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SEISMOSTRATIGRAPHY AND GEOMORPHOLOGY OF THE RIO GRANDE CONE, PELOTAS BASIN (BRAZILIAN OFFSHORE)

SISMOESTRATIGRAFÍA Y GEOMORFOLOGÍA DEL CONO DE RIO GRANDE CUENCA PELOTAS (OFFSHORE BRASILEÑO)

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Resumen

El Cono de Rio Grande es una estructura de la Cuenca de Pelotas localizada en la costa afuera Brasilera. Con la información sísmica 2D e información de pozos, se presenta un modelo del Cono de Río Grande, integrando estratigrafía de secuencias y parámetros geofísicos, por ejemplo: función de velocidades, tratos de sistemas y rasgos geomórficos. El modelamiento geofísico y estratigráfico del Cono de Río Grande permitió establecer ciertos rasgos geomórficos y estratigráficos, e identificar varias secuencias. La integración de datos geofísicos y geológicos, permite establecer elementos como canales, cañones, niveles, escape de fluidos, diques marginales, contornitos y escapes de fluido.

Palabras Claves: Cono de Rio Grande, Geomorfología Sísmica, Estratigrafía de secuencias, Modelamiento 3D.

Abstract

The Rio Grande Cone feature is a large subsurface structure in the Pelotas Basin located on Brazilian Offshore. Using seismic line grids and well log information, we present a model of the Rio Grande Cone that integrates sequential stratigraphy and geophysical parameters, i.e.; velocity function, system tracts, geomorphic features. The geophysical and stratigraphical model from the Rio Grande Cone establish certain geomorphic features and identify various sequences. This integration enables interpretation of geomorphologic elements (channels, canyons, levees, contourites, fluid escapes and pockmarks), and provides the sequence and geological information needed to build a three-dimensional model from velocity model.

Keywords: Rio Grande Cone, seismic geomorphology, sequence stratigraphy, 3D modeling.

INTRODUCTION

Two-dimensional seismic lines have been used previously to reproduce a subsurface model (Castillo *et al.,* 2002). The geomorphology combines disciplines such as seismic and sequence stratigraphy to obtain an approximation of the geological elements in deep water zones. In this paper, geological model approaches in both the spatial and temporal domain were provided by means of seismic reflection for the Rio Grande Cone (RGC) geoform.

The RGC is an offshore part of the Pelotas Basin possessing an irregular appearance; its extension elongates seaward and contains fine-grained sediments (mudstones and shale) as its dominant facies. The RGC comprises the shelf to the northwest and the slope to the southeast, including the break shelf. An echelon, N-NE fault system controls the depocenters that developed across the southern offshore region of Brazil.

The sequences are thin at the near offset and have a pinched outer layer; at the far offset (seaward), the sequences are thicker. Faults were well defined in these thicker areas and cut all of the Rio Grande Cone sequences. A high amplitude reflector running parallel to the seafloor (Bottom simulator reflector, BSR) was observed to extend into deep water and cross the sequences (Rosa *et al.,* 2006). This BSR is an indicator of the presence of a gas hydrate corresponding to one of the largest potential energy resources in the Rio Grande Cone off the shore of Brazil.

GEOLOGICAL SETTING

Southern Brazil it is characterized by the presence of the Rio Grande Rise, which divides the Pelotas and Santos Basins. The mid-shelf fault zone marks the transition of oceanic to continental crust, yielding two of the major offshore sedimentary basins of Brazil: Santos Basin to the north and the Pelotas Basin to the south. These basins correspond to passive, Atlantic-type margins that are splitted by the Rio Grande Rise (Figure 1A). The Rio Grande-Walvis Ridge was a topographic barrier. A salt gulf margin rose in eastern Brazil, whereas to the south (Pelotas Basin), the sedimentation of this transitional period is represented by clastic sediments and some biogenic sediment without salt layers.

The initial rifting between South America and Africa (~130-135 ma.), which resulted in the uplifting of Precambrian to Paleozoic rocks as well as expressive magmatism related to the break-up, provided the necessary conditions for generation of an extensive volcanic-sedimentary sequence. The transitional phase from rift to post-rift, is marked by well-preserved salt deposits in the Santos Basin to the north (Milliman, 1978). These deposits developed during the Aptian and were associated with extreme arid climatic conditions. From the Albian to the recent periods, the oceanic drift stage has continued, generalized by the function of a thermal subsidence mechanism.

Its principal features comprise geoforms and marine facies that resulted from the influence of the relative sea level (Chang & Kowsmann, 1987). During the Miocene, the Rio Grande Cone was formed by a large clastic sediment supply, characterized by a thickness package of up to 5000 m; the thermodynamic subsidence rate, however, is not sufficient to explain these sediment amounts (Fontana, 1996).

The Rio Grande Cone has been characterized seismo-stratigraphically as a sedimentary geoform from the Miocene. It was originally built offshore, in front of the Lagoa dos Patos and Lagoa Mirim. The geoform can be split analogous to Walker's submarine fan classification (Walker, 1978), based on the sedimentary supply and the location of geoforms for all the morphometric divisions (Upper, Intermediate and Lower Cones). These areas were built by the hemipelagic and pelagic sediments from the southern Brazilian, Argentinian and Uruguayan continental areas (crystalline basement and Phanerozoic units, Figure 1B).

From the Miocene until today, the Upper Rio Grande Cone has consisted of levees filled by sandstones and siltstone. The Intermediate Cone comprises the interdigitization of semi-developed levees, with the stratification of sandstones and turbidities associated with the slope. The Lower Cone is a feature with smooth and plane topography supplied by hemipelagic muds and turbidites. Bottom surfaces, or contourites, have been reported along paleocurrent flows because of depositional gravitational processes, such as negative paleotopography (Rio Grande Cone Bathymetric Chart, LEPLAC, 2004).

GEOPHYSICAL INFORMATION

The seismic stratigraphic analyses and modeling were based on two dimensional seismic line grids from LEPLAC-IV and the Brazilian Oil National Agency (Agencia Nacional do Petróleo-ANP, Brazil), using the SAD69 as the reference dataset. The seismic grid was composed of a NW-SE dip (DI, DII, DIII, DIV, DV and DVI) and NE-SW strike lines (SI to S13) with a regional fold of 2400%, a record length of five to ten seconds and lengths of hundreds of kilometers. The survey extended from the end of the shelf to the deep abyssal plain, with an area of 28900 km^2 (Figure 1A). For modeling, the seismic information was 30-45 Hz, with an average velocity of 1900-3500 m/sec and a well log velocity of 90 µs/ft.

