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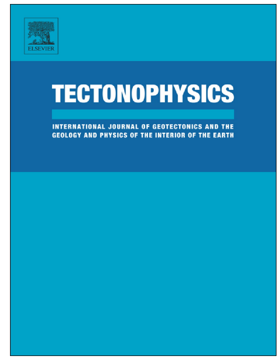

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Tectonic evolution of the Atlantic rift, central sector offshore Uruguay

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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. The proposed new tectonic model will contribute to the knowledge of the hydrocarbon potential of the UCM.

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., 2017a).

The UCM displays significant heterogeneity both longitudinal and perpendicular as evidenced by its structural and stratigraphical variations (e.g. Soto et al., 2011; Morales et al., 2017a; Kirby et al., 2024), probably related to a Precambrian basement with a complex geotectonic evolution, marked by intricate geological processes that have shaped its current configuration (Hueck et al., 2018; Oyhantçabal et al., 2018). Defined as a divergent volcanic- type margin, the UCM is segmented by the Río de la Plata Transfer System (RPTS), a major NW-SE fault zone system located offshore-southern Uruguay (Soto et al. 2011; Conti et al., 2017; Morales et al., 2017a; Rossello et al., 2018; Reuber et al., 2024), which delineates distinct volcanic-sedimentary depocenters. In some areas, these depocenters exceed 7 km in thickness, illustrating the region's dynamic depositional history (Franke et al., 2007; Morales et al., 2017a).

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 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 (Thompson et al., 2018; Conti et al., 2021), 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 aims 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 southern segment of 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. The opening of the austral South Atlantic during the Early Cretaceous coincides with significant magmatic activity, evidenced by extensive onshore magmatism which includes conjugate dyke swarms (Almeida et al., 2013; Will et al., 2016; McMaster et al., 2019, Chauvet et al., 2021), as well as a series of intrusive centers documented in onshore Namibia (Corner, 2000; Corner et al., 2002, Chauvet et al., 2021) and the Paraná and Etendeka continental flood basalts (Peate et al., 1992; Turner et al., 1994, Chauvet et al., 2021). The offshore magmatic counterpart is represented by thick wedges of SDRs (Seaward Dipping Reflectors) located at the continental oceanic transition crust (Geoffroy, 2005; Franke et al., 2007; Stica et al., 2014; Chauvet et al., 2021) and corresponding with high frequency seismic reflector packages, (Wickens and McLachlan, 1990; Gladczenko et al., 1997, 1998; Hinz et al., 1999; Franke et al., 2007; Koopmann et al., 2014; Soto et al., 2011; Stica et al., 2014; Gordon et al., 2017) See figs 1 and 2.

The breakup 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 (Pángaro and Ramos, 2012; Heine et al., 2013; Paton et al., 2016). 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 (de Wit et al., 2008; Kress et al., 2021; Chauvet et al., 2021).

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 (Jungslager, 1999; McMillan, 2003; Broad et al., 2012; Cartwright et al., 2012).

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; Chauvet et al., 2021). 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 that fill these halfgrabens may exceed 6 km in thickness (Stoakes et al., 1991; Tavella and Wright, 1996; Ucha et al., 2004; Morales et al., 2017a; Tugend et al., 2018). In the Colorado basins, Pángaro et al., (2016) and Lovecchio et al. (2018, 2020) 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.

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 southern segment of the South Atlantic Ocean (Franke et al., 2010; Gordon and Mohriak, 2015; McDermott et al., 2018). 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., 2007; Stica et al., 2014; Morales et al., 2017b; McDermott et al., 2018). The top of the syn-rift successions is dated to Valanginian–Hauterivian on the African margin (140–130 Ma) (McMillan, 2003; Broad et al., 2012), 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 (Moulin et al., 2010; Soto et al., 2011; Kress et al., 2021; Chauvet et al., 2021).

According to the geological time scale presenting by Gradstein et al., (2012) as well the identification of magnetic anomalies associated with the oceanic crust domain, the drift of conjugate plates began approximately 135 Ma (Late Valanginian/Early Hauterivian) north of the Agulhas – Falkland Fracture Zone (AFFZ), as marked by the M11 anomaly (Hall et al., 2018) or M10r anomaly (Collier et al., 2017; Chauvet et al., 2021). South of the Rio Grande Rise / Walvis Ridges, the drift initiated around 129 Ma (M2 anomaly), reflecting a 6 My northward propagation along a segment approximately 2500 km in length (Franke, 2013; Collier et al., 2017; Chauvet et al., 2021) (Fig. 1). The magnetic anomalies map presented by Moulin et al. (2010) indicates a pronounced landward offset of the M4 anomaly north of the RPTS. South of the RPTS, M4 anomaly marks the seaward boundary of the SDR. This observation suggests that the SDR north of the RPTS might be younger, potentially due to a significant delay in rift propagation across the transfer zone (Franke et al., 2007; Stica et al., 2014; Chauvet et al., 2021)

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. Biostratigraphy information was restricted to sedimentary intervals younger than the Campanian, except for the last 130 m of the Gaviotín x-1 well, corresponding to Paleozoic pre-rift stage units (Daners et al., 2003).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 4300 ~380.5 km, UY4500 ~ 351.6 Km, UY 9600 ~ 329.9 km, and UY 9700 ~325.2 Km) correspond to ION GXT- UruguaySpan campaign. in which, 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. (2017a), 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 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/top 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 reflectors (Figs. 3, 4 and 5).

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), in contrast to the distal region where the crust exhibited a constant thickness of 10 km on average (Figs. 3, 4, 5 and 6).

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, 4, 5 and 6). 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, 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, with internal chaotic reflectors arrangement, interpreted as volcanoes, were identified (Fig. 6).

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. 3,4, 5 and 6). Associated with the base of the rift sequence, conical features with high acoustic impedance are identified and interpreted as volcanoes. These features display variable base widths, most commonly ranging from 700 to 1000 m and occasionally, the base exceeds 1500 m width (Fig. 6). These features correspond to structural highs and are associated, mainly, with NW oriented faults, and the seismic evidence suggests that these volcanoes remained active long after oceanic crust was formed during the early Barremian-Aptian deposition, except for the volcano associated with F1, which exceeds the top horizon of the first post-rift sequence shown in detail in Figure 6.

Half of the graben structures were identified in restricted areas (Figs. 3, 4, 5 and 6). 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, 4, 5 and 6). 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. 7), with a general NW fault set orientation. Figure 7 presents the crustal thickness of the study area obtained from the 2D seismic data of the ION GXT- UruguaySpan 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, 5 and 6). 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, 4, 5 and 6).

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 regions, and its reactivation was identified during the Cretaceous (Fig. 3,4, 5 and 6). 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 with this fault, which limits the Punta del Este SDR wedge, a conical feature interpreted as volcano was identified. This volcano, associated with F1, remained active during the Barremian – Aptian transgression. (Fig. 6).

