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REMAINING PETROLEUM POTENTIAL OF BRAZIL – STATE OF THE ART 2023

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ABSTRACT

Petroleum and its byproducts will continue to be humankind's primary energy source for at least 50 years. Brazil is already one of the main suppliers of this raw material and will continue as such for the next decades. Several large sedimentary basins in Brazil are practically untouched by exploration, especially in the deep and ultra-deep water realms. There are also large tracts of unexplored areas in basins that already have discoveries, reserves and hydrocarbon production. The objective of this work is to make predictions about the remaining petroleum potential of the Brazilian basins. The predictions are made based on the big data bank acquired by the petroleum industry in Brazil in the last 83 years, based on the most updated concepts in petroleum geology, and mainly on my 45 years of experience as an explorationist. Our final forecast for the remaining petroleum potential of Brazil lies in the range of 50-100 billion barrels of oil equivalent recoverable (boer) (prospective resources, already identified or not, but still needed to be discovered). The basins that will contribute the most to realizing this potential are Santos/Campos, Pará-Maranhão/Foz do Amazonas/Barreirinhas, Pelotas and Paraná; besides, in a lesser scale, but still significant, Sergipe-Alagoas, Espírito Santo, Camamu-Almada, Solimões and Parnaiba. We are perfectly aware that Geology is a complex and astounding science. New data, innovative new technologies and creative concepts never formulated can quickly destroy these predictions, for better or worse.

Keywords: Petroleum potential; Predictions; Sedimentary basins; Brazil.

RESUMO

POTENCIAL PETROLÍFERO REMANESCENTE DO BRASIL – ESTADO DA ARTE 2023. O petróleo ainda será a principal fonte de energia da humanidade por, no mínimo, 50 anos. O Brasil já é e certamente será um provedor ainda mais importante desta matéria prima durante décadas. Há muitas bacias com grande potencial ainda intactas e muitas áreas ainda não exploradas em outras que já possuem reservas e produção. O objetivo deste trabalho é fazer previsões sobre o potencial petrolífero remanescente das bacias sedimentares do Brasil. As previsões são feitas com base no enorme acervo de dados acumulado nos 83 anos de história da exploração petrolífera brasileira, com base nos conceitos mais atualizados da ciência da geologia do petróleo, e, principalmente, com base em minha experiência de 45 anos de atividade no ramo. Nossa previsão final, para o potencial remanescente de petróleo (potencial de recursos prospectivos, identificados ou não, mas ainda não descobertos) de todas as bacias brasileiras fica na faixa de 50-100 bilhões de barris de óleo equivalente recuperável (boer). As bacias que mais deverão contribuir para a realização deste potencial serão Santos/Campos, Pará-Maranhão/Foz do Amazonas/Barreirinhas, Pelotas e Paraná. Em menor escala, mas ainda importantes, Sergipe-Alagoas, Espírito Santo, Camamu-Almada, Solimões e Parnaiba. Temos plena consciência de que a Geologia é uma ciência complexa e surpreendente. Dados novos, tecnologias inovadoras e conceitos criativos nunca dantes imaginados poderão facilmente destruir (para melhor ou para pior) tais previsões.

Palavras-chave: Potencial petrolífero; Previsões; Bacias sedimentares; Brasil.

1 INTRODUCTION

Petroleum (liquids of oil + natural gas, in the classic original definition here employed) was the most important source of energy for humankind throughout the 20th century and it will continue as such for, at least, until the mid-21st century. Countries that hold important reserves of this resource will always have a strategic and economic advantage over countries that are dependent on the import of oil and gas. Brazil has achieved in the last four decades a comfortable level of reserves and production of oil and gas, rising to the category of oil exporter and great consumer of natural gas. The country is nowadays the seventh largest producer of oil in the world. Brazil was catapulted from the position of insignificant player up to the major league of oil and gas, firstly, thanks to the discovery of several fields and giant fields in turbidite reservoirs in the 1980s and 1990s, mostly in the Campos Basin. As the production of oil from the turbidite fields started to dwindle at the turn of the century, Brazil renewed his portfolio in the last two decades with the sensational discoveries of the Pre-Salt super-giant and giant oil and gas fields in the Santos and Campos Basins. Tables 1 and 2 present the most common units of volume of oil and gas as well as the classification of petroleum fields according to the recoverable volumes contained in them; that will be used throughout this work. The average daily Brazilian production of oil and gas in 2023 was 4.344 MMboed, oil being 3.402 MMbopd and gas 150 MMm³pd (Boletim Mensal da Produção de Petróleo e Gás Natural da ANP, December 2023). Brazilian reserves of oil at the end of 2023 topped 15.984 Gbo (1P) and 517.077 Gm³ of gas (1P). The overall yearly oil production achieved 1.242 Gbo, consequently, the R/P (ratio between reserves and yearly production) equaled 12.80 (Boletim de Recursos e Reservas de Petróleo e Gás Natural da ANP, 2023). Brazil exports circa 31% of its production and imports the equivalent of 14% (IBP, April 2023). Due to logistical/operational constraints in its refineries, the country needs to import certain quantities of light oil, some petroleum derivatives and gas. The huge reserves of lighter oil and gas found in the Pre-Salt fields will significantly decrease the necessity of imports of petroleum.

This work aims to provide an updated view of the upstream segment (exploration + production) of the petroleum industry in Brazil and, most importantly, a perspective on the opening of new exploratory frontiers and of the possibility of future discoveries of significant reserves of oil and gas in the country. This work will deal with Prospective Resources (those already identified by indirect means, such as seismic data, or extrapolated based on previous knowledge; but not confirmed yet by well perforations). Such resources have already been mapped or pinpointed one way or another and

TABLE 1 – Units of volumes of oil and gas most employed in the petroleum industry that will be used throughout this work. The horizontal lines indicate the conversion between them. The energy equivalence of gas to oil is expressed as oil equivalent, and it allows for presentation in a single number of combined reserves or productions of oil and gas.

OIL					
VOLUME UNIT	(value)	SYMBOL	VOLUME UNIT	(value)	SYMBOL
cubic meters	1,0	m³	barrels	6,29	b
barrels	1,0	b	cubic meters	0,159	m³
barrels	1,0	b	liters	159,0	l
GAS					
VOLUME UNIT	(billion)	SYMBOL	VOLUME UNIT	(billion)	SYMBOL
cubic meters	1,0	m³	billions cubic feet	35,31	BCF, bcf
billions cubic feet	1,0	BCF, bcf	cubic meters	0,028	m³
ENERGY EQUIVALENCE OF GAS IN BARRELS OF OIL EQUIVALENT					
billions cubic feet gas	1,0	BCF, bcf	thousands barrels oil equivalent	≅ 166,7	boe
billions barrels oil	1,0	b	trillions cubic feet gas	6,0	TCF, tcf
Commonly, the oil companies present their reserves or productions of oil and gas by adding the volume of oil in barrels with the energy equivalent of the gas in oil barrels. This final single result is expressed in barrels of oil equivalent **(boe)**					

TABLE 2 – Units of oil and gas production most employed in the petroleum industry. Classification of oil fields according to their reserves. "Barrels of oil equivalent" is helpful, in the case of gas fields non-associated with oil, to perform the inversion of the energy equivalent of the volume of gas. The classification "big field" is not very used in the industry.

PRODUCTION OF OIL		**PRODUCTION OF GAS**	
barrels of oil per day	bopd bod	cubic meters per day	m^3pd m^3d
		cubic feet per day *standard cubic feet per day*	cfd scfd
COMBINED PRODUCTION OF OIL AND GAS			
barrels of oil equivalent per day (boed)			
CLASSIFICATION OF OIL FIELDS ACCORDING TO RESERVES			
Oil Field	Recoverable resources higher than (boer)		
BIG	100 million boer		
GIANT	500 million boer		
SUPER-GIANT	5 billion boer		
The largest oil field in the world, Ghawar, located in Saudi Arabia, is estimated to have original reserves (produced and to be produced) of *circa* 133-140 billions of boer			

should, through the next three decades, be explored, confirmed by drilling of wells and, once developed; provide the energy and petrochemical necessities of the country as well as extraordinary financial revenues to help in the development of Brazil.

Despite all global efforts in the implementation of alternative energies (solar, wind, biofuels, hydrogen, geothermal, CCSU) as substitutes for fossil fuels (petroleum and coal), trying to show them as trustworthy and economically viable, their contribution to the energy matrix continues to be minor, even when projected for long periods of time. The 2023 edition of *BP Energy Outlook*, published annually by British Petroleum, indicates the continuation of the world´s heavy dependence on fossil fuels until at least 2050. Three different scenarios for the global consumption of energy, based on the technologies presently known and on the countries' willingness regarding the velocity of implementation of the utilization of alternative energies, were considered. The first two scenarios, *Accelerated* and *Net Zero*, are broadly in line with the Paris Agreement COP-21 (2015) and the scenarios outlined by the IPCC (*Intergovernmental Panel on Climate Change* of the United Nations). Such scenarios are strongly "optimistic" regarding the rapid and extensive implementation of alternative energies, the strong decay in the use of fossil fuels, and the increasing effectiveness of CCSU (carbon capture, storage and utilization) initiatives. The third scenario, *New Momentum*, traces the trajectory of the global energy system, taking into account the present conditions and velocities of implementation. The projections out to 2050, according to these three scenarios, indicate the use of fossil fuels in the range of 20% to 60% of global energy demand. If the willingness of the countries and major players in the implementation of the use of alternative energies continues at the present pace, in 2050, fossil fuels will still dominate the global energy matrix. Since this is a very realistic scenario, the implication is that investments in the exploration and production of petroleum will continue and will be necessary to supply the great and persistent global demand for energy for decades.

We can see signs of the predominance of this third *New Momentum* scenario everywhere and every time. The results published by all three-quarters of the major petroleum companies in 2023, including Petrobras, have shown record-breaking numbers one after the other. The revenues and earnings resulting from the increased production of oil and gas reserves are as rewarding as never before. As a result, the companies indicate increasing allocation for investments in accretive initiatives, that is, exploration. The accrual of acreage with a high potential for new discoveries of significant volumes of petroleum continues to be the main focus of the petroleum industry. The projections for global energy demand keep growing, and there is no way to supply it reliably and economically profitablly other than by using fossil fuels, especially oil and gas. All enterprises involving renewable energies need strong subsidies from the government to be economically feasible. Another good indicator that all the initiatives regarding the effective use of alternative energies are predominantly in the talk mode rather than in the implementation mode is that there are no jobs in the market for the army of young people who educated themselves for such tasks. There are also no jobs for the more experienced army of laid-off workers in the petroleum industry, to whom new opportunities in the emerging alternative energies market were promised (GEOExpro, 7 November 2023). Where heavy investments in these energies were made, heavy losses came by. For instance, on 15 November 2023, Siemens Energy reported a 4.59-billion-euro ($5-billion) annual loss, dragged down by a crisis in its wind power unit, a day after a government-backed rescue package was unveiled for the German group. There are, of course, several histories of success in the implementation of solar and wind farms here and there, but they represent only tiny drops of energy in a gallon bucket of the global energy matrix…now and for decades to come. Scenarios of low or zero carbon by 2030 and 2050 are absolutely not realistic!

In Brazil, Petrobras, the largest holder of petroleum reserves booked, by the end of 2023, proved reserves of 10.873 billion barrels of oil equivalent according to SEC (*US Securities and Exchange Commission*) criteria, of which 84% is oil and 16% gas. The company's proved reserves of oil topped 9.210 Gbo (1P, those already developed and in production or ready to be developed) and 9.335 TCF of gas (1P). The overall yearly oil production achieved 817.6 MMbo, consequently, the R/P (ratio between reserves and yearly production) for oil equaled 11.3. For the horizon of 2050, there are 15.7 years without reserves necessary to support any petroleum production. That means the company MUST invest quickly and strongly in exploration to remain an important player in the global energy matrix for at least the first half of this century. Petrobras should follow the tide of major companies' investment in exploration that looms in sight to avoid running out of oil and gas reserves. Having that purpose in mind, contingent resources already discovered and the prospective resources not yet discovered will have to be found/appraised/developed to turn into 1P reserves. Intensive seismic acquisition and abundant drilling of exploratory wells must be in order in the following decades. Only with the booking of reserves (certifiably producible resources) will the company survive as a major global petroleum company up to 2050.

This low R/P scenario is widespread among international oil companies (IOCs, such as ExxonMobil, Chevron, BP, Total and Shell) and several other national oil companies (NOCs, such as Petrobras, Pemex, Ecopetrol). This work strongly points out that petroleum exploration activity (mapping, drilling, discovering and delineating hydrocarbon accumulations) will be kept steady, if not increased, for several decades ahead. The future increasing global demand for energy petroleum will have to be matched in great part by these future discoveries of petroleum fields. This review article intends to pinpoint and discuss the areas in the Brazilian sedimentary basins presenting the greater probabilities of significant discoveries of oil and gas production (Figure 1) for the next 30 years. We tried to do that by consolidating the exploratory and production results achieved in Brazil during the last 83 years (2022-1939), summing up the knowledge thus acquired and spicing it with my experience of 44 years in the petroleum industry.

We are fully aware that a work like this one, which dares to make predictions, takes a significant risk of being denied or becoming outdated very soon. Niels Bohr, Nobel Prize winner in Physics, once said, "*Prediction is very difficult, especially if it's about the future!*". The elaboration of creative geological concepts, never before imagined, extreme economic conditions and new technologies of great impact would be able to change, in a short amount of time, the exploratory status of a basin from abandoned to a new world-class petroleum-producing province. The main message presented here is what Brazil can expect from the petroleum industry in the future based on current knowledge, let us say, the state of the art in 2023.

2 A SHORT REVIEW OF THE PETROLEUM GEOLOGY OF THE BRAZILIAN BASINS

From this chapter on, it is hereby declared that every and any mention of the stratigraphic nomenclature, depositional sequences and ages of the Brazilian sedimentary basins were totally or partially based upon the 31 stratigraphic columns published by Petrobras teams of geologists and geophysicists in the classic publication Boletim de Geociências da Petrobras (BGP), 2007, volume 15, number 2, edited by MILANI et al. (2007). This article is a review of most sedimentary basins of Brazil. It would be an enormous and repetitive effort to mention a specific reference from that Bulletin

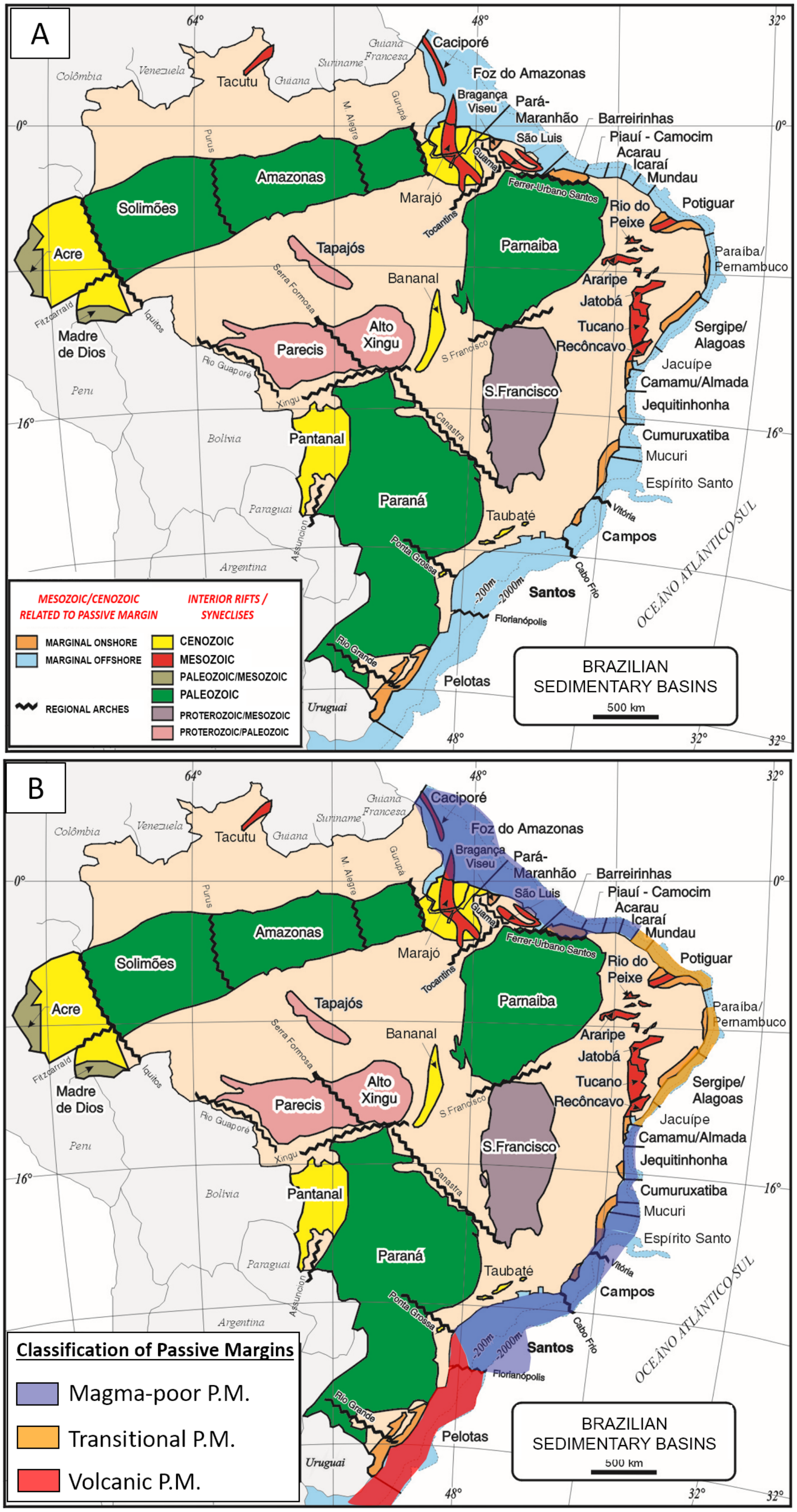

FIGURE 1 – Map showing the Brazilian sedimentary basins, classified according to (A) type and age, and (B) in the case of marginal basins, regarding their underlying crustal characteristics.

every time a stratigraphic name, interval, or age is mentioned. It is already established in the Brazilian geological literature that this number of the BGP is the most complete and updated source on the stratigraphic columns of the country`s sedimentary basins. We would like to express our recognition and gratitude to the dozens of authors and co-authors of BGP 15(2) and their implicit contribution to this article. We stress that nothing different from those articles regarding stratigraphic nomenclature was used in this work.

