Tectonic evolution of the Atlantic rift, central sector offshore Uruguay

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Abstract

The Uruguayan Continental Margin (UCM) is considered one of the most promising frontier areas for hydrocarbon exploration in the South Atlantic. The UCM central sector, corresponding to the transitional region between the Punta del Este and Pelotas basins and where the Rio de la Plata Transfer System (RPTS) is located, exhibits outstanding characteristics such as interruption of the seaward dipping reflectors (SDRs), dislocation of magnetic and gravity anomalies and depocenters, and hyper-thinning of the continental crust. Owing to these characteristics, this sector is a key area for understanding the evolution of the margin during the Atlantic opening and evaluating the real potential of the UCM to contain hydrocarbon accumulations. This study demonstrates the results of a new subsurface mapping method using 2D and 3D seismic data in the central sector of the UCM. Structural interpretations have led to the definition of i) a NW-oriented hyperextended region located where the SDRs are interrupted, characterized by a shallow Moho (<3 km); ii) a set of NW-SE oriented transtensional faults, some of which reach the Moho, which has delineated a series of discrete grabens; and iii) a Barremian-Aptian depocenter with a rhomboidal geometry, exhibiting the greatest thickness over the hyperextended crust region. The central sector of the UCM concentrates on the extensional processes associated with the breakup of Western Gondwana, which controlled the initial phase of the Atlantic opening in this region. The sinistral transcurrent nature of the RPTS plays a crucial role in generating the transtensional stress field in an extensive regional context. This process reactivates basement-inherited structures with a general NW-SE orientation, leading to the formation of subsidence areas.

Keywords: Uruguayan Continental Margin, Atlantic rift, seismic data, magmatic crust

1. Introduction

The Uruguayan continental margin (UCM) spans approximately 207,500 km^2 and extends approximately 350 nautical miles. It is located along the southwest margin of the South Atlantic (Fig. 1), with bathymetry ranging from 20 to over 5,000 m. It lies between the latitudes 34° and 40° S and longitudes 46° and 56° W (Veroslavsky et al., 2017; Morales et al., 2017)

The UCM exhibits pronounced longitudinal and perpendicular heterogeneity, suggesting a complex geological history. The margin is defined as a divergent volcanic- type, segmented by the Río de la Plata Transfer System (RPTS) (Soto et al., 2011) in its central sector and characterized by volcano-sedimentary depocenters that exceed 7 km of sedimentary fill-in certain sectors (Franke et al., 2007; Morales et al., 2017).

Three sedimentary basins developed in the UCM (Figs. 1 and 2): i) the Punta del Este Basin; ii) the southernmost part of the Pelotas Basin, both separated by the Polonio High in shallow waters; and iii) the Oriental del Plata Basin (Fig. 2). The Punta del Este Basin, with a NW orientation (perpendicular to the margin), has been the subject of multiple hypotheses aimed at explaining its genesis, including a) an aulacogen (Yrigoyen, 1975; Introcaso and Ramos, 1984; Stoakes et al., 1991), b) transtensional tectonics associated with a dextral strike-slip shear system, with a NW-SE main orientation (Keeley and Light, 1993; Tankard et al., 1995; Franke et al., 2006), and c) two or more overlapping rift phases (Macdonald et al., 2003; Gerster et al., 2011; Pángaro and Ramos, 2012; Koopmann et al., 2014; Lovecchio et al., 2020). The Pelotas Basin, with a NE orientation (parallel to the continental margin), constitutes a typical passive margin type (Fontana, 1996; Abreu, 1998; de Santa Ana et al., 2005; Stica et al., 2014; Conti et al., 2017). The Oriental del Plata Basin, which corresponds to an oceanic basin, developed in ultradeep water (bathymetries over 4,000 m) over the transitional and oceanic crust. (de Santa Ana et al., 2005; Soto et al., 2011; Velázquez, 2021)

The central sector of the UCM (corresponding to the transitional region between the Punta del Este and Pelotas basins) exhibits outstanding characteristics, such as interruption of the seaward dipping reflectors (SDRs), dislocation of magnetic and gravity anomalies and depocenters, extreme thinning of continental crust, and the thickest portion of Aptian sedimentation (Soto et al. 2011; Marmisolle and Morales, 2022; Novo et al., 2023). These characteristics have been associated, entirely or partly, with a short-lived triple junction during the early stages of Gondwana fragmentation (Conti et al., 2021; Thompson et al., 2018), the development of a pull-apart basin in a transtensional tectonic context (Rowlands et al., 2016); and the occurrence of the RPTS (Soto et al. 2011).