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. 6). These volcanoes were observed with dip changes in faults and were associated with mainly NW oriented highs.

4.3 Polonio depocenter

A rhomboidal depocenter was identified in the region of the hyperextended crust where the SDR was interrupted (Fig. 8). 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 (Figs. 7 and 8). 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, 4 and 5.

Internally, the depocenter exhibits horst and graben structures controlled by a complex NW structural arrangement (Figs. 3, 4, 5 and 6). Many of these grabens are exceptionally deep (approximately 2000 m thick), as indicated by the seismic lines oriented parallel to the margin (Figs 3, 4 and 6).

This subsidence area, strongly controlled by NW faults, accommodates the largest thickness for the first post-rift sequence in the entire UCM. In Figs. 3,4, 5 and 6) 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 analyzed seismic data show that the central sector of the offshore Uruguay, in deep waters, is characterized by a complex arrangement of NW-oriented faults resulting for the interplay of strain along pre-existing lineaments inherited from the basement.

The complex evolutionary history of the Uruguayan basement has been documented by several authors who highlight the amalgamation of cratons and blocks from the Neoproterozoic to the Cambrian, through shear zones and their subsequent reactivations (Sánchez et al., 2010; Oyhantçabal et al., 2011; Pángaro and Ramos, 2012; Oriolo et al., 2016, 2018; Hueck, 2018).

In that sense, an ancient NW lineament through offshore Uruguay has been described previously by

Moulin et al., 2010; Pángaro and Ramos, 2012; Rowlands, et al., 2016; Mann, 2022, among others, could become a focus for the faults reactivation into the transtensional context of the RPTS resulting in a faulted, magmatic and hyperextended crust (Unternehr et al. 2010).

The crustal thickness map reveals the region of the greatest crustal thinning coinciding with the SDR gap, the location of the RPTS, and the development of the rhomboidal depocenter. Also, at this location the LMA (Large Magnetic Anomaly by Moulin et al., 2010, which corresponds to the G anomaly of Rabinowitz and LaBrecque 1979), and the M4 anomaly according to Moulin et al. (2010) appear interrupted with a sinistral offset (Soto et al., 2011; Kress et al., 2021; Chauvet et al., 2021).

The Polonio depocenter develops through the RPTS in an essentially transcurrent tectonic setting, with fault surfaces contributing to translational subvertical displacement and associated with a subordinate Riedel fracture system (Fig. 9). As a result, the horizontal extension associated with the depocenter opening is not particularly significant; instead, the creation of space through the translational displacement component plays a more dominant role. Consequently, it is plausible that both the depositional volume within the Polonio depocenter and the thinning of the underlying crust are primarily the result of extension. The subvertical orientation of the bounding faults aligns with transcurrent faulting, as the maximum principal horizontal stress ($\sigma 1$) and the resulting fault surfaces consistently maintain an angle of less than 45°, typically ranging from 30° to 40°, in accordance with Anderson's Law (Anderson, 1905; Healy et al., 2012).

Shear zones, like this, evolve through the accumulation of strain and displacement, as they connect structural features such as fractures in both length and width, leading to the development of shear networks within the zone (Sylvester, 1988; Fossen and Cavalcante, 2017). Initially introduced in a strike-slip shear zone by Riedel (1929), Riedel fractures are influenced by multiple factors such as lithology, rheology, and the stress regime, all of which govern the characteristics of the damage zone (Kachanov, 1982; Kim et al., 2004; Misra et al., 2015). The resulting structure is further shaped by the type of shear zone involved, whether brittle, semi-brittle, brittle-ductile, ductile, simple shear, or transpression, among others. Moreover, pre-existing fractures can significantly influence the trajectories of newly formed fractures within the shear zones (Chabet, 2019).

The crustal thinning and the geological characterization of the transition to oceanic crust are fundamental for predicting the deformation history and the different final architectures of the divergent margins (Unternehr et al., 2010; Doré and Lundin, 2015). In Unternehr et al., 2010, the authors mention that the distribution of upper, middle, and lower crustal rocks, as well as the upper and lower lithospheric mantle, controls the thermal and rheological evolution of extensional margins.

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, evidencing of strike-slip movements in the region. The Santa Rosa High in the Santa Lucía Basin also uplifted during the Aptian period (Rossello et al., 2000; Veroslavsky, 1999) as well the uplift of external highs in the Punta del Este Basin (Morales et al., 2020) that have been reported associated with the initial phases of the Andean Orogeny.

The NW fault system played a key role in defining the formation of a rhomboidal basin, referred to as the Polonio Depocenter (Fig. 9), where the fault system considerably controlled the first marine ingression flood. Fracture zones underwent varying strain due to the changing stress regimes that evolved over time with the northward propagation of oceanic crust during the austral Atlantic rift. Seismic data across these fracture zones reveal transtensional and transpressive features that remain active well beyond the onset of oceanic crustal spreading. The cooling of magma beneath these fracture zones played a key role in early subsidence, leading to the formation of restricted depocenters during the initial stages of marine transgression (Kress et al. 2021).

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., 2017b) 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 Argentina offshore (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 geological evolutive model shown in Fig. 10 proposes four (4) stages with the aim of explaining the structural framework of the central sector of the UCM, where the RPTS was emplaced, and the role played in the genesis of the Polonio Depocenter. As was mentioned before, prior to the Atlantic rifting, the region was dominated by a continental crust displaying heterogeneity in both dip and strike directions (Moulin et al., 2010; Pángaro and Ramos, 2012; Rowlands, et al., 2016; Mann, 2022). This crust featured inherited basement lineaments from the Gondwanide (NW-oriented) and Pan-African (NE-oriented) orogenies. During the first extension phase of the Atlantic rift, in the Late Jurassic, the NE extension resulted in the formation of NW-oriented grabens (e.g. Punta del Este Basin) which overlaid pre-existing inherited basement lineaments (Franke, 2013; Frizon de Lamotte et al., 2015; Lovecchio et al., 2020; Chauvet et al., 2021). After that, during the NW-extension phase of the Atlantic rift, (Early Cretaceous), enabled the emplacement of the SDRs offshore Uruguay (Franke et al., 2010; Gordon and Mohriak, 2015; McDermott et al., 2018). This phase also marked the initial development of the RPTS, which aligned with the NW path of inherited basement lineaments (Moulin et al., 2010; Soto et al., 2011; Rowlands et al., 2016; Kress, et al., 2021; Chauvet et al., 2021). Then, during Barremian-Aptian, the region underwent maximum transtensional stress, leading to the emplacement of the RPTS and the genesis of the Polonio Depocenter. This transtensional phase was crucial in the formation of the depocenter, which was flooded by the Barremian Aptian transgression, which flooded the depocenter over a hyperextended, magmatic and highly faulted crust. This first post-rift sequence overlapped the faulted SDR wedges and internal highs.