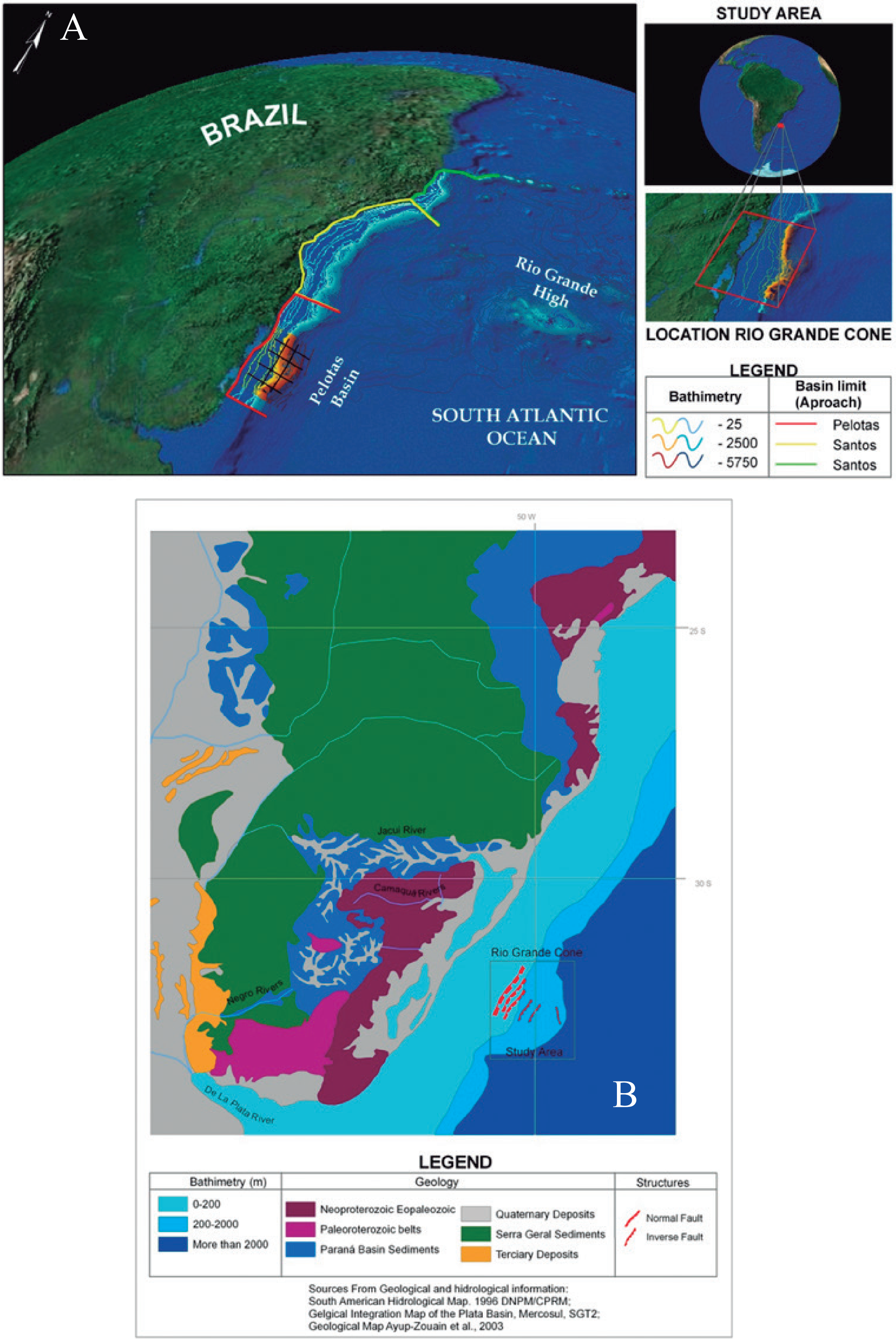

Figure 1. (A) Map of the study area and the Pelotas Basin. The location of Rio Grande Cone shows the survey grid with seismic lines. The image shows the geomorphology of the bottom sea and onshore: continent (including Lagoa dos Patos). (B) Geological map of southern Brazil (after Azup-Zouain *et al.*, 2003).

METHODOLOGY

Different tools (Attributes, Filters and illumination) were applied to optimize the geophysical data. These analyses are included during interpretation, modeling and visualization. Seismic interpretation examined structural, stratigraphic and geomorphologic features along with key surfaces (maximum flooding, maximum regressive and correlative conformity). Correlation procedures for horizons (Posamentier, 2004) are associated with the geological age (Middle-lower Miocene to Recent) of the shallow surface through to the deeper zones when considering surface generation and structural and stratigraphic modeling (Chart Diagram, Figure 2).

The sequence stratigraphic method was applied to several passive margins with lower structural complexity than other settings (Abreu, 1998). The stratigraphic sequence cone is influenced by structural complexity, high sedimentation and sea level changes. Structural, stratigraphic and geomorphologic elements that are integrated with geophysical parameters allowed for in-depth modeling of those parameters influencing the Rio Grande Cone area.

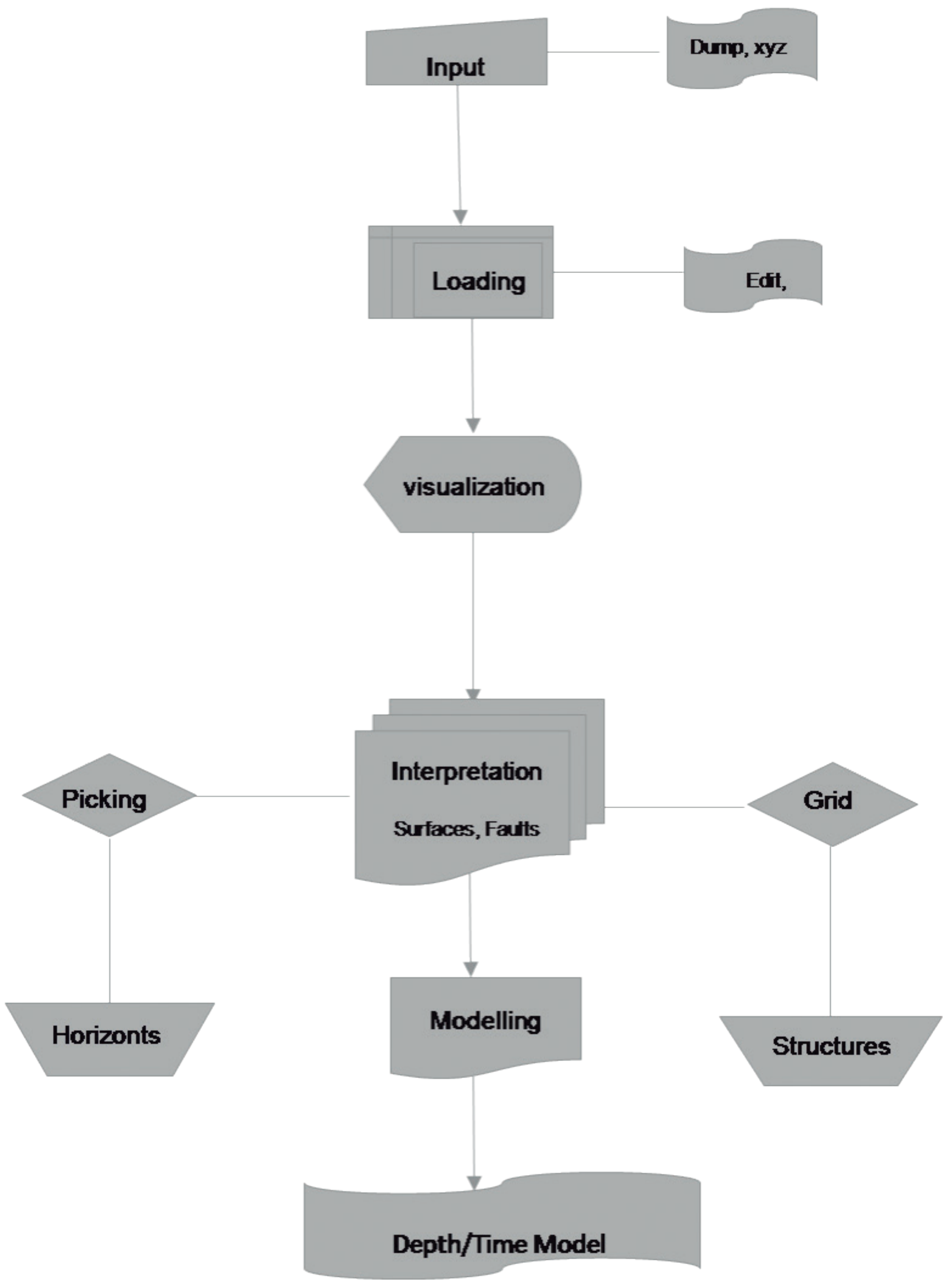

Figure 2. Chart diagram with different sequences used for seismic interpretation.

SEQUENCE STRATIGRAPHY

According to previous authors, the area is comprised of several sequences that could be determined by the seismic terminations and geometry associated with the chronostratigraphic and biostratigraphic information (Figure 3).

The different sequences of the Rio Grande Cone have been identified previously through horizons delineated by seismic reflections from analysis of the Pelotas Basin and cone areas for hydrocarbon exploration (Alves, 1977; Fontana, 1996; Abreu, 1998); at least 12 sequences have been described. The geophysical integration of seismic, well log, gravimetric and stratigraphic seismic interpretations provided evidence of tectonic uplift from the Eocene. The uplift was associated with volcanism caused by the Pacific, Antarctic and African plate collision, along with Andean tectonism, which increased the prograding deltaic system. The Rio Grande Cone is considered a depositional feature formed in the drift phase from the Miocene to the Recent that is more than 4000 m thick. Its megasequences are 50 Ma. and can be divided into second and third order sequences (Fontana, 1996). Other authors have used geophysical information (interpretation with some seismic lines) to describe some sequences related to the Rio Grande Cone (Simões, 2004; Rosabela, 2007); sedimentation was considered the dominant process, and subsidence was related to tectonic and eustasy. We assumed that the sequences originated from the Miocene to the Recent. The cone comprised a sedimentary package with different depocenters that were affected by tectonic influences, sediment supply and eustasy (Figure 4).

