Upgrading vintage data in the Punta del Este and Pelotas basins offshore Uruguay and Southern Brazil

Kyle Reuber[1]*, Bruno Conti[2], Milos Cvetkovic[1], Pablo Rodriguez[2] and Henri Houllevigue[1] present the seamless merge and calibration of >25,000 km² from four separate, vintage 3D seismic volumes into a single volume interpretation tool.

Abstract

The offshore basins of Uruguay and Southern Brazil have a limited oil and gas exploration history. Since the announcements of light oil discoveries on the conjugate margin of Namibia, this area has become an epicentre of interest for hydrocarbon explorers. The Punta del Este and Pelotas basins are considered underexplored and, as such, possess an elevated risk profile. Identifying analogous, conjugate petroleum system elements is a component in the framework to reduce that risk. Additionally, the calibration and integration of subsurface data in the search for the next hydrocarbon discovery is paramount to a successful wildcat. Here, we highlight the seamless merge and calibration of >25,000 km² from four separate, vintage 3D seismic volumes into a single volume interpretation tool. This allows interpreters to gain a contiguous and unobstructed view and, therefore, an understanding of the regional geologic framework. When integrated with existing 2D data, the merged volume has permitted an improved understanding of the basin's evolution, the tectonostratigraphic

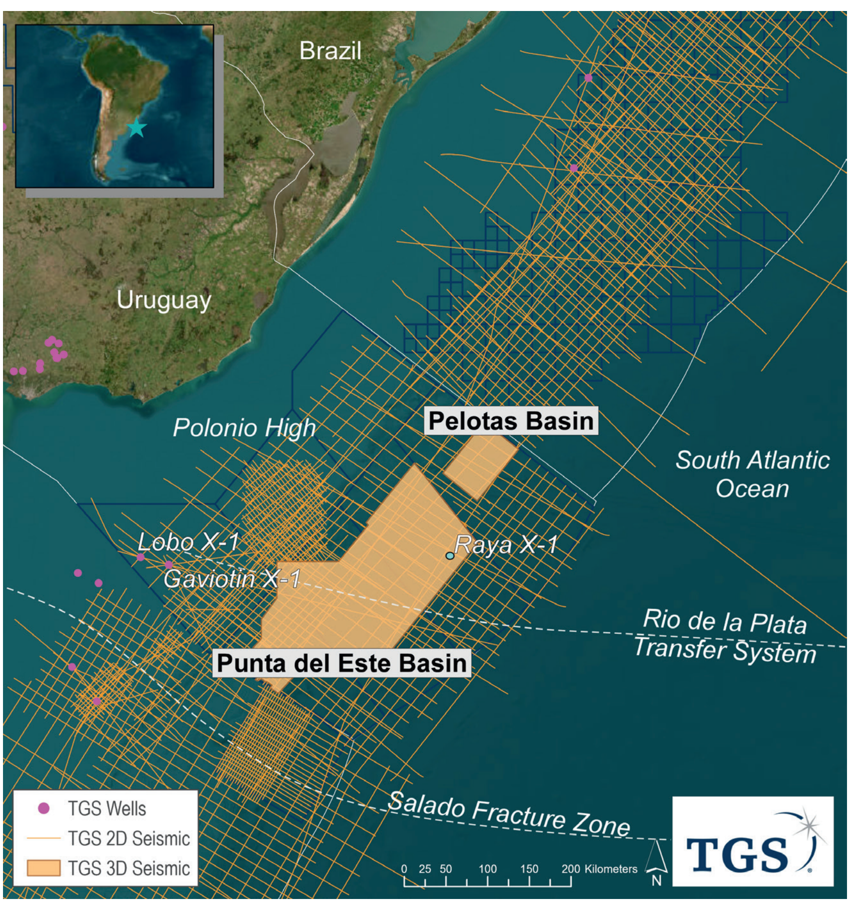

Figure 1 Location map showing the offshore basins of Uruguay and Southern Brazil. Regional structural elements, wells and exploration blocks are also highlighted.

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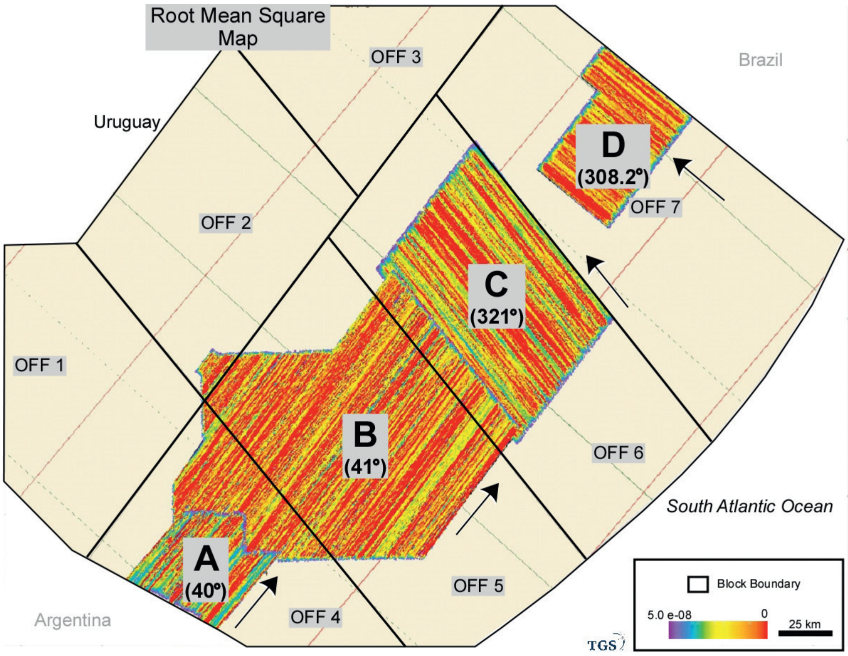

Figure 2 Map showing licence blocks, layout and acquisition direction (in degrees) of different 3D legacy surveys used in the 3D mega-merge project.

history and elements of the prospectivity for the region. As oil companies continue to flock to the region looking for the next discovery, advancing tools in the explorer's toolkit is the key to success.