Brazil is situated upon the South American tectonic plate, on the divergent margin of the South American continent. The South American plate has four well-defined boundaries:

(i) One convergent plate margin along the entire western coast (Pacific) of the South American continent, where the tectonic plates Nazca and Antarctica are in frontal shock with the South American plate, creating subduction zones of the first two plates under the South American plate.

(ii) Two transform plate margins: to the north with the Caribbean plate and to the south with the Scotia plate.

(iii) One divergent plate margin to the east with the African plate, being the Mid-Atlantic Ridge the boundary between the two plates. This divergent margin contains the eastern half of the South American continent, from Venezuela down to Tierra del Fuego in Argentina. The Brazilian coastal region is entirely contained in this margin, with its territorial waters extending to the Economic Exclusive Zone's 200/350 nautical miles limits. It is always helpful to remember that the Brazilian continental margin was the divergent plate margin at the time of the breakup of the Gondwana supercontinent (Early Cretaceous), undergoing all the extensional tectonic stresses and strain characteristic of rifting areas (Rift Stage). As the Drift Stage started (Late Cretaceous), and up to nowadays, this continental margin became an intra-plate setting. Only salt tectonics and gravitational sliding disturbed the deposition of the sediments. For instance, the coastal town of Rio de Janeiro is in a central position of the South American plate, midway between the convergent boundary to the west (Peru-Chile Trench) and the divergent boundary to the east (Mid-Atlantic Ridge).

Consequently, the Brazilian sedimentary basins (Figure 1) are of two major types: (i) intraplate settings, Proterozoic/Paleozoic/Mesozoic intracratonic basins, and (ii) divergent margin settings, Mesozoic terrestrial aulacogens and Mesozoic/Cenozoic terrestrial/marine two-stage marginal basins (Rift and Drift phases). A sub-type of this second group is represented by the transtensional basins of the Equatorial Margin (oblique separation between Africa and South America).

2.1 Intracratonic basins

In the Brazilian hinterland, four major Paleozoic intracratonic basins predominate, followed by (in areal size) smaller Proterozoic and Mesozoic intracratonic basins. The Paleozoic basins, the most important in terms of onshore petroleum potential, present a sauce-shaped geometry with large extensions (hundreds of thousand km^2) and moderate to small depths (7-3 km). These basins were formed during long-lasting phases of cratonic stability of the supercontinent Gondwana, termed Stable Platform Phase (450-220 Ma), sub-phase Large Paleozoic Syneclises (450-250 Ma) (ZALÁN 2004). Such tectonic quiescence was interrupted from time to time by intraplate stresses originated at the Gondwana plate's distant convergent margins. As overall uplifts ensued, regional erosion followed and compartmentalized extensive depositional megasequences (ZALÁN 1991), such as Sloss' sequences or supersequences defined for the North American craton. The sedimentary deposition took place predominantly under extensive blankets of megasequences and their internal transgressive-regressive depositional sequences that wedge out laterally either by thinning or by erosional truncation. Three of such basins present nice surrounding belts of outcrops of their stratigraphic column (Paraná, Parnaíba, Amazonas), while the fourth (Solimões) is entirely covered and hidden underneath Cenozoic deposits.

The tectonic activity recorded in the intracratonic basins is normally of low intensity. Most strain is related to normal and transcurrent faulting. There is one important exception in the Solimões Basin. Due to its proximity with the northern (transform margin) and western (convergent margin) boundaries of the South American Plate the propagation of stresses originated in these borders into the craton created a transpressional belt that affects practically the entire basin. This Jurassic tectonism, dubbed Juruá Orogeny, a novelty in the geology of the Brazilian sedimentary basins, created several en échelon tranpressional folds that hold large reserves of gas and some oil/condensate (ZALÁN 2004).

Another very important type of deformation in these basins, also considered as non-conventional, are the spectacular structures developed by the numerous intrusive bodies of sills, laccoliths and others. They can be observed in outcrops and in seismic sections, and, as explained below, they can also hold commercial reserves of gas (ZALÁN et al. 1985a, CUNHA et al. 2012, MIRANDA et al. 2018).

All Paleozoic Brazilian intracratonic basins were affected by one or two events of large magmatic activity associated to LIPs (*Large Igneous Provinces*). In the north, the Solimões, Amazonas and Parnaíba Basins were covered and intruded by magmatic rocks of the CAMP LIP (Central Atlantic Magmatic Province, climax 201 Ma, local variations between 250-150 Ma, Mosquito Formation) (MIRANDA et al. 2018).This magmatic event was the precursor to the opening of the Central Atlantic Ocean. In the south, the Paraná Basin and vicinities (Pelotas Basin) were covered and intruded by basic to acid magmatic rocks of the Paraná-Etendeka LIP (concentration of ages in 134-133 Ma, variations between 145-127.5 Ma, Serra Geral Formation) (STICA et al. 2014). Similarly to the north, this magmatic event was the precursor to the opening of the South Atlantic Ocean. The Parnaíba Basin presents lavas and intrusions of this age as well (149.5-87 Ma, Sardinha Formation) (MIRANDA et al. 2018); however, instead of being related to the opening of the South Atlantic Ocean, this magmatic event ages seem to had been the precursor to the opening of the Equatorial Atlantic Ocean; the youngest of the 3 Atlantic Oceans mentioned in this paragraph.

2.2 Mesozoic aulacogens

The eastern portion of the Brazilian territory and the adjacent coastal region present several aborted Mesozoic rifts, remnant aulacogens from the opening of the South and Equatorial Atlantic Oceans (Figure 1). Their linear geometries and high-angle orientations relative to the littoral suggest they are the aborted branches of triple junction rift nucleations. They formed during the breaking of the Western Gondwana supercontinent during the Jurassic/Early Cretaceous.

Northeastern Brazil has the Recôncavo/Tucano/Jatobá, the onshore Potiguar aulacogens and several other smaller grabens such as Araripe and Rio do Peixe. There is evidence that points out that these presently isolated grabens were once part of a larger and continuous set of interconnected grabens linked to the larger remnant of the Potiguar onshore aulacogen and, maybe, even to the larger Jatobá/Tucano aulacogen (Figure 1). Continuous Cretaceous/Cenozoic epeirogenic uplift of the Borborema Province (Precambrian basement of northeastern Brazil) caused the gradual erosion and compartmentalization of these smaller grabens. Brazil can surely regret losing this once super-rift system to erosion since the petroleum system present in the Potiguar onshore aulacogen was very bountiful, having yielded significant oil and gas reserves. The Rio do Peixe graben still contains remnants of this petroleum system. Light oil similar to those found in the Potiguar onshore basin was found in water wells.

The sedimentary filling of these aulacogens starts with Paleozoic/Mesozoic strata, once part of large intracratonic blankets (Pre-Rift Sequences), trapped inside the grabens by the collapse that occurred during the rift phase. Early Cretaceous Syn-Rift Sequences comprise most of the filling. In a few grabens, thin Late Cretaceous Post-Rift Sequences cap the basins, erosional remnants of the overall epeirogenic uplift of the Brazilian northeastern precambrian basement. Exception is made to the Potiguar Basin that presents a perfect McKenzie steer’s head model sedimentary filling, with a narrow restricted but thick Syn-Rift Sequence, covered by an overflowing but thinner thermal Post-Rift Sequence.

In the Pre-Rift Sequences, one can find Late Jurassic/Neocomian red beds, sandstones, shales and claystones deposited in desertic to fluvial environments. In the Recôncavo Basin, the main reservoirs (Sergi and Água Grande Fms.) are found in this sequence. The rich and efficient lacustrine petroleum system of these aulacogens is entirely developed in the Syn-Rift Sequences. At the very base, Neocomian lacustrine organic-rich shales constitute the source rocks (Candeias Formation in Recôncavo, Pendência Formation in Potiguar, Barra de Itiúba in Sergipe-Alagoas). These source rocks are responsible for all the petroleum found in the onshore portion of the Recôncavo Basin and the majority found in the onshore Sergipe-Alagoas and Potiguar Basins. Prodeltaic clayey sediments that generate shale diapirs contribute both as seals and as traps to some of the structures containing petroleum fields. Prograding deltaic sequences containing sandstone reservoirs and prodeltaic turbidites constitute secondary reservoirs. The final phase of the rift stage is always the colmatation of the grabens by fluvial sequences. The structural styles found in the aulacogens are the classic ones of any rift: planar rotational normal faults and blocks, listric faults with rollover structures, sometimes associated with shale diapirism, and, in transfer zones, transpressional highs.

In northern Brazil, we have the Tacutu, Caciporé/Marajó and São Luís/Bragança-Viseu aulacogens (Figure 1). The first two are related to the Jurassic opening of the Central Atlantic Ocean and the Albian opening of the Equatorial Atlantic Ocean; the third group only to the Albian opening. Tacutu contains a Pre-Rift Sequence consisting of Jurassic basaltic lavas. Caciporé/Marajó is floored by pre-rift Triassic basaltic lavas and intercalated red beds. Their Syn-Rift Sequences are multiple and contain mostly terrestrial Late Jurassic/Neocomian to Albian sedimentary rocks. Tacutu contains marine evaporites suspected to be of Jurassic age (equivalent to the Louann Salt in the Gulf of Mexico). Caciporé/Marajó shows seismic indications of a syn-rift marine transgression of the Aptian age (Codó Formation). The normal faults in Caciporé/Marajó are also of two generations, formed during the two rift stages of the Central and Equatorial Atlantic Oceans. São Luís/Bragança-Viseu were formed as transtensional grabens related to the breaking of the São Luis Craton during the Albian oblique rift stage of the opening of the Equatorial Atlantic Ocean. These small grabens are rhombohedral and present en échelon normal faults and shallow depths. The sedimentary filling consists of an Aptian Pre-Rift Sequence (immature organic-rich shales of the Codó Formation) and an essentially Albian carbonate/clastic Syn-Rift Sequence. Until now, none of these aulacogens in northern Brazil have presented evidence of the existence of significant petroleum systems in their fillings.

2.3 Passive margin basins

Passive margins are presently classified as a spectrum of types between two extremes: Magma-Poor Passive Margins (MPPM) and Volcanic or Magma-Rich Passive Margins (VPM) (MANATSCHAL 2004; PÉRON-PINVIDIC et al. 2013, 2015, 2019; MANATSCHAL et al. 2014; ZALÁN 2014, 2015). VPMs develop exactly above or in the vicinities of mantle plumes or mantle-derived thermal anomalies that impinge underneath the continental crust of a mega-continent. As a result, the continental crust will be thermally softened/weakened, extended, fractured, hyper-extended, thinned, heavily intruded and covered by basaltic magmatism, and, finally, broken apart. The evolution of the concentration of extensional stresses happens towards the future final continental breakup, and so does the chronology of the formation of troughs. All syn-rift tectonic troughs (grabens) are filled with volcanic material, either basaltic lavas or their volcaniclastic deposits, under the form of sigmoid-shaped laterally aggrading syn-tectonic layers (growth strata) that aggrade and dip toward the future ocean. Such bundles of volcanic strata are called Seaward Dipping Reflectors (SDR) (Figure 2b). MPPM develop far away from these mantle-derived thermal anomalies/plumes, which are out of the influence of and free of the intense volcanism that afflicts the VPM. Consequently, the rifting process (extension, stretching, thinning, hyperextension) happens more moderately and more slowly. Volcanism during the Rift Phase of a MPPM may be null to intensive, but it will never be as abundant and prevalent as in a VPM. MPPM are characterized by predominantly sedimentary-filled rifts, absence of SDR, well-defined distinct crustal provinces (necking, stretching without thinning, stretching with thinning, resistates, hyperextension provinces), followed by mantle exhumation between the hyperextended province and the oceanic crust) (Figure 2a). VPM are characterized by volcanic rifts filled exclusively by SDR, a very wide zone of hyperextension intensively intruded by dykes (frequently erroneously called Transitional Crust) in abrupt contact with the oceanic crust, without an intervening exhumed mantle. These two end-members (MPPM and VPM) are the extremes of a spectrum of passive margins showing elements of one and the other. They are called Transitional Passive Margins (TPM) (ZALÁN 2017a) and are developed at intermediate distances between the VPM and MPPM. TPM are characterized by sedimentary-filled rifts transitioning laterally to volcanic-filled rifts (SDRs) towards the ocean (Figure 2c). The classification of the Brazilian sedimentary basins according to these characteristics is shown in figure 1B.

In this article, only the maritime (offshore) portion of the Brazilian marginal basins will be discussed. The emphasis will be on the *deep* (*water depths > 600 m*) and *ultra-deep* (*water depths > 1800 m*) realms since most of the petroleum potential lies in these regions.

Most Brazilian marginal basins are of the MPPM type (Figure 1B). From Santos to Camamu/

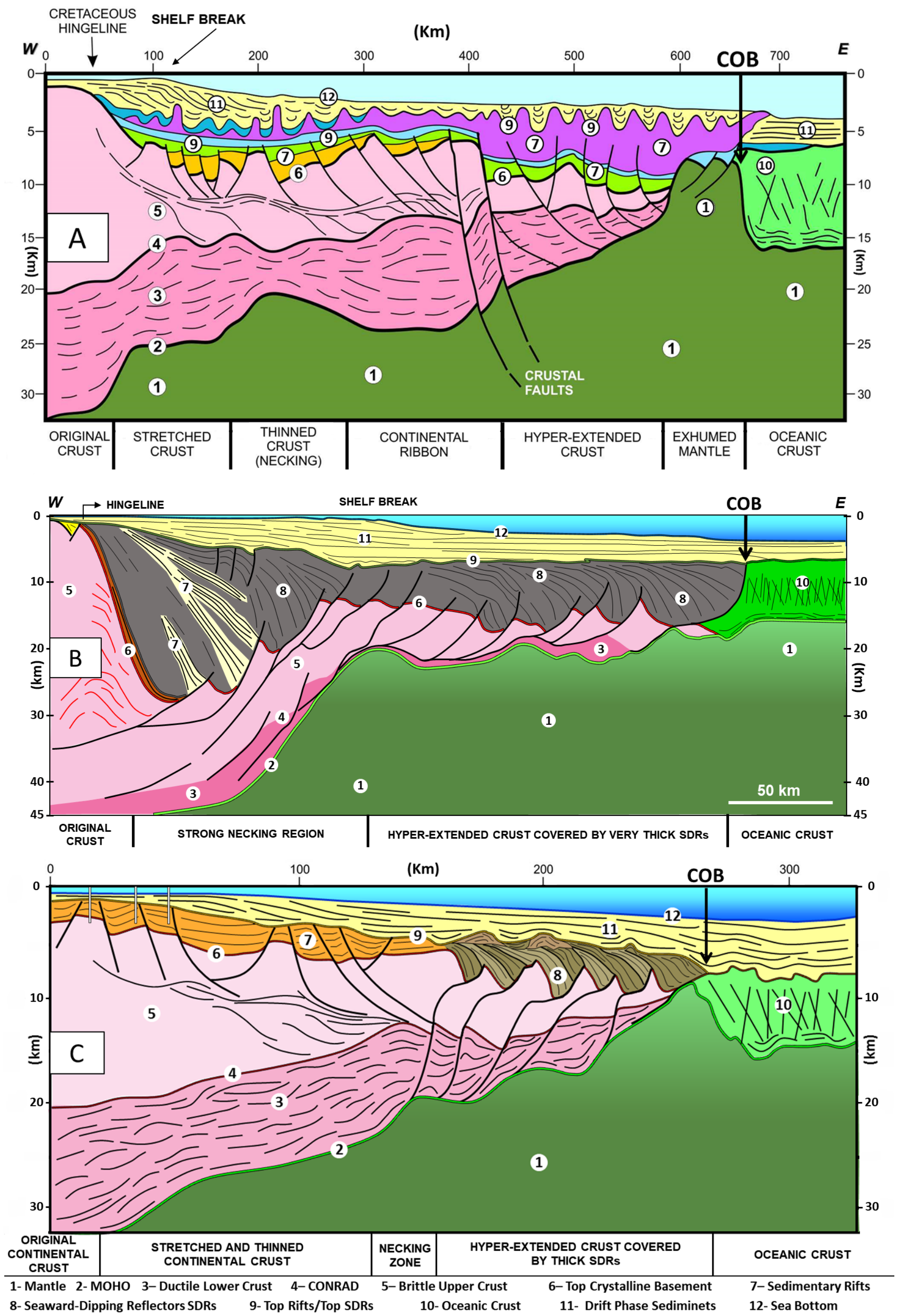

FIGURE 2 – Schematic geological sections of the three types of passive margins according to their crustal structure. (A) *Magma Poor Passive Margin*. It presents a taper continental crustal profile in the offshore direction, with localized neckings (H-Block) and thickening (Continental Ribbons or Resistates). Their grabens are predominantly sedimentary. Exhumation of the mantle occurs at the boundary with the oceanic crust. (B) *Volcanic Passive Margin*. It presents strong crustal necking in the proximal area. Their grabens are filled by SDR spilled over hyper-extended crust. There is no mantle exhumation. (C) *Transitional Passive Margin*. It presents a taper continental crustal profile overlain by sedimentary grabens in the proximal region, that changes into SDR-filled grabens in the distal areas. There is no mantle exhumation.

Almada in the State of Bahia and from the Acaraú sub-basin (in the Ceará Basin) to the Foz do Amazonas Basin in the northernmost portion of the Brazilian margin, all basins present similar crustal characteristics. All are devoid of SDRs, the Rift Sequences are predominantly of sedimentary nature and, when imaged by high resolution and good quality ultra-deep (recording down to 20-30 km depth) seismic sections, they present mantle exhumation between the hyper-extended crust and the typical oceanic crust. Figures 3, 4 and 5C/D display crustal-scale structural cross sections of the Santos/Campos/Espírito Santo and Pará-Maranhão Basins, respectively, illustrating such characteristics. In contrast, figures 5A/B in the Pelotas Basin present the full development of magnificent SDRs, a very strong necking in a proximal (to the littoral) position and a wide, strongly hyper-extended continental crust out to the contact with the oceanic crust (without intervening mantle extrusion).