The marine transgression in this region initially progressed through lower, restricted areas associated with the fracture zones, which are interpreted as sites of crustal thinning and magmatic package sourcing during active extension, followed by subsidence due to concomitant cooling similarly to described by Kress et al., 2021 for the north Argentinian margin. These areas, with locally restricted deep circulation, served as environments where marine organic matter could be preserved. This is particularly significant for hydrocarbon exploration in the Uruguayan margin, as the thickest marine transgression likely occurred in these regions, enhancing the potential for organic matter accumulation and preservation. In a similar way that occurs in the conjugated Orange Basin, where the oldest source rock intervals, dated to the Barremian-Early Aptian, correspond to an age not found in the shallower areas of the basin. It is highly likely that these source rock intervals (Barremian-Aptian) are closely associated with areas of greater subsidence, such as fault zones, making these regions strategic targets for future hydrocarbon exploration (McMillan 2003).

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 (Atlantic rift), 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. In other words, the Polonio Depocenter is consequence of the transtensional tectonics associated with a sinistral strike-slip shear system (RPTS).

From an exploration point of view this region with greater subsidence, such as fault zones, making it strategic targets for future hydrocarbon exploration, regarding the recently successful of the Namibia´s margin associated with Cretaceous plays.

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
EEZ – Exclusive Economic Zone
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**.**

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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.

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Figure captions

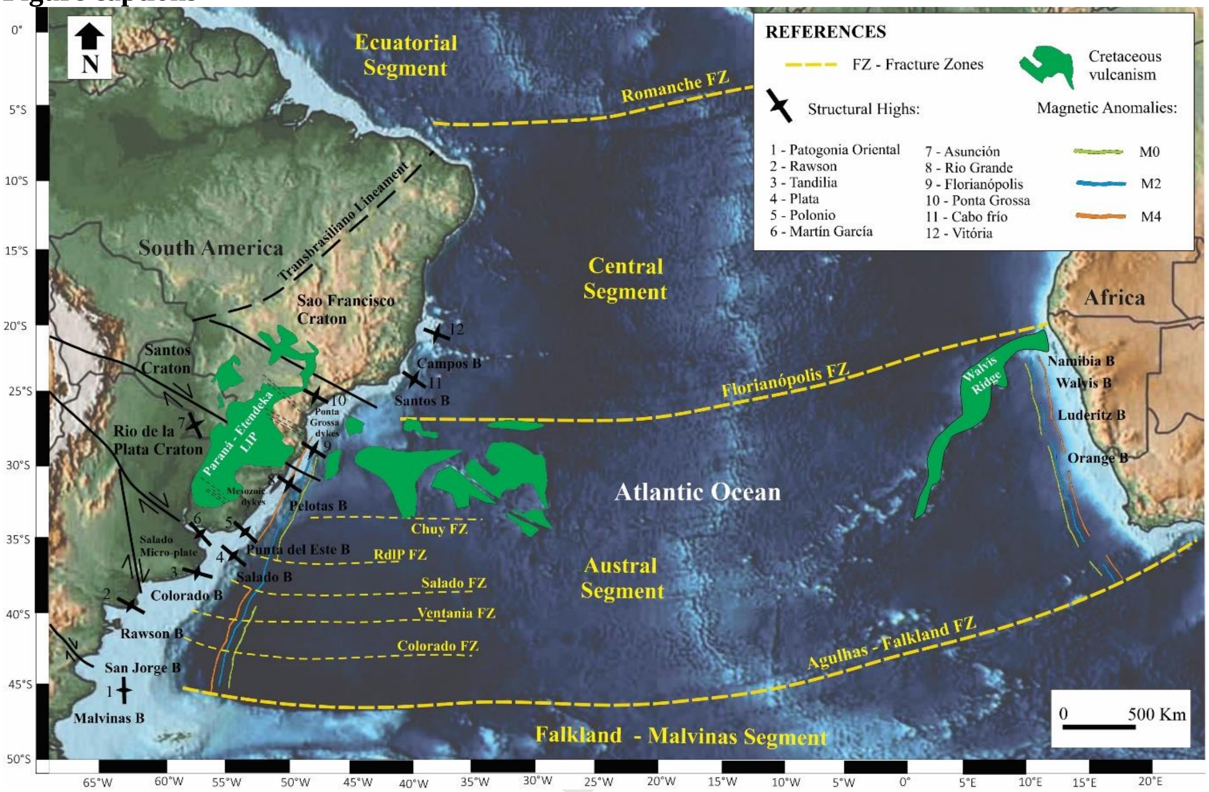

Fig. 1. South Atlantic Ocean subdivision, modified from Franke et al., (2007); Moulin et al., (2010); Soto et al., (2011); Kress et al., (2021); Magmatic anomalies from Moulin et al., (2010) and Chauvet et al., (2021) are added, as well as the structural highs and main Mesozoic magmatism. The base map was obtained from the Scotese Paleo Map Project, (2014).

