WHAT IS HIDDEN IN PUNTA DEL ESTE AND PELOTAS BASINS OF URUGUAY?

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RESUMEN

Los recientes descubrimientos significativos de petróleo ligero en los pozos Venus & Graff, localizados costa afuera de Namibia en la cuenca de Orange, han reactivado el interés exploratorio en las cuencas costa afuera de Uruguay, Argentina y sur de Brasil. Esto se debe a que América del Sur y África comparten la misma historia geológica siendo parte del supercontinente Gondwana y, en consecuencia, de los márgenes conjugados del Atlántico Sur desde el Cretácico Inferior en adelante. Los descubrimientos de petróleo equivalente de miles de millones de barriles, producto de la perforación costa afuera en Namibia, generarán un mayor interés en invertir en exploración en las cuencas conjugadas en América del Sur. La pregunta es: ¿podrían las cuencas costa afuera de Uruguay tener un potencial sistema petrolero análogo? En este documento, vamos a proporcionar una idea de la prospectividad del área.
El objetivo del estudio fue demostrar que las cuencas de Punta del Este y Pelotas frente a las costas de Uruguay tienen áreas extensas que contienen trampas estratigráficas prometedoras en las secciones correspondientes al sinrift (Cretácico Inferior) y postrift (Cretácico Superior y Cenozoico)". El estudio se basó en datos sísmicos 3D y 2D y el análisis de la respuesta de Amplitude Versus Angle (AVA), también conocido como AVO (*Amplitude Versus Offset*). El método en sí, permite la detección rápida de anomalías de amplitud sísmica en áreas con potencial de contener hidrocarburos. Además del trabajo de Además del trabajo de AVO, se utilizó un algoritmo de aprendizaje automático para rastrear todos los reflectores sísmicos y evaluar la variación de sus propiedades de forma de onda en el área.
El análisis condujo a la identificación de posibles ambientes sedimentarios como canales y sistemas de abanicos turbidíticos dentro de los límites de ambas cuencas. Se identificaron múltiples reservorios en niveles estratigráficos análogos a los de los descubrimientos de Venus y Graff, así como al prospecto Gazania localizado en la porción sudafricana de la cuenca de Orange.

INTRODUCTION

The outcomes of a recent geophysical study from the Punta del Este and Pelotas basins of Uruguay are presented in this work. Lately, there has been an increased interest in the offshore region of Uruguay, Northern Argentina and Southern Brazil due to the exploration success in the conjugate Orange Basin off the coast of Namibia and South Africa.

Originally, a part of Gondwana, the African and Southern American tectonic plates split from each other beginning in the Cretaceous period and continued that separation until present day. This rifting resulted in extensive parallel fracture zones on the Atlantic Ocean floor (Chaboureau *et al.*, 2012). The Rio Grande and Tristan da Cunha fracture trails extend across the ocean (Moulin *et al.*, 2005) and making it possible to correlate Namibia's offshore margin directly to Uruguay and partially to Argentina and Southern Brazil.

The recent Namibian petroleum discoveries Graff and Venus have confirmed multi-billion barrels of oil equivalent resources. There are additional prospects in Namibia that are yet to be tested. The estimated resources of both discoveries are being currently evaluated, but they are both large and significant to the industry. In the meant time, there is a speculation that the offshore acreage of Uruguay could hold analogous potential. In this study, we are going to provide an insight into the prospectivity of Uruguay's offshore exploration acreage.