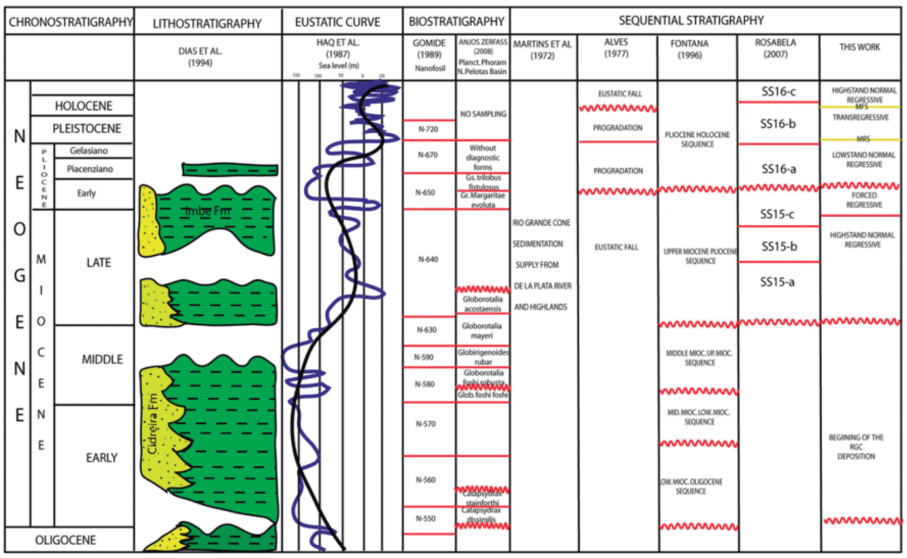

Figure 3. Stratigraphy of different sequences for the Neogene section in the Rio Grande Cone, including biostratigraphy, geology description and eustatic curve. The sketch shows a compilation of the sequence stratigraphy for the Rio Grande Cone from Martins (1972), Alves (1977), Fontana (1996), Rosabela (2007) and this paper.

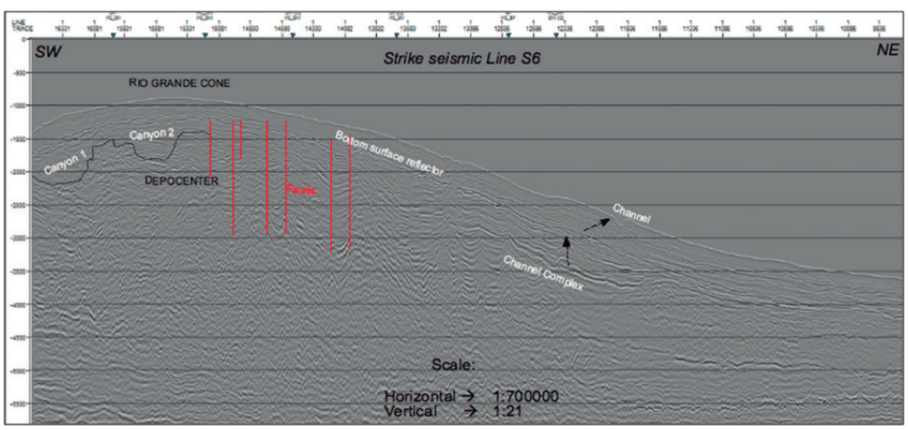

Figure 4. Strike seismic section (S6) line with sequential stratigraphic interpretation from the Neogene interval in the Rio Grande Cone, with the depocenter and migration of complex channels influenced by sediment supply, eustasy and accommodation.

We defined genetic stratigraphic sequences based on the maximum flooding surfaces in a given stratigraphic section using the definition of Galloway (1989). This definition allowed for the delineation of sequence boundaries at a large scale. The sedimentary package of the Rio Grande Cone is classified as a transgressive-regressive sequence (T-R sequence), bounded by recognizable stratigraphic sequences (Embry, 2002), and stacking geometry patterns that delineate key surfaces based on the seismic stratigraphic interpretation. The last conceptual definitions available in the literature (Catuneanu, 2006), defined the stratigraphic sequence from the Rio Grande Cone model using a sequence standardization based on classic interpretations (Fontana, 1996; Abreu, 1998 and Rosabela, 2007), and an additional proposal (Catuneanu, 2006). This interpretation included the definition of a genetic sequence, the nomenclature of system tracts and the timing sequence boundaries for stratigraphic models (Catuneanu *et al.,* 2008). The system tract provided the basic division of the Miocene sequences into genetic packages for the Rio Grande Cone and shows stratigraphic trends according to strata stacking and sea level changes. The strong seismic reflections and geometries enabled the identification of key surface features, including surface unconformity, the maximum regressive surface, the maximum flooding surface and correlative conformity (Figure 5A).