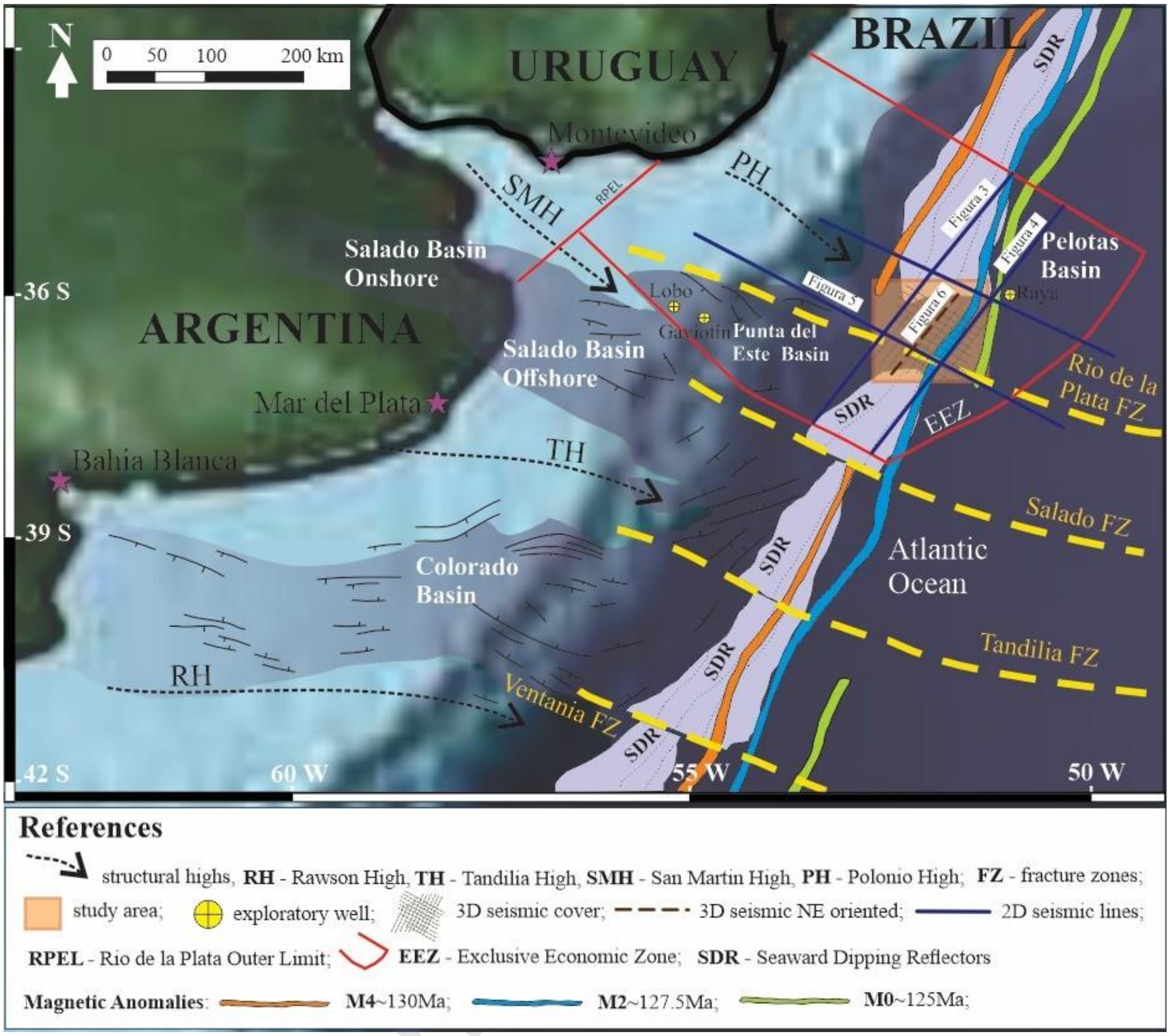

Fig. 2. Northeast Argentinian and Uruguayan continental margins map overlain by basins and the main structural setting of the region modified from Soto et al. (2011), Morales et al. (2017a,b), and Lovecchio et al. (2018). It shows the location of the study area (orange box), and the database used in this study. The location of the 2D seismic lines of Figures 3,4 and 5 is also shown, as well as the location of the 3D seismic line (Figure 6). The Magnetic anomalies are added from Moulin et al., (2010) and Chauvet et al., (2021) The base map for this image was obtained from the Scotese Paleo Map Project, (2014)

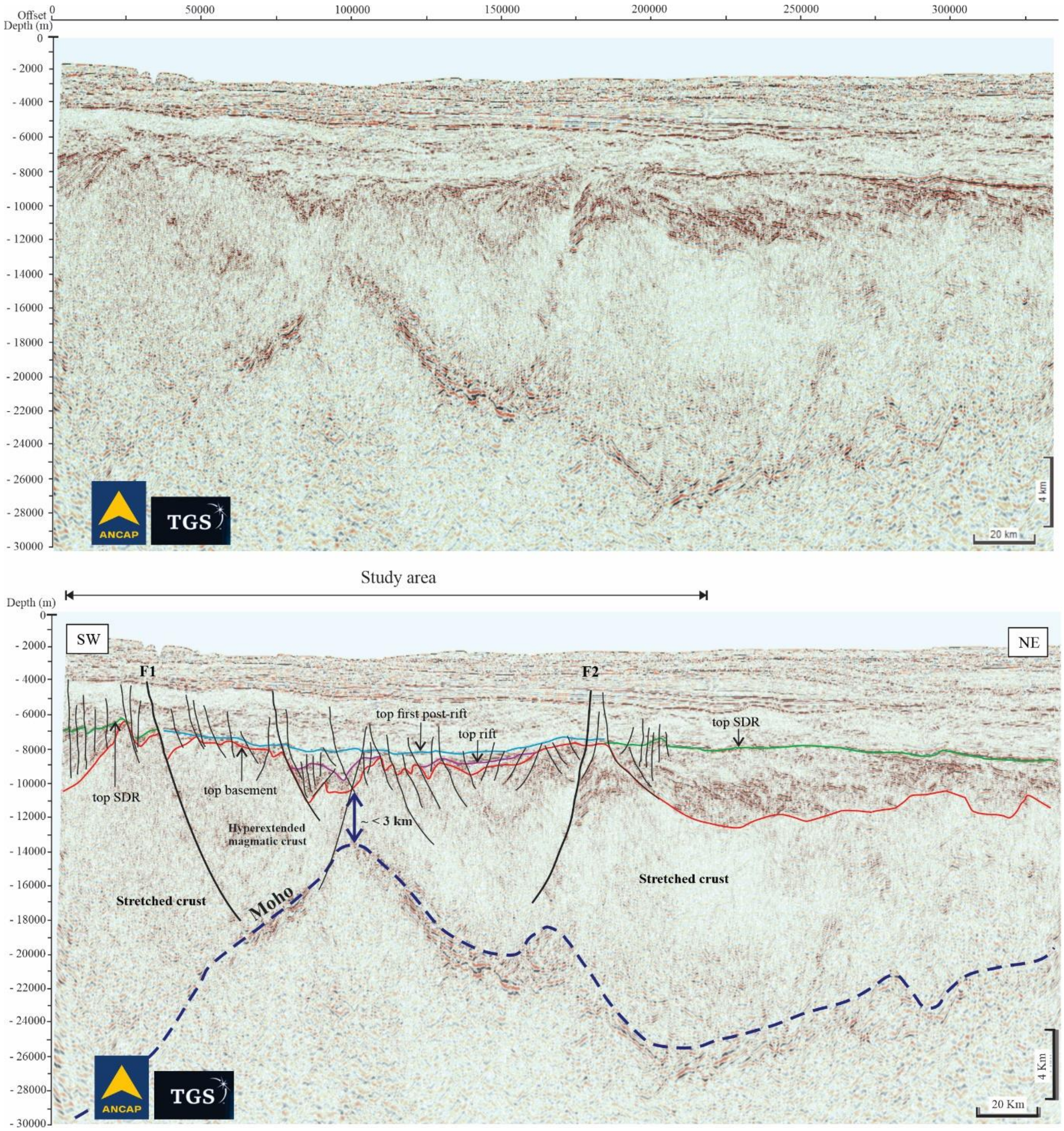

Fig. 3. Interpreted 2D strike seismic line UR12-9600, showing the structural setting, the hyperextended crust, the shallowing Moho in the study area (dashed blue line), and interpreted key horizon: top basement/base SDRs (red horizon), top rift/top SDRs (purple/green horizons), top first post-rift sequence (light blue horizon). The faults are shown in black lines, and F1 y F2 are pointed. See the location in Figure 2.