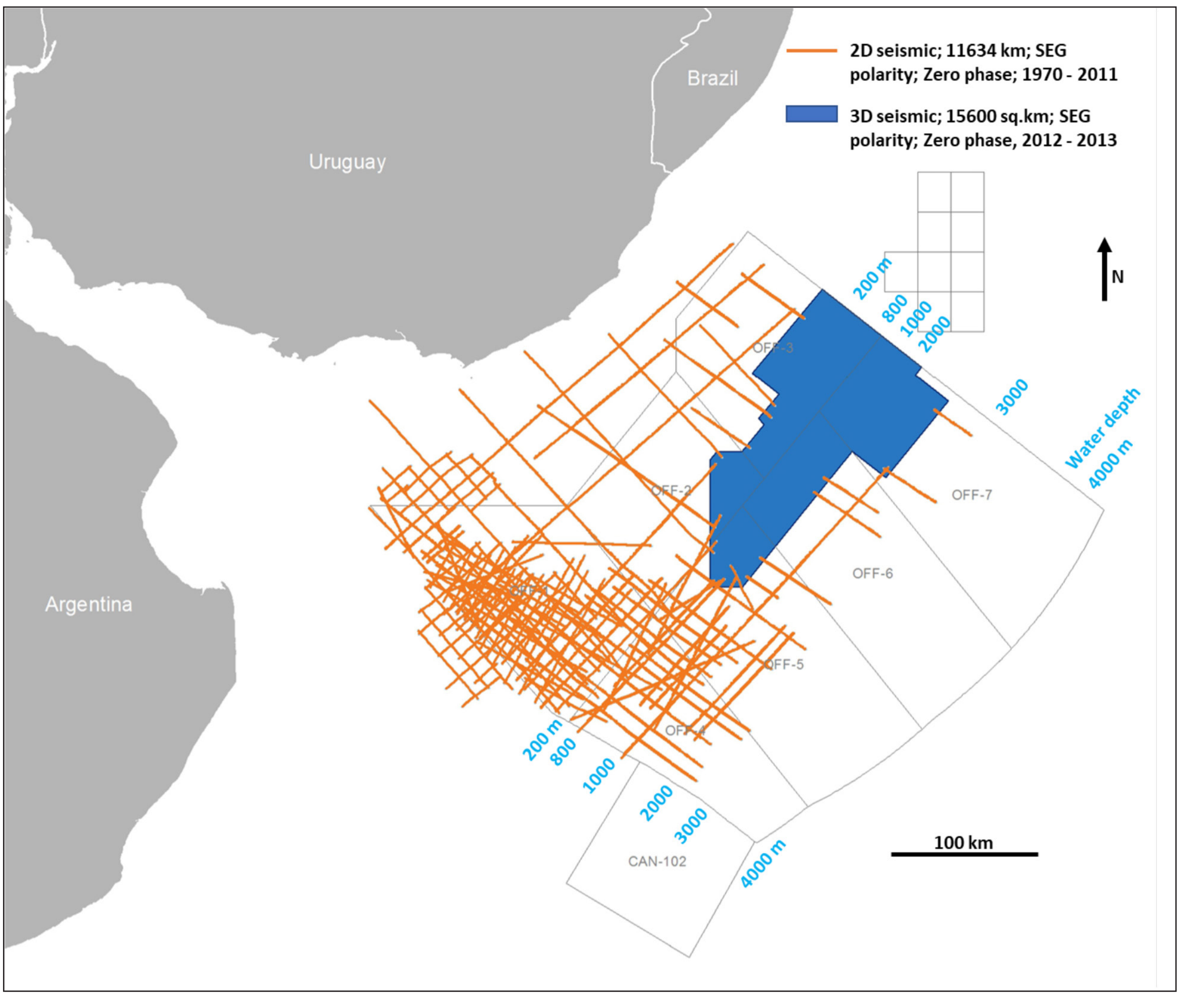


Figure 1. A schematic display of the area of the study. 3D dual-sensor data covers the area of approximately 15600 square kilometers (blue) whereas, 2D data (orange) was shot over 11600 line kilometers.

METHODOLOGY

The methods used in this study include two separate technologies applied independently. First, angle stacks from 3D and 2D (Figure 1) were used in a flow based on AVO (Amplitude Versus Offset) theory to obtain relative acoustic properties of the subsurface. The second method was based on a Machine Learning algorithm for automatic tracking of seismic reflectors and assessing shape properties of the seismic trace corresponding to those reflectors.

Method #1 – Relative AVO based acoustic properties

The method of studying amplitude variation with offset is based on the fact that when a seismic wave encounters a boundary between two lithologies with different acoustic properties, e.g., shale and sand; it would generate a reflection of a certain strength, and its amplitude will depend on the angle of incidence of that wave as well as the bulk properties of these rocks. In simple words, if the seismic energy reaches the boundary between shale and sand at a normal angle, some part of it will be absorbed and another will be reflected. However, if the seismic energy impinges on the shale / sand boundary at an angle different from 0 degrees, the reflection amplitude will be different compared to the first scenario (Fig. 2) (Koefoed 1955).

Seismic records at different angles of incidence are standard deliverables of any modern seismic acquisition survey. They are referred to as Near, Mid and Far angle-stacks. It is worth mentioning that the quantitative comparison of the angle stacks is the essence of the AVO analysis. There are two main AVO attributes - the Intercept and Gradient. The Intercept is a close representation of the seismic section at the angle of incidence equal to 0 ("Zero angle stack"). The Gradient is a measure of the amplitude change from the Zero angle stack to the Far angle stack. Estimates of relative acoustic

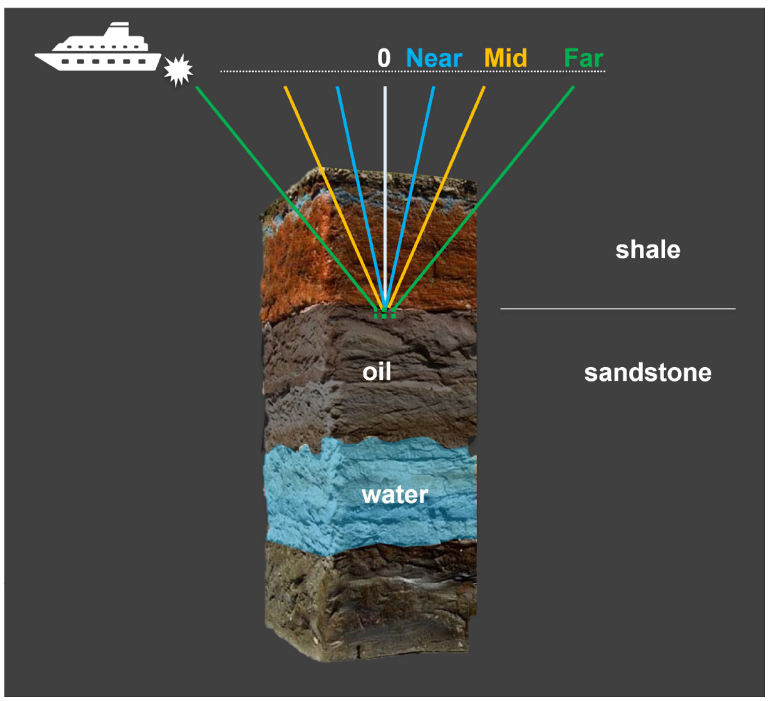


Figure 2. A sketch of a basic AVO concept. The energy reflected at different angles from a reservoir will be affected by the contents of the pore space of that reservoir. A quantitative comparison of the Near, Mid and Far angle stacks is the basic process of AVO analysis.

impedance (rel.Ip) and relative ratio between P and S wave velocities (rel. Vp/Vs) can be produced using a combination of the Intercept and Gradient volumes (Spratt *et al.*, 1993).