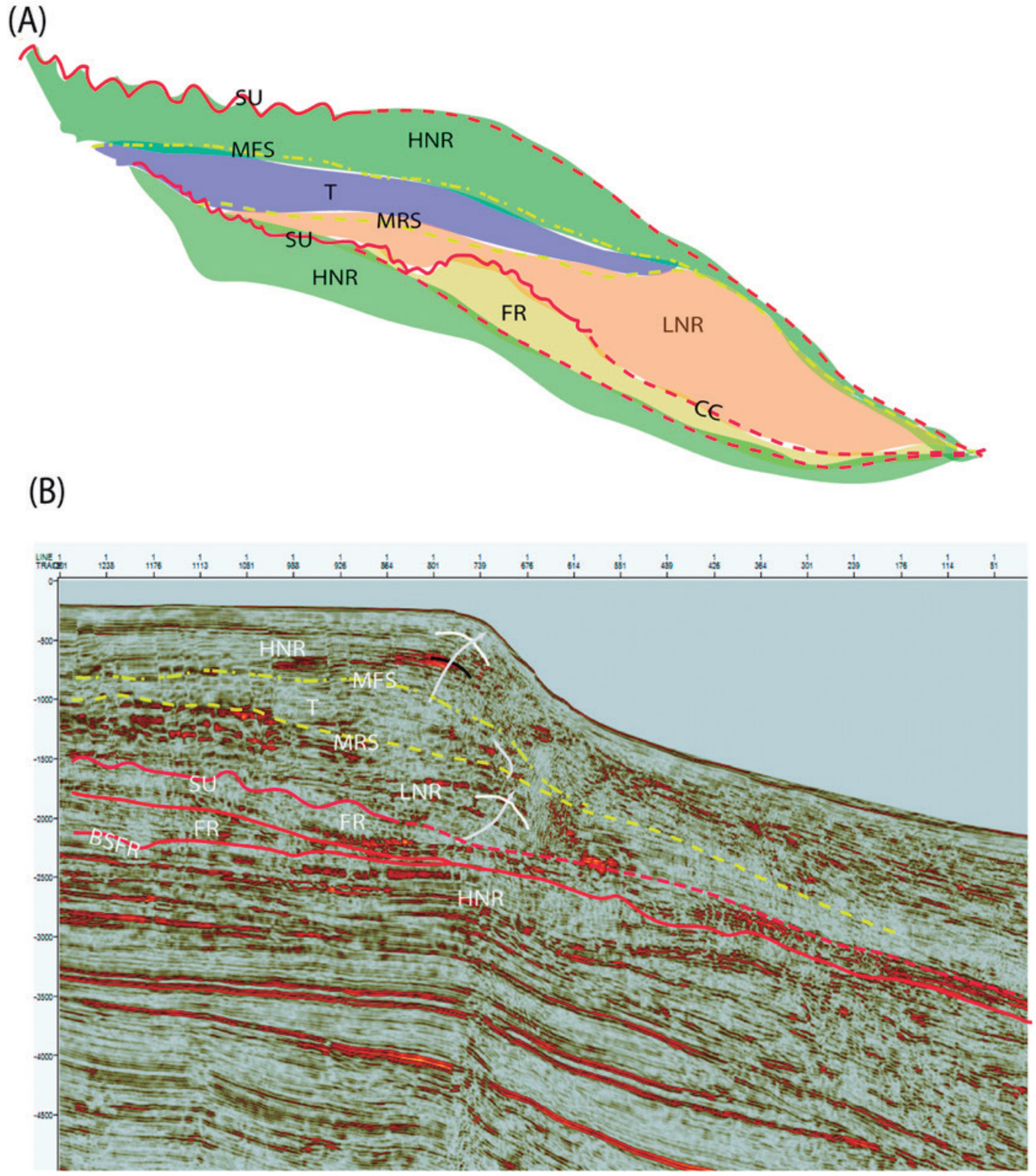

Figure 5. (A): Ideal schematic model representation of the sequence stratigraphy, with regressive and transgressive sequences (highstand, lowstand and transgressive). (B) Sequence stratigraphy interpretation in the dip regional seismic section located in the Rio Grande Cone, southern Brazil. The interpretation shows large-scale system tracts (based in Catuneanu *et al.,* 2008).

Sequence stratigraphy associates each type of shoreline shift with a particular genetic type of deposits. The Miocene sequence package for the seismic section of the northern Rio Grande Cone may be divided into system tracts that consist of three genetically distinct strata: lowstand normal regression, transgression and highstand normal regression. The lowstand normal regression is the lower package, and it corresponds to the early stage of base-level rise, including progradational and aggradational trends (Figure 3, and Figures 5A & 5B). The lower boundary is the subaerial unconformity that extends to the seaward correlative conformity. The upper surface comprises the maximum regressive surface that defines the clinoforms of regression, which overlap with the transgressive strata. Due to their retrogradational stacking pattern, transgressive deposits were identified and delimited at the top by the maximum flooding surface. The maximum flooding surface could be delineate by the stacking pattern of the strata, which change from the lower transgressive to the upper regressive strata (Galloway, 1989) and the final transgressive surface (Nummedal *et al.,* 1993). The upper subdivision sequence displayed progradational strata packing that occurred during the late stage of base-level rise (Highstand normal regression (Figures 5A, &5B).

STRUCTURAL ANALYSES

The Pelotas Basin is a passive margin basin characterized by extensional tectonics and is associated with the rift and drift phases. The Rio Grande Cone is a large structure in the Pelotas Basin that was develope by an extensional regional tectonic, but it is somewhat more complex than suggested by merely the structural point of view. The Rio Grande Cone and the wedge are characterize by retrogradational sequences and a structural style that is different from other places in the Pelotas Basin. The cone is represented in plain-view by polygonal, complex fault systems that extend to kilometers in length, with one principal fault located in the center of the cone sequence (Figure 6).

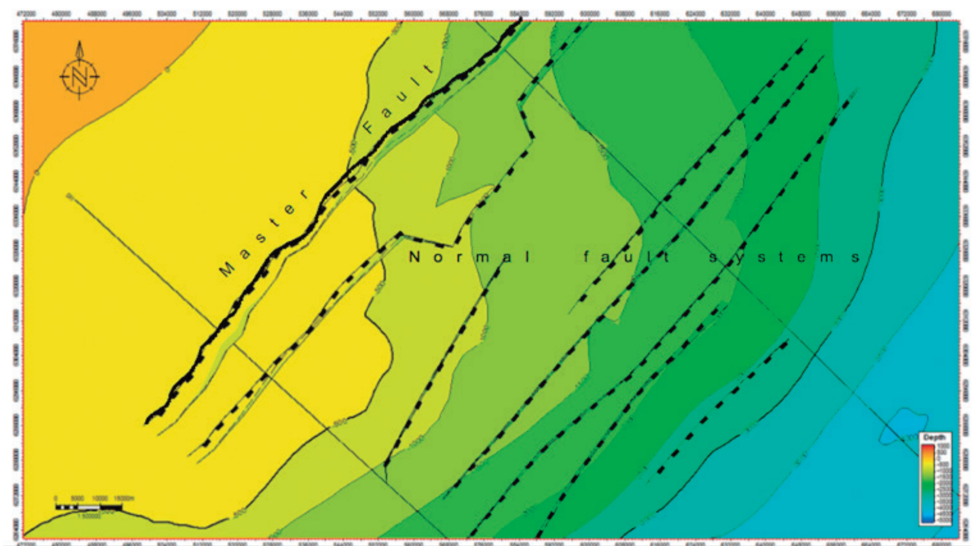

Figure 6. Plan view map with structural mapping of the principal normal faults and contours of the bottom surface. The principal or master fault corresponds to a listric fault (northwestern fault), while the other normal system faults are connected in depth to the master fault.

This large structure has some special features, such as a high sedimentation rate between the Miocene and Holocene (~20 Ma.) and a total sedimentation volume of approximately 200 m/Ma. More than 4 km of sediments were deposited in a restricted area of 28.900 km^2. Despite its structural style, the structure could not be identified by seismic section interpretation directly; therefore, a modeling approach was applied. The modeling permitted a three-dimensional representation of the principal structural elements that characterized the cone. The main tectonic features of the RGC are extensional listric faults and related structures, such as thrusts and folds.

The geometric shape of the RGC is semicircular in plain-view and is arcuated with the main fault system located at the boundary between the platform and the slope. This fault system is represented by the master listric fault, which is connected to the detachment at the lower base of the RGC. The contact most likely bridges the Oligocene and Miocene sediments (Figure 7).

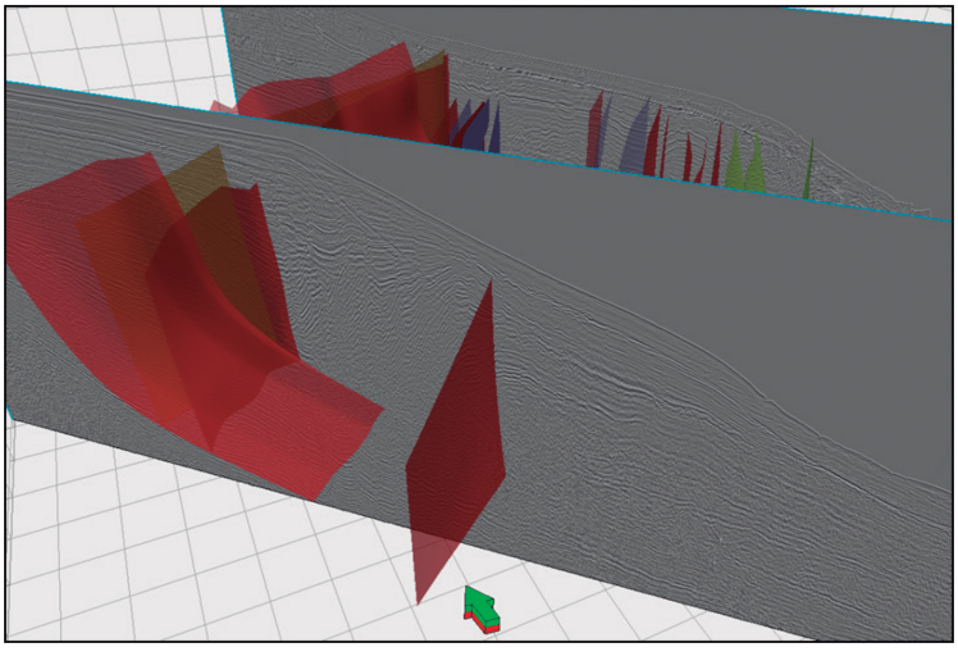

Figure 7. Three-dimensional structural model with features identified in the Rio Grande Cone using seismic sections. The section includes regional normal faults, strike slip faults and vertical faults; the model illustrates fault system planes crossing all sequences of the RGC sedimentary package.

The internal structures recognized in the RGC are the following: (i) normal faults (synthetic and antithetic), (ii) structural highs, (iii) thrusts and related folding, (iv) transcurrent faults, such as Riedel and anti-Riedel faults, and (v) bottom simulator reflectors (BSR).