Introduction

Recent South Atlantic hydrocarbon discoveries on the Namibian margin have drawn the attention of oil and gas explorers back to the basins of Uruguay and southern Brazil. Since 2022, a string of multi-billion-barrel discoveries in the Orange Basin has confirmed functioning world-class Cretaceous petroleum systems. Because early basin histories of conjugate margins are analogous, the South American basins of Uruguay and Southern Brazil (Figure 1) are now considered to contain many of the same petroleum system elements and be equally prospective. A favourable economic and political environment in Uruguay, combined with this new perspective, has led to the entirety of the offshore licence acreage being secured by major global energy players. The December 2023 Brazilian bid round also revealed optimism by operators in the region. In this high-stakes game of hydrocarbon exploration, oil companies seek data and methods to reduce their risk profile while searching for the next giant oil and gas discovery.

This article summarises our regional 3D reprocessing and calibration project results and our observations from the available data library. The results of this study illustrate the importance of regional integration of subsurface data and the application of analogous play concepts that highlight the potential for an oil and gas boom along this margin segment.

Importance of Regional Data Synthesis

Effective interpretation and interrogation of available data involves applying modern seismic processing techniques to extract as much information from the data as possible. The chief goal of calibrating a seismic data library is to permit geoscientists to gain the most accurate understanding and interpretation of the

Survey	YF13 (A)	BG12 (B)	TO12 (C)	TU17 (D)
Survey Area (Sq.Km)	2500	13283	7200	2950
Year	2013	2012	2012	2017
Cable length (m)	7000	6000	8000	8100
Shot Point Interval (m)	25	25	25	25
Group Interval (m)	12,5	12,5	12,5	12,5
Fold	70	60	80	81
Number of cables	10	10	12	12
Cable separation (m)	120	125	100	100
Number of gun arrays	2	2	2	2
Distance between guns (m)	60	62,5	50	50
Source depth (m)	7	8	6	6
Cable depth (m)	9	9	8	12
Trace length (ms)	9730	10050	10242	10002
Azimuth +ve	40	41	321	308,2
Bin size (native)	6.25x30	6.25x31.25	6.25x25	6.25x25

Table 1 Acquisition parameters for 3D legacy surveys.

subsurface, thereby reducing exploration risks. Over a period spanning decades, a reasonably dense grid of 2D seismic reflection data has been acquired in offshore Uruguay and Southern Brazil (Figure 1). Some of these have been renewed through modern processing. Three-dimensional seismic reflection data, by nature, is typically acquired over smaller, high-graded areas or limited to lease block footprints. Offshore Uruguay has four mixed-vintage, mixed-azimuth legacy 3D surveys that were used for this project. These previously discrete volumes have recently been seamlessly merged and calibrated into a single depth-migrated volume. All available seismic and non-seismic data were leveraged throughout the processing and interpretation phases to achieve the most thorough understanding of petroleum systems. This is key as Uruguay and Southern Brazil's offshore basins can still be considered 'frontier' (Figure 1).

Data overview and processing workflows

For this study, we use a comprehensive library of seismic data consisting of 2D and 3D regional datasets for interpretation and attribute analysis. The acquisition of 2D data was sourced from various vintages and most recently reprocessed using modern workflows in 2016. As for the 3D datasets, we have merged and normalised four legacy survey volumes acquired between 2012 and 2017, which were subsequently reprocessed as a standalone, single volume in 2023 (Figures 1 and 2). Details of the main acquisition parameters for each of the four surveys are detailed in Table 1. This table highlights the variability of the parameters and the value derived from a regularised volume for interpretation.

Reprocessing aimed to obtain the maximum quality from the data, minimise the noise, and extract the full bandwidth, with specific attention to recovering the lower frequency signal, compared to the legacy processing. This ensured that we had a sufficiently high signal-to-noise ratio to support velocity model building and imaging. This was achieved by first focusing attention on effectively attenuating noise on the pre-stack gathers and then addressing the source and receiver side ghosts. Attenuating the noise prior to de-ghosting ensures that the various signal processing steps to extend the bandwidth of the data only boost the signal. The reprocessing of the 3D data is described in further detail by Reuber et al. (2023). The result of these mega-merge projects produces a single, high-resolution interpretation volume that greatly reduces risk.

The approach of modern pre-processing workflows utilised de-ghosting and extensive de-multiple passes. The four surveys were normalised in terms of amplitude and phase, using the 2012 survey 'C' (Figure 2) as the benchmark. The vintage data quality of this survey was deemed higher than the remaining three and, therefore, served as the reference volume. Offshore Uruguay is well-known to have challenging acquisition conditions involving rough weather and strong currents, and as such, additional de-noising efforts were required.