If used cautiously, these attributes can indicate potential hydrocarbon accumulations as well as lithology variation across the study area (Reiser *et al.*, 2015). Over the past years, this approach has proven to be a fast and reliable way of scanning large areas for potential leads exhibiting amplitude anomalies without the need to build a low frequency background model (filling the gap between the 0 Hz and the lowest seismic frequency). Given the broadband nature of the Uruguay seismic data used in this analysis, there is a good reliability in amplitude response when exploring for reservoir fairways.

Method #2 - Machine Learning

Usually, it is difficult and time consuming to track multiple seismic horizons for detailed structural and stratigraphic analysis during the data interpretation stage. Limited resources and tight timelines have a direct impact on the number of seismic reflectors being interpreted and used for geophysical and geological (G&G) analysis. Often a geoscientist must extract amplitudes between two horizons or use a window along a surface and extract averaged or mixed responses. Such an approach is biased in many cases and can lead to situations where sedimentary and stratigraphic features are being obscured or eliminated completely during the windowed amplitude extraction.

A more fit for purpose solution can be found in the domain of Machine Learning (ML). Typically, a seismic survey contains millions to tens of millions of seismic traces, and each trace contains a few thousands of data samples. These facts alone already assume there would be billions of data points that could be analyzed by an automated algorithm.

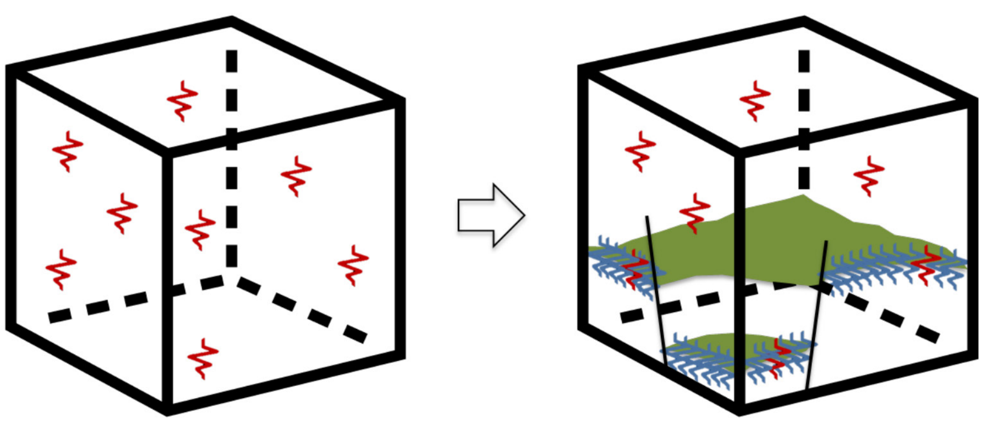


Figure 3. A basic schematic example of the ML method used for tracking seismic reflectors within the 3D data. The left image demonstrates that the seismic volume is being automatically subsampled into initial waveforms. Next, the entire volume is searched for similarities. The initial waveforms can evolve during the analysis.

In this study, we used ML for tracking hundreds of seismic horizons over an area of approximately 15,600 square kilometers (sqkm) in Punta Del Este and Pelotas Basins offshore Uruguay. The data was automatically subsampled into a spatial set of starting waveforms. Next, the algorithm searched for similar waveforms elsewhere within the 3D seismic volume. The stronger the similarity statistics was for the initial and newly found waveforms the more weight and influence they were assigned (Fig. 3). On the contrary, poor match would lead to a modification – an evolution of the starting waveform and looping the search process. Thus, simultaneous data classification, evolution and grouping would allow identification of seismic wave patterns that were repeated over an area. Then it was possible to trace such events with high precision over the entire seismic volume.

GEOLOGY

The offshore Uruguay includes two adjacent sedimentary basins - Punta del Este and Pelotas. Both areas are analogues to the Orange Basin (offshore South Africa and Namibia), because South America and Africa share a common geological history as part of the super-continent Gondwana. Prior to the breakup of Western Gondwana, the South American and African plates were bound together forming a single continent (Mohriak *et al.*, 2003; Moulin *et al.*, 2005; Chaboureau *et al*, 2012). More specifically, most paleogeographic restorations (e.g., Scotese, C.R., 2014) show that the Argentina/Uruguay margin and the South Africa/Namibia margin were attached. During the Lower Cretaceous, the rifting process and later opening of the Atlantic Ocean drifted apart these margins. Thus, the offshore of Uruguay (Punta del Este and Pelotas basins) and Namibia (Orange basin) are conjugate margins that share a common geological history, particularly during the Lower Cretaceous. At this period, oceanic crust was being generated for the first time in the proto-Atlantic Ocean and the first marine ingression (Aptian) developed and deposited hydrocarbon-prone shales (Junslager 1999). Regional seismic lines on both sides of the Atlantic (Uruguay/Namibia) allowed to clearly identify this first marine sequence (Penn, *et al.*, 2016) that represent a world class source rock. This Aptian source rock is responsible for the large oil accumulations associated with Venus and Graff wells (Hedley *et al.*, 2022) offshore Namibia. Also, comparing the stratigraphy and geometry of the basins on both sides of the Atlantic, it is apparent that these basins have a similar evolution, stratigraphy, and geometry. Particularly, during the Post-rift phase (Aptian to Cenozoic) several deep marine depositional systems (turbidites) were developed in the offshore of Uruguay, that are recognized in seismic sections (Gristo *et al.*, 2021). This Cretaceous turbidite play has been de-risked for the region due to the recent discoveries of Venus and Graff offshore Namibia.