The Brazilian MPPM basins can be sub-divided into three sub-groups:

(1) Santos-Campos-Espírito Santo: The formation of these basins is intimately linked to the development and opening of the South Atlantic Ocean, which took place in gradual and progressive stages, from south to north (zipper pattern). In a very simplified way, their tectonic-stratigraphy presents a Pre-Rift Sequence composed of basaltic lavas equivalent to the Serra Geral Formation of the adjacent Paleozoic Paraná Basin. A great portion of the Santos Basin is probably underlain by the entire Paleozoic/Mesozoic section of the Paraná Basin. During the Mesozoic, the Paraná-Etendeka LIP (Large Igneous Province) covered Paleozoic basins that continuously extended over terrains presently situated in Brazil and Namibia. Such Paleozoic sediments and Mesozoic lavas were probably captured by the Early Cretaceous breakup of the Western Gondwana supercontinent and preserved in grabens underneath the Santos Basin (ZALÁN 2017b). The Syn-Rift Sequence is of Barremian to Early Aptian age and is composed of argillaceous terrestrial rocks, lacustrine organic-rich shales and coquinas intercalated with occasional lava flows. Rifting was gradually halted at different times and locations in these basins followed by thermal subsidence with lesser amount faulting. By Late Aptian, several sag basins developed on top of the Syn-Rift Sequence, resembling the typical two-stage steer's head model for aborted rifts. These wide sags were filled by shallow hypersaline lakes, in which microbes flourished and led to the deposition of voluminous strata of microbialites (microbial carbonates) intercalated with occasional lava flows. Informally, these deposits are referred to as the "Sag Sequence" of the Pre-Salt. The continuation of the thermal subsidence into the Early Albian (circa 111 Ma) allowed the episodic invasion of seawaters coming from the north, creating a humongous and widespread evaporite sequence with original thicknesses of up to 2 km. By this time, residual faulting had moved to very distal positions to the east, where the final breakup took place, giving rise to the South Atlantic Ocean. A post-rift stage ensued under the strong influence of halokinesis, with the development of a thick and multi-compositional, essentially marine Drift Sequence (Albian carbonates, Late Cretaceous shales and turbidites, Cenozoic shales/turbidites/carbonates). The Pre-Rift and Syn-Rift Sequences display the classic structural style of rifts: planar rotational blocks and normal faults. The deformation of the Drift Sequence is intensive, mainly because of the halokinetic movement of the underlying salt (domes, diapirs, canopies) and associated normal listric faulting and gravitational sliding. For a good revision of the petroleum geology of the Santos Basin, the reader is referred to the works of SOUZA & SGARBI (2019) and BAPTISTA et al. (2023).

(2) Bahia Sul (Cumuruxatiba, Jequitinhonha, Almada, Camamu Basins): The formation of these basins is also linked to the development and opening of the South Atlantic Ocean in zipper pattern, from south to north. There are two major differences between this group of basins and the first, regarding the Pre-Salt sequences: The age of the Pre-Rift Sequence is Late Paleozoic/Triassic/Jurassic (red beds) and of the Rift Sequence is Neocomian, mimicking the stratigraphic column of the nearby Recôncavo aulacogen. The lithological compositions are essentially clastic, devoid of volcanic/evaporite/carbonate rocks, with rare spotty exceptions. The second difference is the duration of the rift stage that lasted from the Neocomian to the Early Albian (CAIXETA et al. 2014, 2015). Following the zipper pattern of the opening of the South Atlantic, the final breakup and insertion of oceanic crust in Bahia Sul happened around 104-100 Ma (CAIXETA et al. 2014) while in Santos-Campos-Espírito Santo around 112-111 Ma. The Drift Sequence of these basins is similar to that of previous basins in terms of lithology, stratigraphy and structural styles.

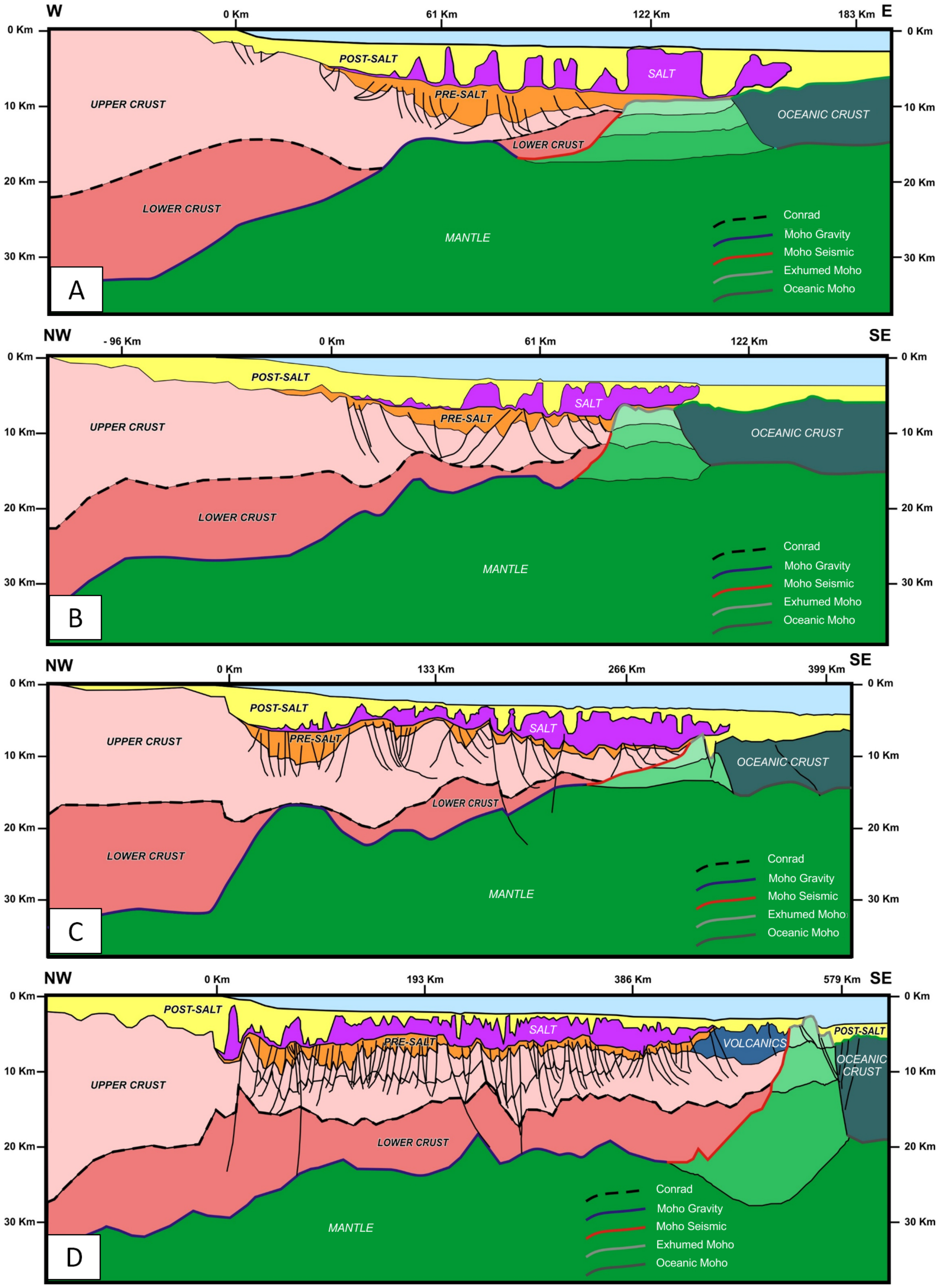

FIGURE 3 – From north to south, four transverse crustal profiles (considering from the base of the salt to the Moho) in the Espírito Santo Basin (A), Campos (B), Santos northern part (C) and Santos southern part (D) (ZALÁN et al. 2011). Notice the gradual widening of the continental crust from north to south, different modes of tapering, localized neckings and mantle exhumation in all of them. Green shades indicate different degrees of mantle serpentinization – interpretation based on ION seismic lines.

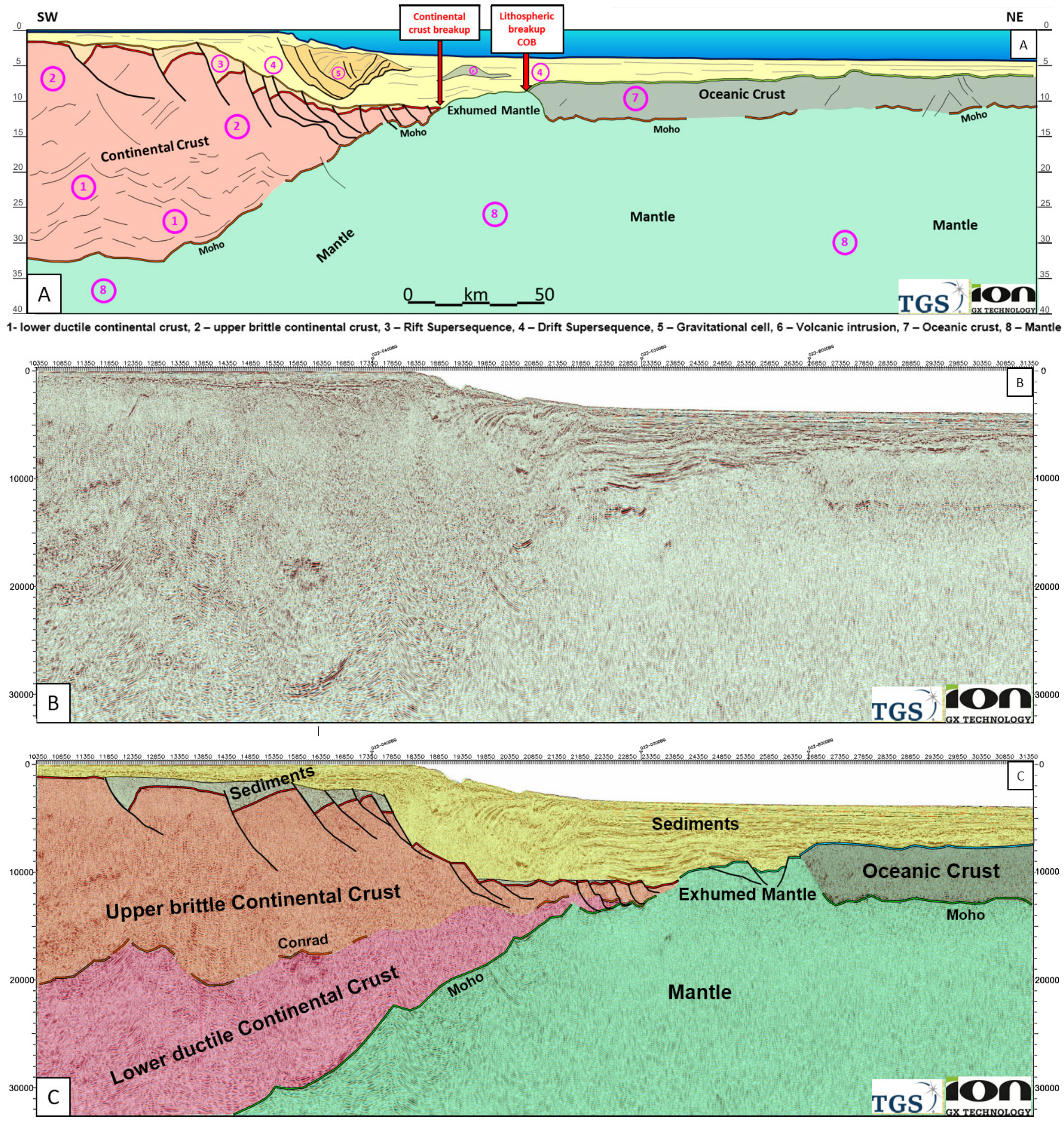

FIGURE 4 – (A) Transverse crustal profile of the Pará-Maranhão Basin, interpreted from a regional ION seismic section, partly shown below (ZALÁN 2015). (B) Zoom view of part of the seismic line without interpretation. Notice the clear expression of mantle exhumation between the taper profile of the continental crust (to the left, in shades of red below) and the tabular geometry of the oceanic crust to the right. (C) Seismic line interpreted. PSDM seismic section down to 33 km.

(3) Ceará (Acaraú and Piauí-Camocim sub-basins), Barreirinhas, Pará-Maranhão and Foz do Amazonas: the formation of these basins is linked to the development and opening of the Equatorial Atlantic Ocean, that took place in an overall oblique-slip stage during the Albian. Dextral transtension was the main drifting mechanism between Africa and South America along the Equatorial Margin of Brazil (ZALÁN 2012). Only the Ceará sub-basins and the Barreirinhas Basin present an underlying Pre-Rift Sequence, composed of Paleozoic strata of the adjacent Parnaíba Basin. The Rift Sequence is of Aptian/Albian age, deposited in rhombic grabens filled by continental/transitional/open marine sedimentary rocks. Most important in this stratigraphy are the Late Aptian organic-rich shales of the Codó Formation, deposited during the first marine transgressions from the Tethys paleo-ocean

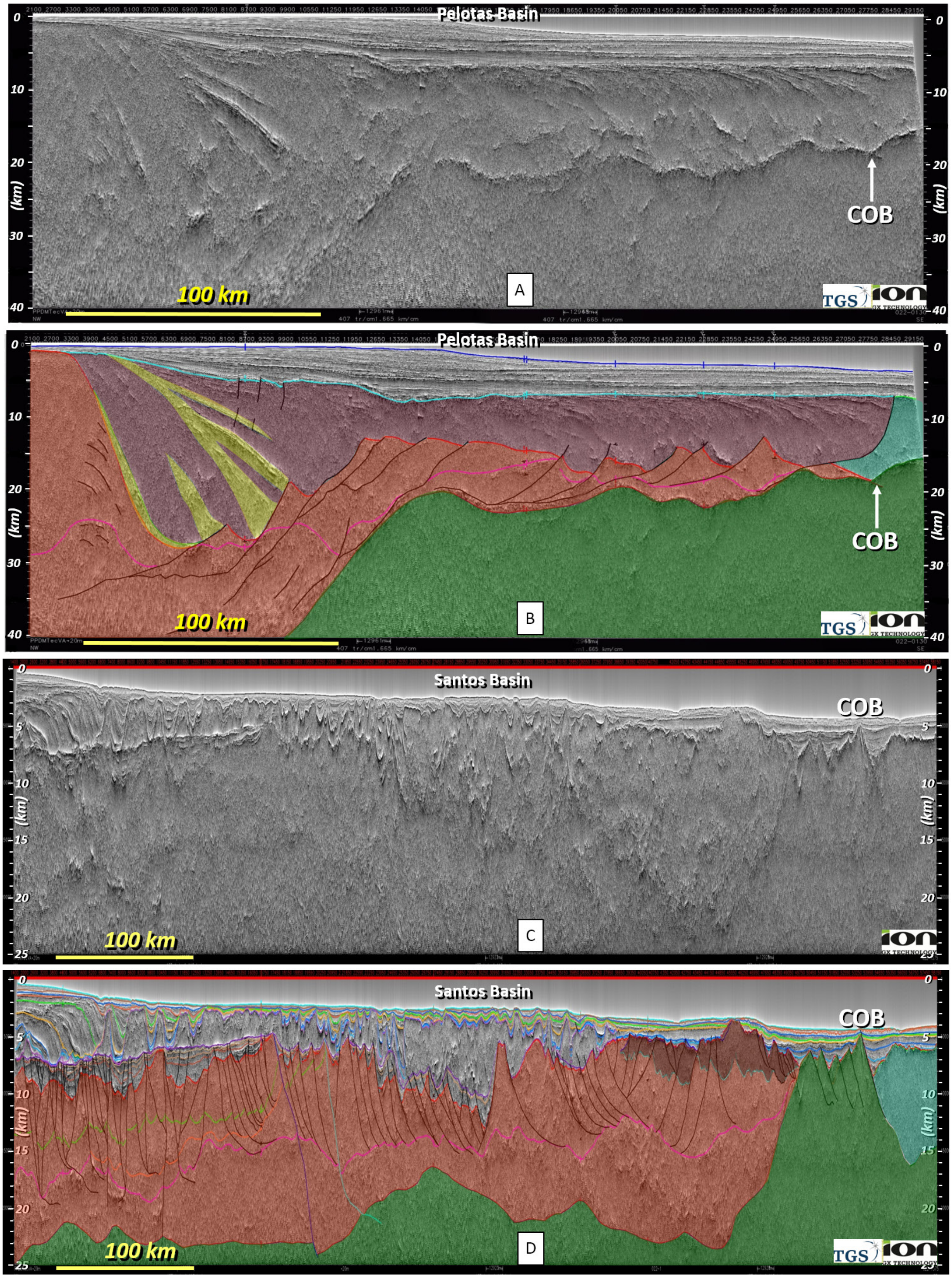

FIGURE 5 – (A) Depth seismic section from Pelotas Basin down to 40 km, non-interpreted. (B) Interpreted. Notice the strong necking of the continental crust (red) followed by hyper-extended crust below the thick section of SDR (purple). There is no exhumation of the mantle (green) at the boundary with the oceanic crust (blue). (C) Depth seismic section from Santos Basin down to 25 km, non-interpreted. (D) Interpreted. Notice the *én boudinage* profile of the continental crust (red), covered by thick sedimentary grabens (yellow). Exhumation of the mantle (green) can be clearly seen between a thick continental crust block (resistate) and the oceanic crust (blue). TECVA display.

to the north. Although these shales never attained thermal maturation for petroleum generation, their counterparts in the Ceará, Potiguar and Sergipe-Alagoas Basins constitute important source rocks for oil and gas. The breakup age in the Equatorial Margin is estimated to be around 100 Ma. An important and uncommon tectonism in the Brazilian offshore basins can be found in the Acaraú and Piauí-Camocim sub-basins of the Ceará Basin. During the lateral dextral separation of Africa and South America along the Romanche Transform (then) Fault, a strong transpression affected the Rift Sequence of these basins and developed an en échelon fold-and-thrust belt that remained in Brazil in the southern side of the fault zone scar. Its Africa counterparts are situated on the northern side of the present Romanche Oceanic Fracture Zone in Ghana. This short-lived tectonism (98-94 Ma) was named Evento Romancheano (ZALÁN et al. 1985b, ZALÁN 2014), and it was responsible for the formation of several positive flower structures and associated thrust faults in these sub-basins. In this group of basins, the shallow water portions are very narrow, while the deep and ultra-deep portions are very wide. The Rift Sequences can be found only in the shallow waters, while the Drift Sequence reigns absolutely in the deep and ultra-deep waters. In these domains, the thickness of the Drift Sequence can reach 8-11 km, resting directly upon the oceanic crust. Its composition is almost totally siliciclastic, constituted by shales and turbidites of the Late Cretaceous and Cenozoic ages. Post-rift volcanism was intense, under the form of enormous intrusive to extrusive volcanic edifices. Some of them perforate the sedimentary section and form present seamounts. Carbonate atolls usually cover the seamounts (e.g., Atol das Rocas in the Potiguar Basin). Some of these seamounts capped by atolls in the geologic past are presently buried in the Drift Sequence. These present and past seamounts make one wonder about numerous paradisiac atoll-topped seamount islands populating the Equatorial Atlantic Ocean throughout its history. Tectonism in the Drift Sequences is practically null; exceptions were made to large gravitational cells that developed impressive fold-and-thrust belts in Barreirinhas and Pará-Maranhão (ZALÁN 2011, OLIVEIRA et al. 2012). The Amazon Cone is a great feature that dominates the Foz do Amazonas Basin, reaching up to 11 km thick. Formed in the last 11 million years and still growing, the Cone represents a composite/multiple gravitational cell with two phases of sliding/contraction having affected different layers in the Cone. Well-defined extensional, translational and compressional realms, with thrust faults and shale diapirs, display intense deformation in both the Cone (Miocene and younger) and Pre-Cone (Eocene to Miocene) sections.