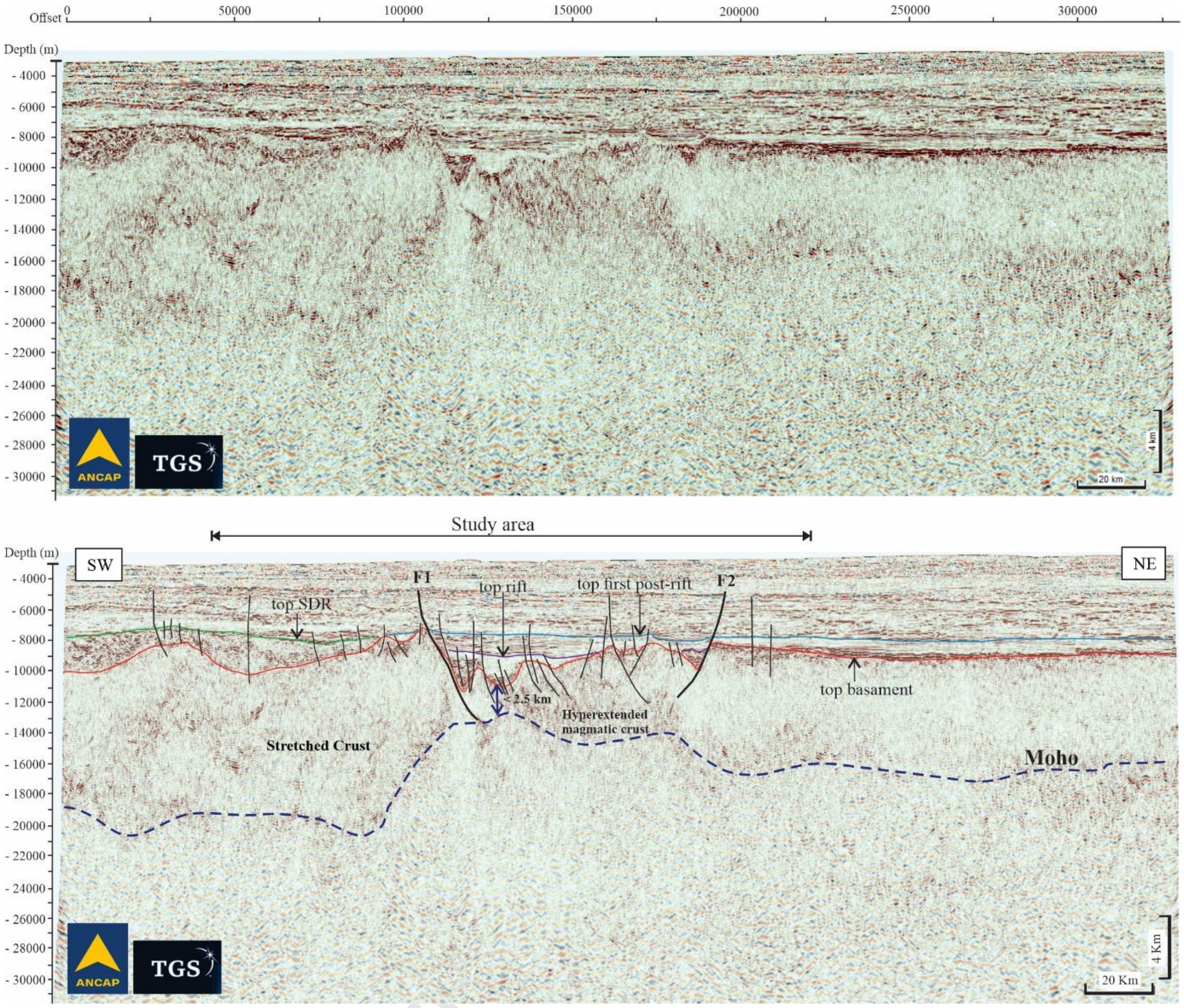

Fig. 4. Interpreted 2D strike seismic line UR12-9700, showing the structural complex arrangement of the study area, and the key horizons: Moho in the study area (dashed blue line), and interpreted key horizon: top basement/base SDRs (red horizon), top rift/top SDRs (purple/green horizons), top first post-rift sequence (light blue horizon). The faults are shown in black lines, and F1 y F2 are pointed. See the location in Figure 2.