The Punta del Este and Pelotas Basins are made up of extensive depositional sequences (Stoakes *et al.*, 1991; Ucha *et al.*, 2004; Morales *et al.*, 2010; Soto *et al.*, 2011). Morales *et al.*, (2017), recognize four mega-sequences: 1) Pre-rift of Paleozoic age, 2) Syn-rift, developed during the Late Jurassic to Lower Cretaceous and represented by half grabens and SDRs, 3) a Transition phase between tectonic and thermal subsidence (from Barremian to Aptian) & 4) Post-rift (since Aptian to present day) where the sedimentation is controlled by eustatic changes in the sea level.

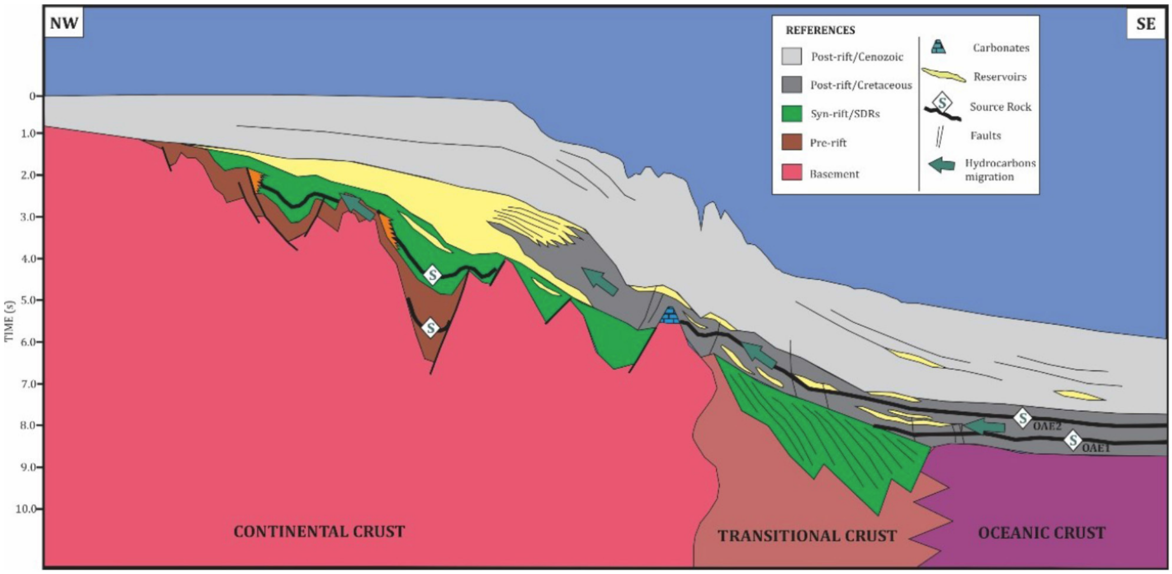
The same authors indicate that the Pre-rift and Syn-rift, as well as the transition and Cretaceous Post-rift sequences of the Punta del Este and Pelotas Basins show evolutionary differences, while the Cenozoic post-rift sequence is more homogeneous in both basins.

Petroleum system

The petroleum systems are described in a conceptual manner for both basins based on recent works by Conti *et al.*, 2017; Arnemann Batista 2017; Morales *et al.*, 2013-2017; and joint ANCAP and Science Faculty studies (Fig. 4). Note that there is limited well information since only three wells have been drilled in the Uruguayan offshore basins to date, and these are – Lobo X-1, Gaviotín X-1 and Raya X-1. The main characteristics of the potential petroleum systems present in each sequence (including source rock, reservoir, seal and trap mechanisms) are summarized below.

The Pre-rift sequence has potential for organic rich marine shales with TOC ranging from 3.6% (Devonian) to 12% (Early Permian) based on onshore well data (Veroslavsky *et al.*, 2003). Both source rocks are known to be immature in the onshore Norte Basin (part of Paraná Basin). However, they are expected to be gas prone offshore due to the thick overburden. The migration pathways are anticipated to be related to faults associated with the extensional phase of the rift. The traps are likely to be mostly structural such as rotated fault blocks and anticlines. The reservoir rocks are expected to be fluvio-deltaic and aeolian sandstones of Lower and Upper Permian age accordingly (Veroslavsky *et al.*, 2003). The main sealing rocks are Permian and Mesozoic shales and some Lower Cretaceous basalts. Source rocks presence, reservoir quality and seal integrity are the major risk factors of the Pre-rift sequence petroleum system.