The Pelotas Basin is the quintessence of a VPM. The basin has an area of 350,000 km^2, and its filling is dominated by a very thick Rift Sequence (up to 20 km) constituted essentially by SDR, covered by a thick Drift Sequence that can reach 11 km in the Rio Grande Cone area (Figures 5A/B). STICA et al. (2014) confirmed the zipper pattern of the opening of the South Atlantic Ocean, from south to north. They determined breakup ages varying from 130 Ma in the southernmost part of the Pelotas Basin to 113 Ma in the northern portion. The thick Drift Sequence is basically siliciclastic in nature, made up of Cretaceous and Cenozoic shales and turbidite sandstones. In the Torres High region, a significant mixed carbonate-siliciclastic platform of Albian age developed with several hundreds of meters of thickness. Deformation is practically nonexistent in the Drift Sequence, except for the Rio Grande Cone, where gravitational sliding structures dominate. Most faults are of the normal type, sub-vertical with very small displacements, related to differential compaction. Residual magmatism from the volcanic rifting affected the basal portions of the Drift Sequence, mainly under the form of sills. The Rio Grande Cone is a copycat of the Amazon Cone as described above but with smaller dimensions. It has the same age, and the sedimentary filling and structural styles are very similar.

The Brazilian marginal basins developed on TPM are Jacuípe, Sergipe-Alagoas, Potiguar and Ceará (Mundaú sub-basin). The first two present Pre-Rift Sequences similar to the Recôncavo Basin (Paleozoic/Triassic/Jurassic red beds). In the Rift Sequence, besides the Neocomian to Barremian strata similar to those in the Recôncavo, there are also Late Aptian to Albian sequences deposited in an extended rifting stage (CAIXETA et al. 2014, 2015). In the distal offshore area, the Albian sedimentary growth strata coexist laterally with SDR packages, thus characterizing the transitional nature of these two basins in the spectrum of MPPM-VPM (CAIXETA et al. 2014, 2015). The Drift Sequence is moderately thick, composed of Late Cretaceous to Cenozoic shales and turbidites. Halokinesis is visible in the proximal areas, generally limited to shallow waters. The Potiguar Basin presents two Rift Sequences (Neocomian-Barremian and Late Aptian) extending into the ultra-deep waters. Their composition is of a siliciclastic nature, essentially continental in the first and continental to transitional in the second. These are followed by a Sag Sequence of the Late Aptian-Early Albian age, still deposited under the influence of normal faulting. Organic-rich shales and calcilutites characterize this transitional sequence. The Drift Sequence is dominantly siliciclastic composed of Late Cetaceous to Cenozoic shales and turbidites. The Mundaú sub-basin (of the Ceará Basin) is very similar to the Potiguar Basin. The only difference lies in the absence of the Neocomian-Barremian Rift Sequence. In this sub-basin and in the Potiguar Basin pockets of halite, some few hundred meters thick, were detected in the Late Aptian-Early Albian Sag Sequences. They were drilled in some wells (Petrobras 1-CES-42 and 1-CES-44) and are displayed as halokinetic diapirs in seismic data acquired in the deep waters of these basins. They are the equivalent of the extensive Aptian salt deposits of the South Atlantic margins. Both basins were heavily affected by basaltic magmatism of the Oligocene-Miocene age, both intrusive and extrusive.

3 THE CLASSIC PETROLEUM PRODUCING PROVINCES

In 2023, the petroleum production of Brazil, coming from all onshore fields (Paleozoic basin and Mesozoic rift basins) and offshore fields (from the Post-Salt and Pre-Salt), attained an average of 4,344,000 boed. By the end of the year, the cumulative production of petroleum in Brazil was 1.418 billion boe (Boletim da Produção de Petróleo e Gás Natural, ANP, December 2023, Encarte de Consolidação da Produção 2023).

3.1 Paleozoic basins

The first geological investigations aiming at hydrocarbons in Brazil started in the onshore Paleozoic basins, especially in the Paraná Basin. Due to its plentiful and beautiful outcrops and geographical location close to the most populated and industrialized regions, the Paraná Basin was the obvious center of attention for geologists at the end of the XIX century. The black shales of the Ponta Grossa (Late Devonian) and Irati (middle Permian) Formations, both of bituminous nature, promised the existence of petroleum in the sub-surface. The first wells were drilled in the region of Bofete, State of São Paulo, in 1892 (GALHANO 2006) without success. In comparison, the famous “Colonel Drake well” in Pennsylvania, considered the initial milestone of the modern Petroleum Age, was drilled in 1859. Before the turn of the century, bituminous sands of the Pirambóia Formation (Triassic), also in the region of Bofete, were identified. A well was drilled inside this small exhumed oil field and recovered 6 barrels of oil. During the first half of the XX century, several exploratory campaigns were executed in the Paraná Basin, led by private and state-owned companies. Several shallow wells were drilled, with a few indicating the presence of oil and gas but none of commercial value. From 1953 onward, with the creation of Petrobras, systematic and organized exploratory campaigns were carried out without any commercial success as well. Ironically, the activities of Petrobras in the basin ended exactly with the discovery of the first commercial accumulation of hydrocarbons in the Paraná Basin, the Barra Bonita gas field (1996), immediately followed by another gas discovery (Mato Rico, 1998). The breakthrough in these discoveries was the realization that the glacial-derived sandstones of the Campo Mourão Formation (Carboniferous) were the primary targets (reservoirs) to be sought in the basin, and not the deltaic sandstones of the Rio Bonito Formation (middle Permian), as considered before. The gas is sourced from the moderately organic-rich marine shales of the Devonian Ponta Grossa Formation. Equally ironic was the fact that although having been the cradle of the petroleum industry of Brazil, the Paraná Basin was the last Paleozoic basin to achieve commercial production of hydrocarbons (from Barra Bonita, 2022) (FRANÇA 2022).

The Amazonas Basin also stirred the Brazilian people´s imaginariness in the 1950s, when three wells drilled in the localities of Nova Olinda and Maués, in the State of Amazonas, found live oil in sandstone reservoirs hosted in glaciogenic channels of the Nova Olinda Formation (Carboniferous) (1954). The amazing view of oil flowing on the surface added to the mystical aura of hidden treasures surrounding the Amazon tropical forest raised high hopes of enormous petroleum accumulations in the sub-surface. Such dreams quickly waned away after several appraisal wells drilled turned out as dusters. Petrobras returned to this play in the 1990s when several wells found only non-commercial quantities of oil and gas. However, these scant results added to the known fabulous richness in organic matter (detected in outcrops and wells) of the marine black shales of the Barreirinhas Formation (Devonian) encouraged the continuity of the search for commercial accumulations. Finally, in 1999, Petrobras discovered gas and condensate in commercial quantities in the Azulão and Japiim fields. Nowadays, Brazilian company ENEVA produces 4,500 boed from these fields (ANP 2022). These discoveries present as main reservoirs the eolian sandstones of the Nova Olinda/Itaituba Formations (Carboniferous), contrary to the commonly held belief of always targeting the classic eolian sandstones of the Monte Alegre Formation (slightly older Carboniferous). All the hydrocarbons found up to now in the Amazonas Basin were sourced from the Devonian black shales of the Barreirinhas Formation.

Ironically, the first Paleozoic basin to achieve significant commercial production was the Solimões Basin, the least known of them then. During the 1970s, the two better-known Paleozoic basins were the Paraná and Amazonas Basins due to their beautiful outcrops and several wells (mostly stratigraphic) drilled. The Parnaíba Basin displays plentiful outcrops, so at least its sedimentary content was already known. The Solimões Basin does not outcrop, being totally covered and hidden by overflowing Cenozoic deposits. No meaningful wells had been drilled then. Thanks to a Hungarian geologist named Peter Szatmari, at that time a consultant to Petromisa (a subsidiary of Petrobras that was searching for commercial deposits of Potassium-rich evaporites in the Amazonas Basin), the Juruá gas field was discovered in 1978. Szatmari identified anticlines of a compressional nature and associated reverse faults in some poor-quality seismic sections shot in very remote areas of the basin. Such a type of structural style was then unfamiliar to Brazilian petroleum geologists, who dealt mainly with extensional regimes in its offshore passive margin basins. It took the trained eyes of an European geologist to recognize compressional structural styles in the otherwise "undeformed" Brazilian Paleozoic basins. A series of similar gas discoveries followed in the late 1970s and early 1980s. All discoveries were located in compressional anticlines, unveiling a pattern of several en échelon trends of folds, always associated with major reverse faults. The remoteness of these discoveries prevented their commercial development. The first commercial field was discovered in 1986, the oil/gas/condensate Rio Urucu field. It was followed by similar discoveries of Leste de Urucu (1987), Sudoeste do Urucu (1988), Carapanaúba and Cupiúba (1989) and Igarapé Marta (1990). These discoveries form the Rio Urucu petroleum province (or Polo Urucu) that, in the last three decades, allowed the Solimões Basin to hold tight to third place among the largest petroleum-producing basins of Brazil. At first, it was third only to the Campos and Potiguar Basins, during which it frequently produced over 100,000 boed. Nowadays, it is third only to the Santos and Campos Basins. Other recent discoveries in this province include the fields of Arara Azul (2010) and Araracanga (2012). The oil produced in the Polo Urucu is the highest valued in Brazil because it is light (> 40º API) and pure (low Sulphur content). All the discoveries of the Solimões Basin present as reservoirs the Carboniferous eolian sandstones of the Juruá Formation. The hydrocarbons were sourced from the Devonian marine shales of the Jandiatuba Formation, generated by unconventional thermal maturation caused by the intrusive Jurassic sills (210-201 Ma) of the CAMP LIP. The *en échelon* trends of folds and reverse faults were formed during a transpressional event that affected the northern part of the Brazilian territory during the Jurassic opening of the Central Atlantic Ocean (Juruá Orogeny, circa 140 Ma, ZALÁN 2004).

Who would have thought that the ugly duckling would become a beautiful swan? By the turn of the XXI century, the Solimões Basin had become the highlight of the four Brazilian Paleozoic basins. The Parnaíba Basin was the Brazil´s least explored and least known Paleozoic basin. The small thickness (< 4000 m) of the sedimentary filling tagged it as the least promising for commercial petroleum occurrence. Its beautiful outcrops presented a large variety of sandstones and basaltic igneous rocks, but there were no organic-rich shales or exudations of hydrocarbons anywhere. The existing 34 wells did not present any significant oil or gas shows, with one lonely exception: Capinzal well drilled by Petrobras in 1987. In this well, right below a diabase sill, the Cabeças Formation (Late Devonian) displayed a free gas column of around 12 m. The evaluation of the logs at that time came out inconclusive, and the well was abandoned. Two decades later, a remarkable team of explorationists from OGX, a short-lived petroleum exploration company, performed a petrophysical re-evaluation of this well and, with the aid of modern high-quality seismic data, matured the out-of-the-box idea that a very unusual non-conventional trapping mechanism could be at work in the Parnaíba Basin. The developed model considered that diabase sills intruded the sedimentary strata under the form of bowler hats, the shape of the famous Charles Chaplin's hat (Figure 6). By jumping strata upward and downward inside a reservoir rock, the sills could form four-way structural closures and encapsulate gas accumulations (CUNHA 2012). This model was tested successfully at the Capinzal location, giving rise to the first commercial gas accumulation in the Parnaíba Basin, the Gavião Real field (2010). With the termination of OGX, this team of explorationists ended up in a new company named ENEVA. They kept applying this successful "Bowler Hat" play model, and a series of similar significant gas fields were discovered and put into production throughout the 2010s (MIRANDA 2014, 2018). Tens of discoveries were accomplished, all of them applying the Bowler's Hat model of sills encapsulating gas accumulations in the sandstones of the Poti (Carboniferous), Cabeças (Devonian) and Piauí (Carboniferous) Formations. The generation of gas is also non-conventional, having been achieved through the thermal effect of the diabase sills upon the marine shales of the Devonian Pimenteiras Formation. If not for this mechanism, there would never be hydrocarbons in the Parnaíba Basin because the small thickness of its filling does not allow the conventional thermal maturation to take place by sedimentary/volcanic burial. The successful result of these exploratory campaigns is nowadays known as Parque dos Gaviões, a complex of 11 commercial gas fields holding certified reserves of 1.17 TCF (equivalent to 195 million boe) (ENEVA 2023). Six fields produce circa 25,000 boed of gas (ANP 2022). By the end of this story, one can say that the ugly duckling did not turn into a swan but into a beautiful…hawk (translation of Gaviões).

A curious fact was learned after the unexpected history of success in the Parnaíba Basin, which is so typical in Geology. The Bowler's Hat model of hydrocarbon entrapment by basic sills, developed and tested in the Parnaíba Basin during the first two decades of the XXI century, was inadvertently tested with success in the Paraná Basin much earlier. In 1984, the extinct company Paulipetro drilled the well Chapéu de Sol 2 and found gas and condensate in a carboniferous glacial-related sandstone of the Itararé Group, right below a diabase sill. The accumulation was deemed as non-commercial. Years later, Petrobras discovered the Barra Bonita gas field in 1996 in a correlated sandstone, which was also below a diabase sill. At the time of these discoveries, the quality of the seismic data and the open grid of the surveys did not allow the optimal visualization of the Bowler's Hat structure. Thus, the structural concept of the trap could not be developed. Only

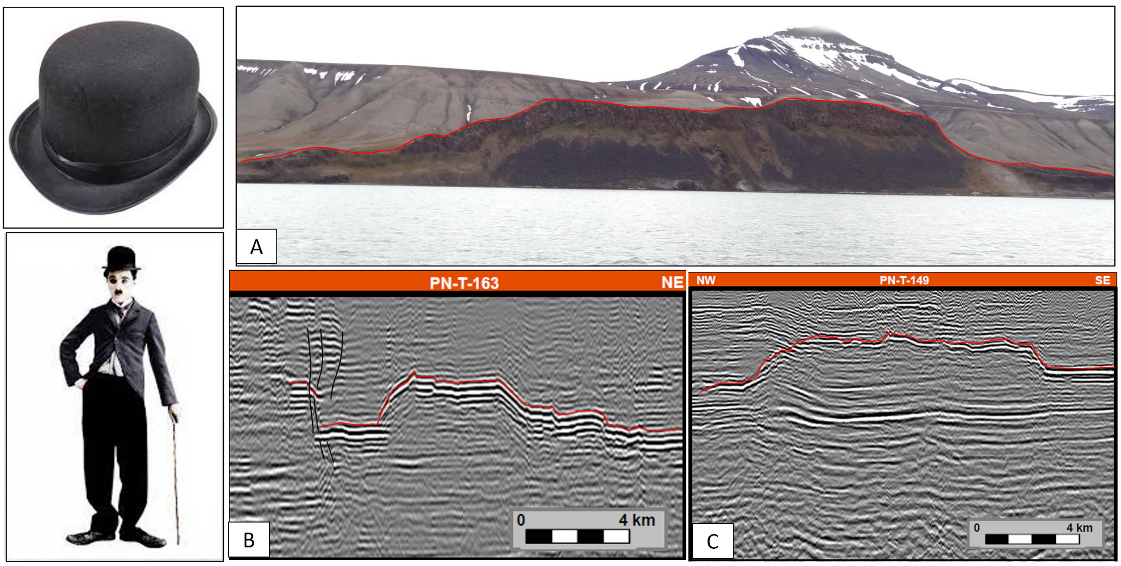

FIGURE 6 – Bowler Hat structure, inspired by the famous hat used by Charles Chaplin. (A) The Bowler Hat structure was formed by a Jurassic diabase sill on the island of Svalbard, Norway. (B) and (C) Time seismic section displaying Bowler Hat structures formed by Jurassic/Cretaceous diabase sills in the Parnaíba Basin (ARAUJO 2015). Red lines follow the top of the intrusions.

two decades later, after the successful exploration of this model in the Parnaíba Basin, after the reprocessing of old seismic data and the acquisition of new seismic data in the Paraná Basin of much better quality, it was found that this unconventional trapping mechanism of hydrocarbons also worked in the Paraná Basin.