The geometry of the cone is well define by the master fault and the connected detachment. This fault system is oriented SW-NE and dips to the SE; it also is recognized by the boundary of the RGC structure. The internal normal faults (synthetic and antithetic) and secondary faults are mostly listric, and in most cases, they are either connected to the detachment or cut across the structure. Many of their planes are described by decollement planes that are either horizontal or occur at a high angle, including antithetic faults.

The normal faults extend through the sedimentary package with some strike planes that cut the faults found externally to the Rio Grande Cone area. These faults, moreover, cut the sequences that join fault propagation folds and are characteristic of the southeast dip seismic lines. Due to strain accommodation, some folding was recognize in the RGC related to rotational deformation (e.g., accommodation and roll-over structures).

The tectonic inversion is present at the end of the RGC structure (the SE portion of the RGC) and is represent by folding (asymmetric folding) and thrusts. The thrusting occurs with vergence to the SE as a result of the compression end of the RGC structure, which is related to the extensional displacement of the entire RGC. The normal faults developed primarily until the Upper Miocene and the Pliocene, indicating that the highest sedimentation rate and deformation occurred from the Middle Miocene to the Pliocene.

On the other hand, the thrusting faults seem to extend to the BSR; a structure identified at the top of the RGC that is associated with hydrate gas. Additionally, there are stack sediments in the extreme SE portion of the RGC.

The progradation zones are the most affected by normal fault systems with vertical or high inclination degrees that converge toward the master fault (145 km width). The master fault can be describe as a structure of approximately 22 km in the listric plane (the western limit of the RGC) and 25 km in length in the detachment plane (the sub-horizontal part of the master fault). The master fault is approximately 145 km wide, as seen in Figure 7.

Consequently, the large supply of sediments is directly relate to the displacement of the master fault and secondary structures and is a result of the sediment overload and flexure of the lithosphere.

STRUCTURAL MODELING

A structural framework was recognize in the seismic sections of the RGC. The structural model includes several stages (Figure 8 A-H), with an emphasis on the extensional and transcurrent faults. First, the location of the fault was indicate using sticks (Figure 8 A). Next, the edition was defined (Figure 8B), followed by fault surface generation (Figure 8C). A linear interpolation grid was applied for the fault surface (Figure 8D) with two principal orientations I, and J (Figure 8F). The grid was delimited by the boundary of the RGC (Figure 8E). The master fault comprised the western limit of the RGC, and the basement of the model was the Oligocene to Paleocene sediments where the sediments are located. In the last two stages, stratigraphic elements such as horizons and sequences were included, then split the grid in a K-wise orientation (figure 8G). Finally, the model was populated.

The three dimensional representation was created using intersection across the model (Figure 8H). The master fault and the single faults comprised the echelon segments that compartmentalized the basin, thereby demonstrating the stratigraphic and geomorphologic interaction.

Tectono-stratigraphic domains established by interpretation and modeling permitted three-dimensional visualization of various elements, including lineaments, faults and other structural elements (Figure 8H). The structures presented in the sedimentary sequences included the following: bedding and their boundaries and structural anisotropies (e.g., fault planes, propagation faults, fractures and folds). The features of all of the elements were characterize by different domains (e.g., bedding planes, pitch out sequences, unconformities, faults, and fault limit planes, Stewart and Reeds, 2003).

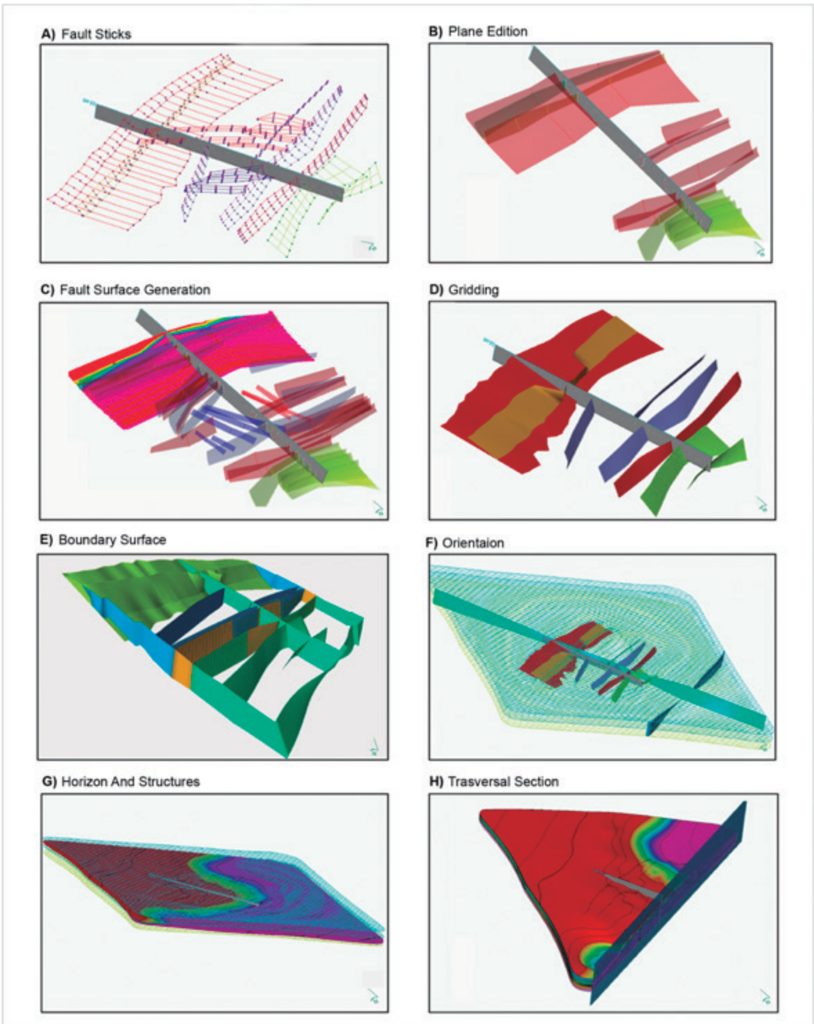

Figure 8. Structural model sketch with extensional and transcurrent faults. Figure 8A, indicates the fault position by means of sticks; Figure 8B, edition; Figure 8C, fault surface generation; Figure 8D Linear interpolation grid applied to the fault surface indicating the orientation of I and J. The grid was delimited by the cone body boundary, Figure 8E. The two last stages include stratigraphic elements, i.e. horizons and sequences that divide the grid in the K direction, Figure 8G. The last stage, was population of the cells model, Figure 8H.

The most important structural element was influence by gravity tectonics along the detachment surface (thin-skinned) that dips to the S-SE, and extended along the cone. This tectonism is relate to load subsidence due to the deposition of a thicker sequence in the Miocene.

Reflections and structures inside the Miocene horizons or surfaces (Horizon 1 to 3), should be considered to determine the structural and reactivation timing. These horizons were used to draw isopachs and to establish the fault movement (or displacement) and timing along the RGC formation. In this model, the faults propagated towards the southeast and are more recent than faults to the northern of the RGC, thus falling upward of the sequence. The fault diagram (Figure 7), shows that few faults were active before the Miocene. This behavior changed after the reactivation of some faults and scatters to the southeastern portion of the Pelotas Basin.

TECTONIC-SEDIMENTARY EVOLUTION OF THE RIO GRANDE CONE

The Pelotas Basin comprises the Rio Grande Cone geoform, whose tectonic elements have been associated with the sedimentary package deposited from the Lower Miocene to the Recent. Seismic sections of the Rio Grande Cone showed geometrical terminations, such as top set, bottom set and foreset (Figures. 9A and B), that could be divided into several zones. In the basal sequence, slumps, turbidities or gravitational flows were recognized.