The Syn-rift sequence is very well developed in the Punta del Este Basin, with grabens and half-graben structures reaching sediment thicknesses of 3 to 4 kilometers. The source rock for this sequence is represented by Hauterivian to Barremian lacustrine shales (Veroslavsky *et al.*, 2004) which developed in the depocenters of the grabens. Their seismic characteristics of parallel and low amplitude reflectors can be easily recognized on sections. The reservoir rocks are associated with alluvial and fluvial sandstones interbedded with the lacustrine shales. The most typically recognized reservoirs of this sequence are stratigraphic traps associated with variations of facies in pinch out sequences and alluvial fans. The shales serve simultaneously as source rocks and intraformational seals. The migration of hydrocarbons should be vertical due to direct contact of the source and reservoir rocks. The main risk factors for this sequence are the presence of the



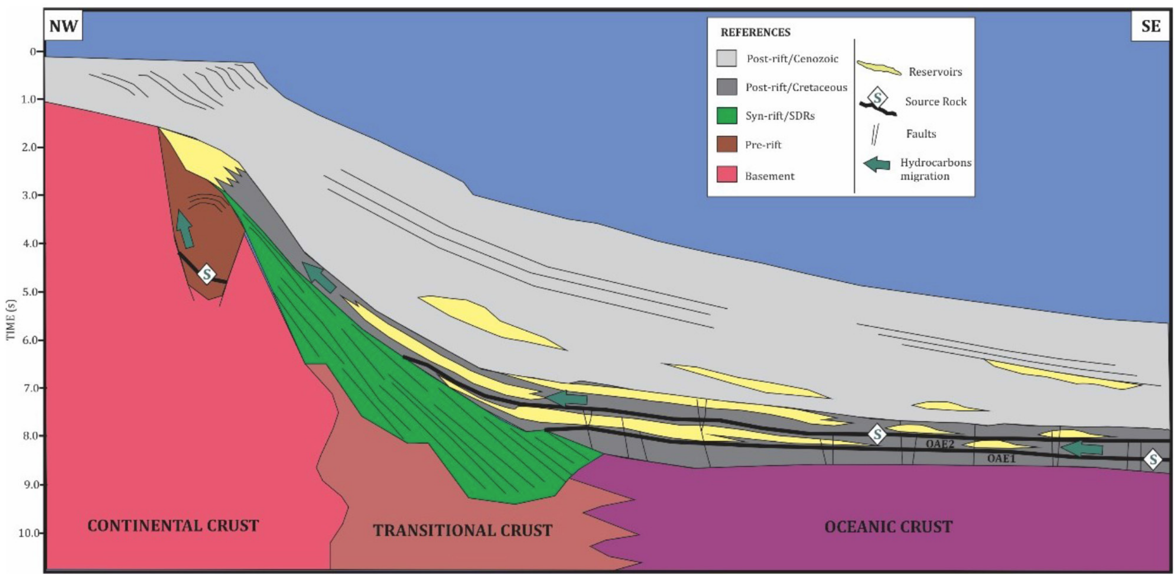


Figure 4. Schematic geological sections of Punta del Este (top) and Pelotas (bottom) basins. Source: ANCAP, Exploración y Producción, (2021), Evaluación de Recursos Prospectivos de Petróleo y Gas en Uruguay.

source rock and seal integrity. The AJ1 well oil discovery (Paton *et al.*, 2007) and the soon to be drilled Gazania prospect are both in the analogous sequence in the Orange Basin of South Africa (Blok-2B, 300 km from North of Cape Town).

The Post-rift sequence includes Aptian and Cenomanian-Turonian marine shales with high organic matter content as the main source rocks. Potential reservoirs of the Post-rift sequence are mostly Cretaceous and Cenozoic sandstones associated with turbidite facies, marine channels and fans which are well developed in the deep and ultra-deep parts of the basins. The migration mechanism is associated with vertical normal faults. However, the migration pathways are a key risk, especially for Cenozoic reservoirs as the Raya X-1 well demonstrated (ANCAP 2020).

The Raya X-1 well drilled a 135 m thick turbidite Oligocene sandstone with good porosity but no hydrocarbons, presumably due to the lack of migration pathways that connect the Cretaceous source rocks (Aptian, Cenomanian-Turonian) with the Cenozoic reservoirs. However, the multi-billion barrels oil Graff and Venus discoveries were made in the same sequence (Aptian and Santonian reservoirs) and type of play on the African side of the margin (Hedley *et al.*, 2022). This, together with the identification of a thick and widespread Aptian marine shale, with source rock characteristics, makes the Post-rift sequence very prospective in the offshore basins of Uruguay.

RESULTS

Since the seismic method is based on measuring sound propagation through subsurface, metrics such as rock density (Rho) and the speed of sound propagation in those rocks are key properties for understanding a reservoir. Attributes such as P-impedance (Ip) and ratio between P and S wave velocities also known as Vp/Vs are common attributes used in reservoir characterization. The Ip is the product of density (Rho) and P-velocity (Vp) of a rock. Similarly, the product of density and S-velocity is the S-Impedance (Is).

$$Ip = Rho * Vp \quad (1)$$

$$Is = Rho * Vs \quad (2)$$

Rocks that have a low density (Rho) and / or a slow Vp would have a low impedance. A low Rho and / or low Vp can sometimes be associated with presence of hydrocarbons in the pore space of a rock (Castagnha, J., Smith, S., 1994). This is because oil or gas are less dense and slower (in terms of sound propagation) fluids than water. However, a low Ip can also be related to a lithology change. In this regard, an additional attribute that is less sensitive to hydrocarbons is required in order to reduce the uncertainty. The shear velocity of a rock also known as S-velocity or Vs is not sensitive to fluids in the pore space. Thus, its derivative - Is - is a useful attribute for understanding lithology changes. Furthermore, a ratio between Ip and Is or Vp and Vs should be a good discriminator for possible fluid changes.

$$Ip / Is = Rho * Vs / Rho * Vs = Vp / Vs \quad (3)$$

Subsequent combination of attributes such as Ip and Vp/Vs can be a powerful tool for minimizing risks when searching for possible leads in an area. The authors must warn though that the mentioned above attributes and their combinations can have their own flaws. For example, a small percentage of gas dissolved in brine can create an anomaly on both attributes which could be misinterpreted as a HC anomaly. Also, seismic tuning effects can cause false bright responses.