We believe that a big irony is in the works to happen in the next decade. Recently (2020), ENEVA acquired exploratory blocks in the northern part of the Paraná Basin, right in the basin´s thickest depocenters (6,000-7,000 m). The same team of geologists/geophysicists mentioned above will study the data and determine the locations of exploratory wells in these blocks. Given the proven technical capacity of this team of explorationists and the exceptional improvement of the seismic quality in the Brazilian Paleozoic basins, it is highly probable that several gas fields will be discovered in those blocks. There are plenty of indications of the presence of gas in the Paraná Basin. The irony is that these blocks are situated close to the route of the Bolivia-Brazil gas pipeline (GASBOL), through which Brazil has been importing gas from the neighboring country at very high costs and the expense of several political perturbations. Imagine the surprise of Brazilians when they discover in the future that the precious commodity was lying practically underneath the pipeline. Why did we not invest in exploration in our territory before paying all the pipeline costs and rushing to buy gas elsewhere? Since the Bolivian gas will be exhausted in the next 5-10 years, this pipeline will probably be used to export gas from the future discoveries by ENEVA in the Paraná Basin.

3.2 Mesozoic terrestrial rifts

The petroleum geology and the oil and gas production in Brazil started in the Recôncavo Basin in 1939, with the discovery of oil in the Lobato well, situated on the outskirts of the capital town of the State of Bahia, Salvador. Immediately after, several discoveries of large-size petroleum fields followed: Candeias (1940), Dom João (1947) and Água Grande (1951). The petroliferous future of Brazil was then established. Similar discoveries followed in the onshore portion of the Sergipe-Alagoas Basin, noteworthy the discovery of the first giant field of Brazil: Carmopólis (1963). The oil production in the Recôncavo Basin peaked at circa 130,000 bopd in 1968, while in the onshore portion of the Sergipe-Alagoas Basin in 1985 (circa 50,000 bopd). The same petroleum system (described ahead) that provided these discoveries and production was later responsible for numerous discoveries in the onshore portion of the Potiguar Basin, starting in 1979. Its peak production reached 90,000 bopd in 1997. The onshore portion of the Espírito Santo Basin also reaped the benefits of this petroleum system, with some discoveries of small size that, at peak production, reached 25,000 bopd (2002). The data regarding production numbers were extracted from MENDES et al. (2019, Graph 4). Nowadays, these terrestrial rift basins are in the mature phase of exploration/exploitation, with decreasing production and remote exploratory possibilities for the discovery of significant new reserves. According to ANP Bulletin (November 2022), the total production from these four onshore basins is in the order of 93,000 boepd (2.3% of the total petroleum production of Brazil).

The common petroleum system responsible for these discoveries can generically be termed “Early Cretaceous terrestrial rifts petroleum system”. In this system, the main source rocks are the freshwater/brackish lacustrine shales of the Berriasian/Valanginian (Early Cretaceous) age, deposited in geological environments similar to those of the large lakes of the western branch of the Great Rift Valley (East African Rift), such as Tanganyika, Malawi and Albert. The reservoir rocks are dominantly sandstones of continental nature (eolian, fluvial, lacustrine deltaic, lacustrine turbidites) and, secondarily, fanglomerates and sandstones deposited in transitional settings. The age of the reservoirs ranges from the Late Jurassic until the Aptian. The main traps are of structural nature, classical of rifting environments, such as planar rotational faults/blocks, horsts, tilted blocks, rollover structures associated with listric growth faults, and, in transfer zones, flower structures. Mixed traps are also common, followed by purely stratigraphic traps in deep basinal turbidites (tight gas reservoirs). Diapirs of shale and of highly fluidized sandstones form a series of small petroleum fields peculiar to the Recôncavo Basin (Figure 7). The Recôncavo was also a pioneer basin in developing non-conventional reservoirs, such as the fractured shales of the Candeias field, which was discovered in 1940 and is still productive.

These Early Cretaceous terrestrial rifts extend into the shallow water portions of the adjacent offshore marginal basins. The Manati gas field, for instance, found in the shallow waters of the Camamu Basin, consists of a classical

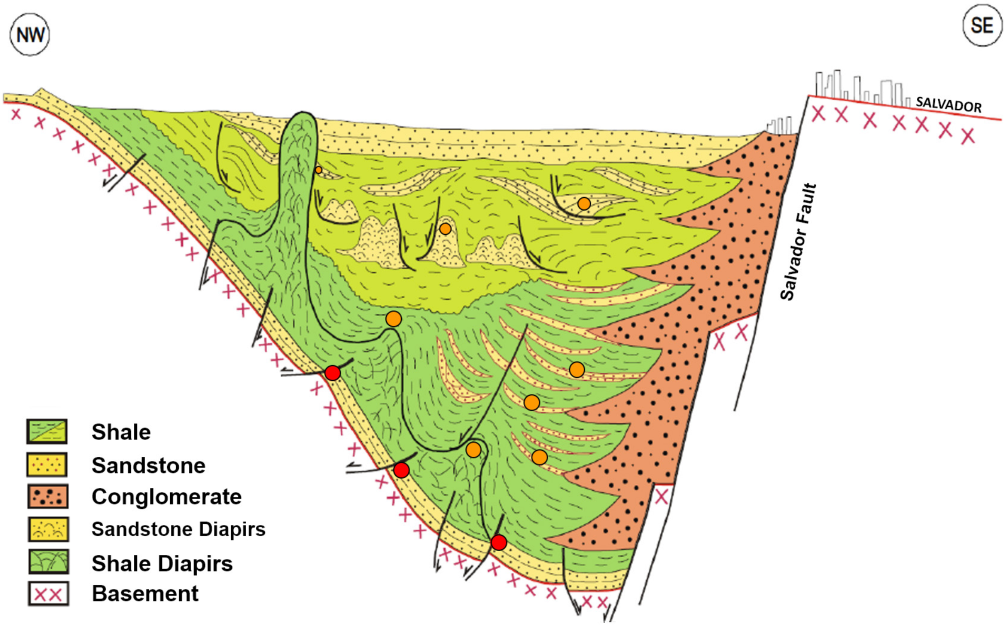

FIGURE 7 – Schematic geologic section (not to scale) in the Recôncavo Basin illustrates several existing petroliferous plays (ZALÁN & LOUREIRO 2013, unpublished). Red circles indicate the main play of the basin: Late Jurassic sandstones (Sergi and Água Grande Formations) trapped in fault blocks and sealed (laterally and vertically) by Berriasian shales of the Candeias Formation (seal and source rock). Orange circles point to other plays: rollover structures affecting deltaic sandstones, culminations and flanks of shale diapirs, fluid sandstone diapirs and basin-center turbidites. All these are deposited in lacustrine environments.

structural trap (structure, reservoir, source rock and seal) typical of the adjacent Recôncavo Basin. In the Potiguar offshore basin, some of the fields producing in the shallow waters, such as the Pescada field, are clearly formed within the maritime extension of the Potiguar Rift. In the Sergipe-Alagoas and Espírito Santo Basins, the rift structures are present underlying its shallow water Drift Sequence but holding no significant accumulations of hydrocarbons today.

In 2023, the production from the terrestrial reservoirs (Paleozoic intracratonic basins and Mesozoic rift basins) was, on average, 213,000 boed, representing circa 5% of the Brazilian production (Boletim da Produção de Petróleo e Gás Natural, ANP, December 2023, Encarte de Consolidação da Produção 2023).

3.3 Post-Salt maritime basins

Although since the 1980s, the majority of Brazilian petroleum production has originated from maritime basins, the new petroleum province known as the "Pre-Salt of the Santos and Campos Basin" became so important for the country that it deserves a chapter to itself. That is why this chapter will deal with all offshore production in Brazil coming from the Post-Salt, that is, the offshore production not coming from the Pre-Salt.

The history of Petrobras success amidst the global petroleum scenario started in 1969 with the drilling of the second maritime well in Brazil. A Third World company that had never drilled a well in the seas discovered, with its second only well, a commercial field that produced a very fine type of oil for almost half a century. The Guaricema field in the shallow waters (water depth of 80 m) of the Sergipe-Alagoas Basin started production in 1973 and continued to produce until 2020. Besides the exploration and operational success, a scientific feat changed the history of offshore petroleum exploration forever. The discovery was achieved in a barely known and poorly understood type of hydrocarbon reservoir: turbidite sandstones.

These sandstones, deposited by turbidity currents in deep water settings, called turbidites, were the big drivers of Petrobras into hydrocarbon production levels never imagined in the 1960s and 1970s, and for several awards conceded for its technological advances and innovations.

First World oil companies and entities bowed to Petrobras in recognition of the company´s significant contribution to the exploration, drilling and development of petroleum fields in deep and ultra-deep waters. After discovering turbidite reservoirs in Sergipe-Alagoas, Petrobras engendered a series of similar discoveries in several other offshore basins: Campos, Santos, Ceará, Potiguar and Espírito Santo. The first giant field in turbidite reservoirs was discovered in the shallow waters of the Campos Basin in 1975 (Namorado field). Another series of impressive discoveries of giant fields followed when Petrobras, under the guidance of famed Director of Exploration Carlos Walter Marinho Campos, decided to adventure into deep and ultra-deep waters. The first two giant oilfields in deep waters (Marlim e Albacora) (Figure 8) were discovered in 1985. Other giant fields were Bijupirá, Marlim Leste, Albacora Leste, Marlim Sul, Espadarte, Barracuda and Caratinga. This phase of success culminated in 1996 when the giant Roncador field was discovered. Drilled in water depths of 1856 m, it established a world record at that time. It was the first commercial field found and developed in ultra-deep waters in the world. Roncador was also the most significant discovery of Petrobras before the Pre-Salt era. As a result, Petrobras received two OTC *Distinguished Achievement Awards* as recognition for its leading-edge technologies in turbidites. For three decades (late 1970s, 1980s, 1990s and early 2000s) Petrobras was the world leader in the exploration, development and production of turbidite reservoirs. When Brazil reached the landmark production of 2 million barrels of oil per day in 2007, circa 80% of its reserves and production came from the turbidite oil fields in deep and ultra-deep waters.

From 2006 on, the importance of turbidites for Brazil continued to be significant, but magnificent discoveries in the Pre-Salt microbialite reservoirs severely overshadowed it. Despite this fact, the 2000s and 2010s witnessed a resurgence of important turbidite fields finds. Petrobras team of explorationists, led by geologist João Claudio Conceição, unveiled several significant light oil and gas discoveries in the deep and, mainly, in ultra-deep waters of the Sergipe-Alagoas Basin: Piranema, Barra, Cumbe, Farfan, Muriú, Moita Bonita and Poço Verde. They are still slated for full production in the 2020s.

Regarding petroleum systems, the turbidite reservoirs are sandstones ranging in age from the Miocene (Albacora Leste) to Albian (Namorado, Albacora). The hydrocarbons found were sourced

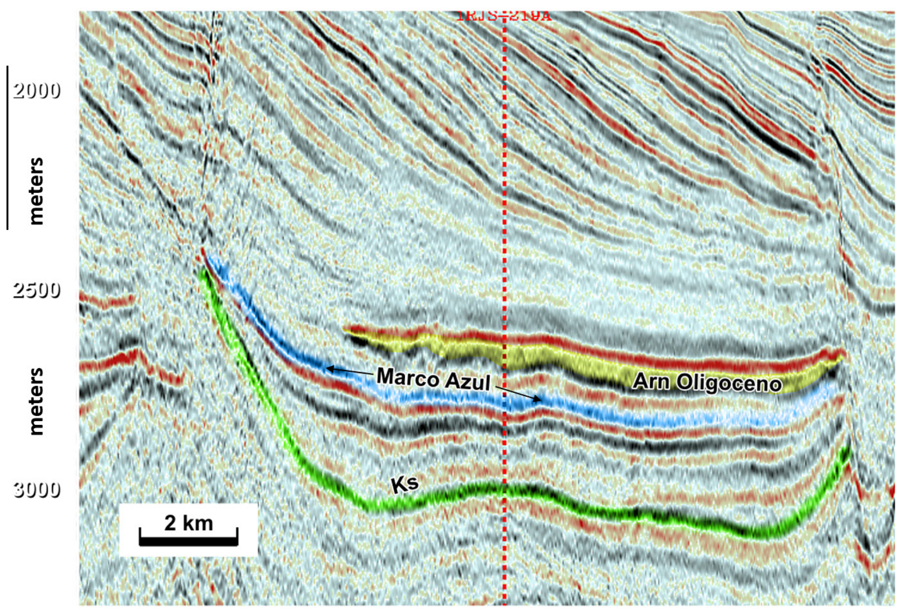

FIGURE 8 – Seismic section (depth) of the giant Marlim oil field, Campos Basin. This field was discovered by drilling the strong amplitude anomaly (in red and yellow), first identified by geophysicists Antonio Pinheiro Lobo and João Oliveira Ferradaes (*in memoriam*, both) at the beginning of the 1980s. The trapping mechanism is purely stratigraphic in nature and the reservoir is an Oligocene turbidite submarine fan whose ultimate recovery will reach 3 billion boer. During peak production, Marlim produced more than 600,000 bopd.

from Barremian saline lacustrine shales (Campos and Santos Basins), Aptian hyper-saline marine shales (Sergipe-Alagoas, Potiguar, Ceará Basins) and Albian-Turonian anoxic marine shales (Santos, Campos, Espírito Santo, Sergipe-Alagoas Basins). Most traps are stratigraphic in nature (in the basins devoid of salt) or mixed structural/stratigraphic (in the basins containing salt). The type of oil found is mostly heavy (Campos and Santos Basin), sometimes light (Sergipe-Alagoas and Santos Basins). Gas is secondary to the massive volume of oil found but can also be significant (Santos, Espírito Santo, Sergipe-Alagoas Basins).

However, not all the discoveries and productions of oil in the Post-Salt sections of the maritime basins come from turbidite reservoirs. Albian shallow marine carbonates are important in terms of reserves and production in the shallow waters of the Campos Basin (Garoupa, Enchova, Bonito, Bicudo, Pampo, Cherne) and of Santos Basin (Tubarão, Coral, Estrela do Mar, Caravela). The accumulations are always of the structural type. Listric faults developed on the top/back of mobile salt gave rise to syn-growth rollover structures in the young Albian shallow water platforms, strongly controlling the distribution of sweet spots of porosities in the carbonates. A curious fact took place in the 2000s when the oil production from the deep water turbidites of Petrobras in the Campos Basin started declining. The team of reservoir geologists/geophysicists working on those fields, led by geologist Delzio Machado, developed an ingenious model where they devised a mechanism of finding the originally shallow water Albian carbonates in the deep waters of the basin inside the ring-fences of the producing fields, right beneath the languishing turbidite reservoirs. This model, informally termed "Wandering Albian Turtles", consists of mapping turtleback structures of Albian age, ruptured by halokinesis and individualized into fragments of the Albian shallow water carbonate platform that slided by gravity on top of the salt towards the slope paleoenvironments. The first well drilled to test this model was a resounding success, leading to the discovery of the Jabuti oil field inside the Marlim Leste ring fence. One well in this field broke the Brazilian daily production record ever achieved by a single well of Petrobras (> 43,588 bopd) in 2009. A series of similar discoveries followed and several "Wandering Albian turtles" full of oil were found inside the turbidite reservoir ring fences. Reserves in the order of several extra hundred million barrels of oil equivalent were delivered to be exploited by the existing production infrastructure. Notwithstanding the success, these same geologists/geophysicists decided to go deeper and found additional reserves in the Pre-Salt Aptian microbialites. Given that the oil in Campos Basin is always derived from the Barremian saline lacustrine organic-rich shales, and that this oil found its way into the Paleogene/Late Cretaceous turbidites and the "Wandering Albian turtles", its presence in the Aptian microbialites was just a matter of geo-logical deduction. The late 2000s and early 2010s were the blooming period of the discoveries of vast oil reserves in the Pre-Salt microbialites. So, why not find more under younger accumulations holding the same oil? The much smaller oil fields in the Albian carbonates of the Santos Basin contain light oil and gas derived from the Albian-Turonian anoxic marine shales.

In 2022, the production from maritime reservoirs of the Post-Salt sequences was, on average, 758,000 boed, representing approximately 20% of the Brazilian production (Boletim da Produção de Petróleo e Gás Natural, ANP, December 2022, Encarte de Consolidação da Produção em 2022).

3.4 Pre-Salt maritime basins

In July of 2008, the Santos Basin was the penultimate oil and gas producing basin of Brazil, with a mere 7,366 boed. The least-producing basin was the Paraná Basin, which, at the time, produced 3,051 boed, not from conventional petroleum production but from the extraction of oil and gas from bituminous shales of the Permian Irati Formation. That meant that in terms of conventional petroleum production, the Santos Basin was, in fact, the least-producing basin in Brazil. Fourteen years later, in December 2022, the production from the Santos Basin was by far the largest of Brazil, with 2,972,252 boed, of which 2,316,462 bopd were oil (Boletim de Produção Mensal da ANP, December 2022). With such production, the Santos Basin would be the 6th largest producer in OPEC and the 10th in global oil production. This fantastic increase of 400x was due to the fantastic "Pre-Salt Play" discovered by Petrobras in 2006.

The Pre-Salt Play of the Santos and Campos Basins constitute a remarkable petroleum province in the worldwide scenario. Discovered in 2006, its production started only two years later. Production hit the mark of 1 million bopd after eight years (2016) and 2 million bopd after

14 years (2022) (PETROBRAS 2020, 2024). The cumulative production by mid-2023 was close to 5.5 billion barrels of oil. The resources discovered by Petrobras are in the order of 40 billion barrels of oil, including proved reserves (those already developed) and contingent reserves (those already discovered but not yet developed). Three super-giant fields (Búzios 13.2 Gboer, Tupi 8.3 Gboer, Iara Complex with eight fields > 5 Gboer) and eleven giant fields (Sapinhoá, Mero, Lapa, Cernambi, Atapu, Sepia, Bacalhau, Sagitário, Júpiter, Pão de Açúcar, Parque das Baleias Pré-Sal, all with more than 500 MMboer) are the highlights of this play. Because of all these, Petrobras received three OTC *Distinguished Achievement Awards* as recognition for its leading edge technologies in the production of Pre-Salt fields.