The intermediate portion (foreset) is characterized by lowstand to transgressive, debris flow and slices deposits. The upper zone presents aggradational sediments with fine material originating from marine deposition. The kilometer-scale fault geometry resulted from tectonic interactions, mass movement and submarine settings. One of the principal structural elements is characterized by a listric fault associated with the fragile zone (Figures 8C and 8D); this fault breaks blocks into many vertical and semi-parallel fractures, which lead to the main structural dip to the SE (Figures 7 and 8). Therefore, these faults are posterior to the deposition and correspond to the Pliocene age, with vergence towards the southeast. The Rio Grande Cone morphology was influenced by the offshore fault plane that is steeply normal towards the shelf. This plane is connected to another plane with an east-southeastern vergence that flattens toward the sea. In this principal fault, the planar failure surfaces that propagate across the fault to the southeast are connected. The detachment is an extensional plane 20 km long and 70 km wide. Post-tectonic seismic features characterize the area, such as mass wasting, slumps, debris flows and turbidities that comprise the submarine mass flow system (Shanmugam *et al.,* 1996). The fault style is associated with fault propagation through the sequence package. The extensional structural model has been used for seismic interpretation, and a guide for the seismic sections has been developed previously (Stewart and Reeds, 2003). Normal faults are related to the architecture sequences of synrift deposits, and this link is supported by geomorphological analyses, including neotectonic and quantitative geomorphology. These observations were made using subsurface data, including three-dimensional seismic data and well information, and they allow us to quantify the sediment supply for large areas (McLeod *et al.,* 2002).

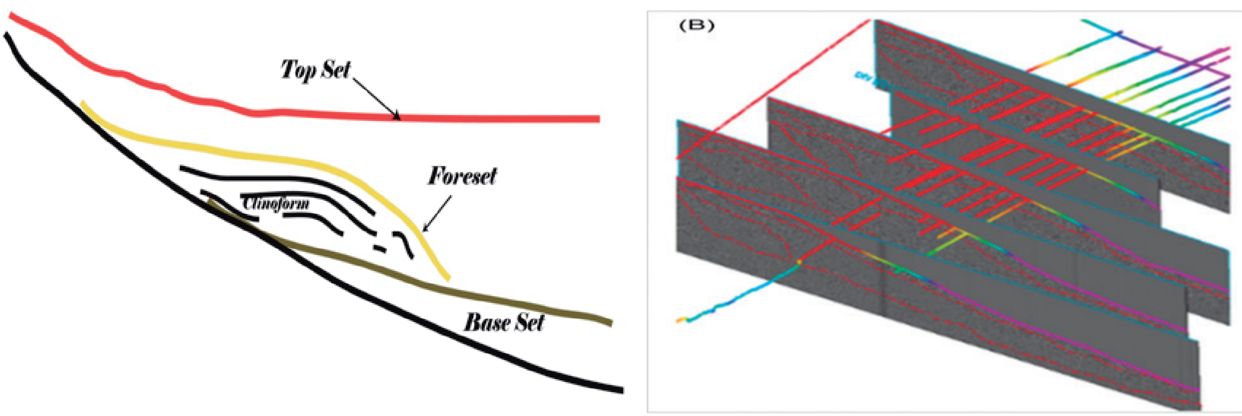

Figure 9. (A) Schematic representation of the termination and geometry of the clinoforms and sequences that determine the progradations found on the RGC, i.e., the topset, bottom and foreset; (B) dip seismic line interpretation (D1-lowest- to DVI) and interpretation of horizon and progradational sequences. The basal sequence is influenced by slumps, turbidities or gravitational flows characterizing the foreset sequence comprised of sediments, debris flows and mass transport complexes.

To the southern of Brazilian Offshore, it is possible to identify fault propagation folds and reverse faults. In this work, such features would be describe as under-developed fault systems compared to the extensional system. The small size of these faults, however, makes modeling difficult.

The sedimentary supply through the RGC was derived from bulk sediments from the covered cratonic areas (such as Paraná Basin sediments and Serra Geral volcanic rocks), including sediment precedents of the Camaquã and Jacuí Rivers, as well as the de la Plata River (Martins *et al,* 2005). This continuous deposition increases the lithostatic load starting at the slip of the master fault alongside the stacking sediments. The deposition continued during this stage, and the slicing of the sequences occurred during synsedimentary faulting. These sediment packages settled into the master fault, with a thick progradational sequence providing lowstand system regressive deposits (Figure 10A). These deposits have little structural influence, except for the presence of the master fault. This basal sequence was followed by deposition of a retrogradational sequence that represents the transgressive system (Figure 10B). Transgressive system is crossed by faults located in the northeast of the cone area. Sediment accumulation during the Tertiary revealed that maximum supply of sediment occurred during the Middle Miocene. After that, accumulation in the Pliocene to the Recent registered a sedimentary charge lower than in earlier periods. The last accumulation corresponds to the highstand regressive system (Figure 10C).

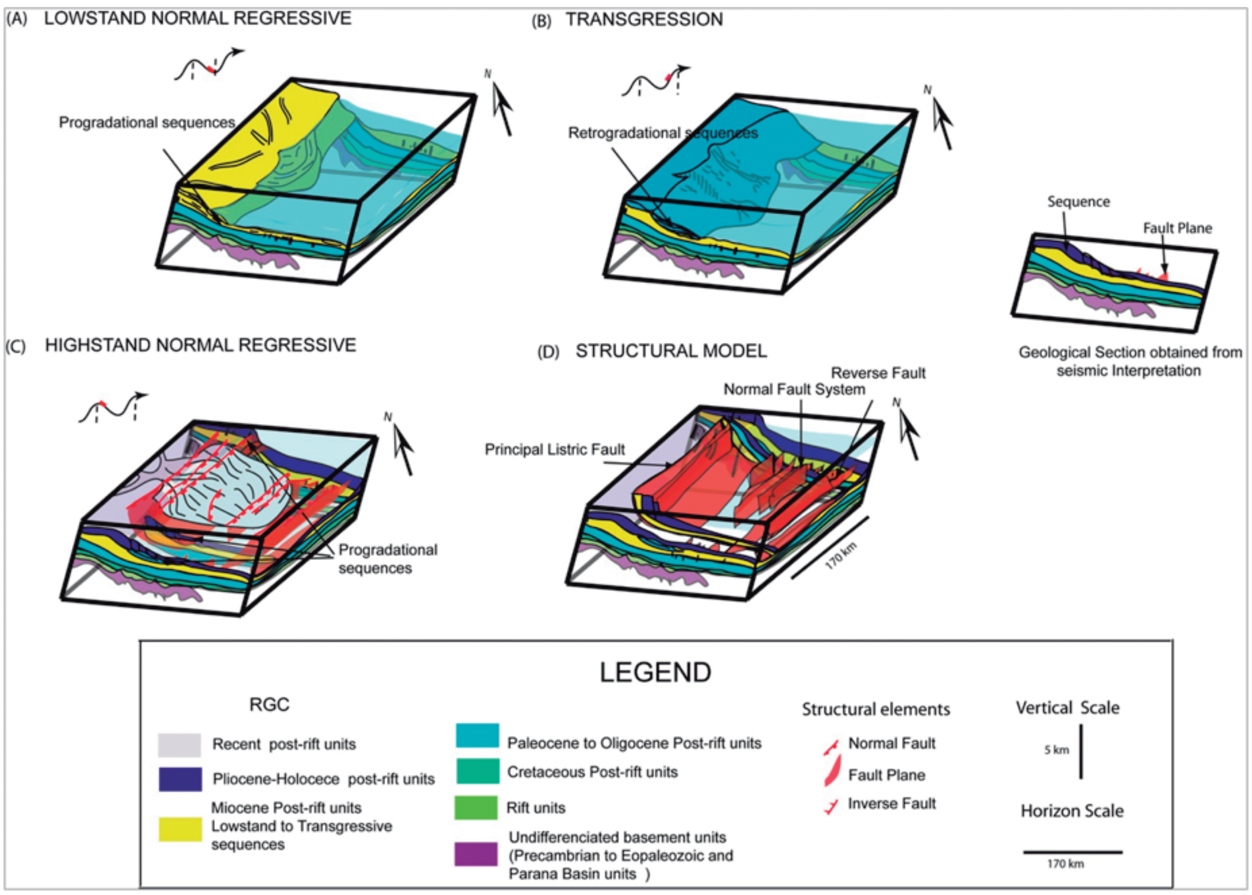

Figure 10. Stratigraphy and structural evolution model of the Rio Grande Cone. Sedimentary packages settled in the master fault, with thick progradant sequences giving rise to lowstand normal regressive deposits (Figure 10A) with few structural influences aside from the presence of the master fault; this settlement was followed by deposition of a retrogradational sequence representing the transgressive system (Figure 10B). This sequence is crossed by faults (normal faults) located northeast of the cone area. Tertiary sediment accumulations show maximum sediment supply during the Middle Miocene. Subsequently, the Pliocene to Recent accumulation registered a sedimentary load lower than earlier periods. The last sedimentary deposition corresponds to the highstand normal regressive deposits, with broad accumulation through the Middle Miocene (Figure 10C).