The relative Ip (rel.Ip) and relative Vp/Vs (rel.Vp/Vs) were produced through an AVO workflow. An example shown on the Figure 5 shows a joint interpretation of these attributes. The displayed surface is a windowed rel.Vp/Vs amplitude extraction along an interpreted horizon (at ~6.5-7 km) in the Lower Cretaceous interval. The red, yellow and orange colors correspond to low rel.Vp/Vs, indicating possible presence of hydrocarbons. The contrasting colors green and blue are high values designating areas with low probability of hydrocarbon occurrence. Dotted black lines have been added to the map delineating a possible marine sand fan reservoir. It is promising that the low relVp/Vs readings are clustered within the outline of the interpreted feature. Also, note that a yellow arrow in the bottom right corner of the image points to an anomaly which is restricted by a fault. This anomaly is only present in the upper block and thus less likely to be caused by a lithology change than by pore fluid content.

The seismic section crossing the horizon in Figure 5 is an overlay of the rel.Ip in grayscale and rel.Vp/Vs as a color drape on top. Multiple arrows point to anomalies in the mid-section that belong to the same geological unit. However, the anomalies are laterally separated from each other. Two conclusions can be made from this observation: First, the anomalies are stratigraphically bound and secondly, this could be a single feature coming in and out of the section. It is important to know that the Graff discovery was made in an analogous deep water sand channel setting (Hedley *et al.*, 2022).

The shallower part of the section shows a prominent water bottom simulating reflector – BSR. The event tends to be parallel to the water bottom irrespective of actual lithology beds it is crossing (see the blue arrow). BSR usually signals the presence of gas hydrates which could be of exploration value (Max, *et al.*, 2006). In addition, according to these authors, BSR can serve as an efficient seal for underlying shallow gas accumulations. Note that the red arrow points to a bend down seismic event below BSR. Such type of feature is also known as pull-down effect. Normally, it is caused by the presence of gas which slows down the P-waves and creates a characteristic smile-like feature on the section.

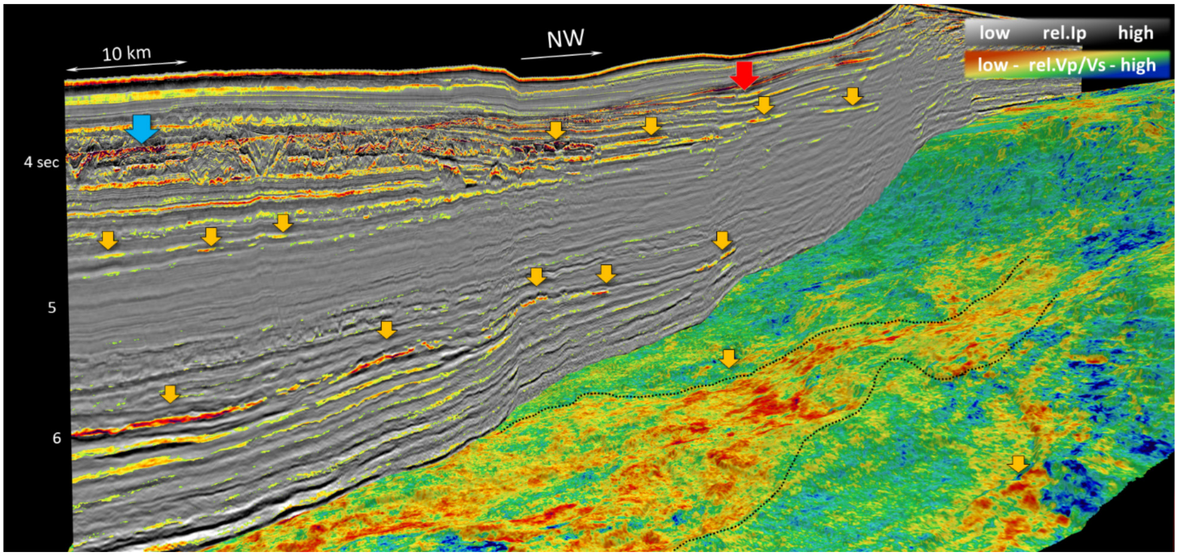


Figure 5. A windowed relative Vp/Vs amplitude extraction along an interface from a Lower Cretaceous interval. The section is an overlay of the relative impedance in grayscale and relative Vp/Vs as a color drape. Clearly seen on this image are BSR, shallow gas anomalies, a channel feature in the mid-section and a possible fan outline on the map.

The Machine Learning outcomes provided access to hundreds of tracked surfaces. The entire ~15600 square kilometer area was scanned to identify possible reservoir fairways that would be good candidates for further analysis. The above-mentioned mid-section anomalies are better seen on Figure 6. In fact, the anomalies seem to belong to the same turbidite complex. The extracted event has similar seismic waveform response where the colors are bright. However, the darker areas indicate that the seismic character starts to change significantly compared to the bright areas. Thus, it is easy to comprehend areal limits of the identified feature.