This study aimed to characterize the structural configuration of the central sector of the UCM in deep and ultra-deep waters to understand its geological evolution during the initial Atlantic rift and early stages of continental drift. A comprehensive understanding of geological processes and their implications will contribute to improving regional tectonic models and a realistic assessment of the hydrocarbon potential that drives exploration efforts in the South Atlantic basins.

2. Geological framework

The origin of the UCM is linked to the West Gondwana breakup, initiated after the Middle Permian and Middle Triassic Gondwanide orogeneses, which led to the Early Cretaceous opening of the South Atlantic Ocean. Since then, the conjugate passive margins of South America and Africa have been established as a consequence of this divergent movement (e.g., Rabinowitz and LaBrecque, 1979; Gladczenko et al., 1997; Heine et al., 2013; Will and Frimmel, 2018; Lovecchio et al., 2020).

The UCM is situated south of the Walvis/Rio Grande ridge within the austral segment of the South Atlantic Ocean (Moulin et al., 2010). In this segment, continental breakup began from the south and progressed towards the north; one of its most distinctive characteristics is the presence of thick wedges of SDRs at the continental oceanic crust transition (Geoffroy, 2005; Franke et al., 2007; Stica et al., 2014; Chauvet et al., 2021).

The South Atlantic Ocean opened between the Rio de la Plata, Kalahari, and Congo cratons, leaving the Late Precambrian Pan African/Braziliano belt to the north and the Late Paleozoic Gondwanides orogenic belts to the south. (Paton et al., 2016; Heine et al., 2013; Pángaro and Ramos, 2012). The break-up axis is roughly parallel to the N-S structural trend of the Pan African/Brasiliano orogenic belts but strongly oblique to the E-W Gondwanides trend (Chauvet et al., 2021; de Wit et al., 2008)

The South Atlantic rift is classically presented as polyphase extensional rifting ranging from the Early-Middle Jurassic to the Early Cretaceous to the Hauterivian, whereas the post-rift deposits started in the Barremian (Broad et al., 2012; Cartwright et al., 2012; McMillan, 2003; Jungslager, 1999). In the Colorado basins, Lovecchio et al. (2020, 2018) also identified that a previous event occurred in the Late Triassic–Early Jurassic corresponding to extensional reactivation of Late Paleozoic–Early Triassic thrusts of the Ventana-Cape Fold Belt.

Several rifted basins with a WNW-ESE-trend oblique to the South Atlantic axis can be found along the Argentinian and Uruguayan margins (Figs. 1 and 2). These basins are related to an extensional rifting event that predates the development of the South Atlantic margin (Franke, 2013; Frizon de Lamotte et al., 2015; Lovecchio et al., 2020). An Early–Middle Jurassic age was assigned to this stage, correlating with Karoo rifting and the N–S extension that ended with the opening of the Weddell Sea (Macdonald et al., 2003; Köning and Jokat, 2006; Lovecchio et al., 2020), which was strongly controlled by pre-existing orogenic structures (Pángaro and Ramos, 2012; Franke, 2013; Lovecchio et al., 2020). The Salado and Punta del Este basins (the northernmost of these basins) are located along a 2.1 Ga suture zone embedded within the Rio de la Plata Craton (Moulin et al., 2010; Reuber et al., 2019; Mann, 2022). The undated syn-rift volcano-sedimentary units fill these half-grabens and may exceed 6 km in thickness (Stoakes et al., 1991; Tavella and Wright, 1996; Ucha et al., 2004; Morales et al., 2017; Tugend et al., 2018).