SEISMIC GEOMORPHOLOGY

Recently, seismic geomorphology is considered for the development of three-dimensional seismic data. Sections and slices provide important information on past land and seascapes in the subsurface (Posamentier, 2004). Images and seismic attribute analyses thus contain tools that permit direct interpretation of the depositional environment (Rafaelsen, 2006). Geomorphology requires gathering and evaluating evidence of system faults, which can be observed by checking lineaments, drainage patterns, channel profiles and gradient calculations (Groeger & Bruhn, 2001). These characteristics can be obtained from surface mapping or satellite and photo interpretation; otherwise, geophysical data could be used to extract subsurface information, such as structural elements, stratigraphy or geomorphology.

The geomorphological aspect of the Rio Grande Cone includes sequence stratigraphy and seismo-stratigraphic analyses from a 2D-grid seismic survey. The principal aim of this work is to obtain a 3D geomorphological model that describes the features of the RGC that have been affected by the sediment supply.

The seismostratigraphic analyses describe the sequences of the upper, modern deposits. These deposits are considered transitional and marine environments that were influenced by hydrological sediments, and channel and canyon geometry, with materials loaded on the slope. The seismic-stratigraphic analyses were followed by geomorphological analyses, including the identification and description of geoforms, along with geological and geophysical correlations at different subsurface depths or time intervals (Figure 11).

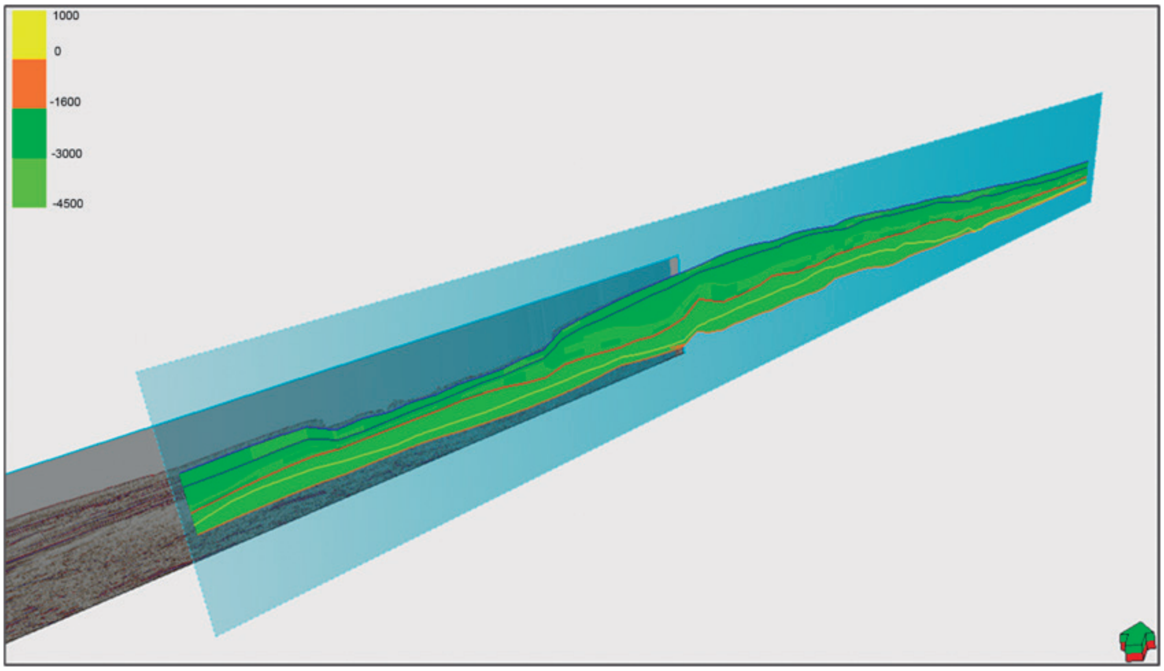

Figure 11. Regional dip lines with seismic interpretation describing the break shelf and clinoform and progradation sequences, showing lateral migration and pitch out toward the far offset. Surface lines correspond to possible lines for the velocity model and correlation.

The geomorphological features that were observed by seismic interpretation suggest possible drainage patterns, canyons, channel systems (Figures 12 and 13) and contourites. The submarine canyon includes a complex channel system that presents a rectangular drainage area with south-southern trending. The system is linked to shorter tributaries with east-west trending caused by bedding, tilting subsurface and S-SE trending preferential erosion. Based on the geomorphological features, at least five subsystem drainages were observed in the RGC, including canyons and distributary channels.

The canyons located in the central region had variable lengths of 85 km. to 48 km. (channel systems CC3, CC4 and CC5). The end of the canyons are close to the system faults and were affected by the complex faulting that controlled the form and trending of the canyons. The extreme end of the canyon system can reach 56 km (channel systems CC1 and CC2). The tributary channels of the canyons are between 3 and 11 km long (Figures 12 and 13), and the channel area is comprised mostly of fine-grained material (such as mudstones and shale).

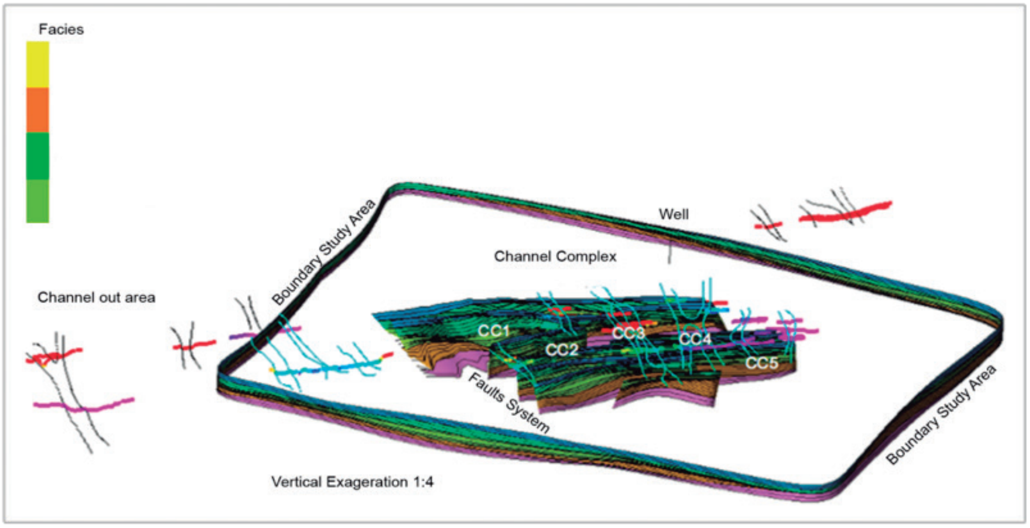

Figure 12. Seismic strike section and system channel complex identification. Channel position after geobody modeling.