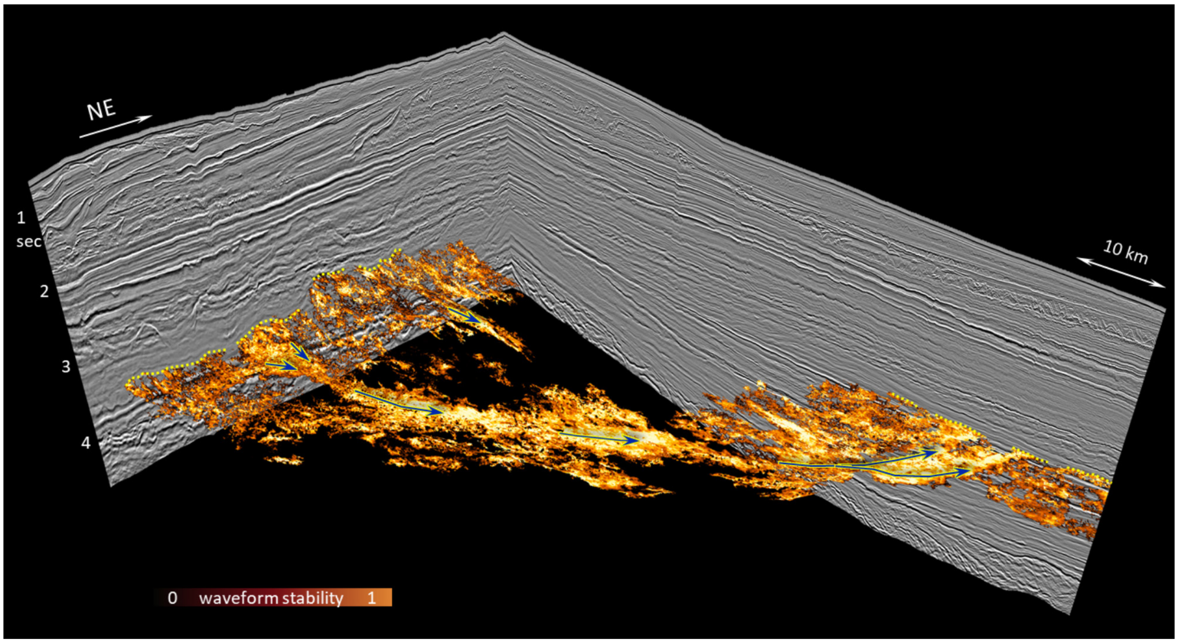


Figure 6. The extracted ML attribute - waveform stability metric. This attribute can be used for tracking possible lithology changes, structural patterns or even geo-bodies. The presented feature can be interpreted as a possible turbidite complex.

The key surface extracted with help of ML is shown on the Figure 7. It is a display from Lower Cretaceous interval with some notional interpretation. It shows details of multiple turbidite fan geometries and feeder channels present in the area. The identified features are converging towards the deeper water edge of the survey suggesting that their predominant clustering happens within the extent of this seismic survey. Finally, the display on Figure 8 is another feature approximately 750 km^2 in size, extracted from the interval where leads analogous to Graff may occur. Blue arrows indicate the direction of the sediment dump, and the yellow dotted lines show the interval where the attribute was extracted from. The green arrows point to the regional erosional unconformity. It is possible that the displayed turbidite features were exposed to the erosion too. That is why some of them are fragmented e.g., the event on the right-hand side of the display. A channel character can be seen on the seismic section however some part of the channel is missing and only a part of it is preserved in the deeper portion.