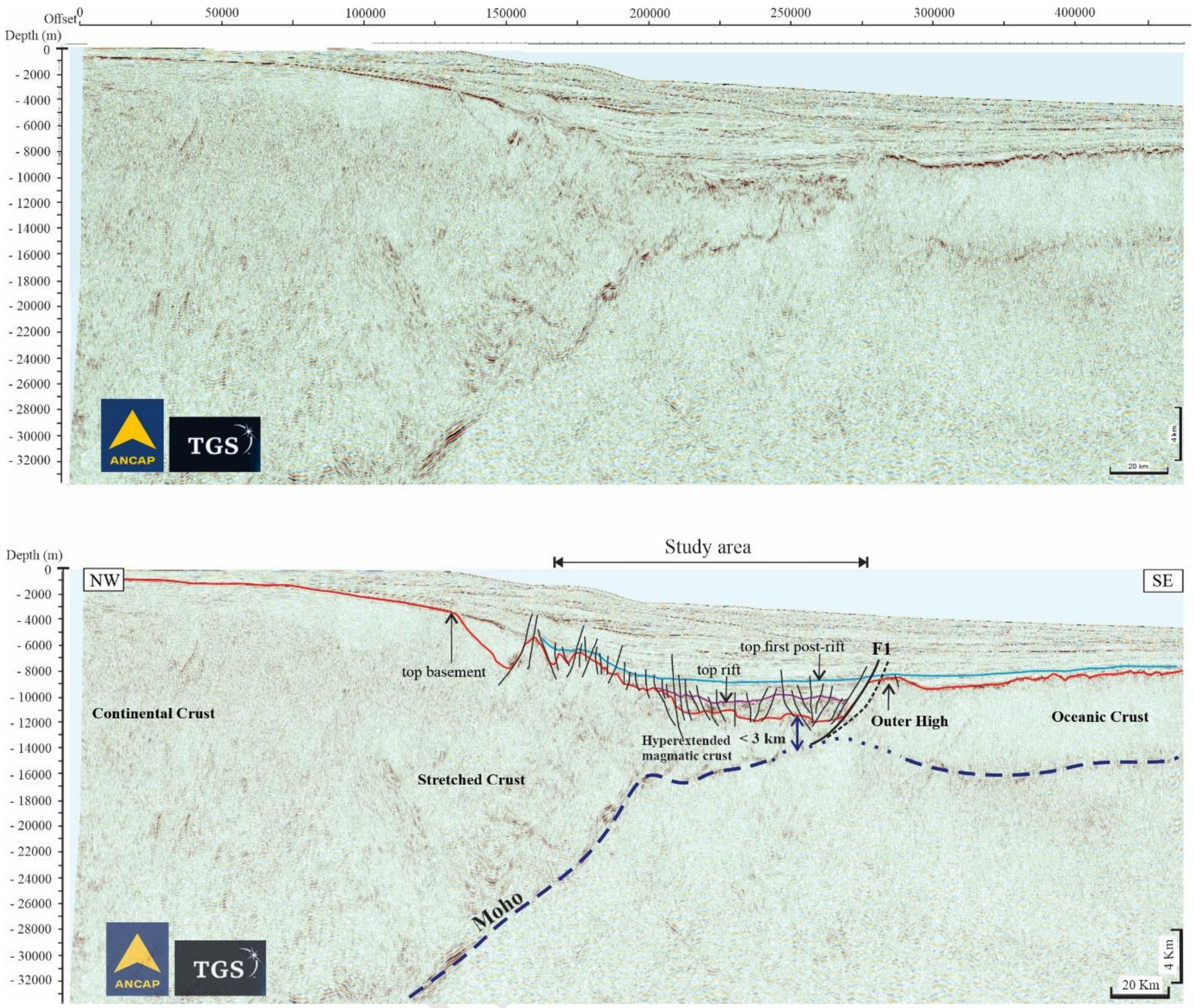

Fig. 5. Interpreted 2D dip seismic line UR12 – 4300, showing the structural setting, stretched crust, the hyperextended magmatic crust, the shallowing Moho in the study area (dashed blue line), and interpreted key horizon: top basement (red horizon), top rift (purple horizon), top first post-rift sequence (light blue horizon). The faults are shown in black lines and ended E-W oriented F1 towards ultradeep water is pointed. See the location in Figure 2.

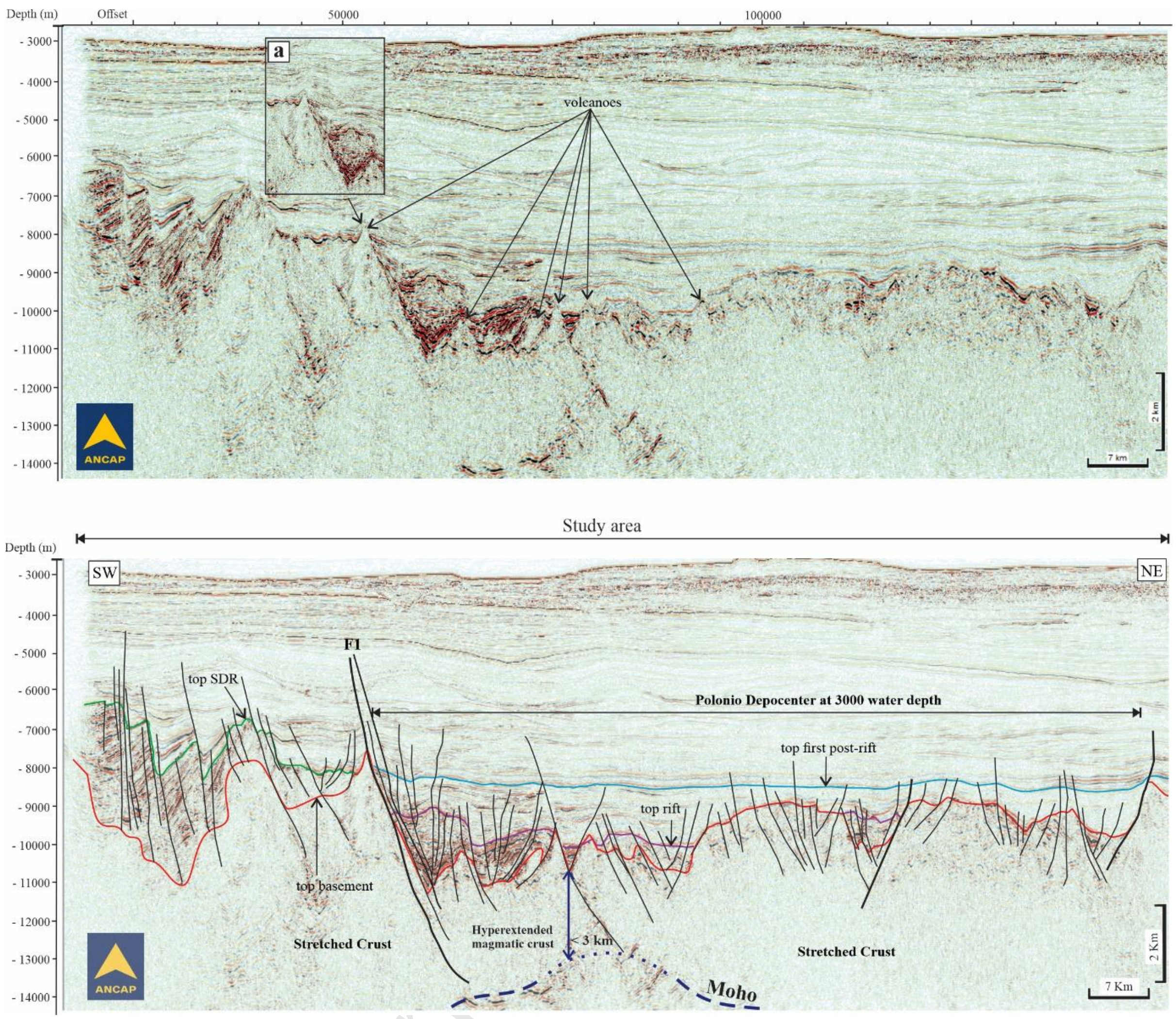

Fig. 6. (*Above*) 3D seismic line (Inline 7700), NE oriented, with conical figures pointed out and interpreted as volcanoes and detail of the volcano on F1 in box **a**. (*Bottom*) 3D seismic line interpretation, showing the structural setting, stretched crust, the hyperextended magmatic crust, the shallowing Moho in the study area (dashed blue line), and interpreted key horizon: top basement/base SDRs (red horizon), top rift/top SDRs (purple/green horizons), top first post-rift sequence (light blue horizon). The faults are shown in black lines, and F1 is pointed. See the location in Figure 2.