Seismic velocity model building was employed through a tomography-based approach. For the initial phase of this process, the water velocity function is derived from onboard direct temperature and salinity measurements and then laterally smoothed and averaged across the volumes. This function is then laterally smoothed and averaged. For this project, this vertically varying function with lateral variations has initially failed to flatten gathers at the water bottom level sufficiently. Consequently, long-wavelength water column tomography was introduced to enhance gather flatness and improve imaging at the water-sediment interface. The initial vertical transverse isotropy (VTI) model was derived from underlying 2D data (Figure 1). Interpreted regional surfaces guided this stage of the

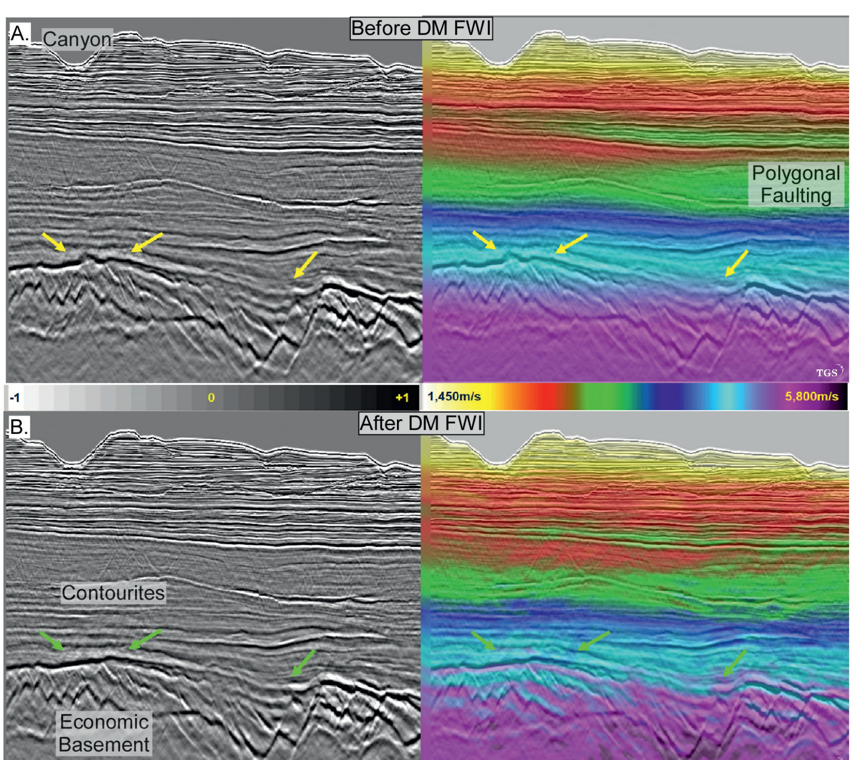

Figure 3 Kirchhoff PSDM stacks and velocity overlays showing: A) 'before' DM FWI application and B) 'after' DM FWI updates.

model building: 1) water bottom; 2) Eocene unconformity; 3) Top Cretaceous; and 4) regional 'economic' basement. These underlying 2D models were constrained by satellite and marine gravity and magnetic data, providing an appropriate starting model for the regional-scale size of the survey. The next steps involved two passes of reflection-based tomography, aided by interpretation-driven edits around several large submarine canyons. Reflection-based tomography remains the primary tool in our model-building workflow because it facilitates gradual, geologically plausible data-driven updates with short turnaround times. Extensive post-processing techniques are applied in the conventional Kirchhoff Tilted Transverse Isotropy (TTI) Pre-Stack Depth final migration and post-processing phases. Quality control checks are performed on these models and migration results at each stage of the workflow in order to maintain AVO fidelity. These steps ensure a seamless, high-density, high-resolution dataset suitable for exploration and development purposes.

Dynamic Matching Full Waveform Inversion

With the intent to deliver 'drill-quality' data, a subset of data is extracted for testing purposes in a more detailed model-building phase. This smaller volume is processed via a proprietary dynamic matching full waveform inversion (DM FWI) model-building phase. This stage also includes high-resolution shallow hazard imaging. The subset cube is positioned between surveys A and B (Figure 2) (Pralica et al., in review). To test the effectiveness of the workflow, the area selected was identified as a 'worst-case' scenario due to its relatively shorter maximum offsets of 6 km and 7 km, respectively. Additionally, this region is characterised by strong seasonal currents and complex bathymetry, resulting in the lowest Signal-to-Noise ratio (SN) compared to the rest of the survey area.

The DM FWI workflow was implemented across four frequency bands, progressively working from the lowest usable frequency up to 15 Hz. The initial velocity model for FWI is derived from a tomography model, which is regionally constrained and guided by interpretation. Borehole and drilling data from the Raya X-1 well (Figure 1), the only well within the 3D coverage, is also integrated at this stage. Limitations due to acquisition offset and azimuth required additional updates in the final band of DM FWI with post-DM FWI long-wavelength tomography alongside additional model conditioning.

A clear uplift can be observed when comparing the before and after results between Kirchhoff Pre-Stack Depth Migration (PSDM) stacks with velocity overlays and the application of DM FWI (Figure 3). Arrows within Figure 3 indicate where DM FWI updates have notably enhanced imaging quality, predominantly coming from fine-scale adjustments throughout the sediment overburden. Detailed improvements are also noted in the shallow basement section, which is thought to be composed of basalt flows with intercalated sedimentary units. Neither standard tomography applications nor detailed interpretation can produce the details revealed by DM FWI (Seet Li et al., 2023).