The final rifting stage occurred during the Late Jurassic–Early Cretaceous, with extensional WNW–ESE faults developed in the outer 100–200 km of the margin, parallel to the NNE-striking continental oceanic crust transition. This final rifting stage involved the emplacement of SDRs and resulted in the opening of the South Atlantic Ocean. At this stage on the Argentinian-Uruguayan conjugate margins, NE syn-rift structures were poorly developed and formed small half-grabens approximately 1 km in thickness (Franke et al., 2007c; McDermott et al., 2018; Morales et al., 2017c; Stica et al., 2014). The top of the syn-rift successions is dated to Valanginan–Hauterivian on the African margin (140–130 Ma) (Broad et al., 2012; McMillan, 2003), but the base has never been drilled.

The SDRs are segmented by a series of fracture zones (Franke et al., 2007) that may have acted as rift propagation barriers, delimiting distinct compartments, as reflected in the distribution and thickness of the post-rift sediments. Within these fracture zones, the RPTS, which segments the UCM in its central part, presents a significant sinistral offset, probably owing to inherited structural signatures from the pre-breakup features (Kress et al., 2021; Soto et al., 2011; Moulin et al., 2010).

3. Methodology and database

This study used 2D and 3D high-resolution seismic data, geological and geophysical information from the three exploratory wells drilled in the UCM (Fig. 2), and gravity and magnetic regional data.

The information provided by the wells was limited because the Lobo x-1 and Gaviotín x-1 wells are located very close to the basin border in proximal depositional systems. Therefore, the drilled Mesozoic sedimentary interval comprised continental coarse-grained clastic lithologies with almost no fossil content. Biostratigraphic information was restricted to sedimentary intervals younger than the Campanian, except for the last 130 m of the Gaviotin x-1 well, corresponding to Paleozoic pre-rift stage units. The Raya x-1 well only reached the Eocene-Oligocene boundary (Morales et al., 2020). Therefore, the greatest contribution to understanding the UCM for this type of study was based on the interpretation of seismic data, allowing a better understanding of its stratigraphic architecture.

The 3D seismic data covered an area of approximately 13,300 km^2 on the UCM slope. It was acquired from Polarcus (2012–2014) and processed using PGS Geophysical (2013–2014). The acquisition parameters corresponded to a 10 × 6,000 m @ 9 +/- 1 m streamer length and a 125 m separation between streamers. The 2D seismic data (lines UY 4200, UY4300, UY 9700, and UY 9600) were originally acquired and processed by ION for the Uruguay Span campaign. Notably, long streamers were used to achieve deep penetration for this acquisition, thus identifying the Mohorovicic discontinuity (Moho).

All seismic data were interpreted in depth using The Kingdom Suite software (Geophysics and Geology modules, 2023) and tied using a synthetic seismogram constrained from the sonic log and check shot data of the Gaviotín x-1 well. For regional correlation, the key horizons and ages suggested by Hinz et al. (1999) and Morales et al. (2017), among other authors, were used based on regional assumptions for the UCM.

The following activities represented the workflow: a) fault mapping, b) interpretation of key seismic horizons, and c) assembly of structural contour and isopach maps. This included the manual mapping of horizons extending through arbitrary lines (composed of dip-strike lines). Flattening techniques were applied to improve the interpretation of faults and their relationships with the sequence morphology. The key horizons tied to the available well data served as the foundation for both the stratigraphic and structural interpretations, allowing the identification of discontinuities. The tectonic-sedimentary model was reinforced by interpreting large faults that could be identified in several seismic sections, discarding isolated and minor faults.

4. Results

4.1. Seismic interpretation

In the central sector of the UCM, four key horizons were interpreted using the 2D and 3D seismic data: the Mohorovicic discontinuity (Moho), top basement/base SDRs, top rift/tope SDRs, and the top of the first post-rift sequence. The four horizons corresponded to regional unconformities, and the reflectors between them corresponded to the lithologies of the basement, SDRs, or depositional sequences. Geological interpretation was based on the seismic characteristics of the reflector (Fig. 3 and 4).