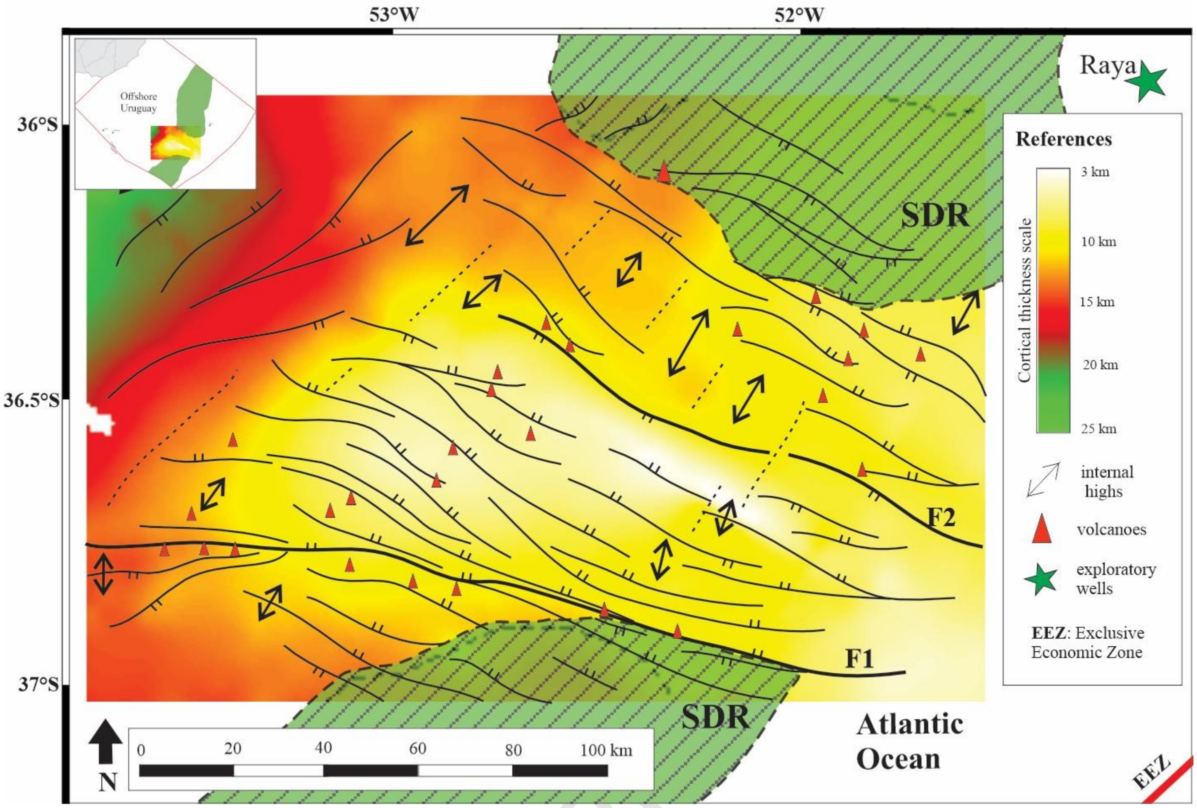

Fig. 7. Crustal thickness map. The transition region between the Punta del Este and Pelotas basins, which is not represented by SDRs, is highly faulted (the main orientations of the curvilinear faults are NW and WNW). In the same region of the SDRs gap, represented in light yellow to white colors, lies the offshore region of Uruguay where the crust, magmatic nature, is hyperextended with a thickness of less than 3 km.

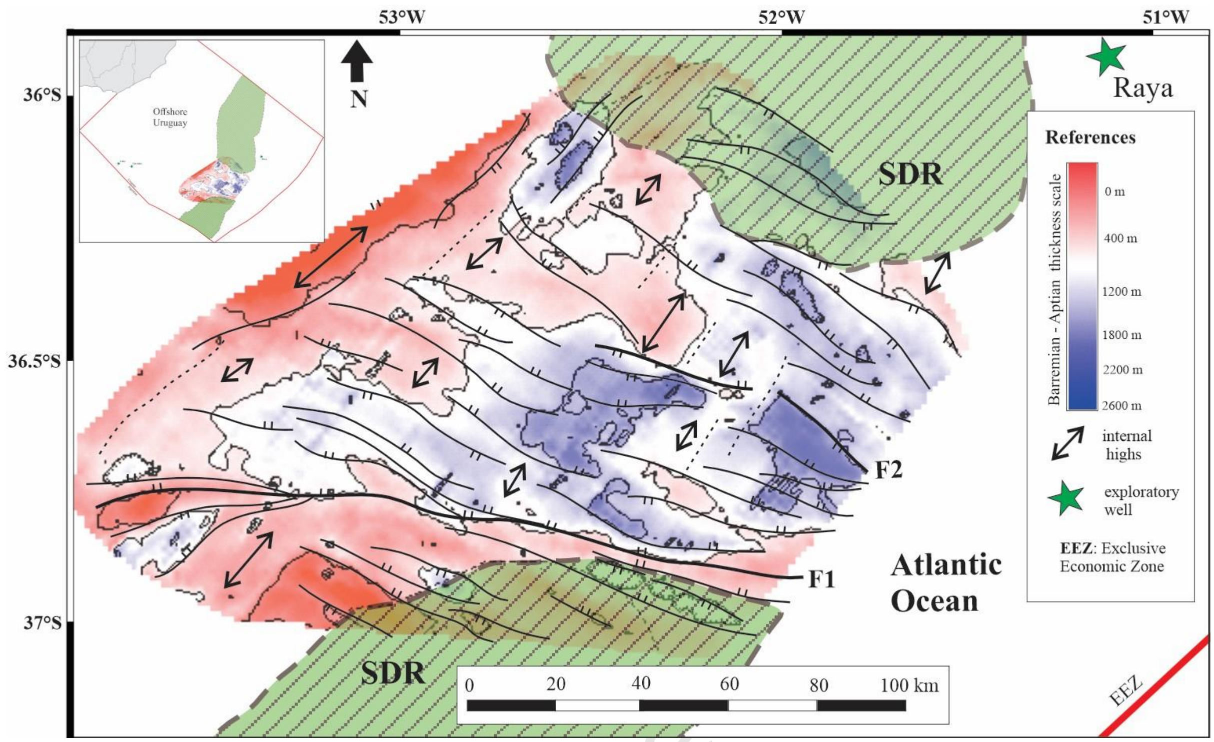

Fig. 8. First post-rift (Barremian-Aptian) isopach map, describing the Polonio depocenter controlled by NW and WNW faults and rhomboidal shape, with major E-W axis. Blue colors represent depocenters, while red colors represent high areas.