In addition to resolving shallow gas accumulations and Bottom-Simulating Reflectors (BSR), the updated models provide vertical and lateral delineation of deep marine sediment systems in terms of velocity contrasts and lithologies (Figure 4). Enhanced imaging within the subset cube is also visible in the deeper Cretaceous section, where a higher frequency of faults, primarily polygonal, is apparent due to slower velocities. In the deeper section, while similar vertical updates are observed, some of these details were smoothed out as they may represent artifacts rather than real geological features. Similar steps to scale back details were taken in the deepest part of the subset model, particularly at the top of the basement. At that interval, updates do not markedly improve or degrade the image or gather flatness.

Seismic attributes

The analysis of seismic attributes has been shown to be effective as an interpretation tool to resolve subtle geological features, lithologies, complex structural trends and prospective sweet spots within the data. They often reveal features and patterns that might otherwise go unnoticed. In this project, geometrical and amplitude attributes were used in two different ways: 1) for quality control (QC) of data and models during the processing stage and 2) as advanced interpretation tools.

AVO attributes, such as RMS amplitude and various combinations of angle stacks (Figure 5), were derived at multiple stages of processing for analysis. The first rounds of attributes were calculated on the preliminary intermediate Pre-Stack Depth Migration (PSDM) datasets. These attributes were essential in identifying prospective AVO (Amplitude Variation with Offset) play types II and III, allowing us to enhance their imaging throughout the project lifecycle. The final data

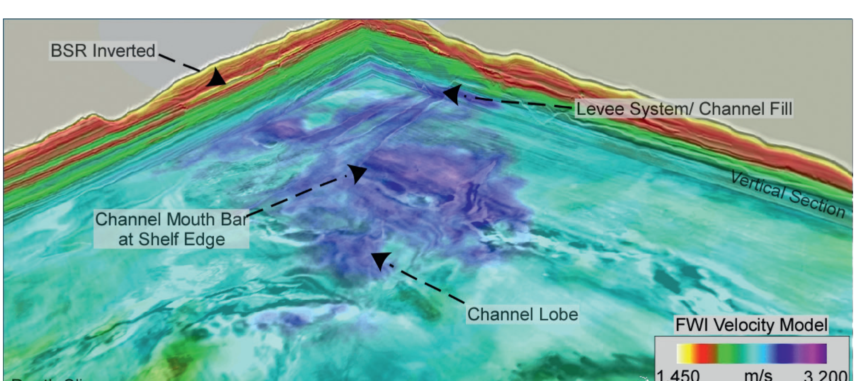

Figure 4 Lithology interpretation aided by high-resolution DM FWI model. Seismic facies inference of channel complex elements, shelf incisions and channel lobes are highlighted by detailed velocity model.

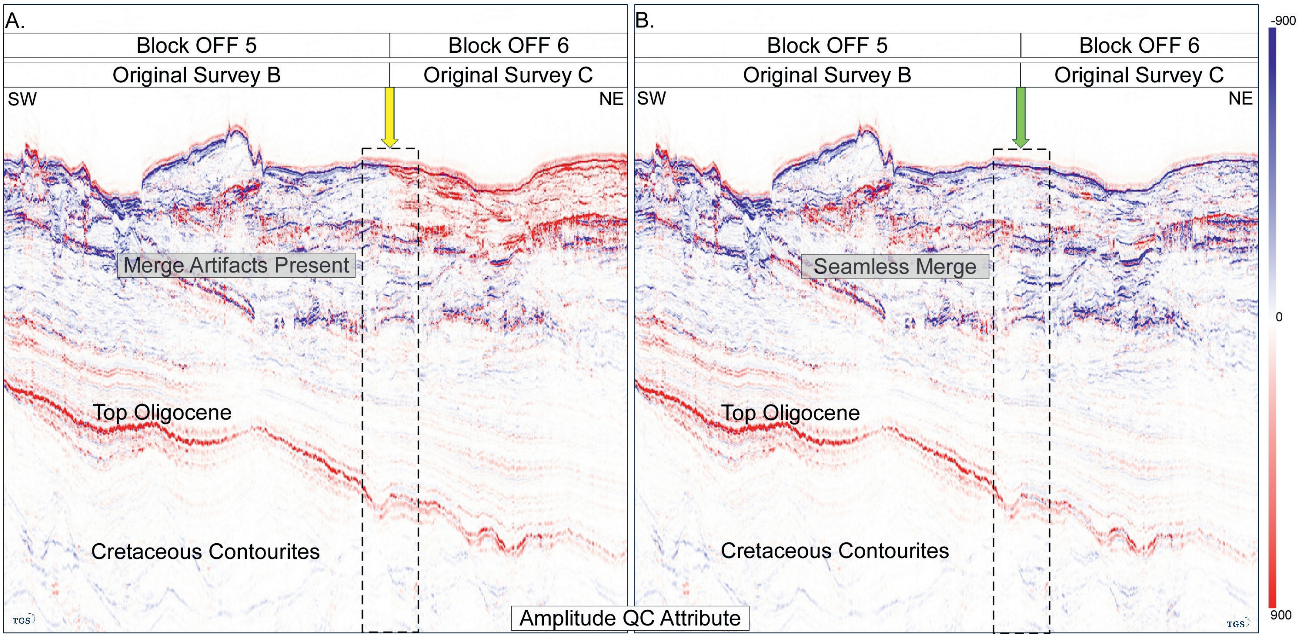

Figure 5 Combination of angle stacks used as a QC amplitude attribute. A) Section illustrating the use of all available offsets for angle stack generation. Resulting seam in the shallow region is highlighted. B) Demonstrating of 'seamless' merge utilising same ranges of nearest offsets.