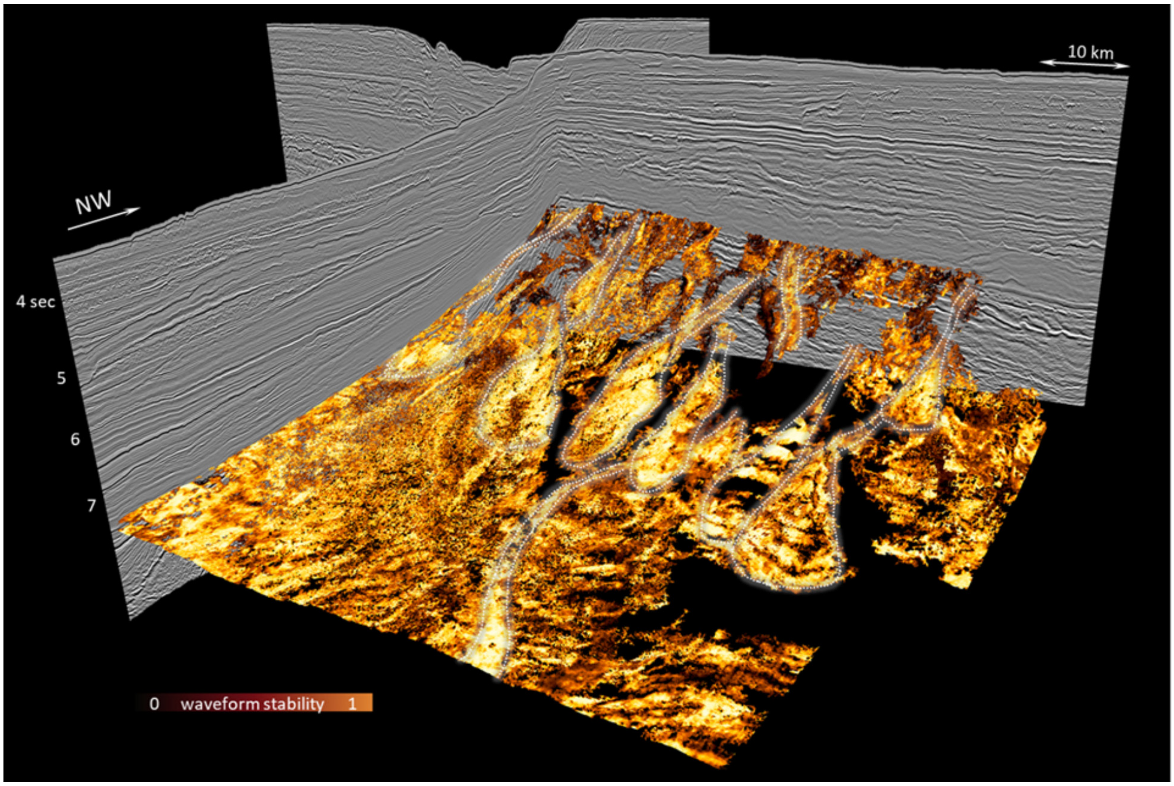


Figure 7. A waveform stability map from Lower Cretaceous, indicating possible presence of a well-developed complex of turbidite fans and channels in the study area. Some of these features could be potential stratigraphic analogues to the Venus discovery.

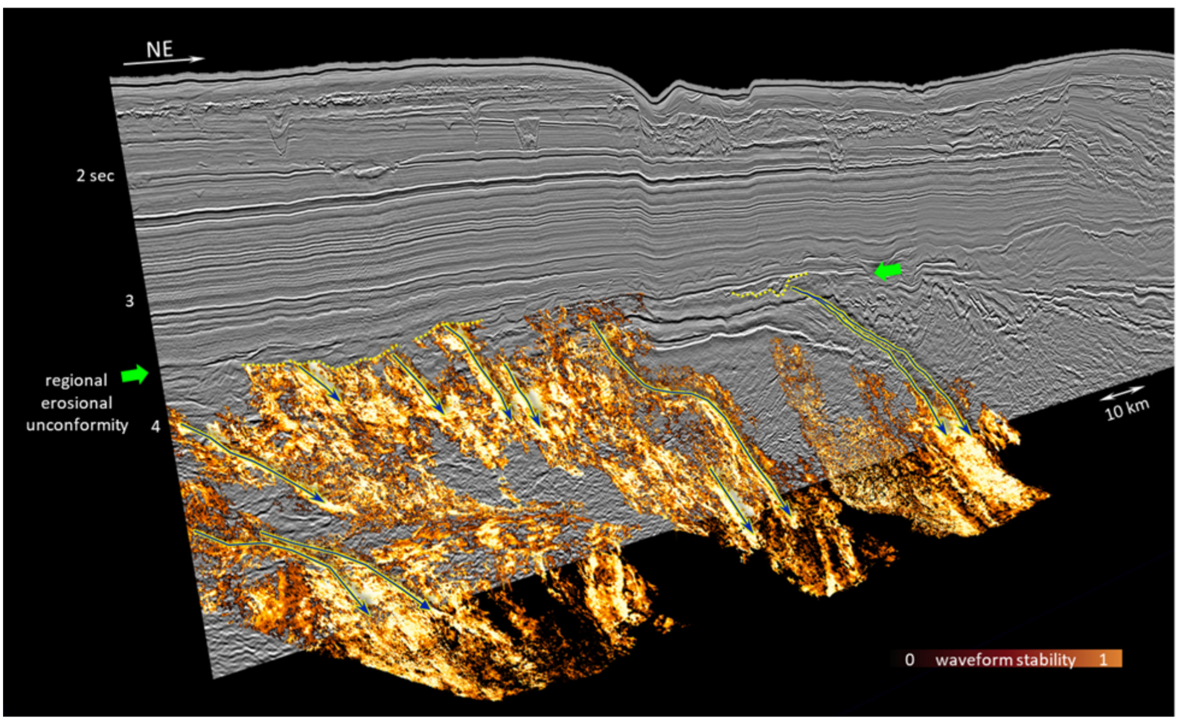


Figure 8. Same attribute corresponding to seismic trough extracted from the interval where opportunities analogous to Graff may occur. It shows possible laterally extensive turbidite features.

It is important to mention that the presented ML maps are quite different from the traditional windowed attributes like Average, Minimum, Maximum and Root Mean Squared amplitudes (RMS). The last are normally cleaner but demonstrate a mixed response from an interval. On the contrary the ML attribute presented in this paper shows extreme detail at a seismic sample level. There is a bit of a noise present in the displays however, there is no averaging, conditional sorting, or mixing of the seismic character in a window. This results in preservation of the fine detail of the identified features. Thus, the ML method demonstrated in this paper can serve as a useful tool for mapping complex stratigraphic prospects.

CONCLUSION

The main goal of this work was to investigate if Punta del Este and Pelotas basins offshore Uruguay contain promising stratigraphic traps in the Syn-rift and Post-rift sequences. The presented AVO based seismic analysis, as well as the application of the ML for detailed tracking of seismic reflectors, have proven to be very efficient tools for screening seismic data within the study area. Prospective sedimentary environments such as turbidite channel complexes and fan systems were identified. Their stratigraphic levels are analogous to those of Venus and Graff discoveries as well as the Gazania lead in the Orange Basin.

Most of the reservoir fairways identified in the area have a stratigraphic component for hydrocarbon trapping. However, the main risks of the petroleum systems in each basin are both the trapping mechanisms and migration pathways. Given the lack of well data and the named risks, it is crucial to extract the most out of existing or future seismic data. The AVO methodology and the latest advances in the ML will also be of great help in studying the source rocks in more detail.

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