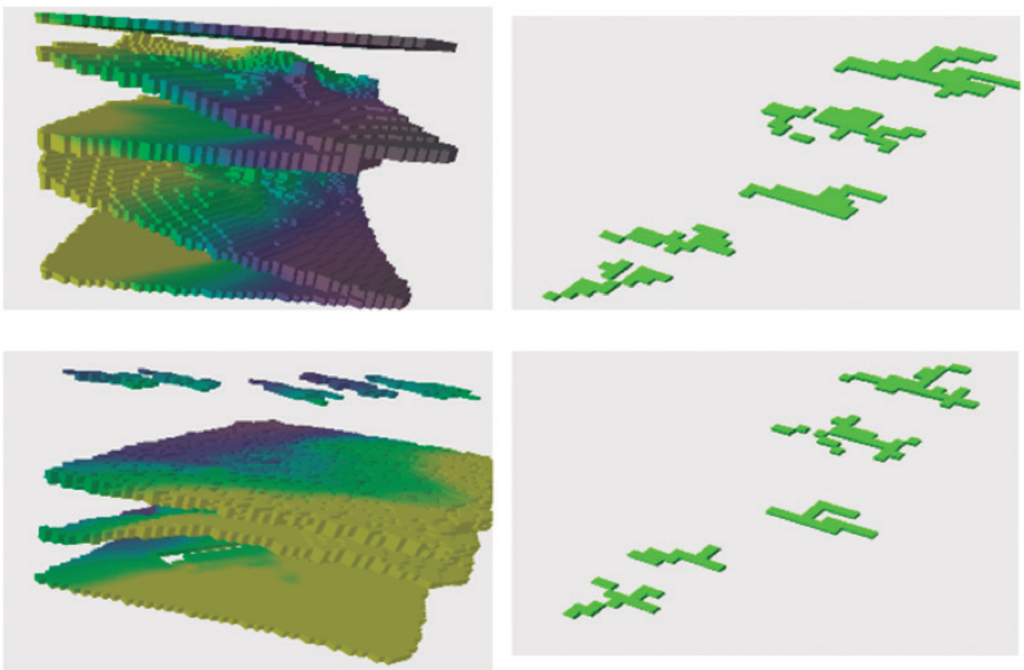

Figure 13. Different flattened sequences describing the orientation and different compartmentalization classes of actual geoforms, i.e., channels and contourites.

In the Rio Grande Cone, the larger structures developed slices, slumps and mass transport complexes that were controlled by the normal fault system in the proximal and intermediate areas. The reverse faults and folds were the main structures in the RGC distal region. Undulation reflections are characteristic forms of sediment waves originating from currents flowing across the seabed. Such reflections were identified on the seismic package because it contained at least two wave-shape units (Schwab *et al*, 2007).

This architectural element characterizes the Rio Grande Cone slope. Sediment wave and bottom-current deposits were described in different areas and could be found in channels or canyon mouths. This morphology corresponds to the expression of bottom-current activity on the near offset and the northwestern slope. The Miocene sequence slope is characterized by seismic facies represented by turbidities, which had been reworked by contourite currents in some places.

The Rio Grande Cone geoform is a pitch out that extends along the NW-SE shelf to the offshore. This pitch out has predominant clinoforms that correspond to a regressive clastic succession. Their thicknesses are between 1 and 2.5 km, and they comprise the Rio Grande shelf, slope and the oceanic floor. The slope contains different sediments.

In the last several decades, studies of offshore hydrocarbon have reported escape flow structures, called pockmarks, in shallow waters (30-100 m) and deeper zones (~3000 m). Structural surfaces along the rock layer, diapir, anticline and polygonal faults have created pathways for deep fluid migration. These pockmarks are associated with buried reservoirs of biogenic gas, termogenic oil, interstitial water, or a mixture (Gay *et al*., 2005; Andresen *et al*., 2006). The fluid escape is located in the final shelf portion of the RGC slope and is related to slides, slumps and submarine turbidites (Rosa *et al.,* 2006). Fluid escapes are indicated by vertical faults and the presence of chimneys in seismic sections. The escapes can be identified by their characteristic anomalies (multiples, BSR) and occur where pockmarks and pipe tubes are evident and associated with polygonal faults, slides and slumps.

The final of the Rio Grande Cone, is shown in the computational model that corresponds to the geoform. The model can be understood in terms of the geophysical, structural and geomorphological elements of the seismic-stratigraphy. The estimated volume of the sediment supply in the RGC is approximately 5.024943×10^{12} m³, based on the final 3D model (Figure 14).

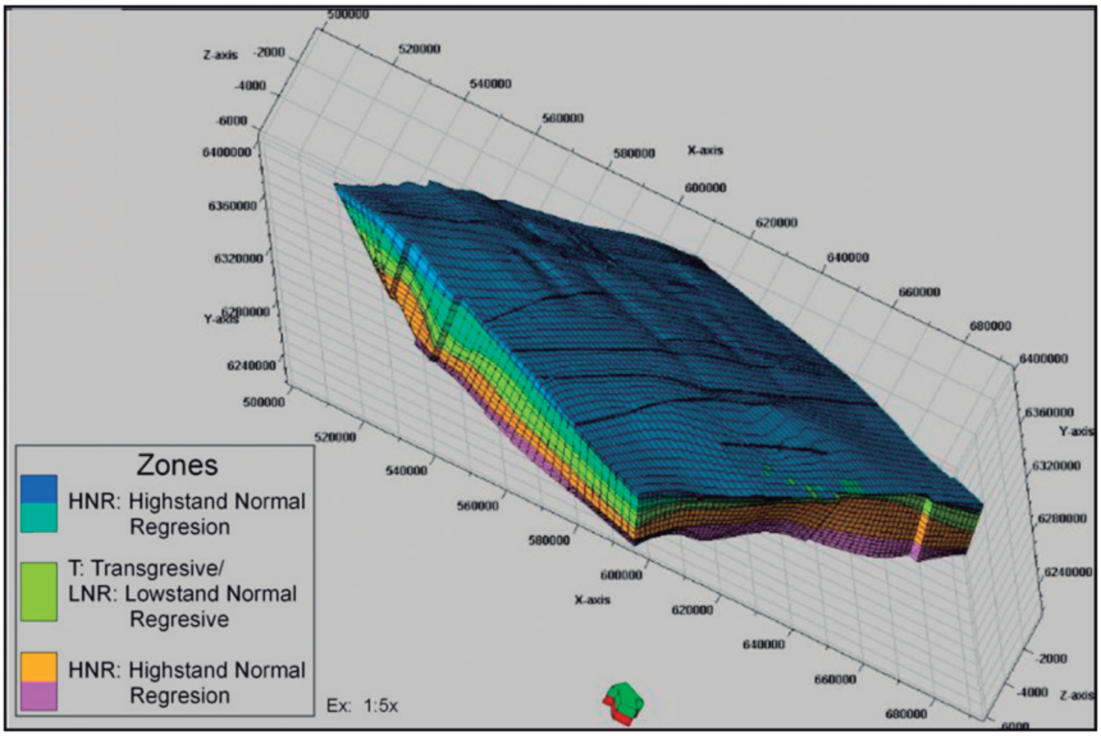

Figure 14. Three-dimensional computational model of the Rio Grande Cone, containing stratigraphic sequences, faults, channels and elements obtained from seismic interpretation.

CONCLUSION

2D seismic information establishes a regional approach for geobodies associated with a depth or the temporal domain. The sedimentation in the Rio Grande Cone is affected by extensional faults that cut sedimentary sequences from the Miocene to the Recent. However, recent sediments are not often cut by these extensional faults, but fluid escape zones can be recognized by seismic anomalies, such as diffractions or velocity pull-ups, in the upper section of the RGC.

Three-dimensional modeling and visualization revealed the presence of structural, stratigraphic and geomorphologic elements that can be integrated for analysis of the evolution of the RGC. The canyon and channel systems are the most important geoforms in the prominent body of the RGC.

Structures and deformations in the RGC are associated with subsidence and mass movement or fluid flow. The prominent faults correspond to dislocated blocks with polygonal forms in plain view, whereas in seismic sections, these faults are described as vertical segments and planes corresponding to posterior structures relative to the sedimentary deposition. The master fault of the RGC extends 25 km along the listric portion and 22 km along the detachment. Many secondary subvertical extensional faults connected to the main extensional fault were also observed.

These analyses include geomorphologic elements that integrate structural and stratigraphic interpretation, demonstrating the influence of tectonostratigraphy on the package sequence geoform, which was affected by tectonics, sedimentary supply and isostasy. Tectonic subsidence played a very important role during development of the RGC, mainly by overloading sediment (due to a very high sedimentation rate) and extensional faulting in the proximal and intermediate areas. In the distal portion, reverse faults are the main characteristics of the RGC.

The generation of three-dimensional models offers a good understanding of the structural trends, fault types, features, geoforms and the relationships between subsurfaces and therefore provides the necessary information to estimate the sediment supply volume and outline the hydrate gas reservoir in the RGC.

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