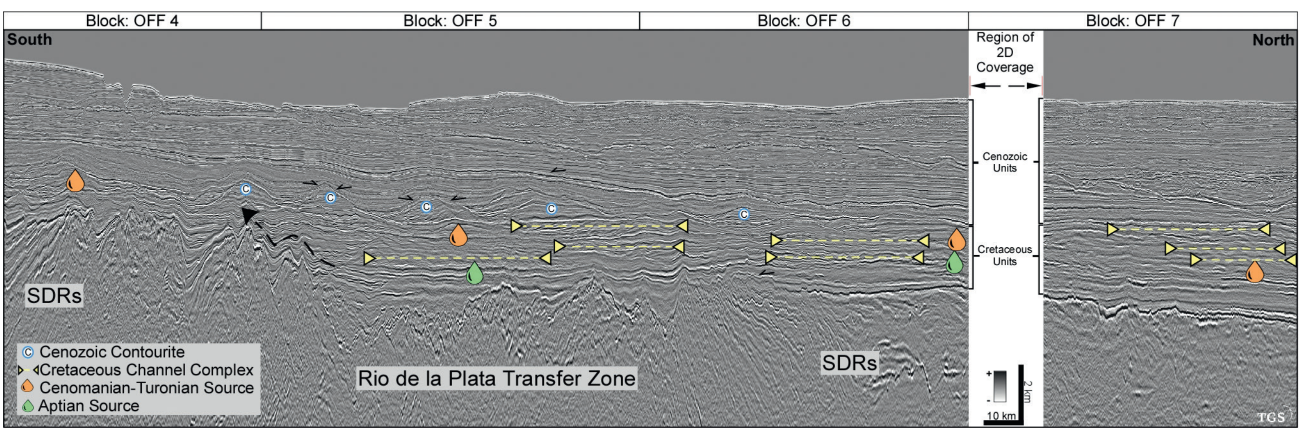

Figure 6 Representative 3D inline example from the seamlessly merged 3D volume in offshore Uruguay. Aptian and Cenomanian-Turonian source interval are interpreted in the basin and overlying Late Cretaceous-Tertiary units contain an array of seismic facies favorable for accumulations of oil and gas.

migration showed significant improvement in resolution and certainty for identifying seismic facies representing potential reservoir packages.

Coherency (or 'semblance') attributes were crucial in highlighting discontinuities in the data, such as faults, fractures and channel boundaries. These attributes were used for quality control steps during processing to ensure a seamless volume merge between different surveys. Coherency and curvature attributes were also utilised to optimise migration aperture, as larger apertures may increase noise levels without necessarily improving dip imaging in the deep section. Amplitude and phase extractions along key regional horizons were also checked at each stage.

Regional geologic overview

The offshore regions of Uruguay and southern Brazil share similar basin evolution stages and stratigraphic sequences. In the deepwater, sub-basin divisions are made into the Punta Del Este (PdEB) and Pelotas Basins (PB) (Figure 1). The Punta Del Este Basin (~50,000 km^2) contains a margin segment with a 140 km wide region of syn-rift horsts and grabens in southwestern offshore Uruguay (Figure 1). The PdEB is limited in the south by the Salado Fracture Zone and to the north by the Polonio basement high and the Rio de la Plata Transfer system (RdlPTS) (Figure 1). The RdlPTS (Soto et al., 2011) is a complex structural region that marks the boundary between the Punta del Este and Pelotas Basins. The PB spans offshore acreage (~300,000 km^2) of Uruguay and southernmost Brazil. This region is positioned between the Florianopolis and Austral-Malvinas Fracture Zones (Figure 1). These fracture zones can be traced across the South Atlantic to link the conjugate margins of western Africa and South America. Plate reconstructions restore the sub-basins of Namibia to the sub-basins of Uruguay and southern Brazil.

The Early-Cretaceous development of the South Atlantic basin occurred in a magma-rich setting. The scissor-like opening occurred from south to north along zones of pre-existing weakness in the South American and African Plates. During this phase, variable basement architectural fabrics produced differing magnitudes of continental syn-rift extension and the location of oceanic transforms. As extension continued, igneous intrusions at rift shoulders eventually progressed to final crustal rupture with excess magmatic production at the incipient spreading ridge. At this transitional phase, seaward dipping reflectors (SDRs) (Figure 6) are formed as subaerial flow originating from the newly formed spreading centre. These sub-aerial SDRs progressively rotated basinward as the spreading at the axis continued and the distance between the two continental domains increased. Eventually, the magmatic supply waned, and the once super-charged spreading ridge began to produce normal oceanic crust.

The progression to the Volcanic Passive Margin (VPM) phase described above pre-dated the deposition of the prolific source rocks that have forever changed the oil and gas landscape in the conjugate margin of Namibia. Analogous basin elements such as 1) deposition of thick passive margin stratigraphic packages, 2) sufficient burial for maturation, and 3) an effective seal deposition. All appear to be present in the Punta del Este and Pelotas Basins.