Figure 9 displays the magnificent Tupi structure, which peaked in January 2020 at 1,329,000 bopd in production. For the sake of curiosity, this gigantic structure may have an additional play, the Pre-Pre-Salt Play. There is a high probability that the reflective section under the Pre-Salt would be equivalent to the nearby Paleozoic intracratonic Paraná Basin, constituting a Pre-Rift section (Figure 9). In this model, the eolian sandstones of the Botucatu (Jurassic) and Pirambóia (Triassic) Formations would comprise the reservoirs to be targeted, right underneath the basaltic lavas of the Serra Geral Formation (Early Cretaceous). The hydrocarbons could be sourced from the mature/over-mature Permian Irati Formation, contrary to what happens in the terrestrial Paraná Basin, where its organic-rich shales never attained sufficient burial for thermal maturation. With every improvement in resolution undergone by seismic data, the underlying Paraná Basin becomes clearer in the central part of the Santos Basin.

Another droll trick played by our science, Geology, took place during the dawn of the Pre-Salt Play. Although the official discovery of the

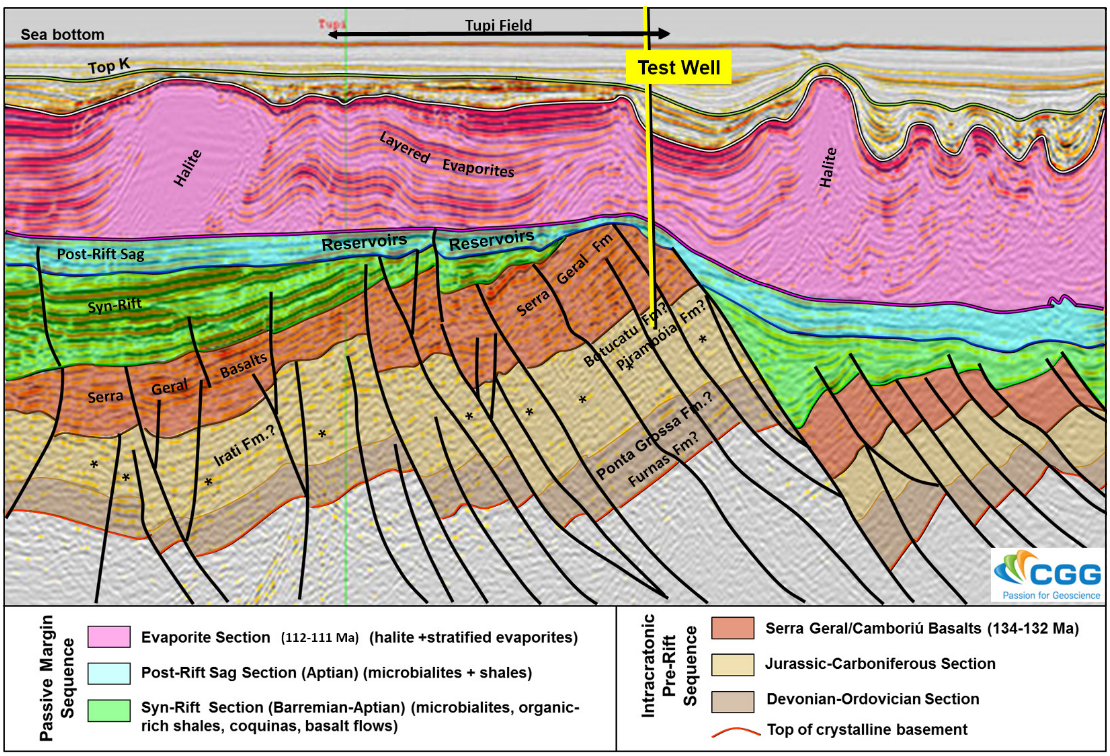

FIGURE 9 – The seismic section of the super-giant Tupi oil field in Santos Basin illustrates the stratigraphy of the Pre-Salt section. The interpretation indicates the possibility of a thick pre-rift section, equivalent to the Paleozoic section of the adjacent Paraná Basin. A funny name for this section would be the *Pre-Pre-Salt section*. A test well (here suggested, in yellow) would investigate the occurrence of the known excellent eolian reservoirs of the Jurassic Botucatu and Pirambóia Formations, right below the Serra Geral lava flows (present economic basement of the basin), containing oil sourced from the organic-rich Permian Irati Formation; within the structural closure of the Tupi structure (modified from ZALÁN 2017b).

Pre-Salt Play was tagged in 2006 in the Santos Basin, with the drilling of the first two exploratory wells, Paraty (discoverer but non-commercial) and Tupi (discoverer of the first commercial accumulation), the first producing well of the Pre-Salt was located far away, in the Campos Basin (well ESS-103). This well was already a producer of oil in the Late Cretaceous turbidites of the Jubarte field. However, it had been drilled to much greater depths and into the Pre-Salt section. There, a large column of oil (around 100 m) had been identified in carbonate reservoirs that the petrophysicists poorly understood regarding electric log responses and textures/porosities/ permeabilities. When the secrets of these curious reservoirs, the microbialites, were unraveled in those two pioneer wells, the geologists understood that the Pre-Salt section of ESS-103 had discovered something similar and was immediately put into production in 2008. This Pre-Salt accumulation became part of a larger giant field later (Parque das Baleias Pré-Sal), and the well ESS-103 made history as the real discoverer and first producer of the Pre-Salt Play. For interested readers, we strongly recommend reading the book "Pré-Sal: a saga" (MACHADO 2018), where one can find a pleasant and trustworthy narrative of how these fantastic discoveries were accomplished behind the scenes of Petrobras. Most importantly, written by one of the discoverers himself.

The secret to this fantastic petroliferous play is the optimal convergence of three items of the petroleum system, each presenting very peculiar characteristics:

(i) Rich *source rocks* (Late Barremian to Early Aptian) (Itapema Formation in Santos, Coqueiros Formation in Campos). The syn-rift black shales are very rich in algal organic matter typical of saline lacustrine environments and prone to generating oil of excellent quality. The residual organic matter content of these shales can attain values of up to 15% to 20%. The present analogs to such an environment are the modern lakes of the Eastern Branch of the Great Rift Valley of East Africa (Lakes Turkana, Bogoria, Magadi, Naivasha, etc.).

(ii) Potent *reservoirs* (Late Aptian) (Barra Velha Formation in Santos, Macabu Formation in Campos) composed of microbial carbonate rocks presently known as microbialites, formerly termed stromatolites. They formed in several different ways but were always associated with vast inland hypersaline lakes with dimensions equivalent to epicontinental seas. They were deposited in shallow platforms, in shoals throughout the lakes, or as travertine buildups formed by hydrothermal vents. These reservoirs have fantastic permeability/ porosity characteristics, presenting world-record maritime productions. Tens of wells produce at rates over 20,000 bopd, several above 50,000 bopd, with peak productions of 65,000 bopd achieved. FETTER et al. (2018), MAAS et al. (2023) and VITAL et al. (2023) provide an excellent summary of the depositional models of these microbial carbonate reservoirs, as well as superb examples from producing fields. In two oil fields, Búzios and Mero, coquina beds underneath the microbialites also constitute very important holders of reserves.

(iii) Perfect *seal rocks* (Late Aptian to Early Albian) (Ariri Formation in Santos, Retiro Formation in Campos). All the area encompassed by the Pre-Salt Play is covered by a continuous thick package of marine evaporites, constituted by a massive basal mobile halite bed covered by several other types of stratified salts. Although the average thickness of the evaporites over the Pre-Salt is in the order of 2,000-2,200 m, their thicknesses can vary from practically zero to several thousand meters throughout the play. The record evaporite thickness drilled by a well targeting the Pre-Salt was 4,850 m (Monai well, Espírito Santo Basin). The efficiency of retaining all petroleum generated is practically 100%. All four-way closure structures existing at the base of the salt have a high probability of trapping hydrocarbon accumulations in the Pre-Salt reservoirs. (Figure 10). Another fantastic serendipity nature provides in the Pre-Salt Play is that the salt+evaporite package presents a high thermal conductivity, so it "drains" a lot of heat from the Pre-Salt section. As a benefit, the source rocks in depths over 7,000 of overburden are still situated in the oil window of hydrocarbon generation instead of in the gas window, as would be expected if not for the presence of this thick seal layer.

Besides, the existence of an underlying crustal structure favorable to the formation of two large depocenters over thinned/hyperextended crust controlled the location of the Internal and External Kitchens (of hydrocarbon generation). These kitchens flank and run parallel to a NE-SW-trending crustal resistate whose surficial expression is a central structural high with great power of focalization (External High). Hydrocarbons generated in the kitchens flow towards the External High. An optimal geometry of the underlying

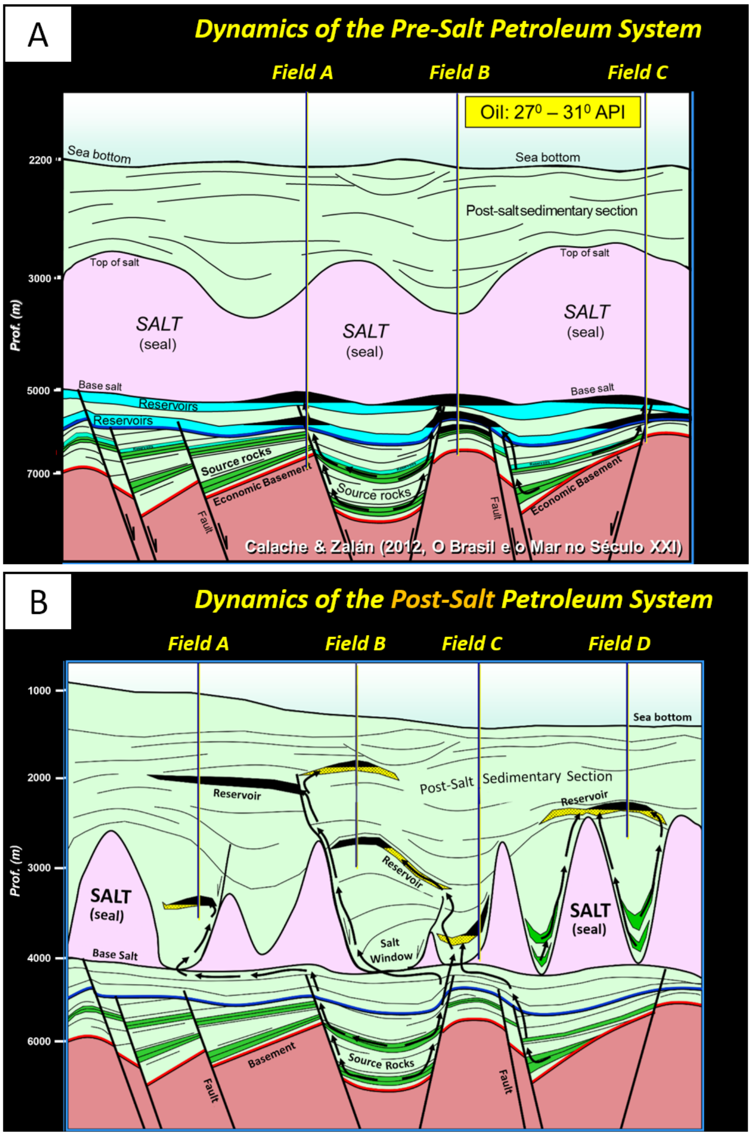

FIGURE 10 – Schematic geologic sections illustrating the working Pre-Salt and Post-Salt petroleum systems (CALACHE & ZALÁN 2012).

continental crust contributed significantly to the richness and bounty of the Pre-Salt (Figure 11).

The petroleum system of the Pre-Salt Play is the same throughout the Santos and Campos Basin and the southern part of the Espírito Santo Basin. It comprises an area of circa 500,000 km^2 (slightly larger than the State of California). In 2010, the Brazilian government created the Pre-Salt Polygon, an area of circa 150,000 km^2 that was supposed to encompass all of the Pre-Salt Play's significant reserves and prospective resources. It also served to delimit the Production Sharing Regime of the Exploration and Production activities unique to the Pre-Salt in Brazil. The same source rocks, reservoirs and seals worked together to yield the Pre-Salt richness. The comprehension of the overall functioning of this petroleum system must be done based on the understanding of how the subjacent continental crustal structure strongly controlled the distribution of the different items that constitute the elements of this petroleum system (ZALÁN et al. 2019a, 2020) (Figure 11). The following four paragraphs must be read with figure 12 as the reference.

3.4.1 The Internal Kitchen

All petroleum found up to nowadays in the Pre-Salt Play was sourced from the organic-rich

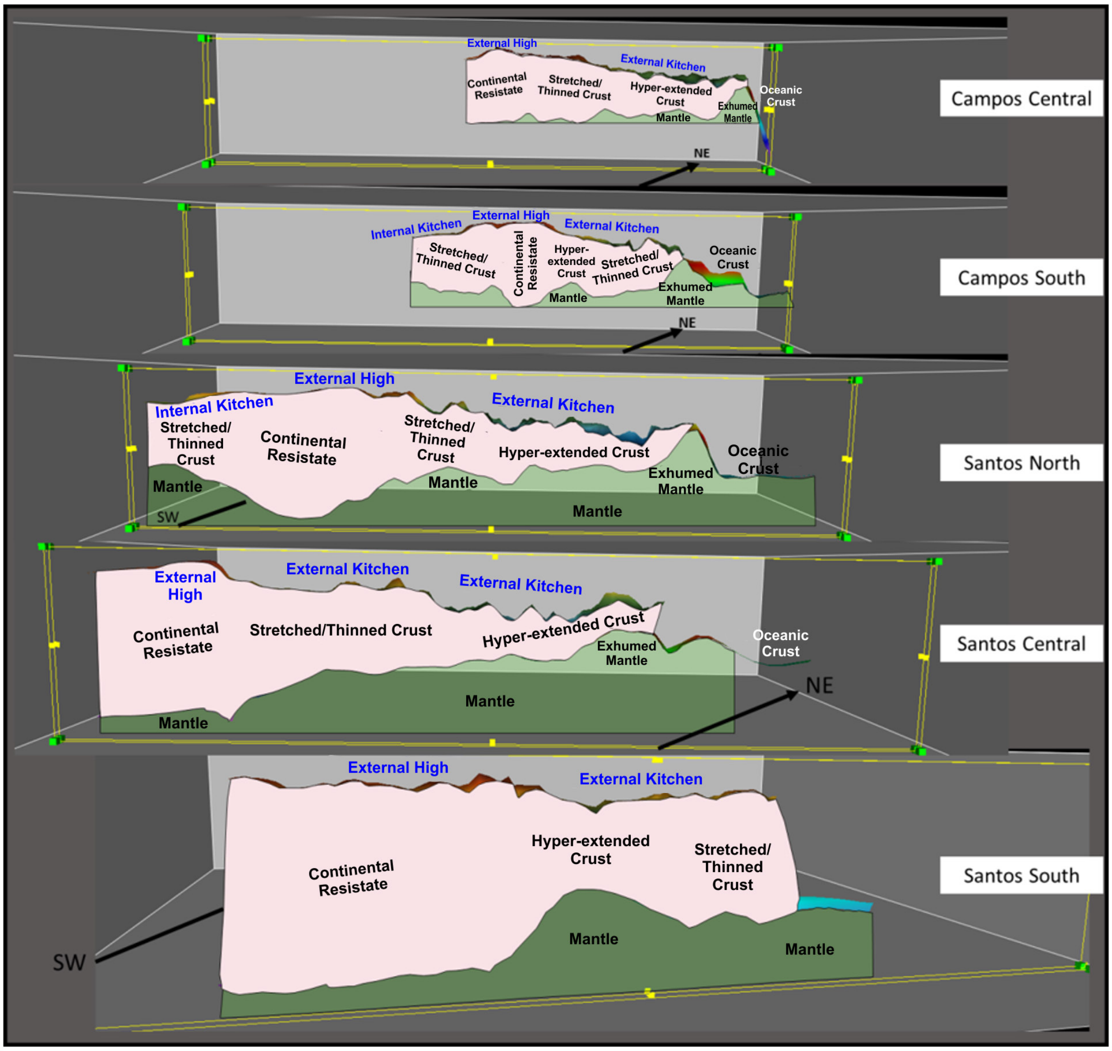

FIGURE 11 – Perspective view, from the southwest (bottom) to the northeast (top) of the changing continental crustal profile (from the base of the salt to Moho, pink color) of the Santos and Campos Basins. The structural inheritance of the Pre-Salt petroleum system´s basement controlling elements becomes clear. The External High is located upon a resistate (a rigid and thick crustal block), being flanked by terranes less resistant to extension, hyper-extended or stretched and thinned, upon which the Internal and External Kitchens developed.

shales deposited in shallow saline water lakes of the Barremian/Early Aptian (equivalent to the local Jiquiá Stage) syn-rift phase of the evolution of the basins. The thickest and deepest shales occur in the internal portion of the basin, between the Cretaceous Hingeline and the extensive structural high termed External High. These shales were drilled/sampled/analyzed in several exploratory wells drilled by Petrobras, especially in the Campos Basin. Their thicknesses are in the order of several tens of meters and frequently occur intercalated with coquinas beds. Besides the petroleum found in the Pre-Salt Play, these shales are also responsible for all the petroleum found in the Post-Salt Play of the Campos Basin, in the oil fields situated on top and to the west of the External High. Significant volumes of oil and gas in the Post-Salt Play of the Santos Basin, to the west of the External High, were also sourced from these shales. The term Internal Kitchen is employed to designate all the internal grabens of these basins that contain the lacustrine shales of the Jiquiá Stage.