The Moho discontinuity was identified only in the 2D seismic lines from the ION GXT- Uruguay Span campaign. This corresponded to discontinuous reflectors with high acoustic impedance contrast. In the central region of the study area, the Moho showed a sudden inflection in both the strike and dip directions, forming a hyperextended crust that reached a thickness of 3 km or less. Towards the proximal region of the study area, the crust had the greatest thickness (>20 km), whereas in the distal region, the crust exhibited a constant thickness of 10 km on average (Figs. 3 and 4).

In the study area, the top basement was a composite horizon that included the base of the SDRs and represented the top of the pre-rift (Figs. 3 and 4). This horizon constituted an angular unconformity between the rift filling and the pre-rift basement and was characterized by a continuous reflector with high acoustic impedance. Within the central sector, which was characterized by a hyperextended crust and the absence of SDRs, the basement reflector characteristics suggest volcanic lithologies indicative of a magmatic crust. Several conical structures, interpreted as volcanoes, were identified.

The rift phase, characterized by extensional tectonics, developed over continental and magmatic crusts and was marked by the presence of normal faults responsible for the mechanical subsidence of the basin. In the study area, the top of the syn-rift was a diachronic surface defined by the truncation of the underlying reflectors (only identified in the central sector) and by the top of the SDRs. In the SDRs gap area, the rift sequence was characterized at the base by subparallel reflectors with high acoustic impedance, interpreted as volcanic and volcaniclastic lithologies, and towards the top by reflectors with variable impedance and continuity, interpreted as sedimentary units. The SDRs were identified as wedges of arcuate reflectors dipping seaward that developed in the southwestern and northeastern sectors of the study area. The SDR reflectors were divergent and characterized by a high acoustic impedance and a diffuse baseline (Figs. 3 and 4).

Half of the graben structures were identified in restricted areas (Figs 3 and 4). The seismic interpretation enables the definition of a series of continuous reflectors that overlap over the flexural side. Towards the top of the sequence, these reflectors were truncated, delineating an unconformity. This erosive surface, characterized by continuous and high-impedance reflectors, was mapped as an intermediate horizon (Hi) corresponding to the top of the syn-rift phase.

The first post-rift sequence was identified as overlapping over the SDR wedges, hyperextended crust, and oceanic crust. This sequence was characterized by a homogeneous package of parallel and subparallel reflectors, predominantly with low and intermediate acoustic impedance contrasts (Fig. 3 and 4). The top of this post-rift sequence corresponded to a continuous reflector with high and intermediate acoustic impedance.

4.2. Structural arrangement

The study area is extremely faulted in a complex arrangement (Fig. 5), with a general NW fault set orientation. Figure 5 presents the crustal thickness of the study area obtained from the 2D seismic data of the ION GXT Uruguay Span campaign.

An NW-oriented hyperextended region was identified where the SDRs were interrupted. The hyperextended region spans over 90 km, with a width of 30 km at its northwestern extremity and narrowing down to 10 km in ultradeep waters towards the southeastern region. It is characterized by a shallow Moho, with a cortical thickness ranging between 3 and 4.5 km, notably in the central area, reaching less than 3 km (Figs. 3, 4, and 5). The hyperextended region is represented by a magmatic crust controlled by two major faults, identified as F1 and F2. These NW-oriented faults are very deep and reach the Moho (Figs 3 and 4).

The WNW-oriented F1 fault, located in the southern region of the study area, experienced a small change in orientation to W-E towards ultra-deep waters and proximal areas, and its reactivation was identified during the Cretaceous (Fig. 3 and 4). Throughout its path, F1 is curvilinear, dipping into the ENE, exhibiting significant changes in penetration depth, and reaching the Moho in regions where significant crustal stretching was identified (Figs. 3, 4, and 5). Along this fault, which limits the Punta del Este SDR wedge, a series of conical figures associated with volcanoes were identified.

The F2 fault is in the NE sector of the study area and exhibits a NW orientation dipping into the WSW. In ultradeep waters, F2 experienced a slight change in orientation to E-W, similar to F1.