Punta del Este and Pelotas Basin Stratigraphy

PdEB and PB exhibit a geological evolution mirroring that of other South Atlantic margin basins**,** progressing through pre-rift, syn-rift and post-rift stages (Conti et al., 2017; Morales et al., 2017).

During the pre-rift phase, remnants of a volcano-sedimentary sequence were deposited within a western Gondwana intracratonic basin during the Paleozoic era. Its distribution is primarily associated with the shallower segment of PdEB and PB, predominantly preserved within half-graben structures, albeit partially eroded on the highs. This sequence, consisting of interbedded shales and sandstones, was drilled in PdEB and the Brazilian portion of PB (Ucha et al., 2004; Bueno et al., 2007.)

The Late Jurassic to Early Cretaceous syn-rift phase consisted of the infilling of grabens and half-graben structures with a mix of alluvial-fluvial and lacustrine deposits, interbedded with volcanics and volcaniclastics (Bueno et al., 2007). Units from this sequence were drilled in the shallower segment of PdEB and PB. However, the main syn-rift depocentres remain undrilled. While the half-grabens in PdEB trend mostly in the NW-SE direction, those in the Pelotas Basin exhibit an NE-SW orientation (Morales et al., 2017). Moreover, in the deepwater segments of both basins, the syn-rift phase is characterised by thick SDR packages (Figure 6 & 7), with a notable gap between the SDRs wedges of PdEB and PB corresponding to the RdlPTS (Figure 6). This gap between SDRs wedges is constituted by a depocentre that controlled the sedimentation of that sector during the Cretaceous post-rift and was an important influence for the deposition of organic-rich source intervals and reservoir rocks (Figure 6).

The post-rift phase represents the sequence with the highest sedimentary thickness, commencing in the Early Cretaceous period under newly formed marine conditions (Figures 6 and 7). It can be divided into a Barremian-Aptian transition phase, predominantly recognised in PdEB, and a subsequent drift phase. The transition phase, deposited during a stage of thermal subsidence immediately after the syn-rift, is marked by sedimentary sequences lacking shelf and slope geometries in seismic facies (Morales et al., 2017). The Aptian-present drift phase is characterised by a sedimentary wedge shaped by sediment supply, basin subsidence, and eustatic changes. Notably, this phase sees the developments of prograding geometries associated with the establishment of paleo-shelves and paleo-slopes (Morales et al., 2017) (Figure 7).

Petroleum systems discussion

Utilising the existing data and current understating of the basin, the analysis of each PdEB and PB tectonostratigraphic phase in terms of petroleum systems indicates that the pre-rift sequence presents the highest exploration risks. This designation is asserted primarily due to its high burial depth. This assessment leads to potential source rocks being overmature and reservoir intervals exhibiting low porosity and permeability. The syn-rift phase has been tested in two exploration wells (Lobo X-1 and Gaviotin X-1, Figure 1), with no success in PdEB and PB (Brazil). Across the South Atlantic, this same sequence has produced

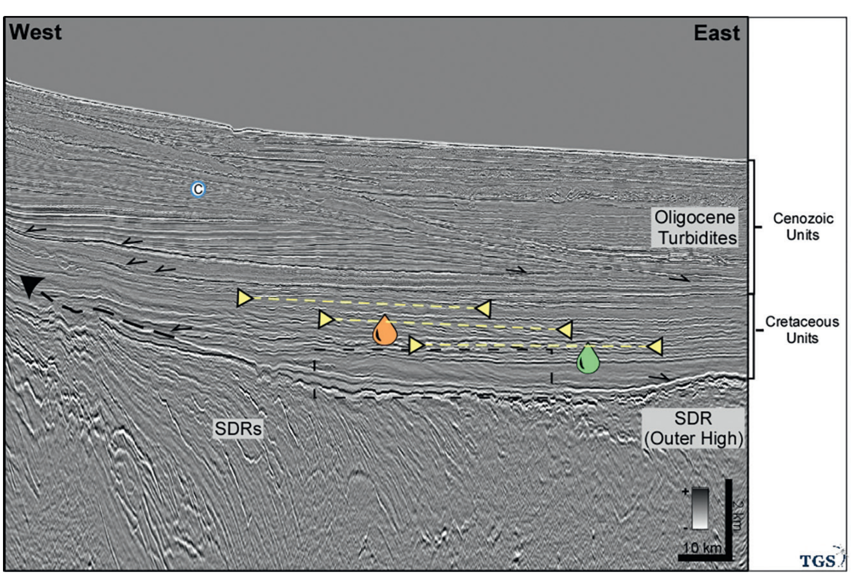

Figure 7 Representative 3D Crossline example from the merged 3D volumes, showing similar elements to Figure 6.