3.4.2 The Importance of the External High as a regional focusing high of the Pre-Salt system

The External High is a complex group of agglutinated structural highs that, as a whole,

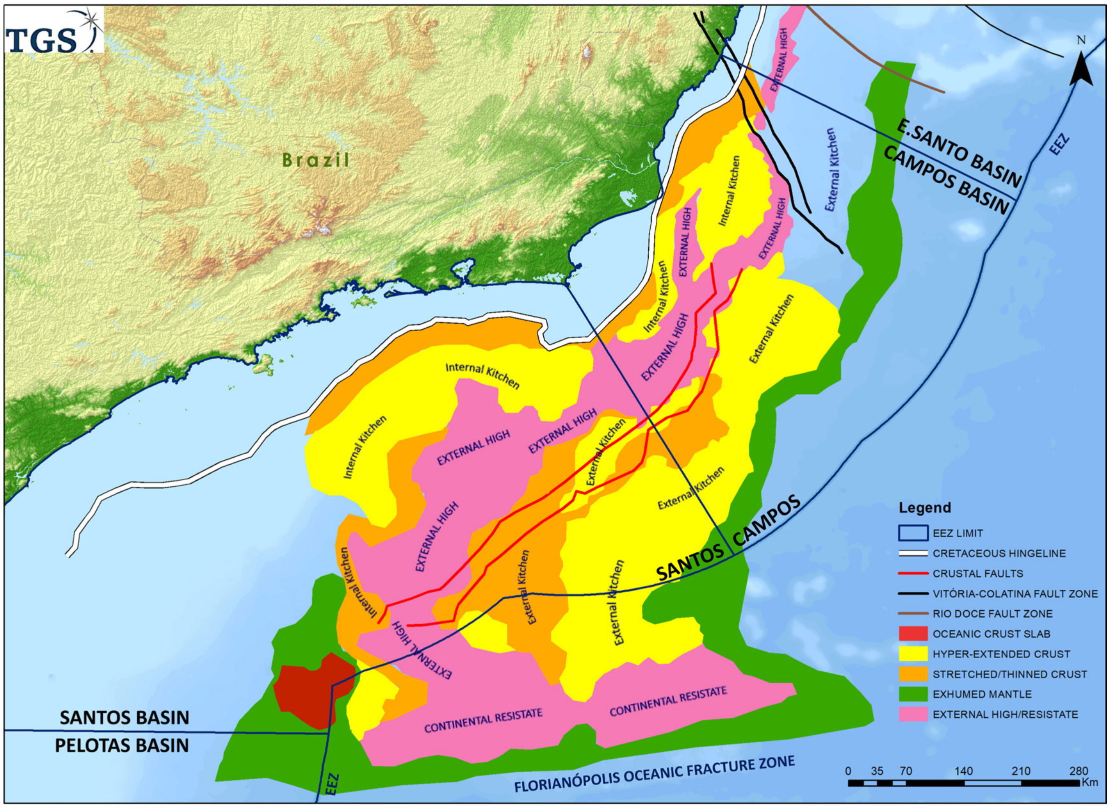

FIGURE 12 – Map of the crustal provinces of the Santos and Campos Basins (modified from ZALÁN et al. 2020b). The hyper-extended and stretched/thinned terrains contain Internal and External hydrocarbon kitchens. The surface expression of the continental resistate is the External High. A belt of exhumed mantle surrounds the continental crust of these basins. The Crustal Faults are a trend of very deep faults that root into the mantle and probably constitute the migration route of mantelic CO_2 to some of the Pre-Salt reservoirs. The Crustal Faults possibly represent the collapse of the eastern margin of the continental resistate (External High) due to the abrupt crustal thinning at its contact with the hyper-extended terrains.

present their economic basement and sedimentary cover in structural levels well above the neighboring terrains. They form a long, wide and continuous NE-SW-trending structural high in the Santos Basin, deflecting to an N-S-trending high in the Campos Basin, cutting the basins through its central portion, similar to the backbone of a human skeleton. The External High is the surficial expression of a continental resistate that presents a deeper underlying Moho, creating a significantly thicker continental crust underneath it relative to the adjacent thinned/stretched/hyperextended terrains. Due to isostatic compensation, this feature ended up elevated relative to these adjacent terrains (Figure 2A) in both basins. It separates an internal subdued area of thinned/stretched/hyperextended terrain to the west, narrow in Campos and wide in Santos, from another much wider subdued area of mostly hyperextended terrains to the east, in Santos and Campos (see figures 2, 3, 11). These two subdued areas constitute the Internal and External Kitchens, respectively, where grabens are much more plentiful and deeper, containing source rocks in greater quantity and depths adequate to generate oil and gas.

This geometry of a central high flanked by two hydrocarbon kitchens was highly favorable to focalizing fluid migration toward the structural culminations of the External High. The External High concentrates <u>all</u> commercial discoveries of the Pre-Salt in the Santos and Campos Basin and most of the Post-Salt discoveries in the Campos Basin (Figure 13). All oil found in the Pre-Salt and the majority found in the Post-Salt in both basins have been geochemically correlated to the source rocks of the Internal Kitchen. In significant part, this is due to the immense load of piles of clastic sediments (Juréia Formation) derived from the erosion of

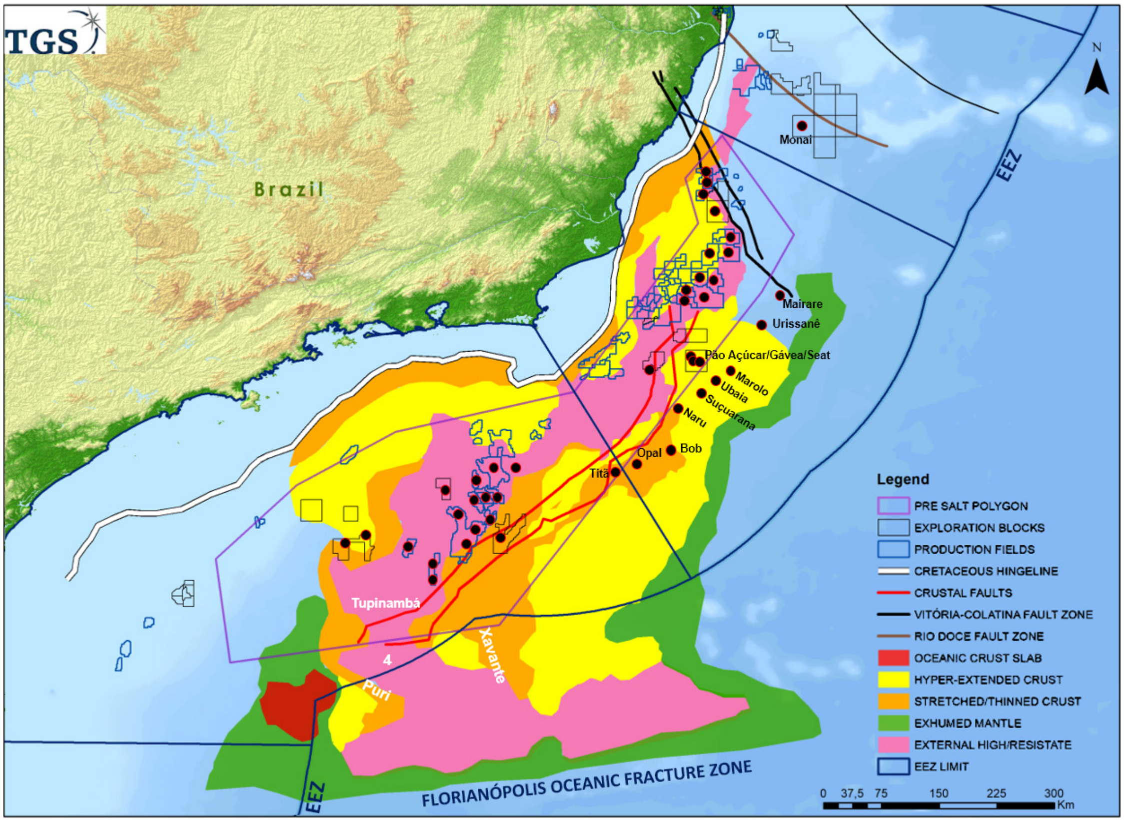

FIGURE 13 – Map of the crustal provinces of the Santos and Campos Basins (modified from ZALÁN et al. 2020b) displaying all ring fences of the Post-Salt and Pre-Salt fields, the Pre-Salt Polygon and, in black dots, the discoveries in the Pre-Salt (economic or non-economic yet). The focusing control of the External High upon all these discoveries is remarkable. The Pre-Salt discoveries named in black are recent finds made in the External Kitchen realm. The prospects in white represent mapped Pre-Salt structures that could hold giant petroleum accumulations in the southwest extension of the External High in the Santos Basin.

the rapid uplift of the Cretaceous Serra do Mar coastal ranges during the Coniacian-Maastrichtian) (ZALÁN & OLIVEIRA 2005). The load coming from west to east was gradually dumped upon the External High, tilting it towards the west and placing its strata in a very favorable position to receive the hydrocarbons from the Internal Kitchen migrating from west to east upwards, towards the internal structural culminations of the External High.

3.4.3 The External Kitchen

The terrains situated to the east of the External High are situated upon predominantly hyperextended continental crust and some stretched/thinned crust. They constitute the end of the crustal taper profile that characterizes the MPPMs from proximal (nearshore) to distal (offshore) domains (see figures 2A, 3 and 11). The extension was extreme in this region, with intense magmatism and fewer typical sedimentary grabens than in the Internal Kitchen, although with a markedly higher degree of deformation. Usually, these grabens are shallower and present several syn-rift sequences, individualized by angular unconformities, with different intensities of blocks and fault rotation. Their seismic facies indicate a higher content in volcanic (volcanos, lava flows) and intrusive igneous rocks. Their abundance visibly increases towards the zone of final rupture, the COB. The Pre-Salt Play is also a proven petroleum system in the External Kitchen. Significant reserves of gas and condensate were found in the Pão de Açúcar, Gávea and Seat fields in the Campos Basin. Oil had also been found in the adjacent block BM-C-34. The analyses and geochemical correlations performed indicated depositional environments for the source rocks similar to those found in the Internal Kitchen but different enough to be clearly distinguished from the other. Despite this, the potentiality of the External Kitchen as a supplier of large volumes of oil and gas has been questioned in the last three years as a result of several dusters or sub-commercial finds of gas (Mairare, Urissanê, Marolo, Naru, Opala, Bob, Titã, Monai in Espírito Santo) (Figure 13). These wells were drilled targeting the Pre-Salt Play in 4-way structural closures mapped in the External Kitchen. Gas was the prevailing hydrocarbon found, and the quantities up to now were not deemed commercial. In some wells, the CO_2 content was very high (Peroba). Since the microbialite reservoirs were found in these wells and the kilometric salt coverage was present, the conclusion was that there should be a deficiency in terms of source rock richness or maturation level in the External Kitchen. All the differences in the lithological filling of the grabens and the amount of deformation listed above must have contributed to a different development, preservation and maturation of the possible source rocks in the External Kitchen, which was different from the conditions found in the Internal Kitchen. However, the area of the External Kitchen is too large to be condemned to oblivion because of the drilling of less than a dozen and a half wells. The wells did not penetrate below the targeted reservoirs; thus, the filling of the External Kitchen grabens is still unknown. Major companies have made significant investments in the acquisition of blocks in this distal region; consequently, it is expected that a re-evaluation of the results obtained and a consequent shift in the exploratory tactics should occur before the next wave of exploratory wells in the External Kitchen takes place.

Em 2023, the production from Pre-Salt reservoirs attained an average of 3,304,000 boed, representing circa 76% of the Brazilian petroleum production (Boletim da Produção de Petróleo e Gás Natural, ANP, December 2023, Encarte de Consolidação da Produção em 2023).

4 REMAINING POTENTIAL IN TERRESTRIAL BASINS

From this chapter, the basins with remaining potential will be tentatively presented in decreasing order in terms of petroleum potential associated with the probability of occurrence of large discoveries as predicted.

4.1 Paleozoic basins

The Brazilian Paleozoic basin with the greatest petroleum potential at present is, undoubtedly, the Solimões Basin (also known as Alto Amazonas Basin in old literature). The Solimões Basin presents one proven petroleum system: Jandiatuba-Juruá. Discovered in 1986, the Rio Urucu petroleum province (or Polo Urucu) is a complex comprising seven producing fields that have been delivering tens of thousands of bopd of the highest quality in Brazil, as well as tens of million cubic meters of gas per day, for the last three decades. The Juruá field (not developed yet) contains an *in place* volume of gas in the order of de 1 TCF (equivalent to 167 million boe). ENEVA has recently acquired it. Once in production, its gas volumes will be similar to those produced at Polo Urucu, bringing energy and progress to the remote Amazonian State of Rondônia or to its home State of Amazonas. The same is true for several other already discovered gas fields that are close and in trend with the Juruá field, all of them associated with the hanging wall of the long Juruá reverse fault. However, looking further into the future, the perspectives for new discoveries of large volumes of petroleum in the basin are modest. First, because Petrobras worked uninterruptedly and intensively for 45 years in the basin. The company shot hundreds of thousands of kilometers of 2D and 3D seismic all over the vast forest cover, drilled hundreds of wells and discovered tens of gas/condensate fields, some with oil, by applying the successful compressional anticline/reverse fault model. The seven best discoveries were cherry-picked from these to compose the Polo Urucu. A fantastic 700 km-long complex of pipelines was constructed through the tropical forest, half sub-aerial, half sub-fluvial, to transport the gas/condensate/oil production to a refinery in the jungle capital town of Manaus. Second, any other discovery (already known or to be still discovered) will take place in the middle of the dense and pristine Amazonian forest. Two risks affect the economic feasibility of such projects: (i) the enormous distance from large energy-consuming population centers, and (ii) the intense pressure that environmentalist groups will exert against their development in the heart of the Amazon forest. Although the geologic risk for finding new discoveries is low, so it will be the chance for commerciality. I do not believe that, except for ENEVA, which already has a gas field of large dimensions situated close to the pipelines that serve the Polo Urucu, other private companies will invest in exploring the Solimões Basin.

The Paleozoic basins will continue to bring good surprises to Brazil and wealth to the Brazilians, especially the Parnaíba Basin. We should look at the work done up to now by ENEVA in this basin, and we should hope that other companies will follow in their footsteps on how to proceed in the exploration of the Brazilian Paleozoic basins. The recipe seems to be: (i) to come up with an innovative, out-of-the box geologic model; (ii) to test it with the drilling of key wells, guided and based on the best available seismic data possible; (iii) if successful, new blocks and new seismic data should be acquired and the model replicated elsewhere; (iv) geologists, engineers and economists should get together and devise a novel model for the exploitation of the discoveries, aiming the most efficient way to monetize and profit from them. Eneva`s "*reservoir-to-wire*" model allowed the gas to be produced and carried through short pipelines to small thermoelectric plants that feed the local grid of the main transmission lines of Brazil. It is a quick and efficient way to monetize gas discoveries. The Parnaíba Basin will unveil several new modest-sized (tens to hundreds of BCFs) gas fields contained within bowler hat sills. Applying this exploratory model and the "*reservoir-to-wire*" exploitation model will allow the company, or companies, to enjoy profitable E&P activities for a few decades ahead. However, to a sizeable leap in the size of the reserves to occur, a new geological model will have to be devised, one in which the dimensions of the trap should not be limited by the small dimensions of bowler hat sills. In such a model, much larger structural closures will have to be looked upon, folds created by compressional stresses of some sort or by faulting. The sealing rock could still be a large sill, but, most probably, another argillaceous sedimentary rock will be needed. The age of such structures should be older than the igneous events of the Jurassic/Cretaceous to have been present when the gas was generated by the sills intrusions into the Devonian source rocks.

The acquisition of exploratory blocks in the Paraná Basin by ENEVA heralds an exciting future for this basin. If the geologists can successfully apply the Bowler's Hat model, as the preliminary results described above indicate, the number of discoveries of gas fields and volumes therein will be greater than in the Parnaíba Basin. The Paraná Basin is twice as large as the Parnaíba Basin, its depth is also twice as deep, and it is situated below Brazil's greatest industrial and agricultural centers. The generation of gas occurred both by conventional (overburden of the Devonian Ponta Grossa Formation) and non-conventional ways (direct contact of intrusive rocks into the Permian Irati Formation). Hopefully, ENEVA will be able to innovate again and develop a monetizing model of the *reservoir-to-major pipeline,* which will not require the construction of thermo-electric power plants. That is because the Bolívia-Brazil (GASBOL) gas pipeline passes near ENEVA's blocks, and any discovery of a gas field could be immediately linked to the existing pipeline (Figure 14). As highlighted previously, Brazil has imported gas from Bolivia at very high costs and is subject to severe political turmoil. Bolivian gas reserves are exhausting at a very rapid pace. The GASBOL pipeline will be empty shortly, and we are looking for alternatives to fill it out. It is quite possible that another geological irony could take place with a successful exploratory campaign by ENEVA and the consequent expansion of its activities throughout the Paraná Basin. Large reserves of gas could be found very near or right below the GASBOL route. The Paraná Basin has potential to present large gas discoveries, in the order of several TCFs, be it through the application of the Bowler's Hat model or the discovery of large conventional structural trapping. We emphasize that geological creativity, exploratory persistence, commercial insights and a favorable legal-tax regime will be fundamental in the full development of the petroleum potential of the Paraná Basin. We forecast the discovery and development of numerous gas fields that the local industries and the agribusiness of Brazil's Southeast, Central West and South regions will promptly use. The occurrence of oil in such discoveries is possible but in very subordinate amounts to the large gas reserves predicted to be found.

The Amazonas Basin also presents two proven petroleum systems: Barreirinhas-Monte Alegre and Barreirinhas-Nova Olinda. ENEVA already produces gas from the second (Azulão field). The basin, however, has three major problems: (i) low seismic resolution, (ii) an enormous amount of basic igneous intrusions displaying the most varied shapes among the Brazilian Paleozoic basins, and (iii) extensive tropical forest cover. The first problem is derived, in great part, from the second. The amount and the diversity in shapes of igneous intrusions throughout the entire stratigraphic column are phenomenal. These create severe problems of energy absorption and velocity fields.