In addition to the prominent F1 and F2 faults, a notable concentration of NW-oriented faults is observed between them. In proximal areas, fault systems exhibit greater continuity than faults identified in ultra-deep water. The SDR wedges of the Punta del Este, present in the study area, are strongly affected by NW-oriented faults, making their limit towards the central sector difficult to map. Meanwhile, the Pelotas SDR wedges showed a lower frequency of faults; however, two distinct fault subgroups were observed. One of them, located in the distal part, has a preferential NW orientation, whereas the other, mainly located towards the proximal region, has a NE orientation.

Generally, the set of NW faults describes a curvilinear trajectory, exhibiting changes in the penetration depth and, in some cases, in the dip direction (Figs 3, 4, and 5). In ultra-deep waters, between the F1 and F2 major faults, the fault system presents a slight rotation to the W-E orientation, drawing a ponytail.

The faults identified near the southern end of the Polonio High are extensional and NE-oriented, corresponding to Atlantic rifting.

The structural analysis identified several conical features associated with volcanic structures (Fig. 5). These volcanoes were observed with dip changes in faults and were associated with mainly NW-oriented highs (Figs. 3, 4, and 5).

4.3. Polonio depocenter

A rhomboidal depocenter was identified in the region of the hyperextended crust where the SDR was interrupted (Fig. 6). This subsiding area developed across the central sector, exhibited a main E-W orientation controlled by a set of NW-trending normal faults and expanded towards the east in ultradeep water (Fig. 6). The southern limit of the depocenter was defined by F1, a major deep fault-oriented WNW, as defined previously. The northern limit is the southern end of the Polonio High. The structure's closure was observed towards the ultra-deep waters. Although the database did not cover the area towards deeper waters, in the 2D seismic lines, it was observed that the depocenter closes over a high region, as can be inferred from Figs. 3 and 4.

Internally, the depocenter exhibits horst and graben structures controlled by a complex NW structural arrangement (Figs. 3, 4, and 6). Many of these grabens are exceptionally deep, as indicated by the seismic lines oriented parallel to the margin.

This subsidence area, strongly controlled by NW faults, accommodates the largest thicknesses for the first post-rift sequence in the entire UCM. In Figs. 3 and 4, in contrast to the SDRs and oceanic crust, where this sequence has a constant thickness of 800 m; in the Polonio depocenter, it develops thicknesses that exceed 2,000 m, represented in the Barremian–Aptian isopach map in dark blue colors.

5. Discussion

The NW-oriented faults identified in the central sector of the UCM were situated over the pre-existing structural lineaments inherited from the basement, as shown by the hyperextended crust. An ancient lineament through offshore Uruguay was identified (Mann, 2022; Pángaro and Ramos, 2012; Moulin et al., 2010) and could become a focus for crustal thinning and extension, being reactivated in the transtensional context of the STRP. Therefore, NW faults, such as those identified in the Punta del Este SDRs, can be interpreted as synthetic faults. In contrast, the NE-oriented faults, including those that affect the SDRs of Pelotas, can be interpreted as antithetical faults (Fig. 7). As the faults are curvilinear, they define the horsts and grabens in a transcurrent regimen (Fig. 7).

The NW fault system played a key role in defining the formation of a rhomboidal basin (Fig. 7), referred to as the Polonio Depocenter, where the fault system considerably controlled the first marine ingression flood. The early phase of the post-rift corresponds to the transgressive systems tract characterized by basal marine onlap and a retrogradational stacking pattern (Morales et al., 2017) and is correlated with the seismic sequence mapped offshore in Uruguay (Grassmann et al., 2011). The top of this early sequence corresponds to the AR2 horizon mapped by (Hinz et al., 1999) and with the first marine transgression of offshore Argentina (Kress et al., 2021), suggesting an Aptian age for this sequence.

The subsidence area of the Polonio Depocenter is probably the result of mechanical and thermal subsidence, where the marine sequence first filled the lower areas and subsequently onlapped the internal highs and the SDRs, allowing the largest Barremian-Aptian thickness (>2,500 m) documented for the Austral Segment of the Atlantic Ocean.