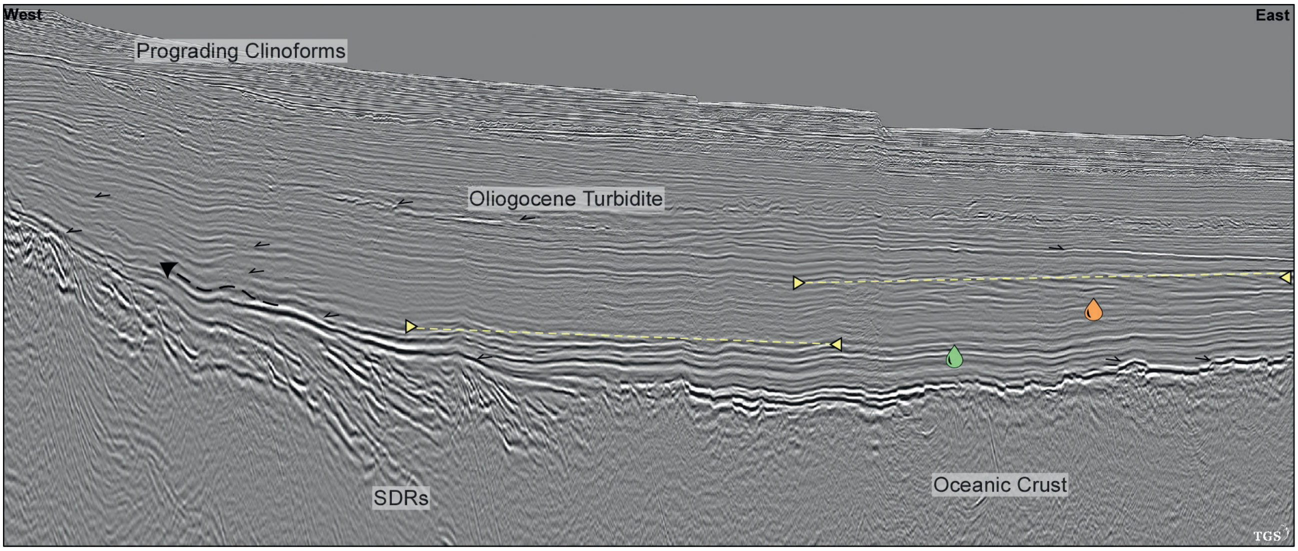

Figure 8 Representative 2D dip line from the Pelotas Basin, offshore Brazil. This line shows the extension of the depositional systems into southern Brazil.

moderate successes in the Orange Basin. On the African margin segment, proven lacustrine source rock and a discovery (AJ-1 well) offshore South Africa have been recorded (Paton et al., 2007). Attempts to test an extension of this play in a recent exploratory well resulted in a non-commercial accumulation. In Uruguay, the most recent post-rift exploration target in the PB was carried out in 2016 with Raya X-1 (Figure 1), in a water depth of 3304 m. Results from this well were highly anticipated, as the water depth at the borehole was a world record at the time. This wildcat targeted an Oligocene turbidite system, but unfortunately, the results indicated that the well was dry and lacked hydrocarbons. Similar outcomes along the margin highlight the risk of plays associated with the Cenozoic post-rift sequence due to the lack of effective migration pathways connecting Cretaceous source rocks with the Cenozoic reservoirs.

Subsurface data in the Punta del Este and Pelotas Basin show many direct and indirect hydrocarbon indicators, including fluid inclusions, gas shows, AVO anomalies and CSEM anomalies. The analysis of micro-seeps and oil slicks further supports evidence of a functioning petroleum system(s). These data points and the recent high-quality oil discoveries in the Orange Basin (Venus, Graff, Jonker, Mopane, etc.) highlight the Cretaceous post-rift sequence as the most prospective (Conti

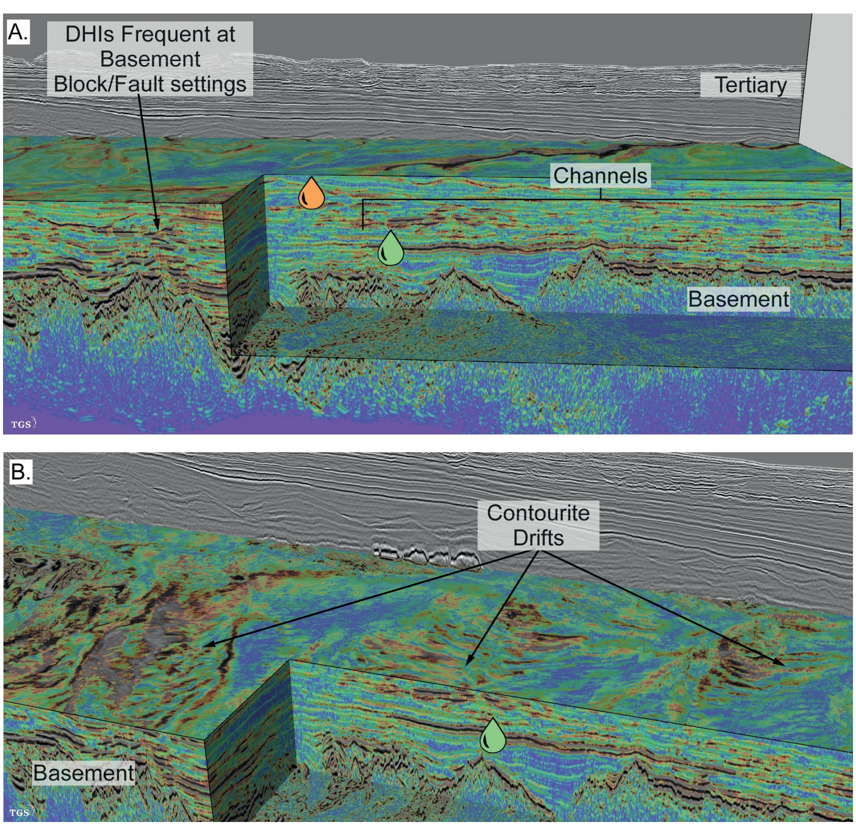

Figure 9 Examples (A and B) of the merged 3D volume showing early basin-fill distribution of stratigraphic features (contourites, channels, levees) to the Aptian and Cenomanian Source Units. 3D volume views are composed of RMS (Root Mean Square) seismic attribute and raw-stack data.

et al., 2023). From here, we highlight the details of the largely unexplored Cretaceous post-rift sequence petroleum system of PdEB and PB.