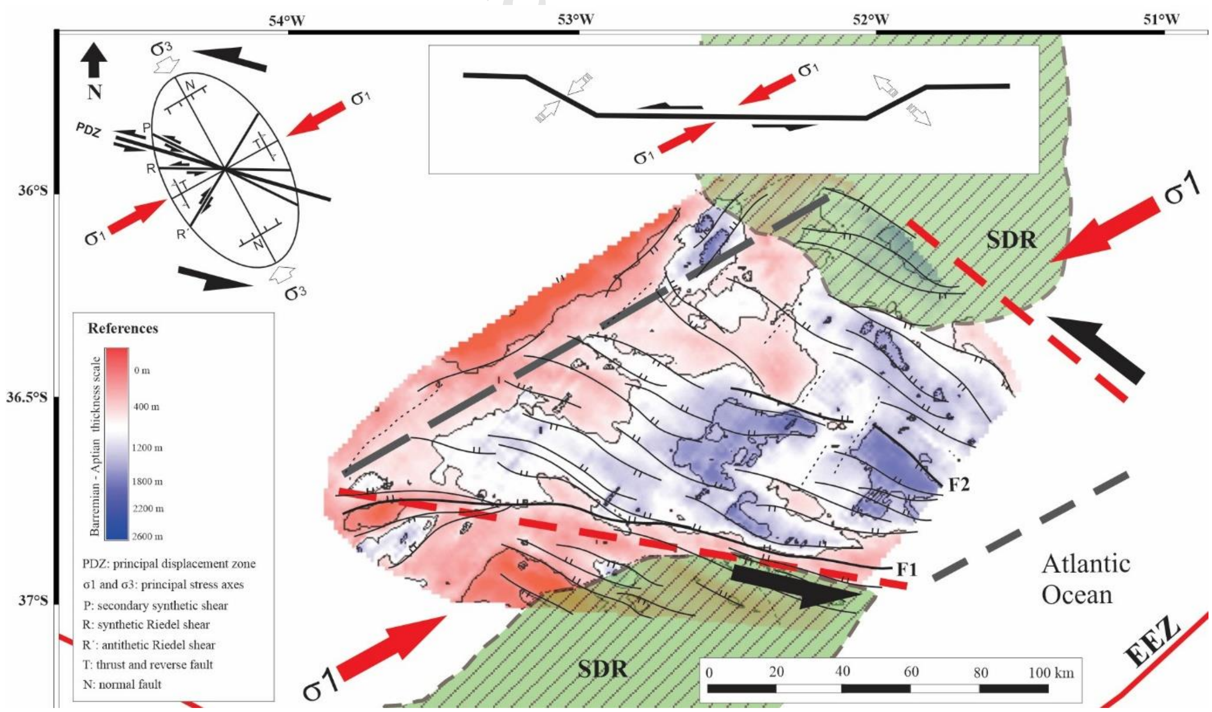

Fig. 9. Polonio depocenter. The NW fault system defines a rhomboidal basin formation, with major E-W

axis, where the early phase of the post-rift (Barremian–Aptian) flooded. The Riedel system model is also shown. The regional location of the map is shown in Figure 8.

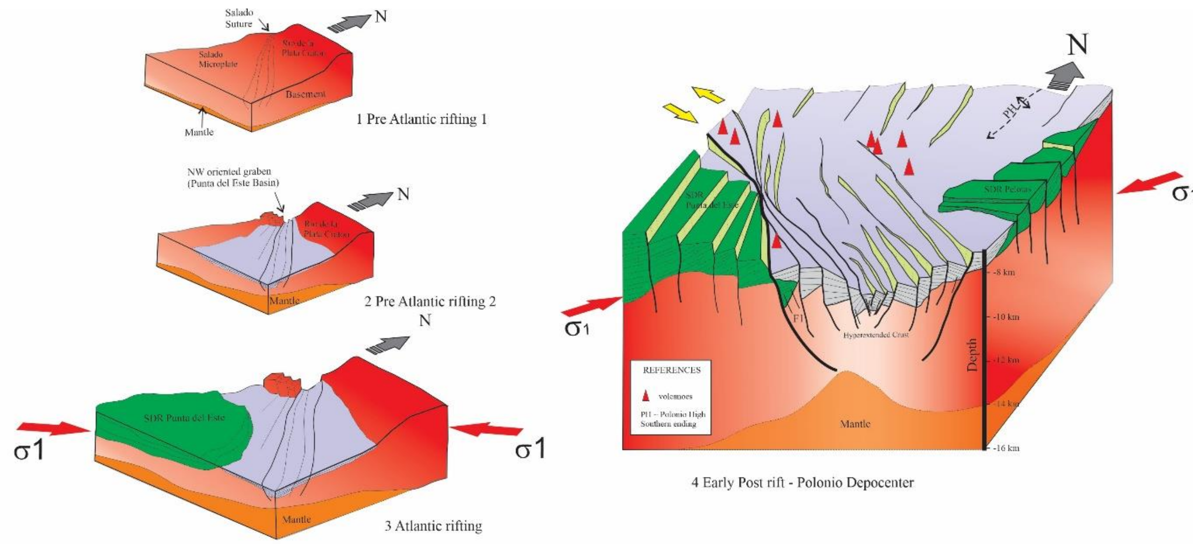

Fig. 10. Evolutive Model of the genesis of the Polonio Depocenter. **Pre-Atlantic rifting 1**: Previous the Atlantic rifting, the region was characterized by a continental crust approximately 30 km thick, exhibiting heterogeneity in both dip and strike directions. This crust was marked by inherited basement lineaments from the Gondwanide (NW-oriented) and Pan-African (NE-oriented) orogeneses. **Pre-Atlantic rifting 2**: During the Late Jurassic, the northeast (NE) extensional phase led to the formation of northwest (NW)-oriented grabens, such as the Punta del Este Basin, which overprinted pre-existing inherited basement lineaments. **Atlantic rifting**: In the Early Cretaceous, the NW-stretching phase of the Atlantic rift enable the emplacement of the Seaward Dipping Reflectors (SDRs) offshore Uruguay. At this moment the early emplacement of the Río de la Plata Transfer System (RPTS) followed the trajectory of inherited basement lineaments. **Early post-rift**: During the Barremian-Aptian, the region experienced maximum transtensional stress, marking the formation of restricted depocenters during the initial stages of marine transgression and the genesis of the Polonio Depocenter. This transtensional phase played a critical role in the formation of the depocenter. (Based on Moulin et al., 2010; Franke, 2010, 2013; Soto et al., 2011; Frizon de Lamotte et al., 2015; Gordon and Mohriak, 2015; Rowlands et al., 2016; Lovecchio et al., 2020; Kress, et al., 2021; Chauvet et al., 2021)

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

Highlights

- The UCM central sector is linked to the breakup of Western Gondwana.
- NW-oriented transtensional faults were identified, some of which reached the Moho.
- A Barremian-Aptian depocenter with rhomboidal geometry has the greatest thickness.