The complex structural arrangement with curvilinear path faults, dip changes, and ponytails, such as terminations, suggests the action of a transtensional regime, as proposed by Rowlands et al. (2016) and Soto et al. (2011) for offshore Uruguay. In the southern onshore region of Uruguay, a comparable tectonic regime was described for the same period. The Santa Lucía-Aiguá Merín (SaLAM) corridor (Rossello et al., 1999), which triggered the origin of the Santa Lucía and Laguna Merín onshore rift basins during the Mesozoic, showing an initial extensional phase and later a transcurrent phase, is evidence of strike-slip movements in the region. The Santa Rosa High in the Santa Lucía Basin also increased during the Aptian period (Rossello et al., 2000; Veroslavsky, 1999). The uplift of the external highs in the Punta del Este Basin (Morales et al., 2020) is associated with the initial phases of the Andean Orogeny.

The geological model shown in Figure 8 illustrates a snapshot of the late Barremian-Aptian period, presenting the role of the RPTS during the initial Barremian-Aptian transgression, which flooded the Polonio Depocenter over a hyperextended and highly faulted crust. The first post-rift sequence overlapped the faulted SDR wedges and internal highs. The volcanic features identified in the central region were controlled by NW-oriented faults during the early development of the Polonio Depocenter.

6. Conclusion

This study presented the results of novel subsurface mapping using 2D and 3D seismic data.

The study area, in the central sector of the UCM, served as a focal area for extensional processes linked to the breakup of Western Gondwana, thereby influencing the initial phase of the Atlantic opening within this region. Soto et al. (2011) had difficulty comprehending this central region because of the limited seismic coverage at that time.

The structural interpretation elucidated a NW-oriented hyperextended magmatic crust, delineating the gap between the SDRs wedges, which exhibits a shallow Moho (< 3 km).

Furthermore, a series of NW-oriented transtensional faults were identified, some of which reached the Moho. These faults play a pivotal role in crustal stretching, affecting SDRs and outlining a distinct depocenter (Polonio Depocenter) comprising an internal arrangement of horsts and grabens. The boundaries of this depocenter, delineated by two major NW-W oriented faults that reach the Moho, define a rhomboidal depression that extends into ultra-deep waters, thereby exerting depositional control over the first Aptian marine ingression.

Within an extensional regional context, the sinistral transcurrent nature of the RPTS generates a transtensional stress field that causes the reactivation of structures inherited from the basement with a general NW-SE orientation.

Finally, although this study focused on the structural analysis of the central offshore sector of Uruguay, a similar analysis of the deeper sector remains pending. In this regard, this study had limitations in characterizing the easternmost part, towards deeper waters, of the rhomboidal depocenter due to the absence of 3D seismic data and the scarcity of 2D seismic data in that sector. Likewise, it would be beneficial to continue with a more detailed characterization of the magmatic crust described, as well as a more comprehensive analysis of the structural control exerted during the initial post-rift sequence.

Glossary

ANCAP – Administración Nacional de Combustibles, Alcohol y Portland

CONICET – Consejo Nacional de Investigaciones Científicas y Técnicas

FZ – Fracture Zone

MEC – Ministerio de Educación y Cultura

PEDECIBA – Programa de Desarrollo de Ciencias Básicas

RPTS – Rio de la Plata Transfer System

SaLAM – Santa Lucía – Aiguá - Merín

SDR – Seaward Deeping Reflector

UCM – Uruguayan Continental Margin

UDELAR – Universidad de la República

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest**.**

Acknowledgements

The authors would like to thank ANCAP to provided data, IHS for granting a Kingdom software license to the Instituto de Ciencias Geológicas of Universidad de la República.

Author contributions

Josefina Marmisolle: conceptualization, Methodology, Investigation, Writing, Visualization. **Ethel Morales:** Methodology, Investigation, Writing. **Eduardo Rossello:** Investigation, Writing, Visualization. **Matías Soto:** Investigation. **Javier Hernández-Molina:** investigation.

Funding

This study contributes to the framework of the Agencia Nacional de Investigación e Innovación (ANII) Project FSE 2017-1447979.

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