Multiple boreholes in West Africa confirm that source rocks associated with the Cretaceous post-rift megasequence are marine shales from the Aptian (OAE 1) and Cenomanian-Turonian (OAE 2) ages. Although the Aptian sequence has not yet been drilled in the conjugate region, it is correlated with its Namibian counterpart, identified by seismic facies correlation in seismic data as the first marine transgression of the basins. The Aptian sequence reaches up to 1000 m in a Cretaceous central depocentre area offshore Uruguay, associated with the RdlPTS. This interpreted thickness suggests that the hydrocarbon generation potential in this interval is highly significant, assuming the organic properties are comparable to those documented in the source interval on the conjugate margin.

The BPS-6a well in the Brazilian side of the Pelotas Basin, drilled in 1995, reached a thin organic-rich Cenomanian-Turonian (C-T) sequence with high TOC values (ANP, 2004) in the younger interval. It is likely that the quality, thickness, and maturity of this source rock will increase in the deep sector of the basin. In that regard, a recent work by Rodríguez et al. (2023) identified its potential as a source rock in the deepwater segment offshore Uruguay. Here, the C-T source rock was associated with an AVO type IV anomaly response in seismic data and an extensive but subtle high resistivity response within the CSEM data.

The presence and quality of reservoirs for the Cretaceous post-rift sequence have been confirmed as high-quality sandstones. These sand-rich intervals have been documented in the PdEB and PB through exploration well data. For instance, the Lobo X-1 and Gaviotin X-1 (Figure 1) wells of PdEB demonstrate porosity values ranging between 18% to 25% in Cretaceous post-rift reservoirs (Conti et al., 2023).

Numerous channel systems and turbidites throughout the thick Cretaceous post-rift column in the central to distal segment of PdEB and PB have been identified with 3D seismic data (Figure 9), some of them showing strong analogies with the Orange Basin Namibian discoveries. Offshore discoveries in the Orange Basin have confirmed the existence of at least two highly effective play types (Hedley et al., 2022), one associated with Lower Cretaceous reservoirs (e.g., Venus-type) and another with Upper Cretaceous reservoirs (e.g., Graff-type). Both essentially stratigraphic play types, consisting of submarine fans and channel systems, appear to be fed by the Aptian Source rock, although the contribution of the Cenomanian-Turonian source rock to the Upper Cretaceous play cannot be ruled out.

Many of the identified prospects recognised in PdEB and PB for the Cretaceous post-rift sequence are connected through faults to the Aptian source rock, ensuring an effective migration pathway. This is illustrated in Figure 9 by the extension of faults into the lowermost basin fill above a rugose basement expression. Finally, it is worth noting that the Cretaceous post-rift sedimentary package is overlain by a thick transgressive marine Paleocene shale, acting as a regional seal for hydrocarbons, as supported by well data (Conti et al., 2023).

Underexplored region

Most of the 20 exploratory wells drilled in PB (Brazil) were located either in the emerged part of the basin or in shallow waters over the continental shelf, targeting various proximal Cretaceous or Tertiary reservoirs. On the other hand, of the three wells drilled offshore Uruguay, two of them (Lobo X-1 and Gaviotin X-1) located in shallow waters of PdEB, targeted syn-rift structures and the other (Raya X-1), located in the ultra-deep sector of PB (3404 m water depth) only reached the Cenozoic post-rift sequence, targeting an Oligocene turbidite. Thus, none of the 23 wells of the region of PdEB and PB tested the Cretaceous post-rift in the deepwater sectors, remaining a largely unexplored area. This is important to note because, as mentioned before, the Cretaceous post-rift sequence in the deepwater sector is where most of the exploration success in the Orange Basin is concentrated and will be a key region of future exploration in both PdEB and PB. Despite the lack of wells, the significant coverage of high-quality 3D seismic data in the area will help to mitigate geological risks and facilitate decision-making for new drilling operations.

Summary

Although much of the area remains underexplored, the conjugate discoveries on the Namibian margin have prompted operators to capture acreage in a ‘gold rush’ fashion, with the aspirations to replicate those successes on the South American equivalent. This is demonstrated by explorers capturing 100% of the Uruguayan lease blocks and record-breaking results in Brazil’s 2023 Permanent Offer lease round.

A thorough analysis of available data in the region has resulted in a library of leads and prospects across various play types. The play elements span various seismic facies from a recognisable Aptian source interval, including a potential Cenomanian-Turonian organic-rich shale, to mapped depositional fairways along the margin. Additionally, the Namibian-type plays targeting Cretaceous channels and fans on this margin are similar in age and position relative to the paleo-shelf. Seismic facies related to channel complex and fan deposition overlie the Aptian source interval and are common within these basins. Leads have also been identified at fault-bounded traps, where the faults originate from the economic basement into overlying Mid-Late Cretaceous units. An inventory of DHIs has also been compiled where amplitude anomalies and angle-stack response suggest hydrocarbon accumulation in subtle structures.

Industry experts are anticipating great successes in offshore Uruguay and Southern Brazil. As exploration and drilling programs are drafted data providers race to provide the technology and data coverage needed ahead of this expected oil boom in this emerging hotspot.

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