration in a basinward direction. The considerable base-level fall characterizing this tract results in a very significant unconformity in the Uruguayan continental margin, which erodes an important portion of the underlying sedimentary record. Clinoforms with offlapping pattern show an increase in sediment supply and depositional energy (Severiano Ribeiro, 2000).

5. Conclusion

The sedimentary package studied for the Uruguayan offshore basins (Eocene-Lower Oligocene) characterizes a margin with an aggradational to retrogradational architecture, in which three sedimentary cycles, represented by third-order depositional sequences, A, B and C, from base to top, can be identified.

Sequence A is represented by four sedimentary tracts (lowstand and highstand normal regression, transgressive and falling-stage) representing a full base-level variation cycle. In sequence B, only the lowstand normal regression systems tract was recognized. Whereas sequence C, at the top, is composed of three depositional systems tracts: lowstand, transgressive and falling-stage.

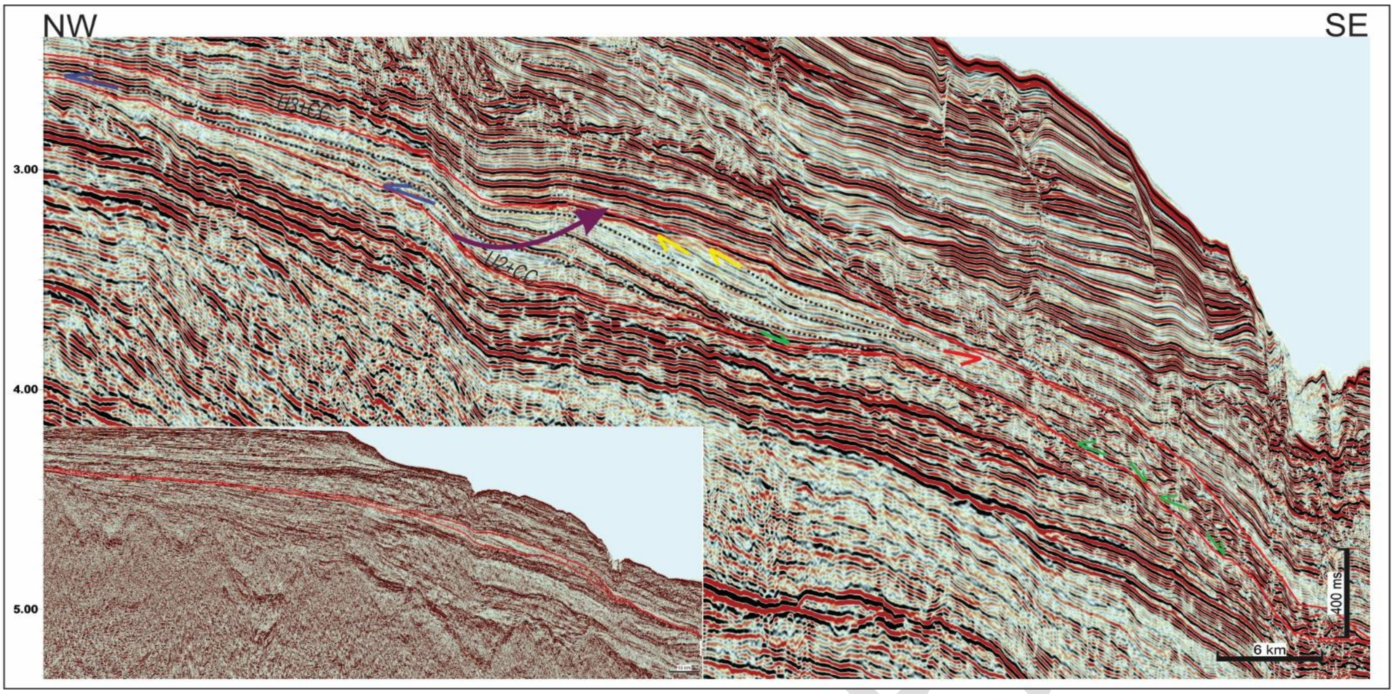

Fig. 12. red arrows = Truncation; yellow arrows =Toplap; red line= U2+CC and U3+CC.

This work evidences a greater differentiation of the depositional systems for the sedimentary interval at the UCM. Moreover, the characterization and understanding of seismic units contribute to increase the stratigraphic knowledge of sedimentary basins of the Uruguayan continental margin, which may be used as a basis to outline predictive models that may assist in the exploration of energy resources.

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