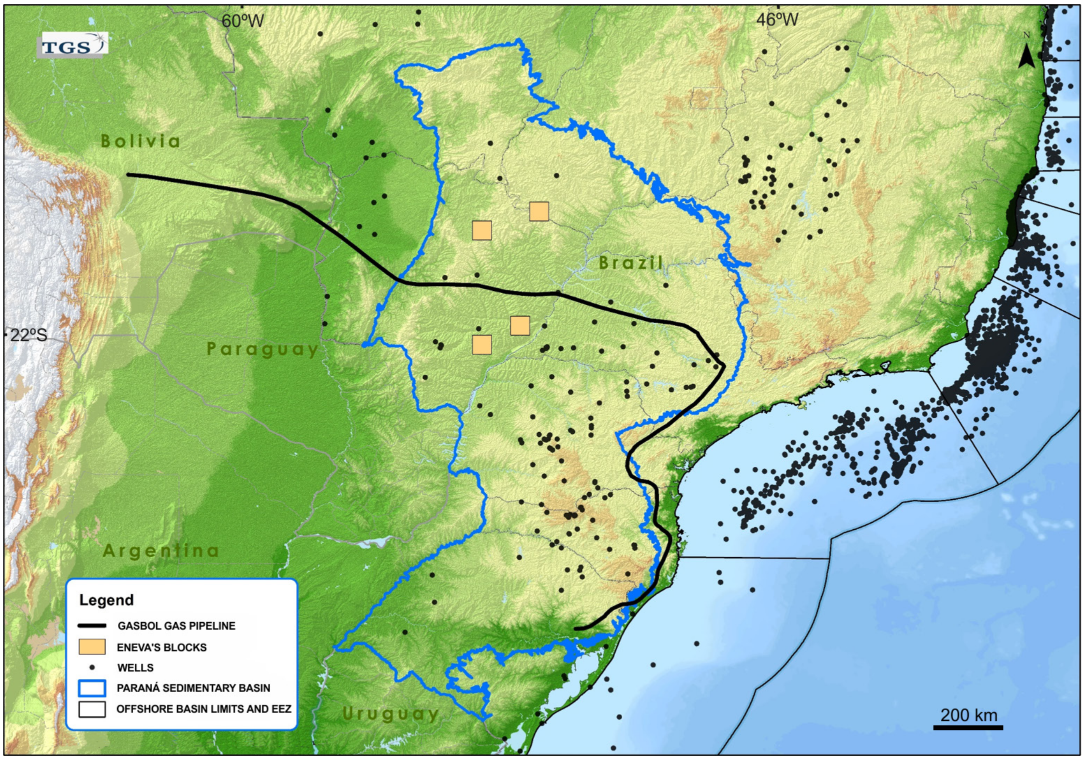

FIGURE 14 – Map of the Paraná Basin (in blue) showing the location of four exploratory blocks acquired by ENEVA (in orange) and their proximity to GASBOL (black line). The blocks are 60-200 km from the gas pipeline.

The intensity of the magmatism increases from the west (formerly called Médio Amazonas Basin) to the east (formerly called Baixo Amazonas Basin). In this last subdivision, the seismic resolution is practically nil. The positive aspects that can be pointed out in the Amazonas Basin are: (i) the existence of tectonic structures, such as faulted blocks and domes associated with igneous intrusions, besides stratigraphic traps (as is the case in the Azulão Field), and (ii) the existence of two great populational/economic centers within the basin, Manaus and Santarém. These two cities allow the development and transport of liquids discovered in their vicinities through highways (in a 200-300 km radius). We believe, however, that the negative aspects surpass the positive. We presage that the Amazonas Basin, despite its proven petroleum potential, will not aggregate large discoveries and productions of petroleum to the Brazilian economy in the following decades.

The exception possible would be ENEVA, if by taking advantage of the experience acquired in the development of Azulão and Japim fields, and of the infrastructure developed in the Silves area, it could find and develop several similar nearby discoveries. As such, small fields could be commercial when developed as clusters. This seems to be the case with the recently announced discovery of Anebá, which reportedly found small volumes of oil and gas in 5 different reservoir levels (< 10 million boer) (GAFFNEY CLINE 2023).

4.2 Mesozoic basins

The classic producing provinces of Recôncavo, Potiguar, Sergipe-Alagoas and Espírito Santo Terra are presently in the mature to overmature stages of exploration/production. All of them had no significant discoveries for decades, had already passed through their peak and plateau stages, and presented strong declining production curves. Their present stage of production is characterized by exhaustion of the already producing fields and gold-digging sporadic new small similar discoveries, effected by several small- to medium-sized domestic companies. Although insignificant in the national economy, this stage is very critical to the Brazilian petroleum industry because it is in such an environment that these companies will acquire operational experience, get used to exploratory risk, and reap the usually high rewards of successful petroleum industry activities. As time goes by, several new Brazilian petroleum companies will survive and establish the basis for a strong and diversified national petroleum industry. These companies will then be ready to tackle more challenging exploratory and production environments, such as the deep and ultra-deep water realms.

For these basins, we expect such companies to try stabilizing the production curves by optimizing the efficiency in reservoir management and applying new technologies to increase the recovery factor. It is also expected that discoveries of additional petroleum reserves around the fields will take place at shallower or deeper depths than the classically producing reservoirs. The ever-increasing gas-demanding environment will also help to economically develop untapped gas reserves that were recently disregarded, used for re-injection into the reservoirs or flared.

Regarding real discoveries of new reserves, they will certainly occur. Most of them will be small, with volumes of a few hundred of thousand to a few million barrels of oil equivalent recoverable, either inside or outside existing ring fences. There will always be space for discovering small accumulations imperceptible in old seismic data, later highlighted in modern reprocessing or by using sophisticated seismic attributes. New creative geologic concepts will allow for finding new accumulations in deeper reservoirs or unique trapping mechanisms. In this last hypothesis, given its uniqueness, there are small probabilities that the newly discovered accumulations may be in the range of tens of million barrels of oil equivalent recoverable.

We here disregard the hopeful belief that the use of hydraulic fracturing (fracking) of non-conventional reservoirs, especially of organic-rich shales (source rocks), could significantly increase the recoverable petroleum potential of these mature to overmature basins, as touted by some geoscientists. Brazil and the Brazilian geology of its basins do not present favorable conditions for the profitable use of this technique. This technique requires (i) a massive volume of oil/gas in place, (ii) a huge amount of water (scarce in most of these terrestrial basins), (iii) an abundance of specific fracking operational equipments not available in the country, (iv) it presents very high costs due to the necessity of drilling hundreds to thousands of wells and, last but not least, (v) the ever opposition of environmental groups towards the use of this method. The impediments are mainly of an operational and economic nature.

Of the four basins cited above, we classify the Recôncavo and Potiguar Basins as having greater potential in reserve replenishment and stabilizing or even slightly increasing the current production curves. Sergipe-Alagoas comes next with a significantly lower potential and probability for such accomplishments. Regarding Espírito Santo Terra, the probability of achieving such feats is close to zero.

There is a fifth Mesozoic terrestrial basin that deserves a special observation. The Tucano Basin is the physical continuation of the Recôncavo Basin (Figure 1). Of the larger Recôncavo-Tucano-Jatobá rift complex, the Tucano is the largest graben, more widespread and much deeper. Geologically, it is practically unknown. Because it is too deep (> 6.000 m of drilled sedimentary section) and has few wells drilled with a significant penetration, the petroleum potential of this basin is still a mystery. The thick sedimentary column led to a poor seismic resolution in the first surveys acquired in the basin. Few wells in the east and south were drilled through its complete but thin and shallow stratigraphic section. Based on this scant data, present knowledge indicates that the sedimentary filling of the Tucano Basin has a greater sand/shale ratio than the better-known Recôncavo Basin. Thus, the chances of having the full development of the lacustrine organic-rich shales of the Candeias Formation, as well as of younger prodeltaic shales that act as seals, would be much less. The present petroleum potential estimated by the industry is very low. There is, however, a certain probability that during the stage that saw the development of the freshwater lakes in the Neocomian, in which the organic-rich Candeias shales were formed, such lakes extended into the Tucano Basin. After all, the belief in the greater sand/shale ratio is based on the shallower portions of the wells that did not drill enough into the basal section. If that comes out to be true, the Candeias shales could act as source rocks and seals for the classic accumulations of Sergi/Água Grande reservoirs against downthrown blocks of normal faults. At such depths, the gas would be the petroleum phase expected. It would be necessary for a medium-sized company to be willing to play this high-risk/high-premium play. The reward would be the discovery of large gas accumulations close to an industrial center (Salvador). On a positive note, the southern part of the Tucano Basin, close to the Recôncavo Basin boundary, has already produced gas in a few decommissioned fields. Because it is so poorly known, predictions about the petroleum potential of this basin are not accessible. Based on present knowledge, the probability of discovering commercial oil and gas accumulation is very low. However, the same ignorance about its geology should allow bold geologists to think out of the box and create novel concepts that could lead to the unexpected discovery of large volumes of gas.

4.3 Proterozoic basins

We do not foresee large gas discoveries in the Brazilian Proterozoic basins, much less oil. Of the two large Proterozoic basins that present any indication of the presence of hydrocarbons, the São Francisco and Parecis Basins, the first is the only one that has a minimal probability of containing minor gas accumulations, profitable only to small entrepreneurs and/or companies.

The São Francisco Basin, with an area of circa 380,000 km², displays on its surface several exudations of gas undoubtedly of petroleum origin but invariably dry (composed exclusively of methane). These occurrences instilled Petrobras into exploring the basin in a conventional way in the 1980s by shooting 2D seismic and drilling four wells that resulted in dryness. Decades later, a small Brazilian company named PETRA acquired an enormous amount of 2D seismic lines shot along existing highways, roads and trails (crooked lines) that guided them in the perforation of tens of wells, several of them with shows of gas. Some of these presented short-lived gas production in drill stem tests, with flames of several meters long lasting several days in a row. Companies like Brazilian IMETAME and ORTENG also drilled a few wells with similar results. At the end of these exploratory campaigns, the geological conclusion was that the basin has a proven petroleum system for gas. On the other hand, the quality of the reservoirs is very low, with permo-porosity values that fall into the non-conventional category (tight gas sandstones). In doing so, their exploitation would demand the use of hydraulic fracturing (fracking). As mentioned above, Brazil does not have, and, in my opinion, it will never have, the necessary operational requirements, water availability, and an economic environment to allow such exploitation to be profitable. Large extensions and large volumes of gas-saturated Proterozoic sandstones and hundreds to thousands of wells would be necessary to release significant gas volumes to the surface. Given Brazil´s operational and economic impediments, the future exploitation of such reservoirs is doomed. The quantities of gas found up to now were always minimal, either in extension or vertical columns. Additionally, the eternal opposition of environmental groups towards this technique, especially onshore, will always be a difficult hurdle to overcome. Unless a lucky private entrepreneur finds a conventional gas accumulation that requires a minimal amount of conventional fracturing, obtaining a persistent production for a few years, we do not forecast the discovery of commercial gas accumulations in the São Francisco Basin.

The Parecis Basin is slightly smaller than the São Francisco Basin. It also presents some exudations of gas on its surface; additionally, one of dead oil is in marginal outcrops of its sedimentary filling surrounding the basin. Petrobras, as usual, was the pioneer in the exploration of the basin by shooting some scant seismic and drilling three wells (two stratigraphic and one exploratory). ANP did an excelent job by shooting several 2D seismic sections of good quality and drilling two stratigraphic wells. Two of such drillings presented feeble shows of gas and some bituminous residues. The results of these exploratory activities and the geological knowledge obtained up to now are not favorable to forecast any medium or large probability that any petroleum company will decide to invest in the exploration of the basin shortly; or in the distant future as well.

In summary, the Brazilian Proterozoic basins, as several other Proterozoic basins worldwide, present indications of petroleum generation and occurrence in its sedimentary fill. The indications of gas in the subsurface and at the surface are numerous. However, such occurrences seem to be related to small pockets or fractures, which, once in testing, deplete or dry out very quickly. The great ages of the reservoirs, the consequent diagenetic tight nature, and the large time span during which these basins have been exposed and weathered at the surface (practically throughout the whole Paleozoic), seem to be significant deterrents to commercial discoveries.

5 REMAINIG POTENTIAL OF MARITIME BASINS

As in the previous chapter, the basins with greater potential will be presented in decreasing order of forecasted petroleum potential associated with the probability of the occurrence of large discoveries as predicted.

5.1 Pre-Salt

There is absolutely no doubt that the Pre-Salt of the Santos and Campos Basins is, still, the play with the largest probabilities of yielding new discoveries in the order of a few to dozen billion barrels of oil equivalent recoverable. Besides being a petroleum system that has been exhaustedly proven, it still presents numerous conventional four-way closures, with large to medium sizes, that have still not been tested. As a matter of being coherent with the current legal-fiscal regime, we are going to discuss the potentiality for new discoveries in two different areas, as defined: (i) inside the Pre-Salt Polygon, and (ii) outside the Pre-Salt Polygon (Figure 13). Both possess the potential for new discoveries in the order of billions barrels of oil equivalent recoverable.

The area inside the Pre-Salt Polygon encompasses the vast majority of the known discoveries and producing fields of the Pre-Salt Play. There are still tens of non-tested four-way closures within it, despite the careful geological screening that Petrobras has performed in the entire Santos Basin in the last 16 years. How could that be? A few reasons of geological/economic/operational nature for that could be thought of: (i) the areas of such structures could not compete with the size of the giant and super-giant fields discovered, (ii) the evaluated chances of geologic success were lower than of those of the discoveries, be it due to reservoir seismic facies or to the absence of proper salt seal, (iii) because of predicted high contents of CO_2, (iv) for not having been offered yet in formal bids by ANP to the industry, and (v) for having been overlooked in areas of older and/or poorer quality seismic surveys.

The remaining interest latent in the international industry for the Pre-Salt Polygon became clear during the 1st Permanent Offer of Blocks in Production Share mode, promoted by ANP in December 2022. Eleven blocks were offered to the industry inside the Pre-Salt Polygon, all containing large undrilled 4-way closure structures, ten of them of large sizes (Figure 15). Two such structures are highlighted here because they carry very high probabilities of holding giant fields: Água Marinha and Tupinambá (Figures 15, 16 and 17). Água Marinha has a closed area of around 200 km² and may contain half a billion boe in place (ÁVILA 2020). Although one of the smallest offered structures, Água Marinha has the highest chance of geological success. Its location is close to the main hub of producing fields in the Campos Basin, the structure is prominent, and the seismic facies of the reservoirs are just right (Figure 16). After fierce competition, the group formed by Petrobras/TotalEnergies EP/Petronas/Qatar Energy won the right to explore the block. Prospect Tupinambá (Figures 13, 15 and 17) presents an enormous closure of several thousands km², having had three wells drilled on its flanks by Exxon. Two of them presented shows of oil; the third was dry. The remaining undrilled higher closed structure has an area of around 800 km² and could contain a very significant "attic oil" (Figure 17). ANP evaluated Tupinambá as being able to contain 4.9 billion boe in place (ÁVILA 2020). The structure has been leaking oil from its crest for some geologic time, since the leaked fluids formed a small petroleum field in Upper Cretaceous turbidites right above the culmination of the Tupinambá structure. This small Post-Salt accumulation is a clear bright spot displaying a flat spot. Several bright flags can be seen along faults that emanate from the crest. Petrobras, using a ROV, detected an important oil seepage at the present sea bottom right above the top of this structure. The oil was geochemically characterized as Pre-Salt oil. Despite this long-term leakage, all these indications point to the fact that Tupinambá Prospect still has a significant oil accumulation in the Pre-Salt microbialites. BP acquired the right to explore this block in December 2023. Additionally, other examples of smaller undrilled structures in the Pre-Salt, inside the Polygon, displaying beautiful examples of hydrothermal travertine buildups, are also presented (Figure 18).

For the sake of completeness, there are other types of attractive plays inside the Pre-Salt Polygon besides the classical Pre-Salt. These plays also present high probabilities of constituting important petroleum fields. Post-Salt Cretaceous/Cenozoic turbidites and Albian carbonates, already producers in a few fields outside the Polygon, present strong seismic indications of petroleum's presence. One of such opportunities is located in the Ametista Block. There, a Central Buildup Prospect (aka Ametista Prospect) is constituted by an enormous buildup of circa 200 km² formed by a probable Albian carbonate atoll developed amidst volcanic constructions. Thick stratified tabular facies containing marginal clinoforms and collapse structures (V-shaped features characteristic of

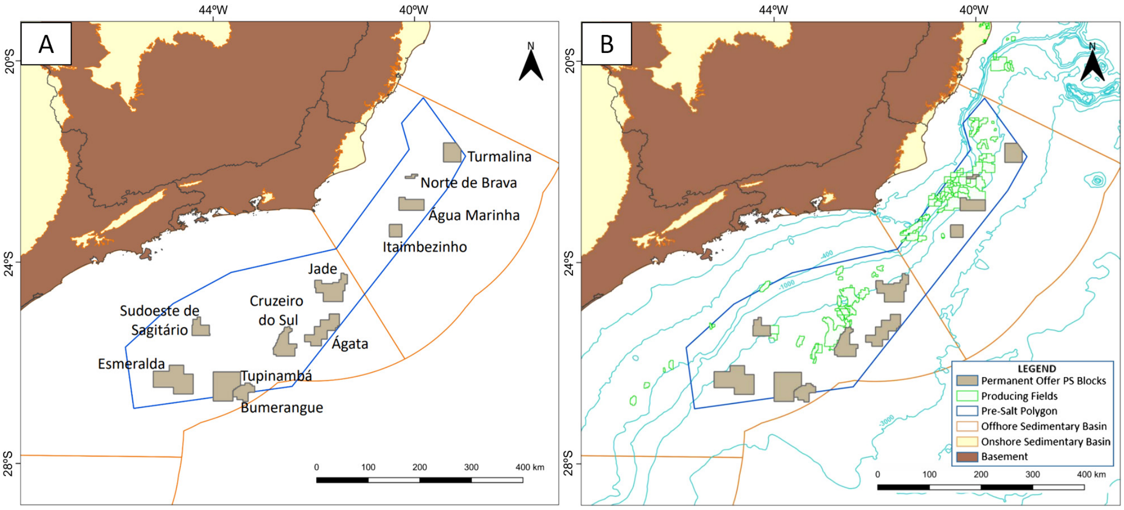

FIGURE 15 – Maps from ANP presenting in (A) 8 blocks containing undrilled Pre-Salt prospects inside the Pre-Salt Polygon (blue) (ÁVILA 2022). (B) the same map as the previous one also shows the ring fences of producing fields (green). This map is helpful to visualize the large extension of areas not yet explored inside the polygon. The Pre-Salt Polygon encircles the most promising regions for discoveries in the Pre-Salt, and its elongation and width roughly coincide with the outline of the External High.

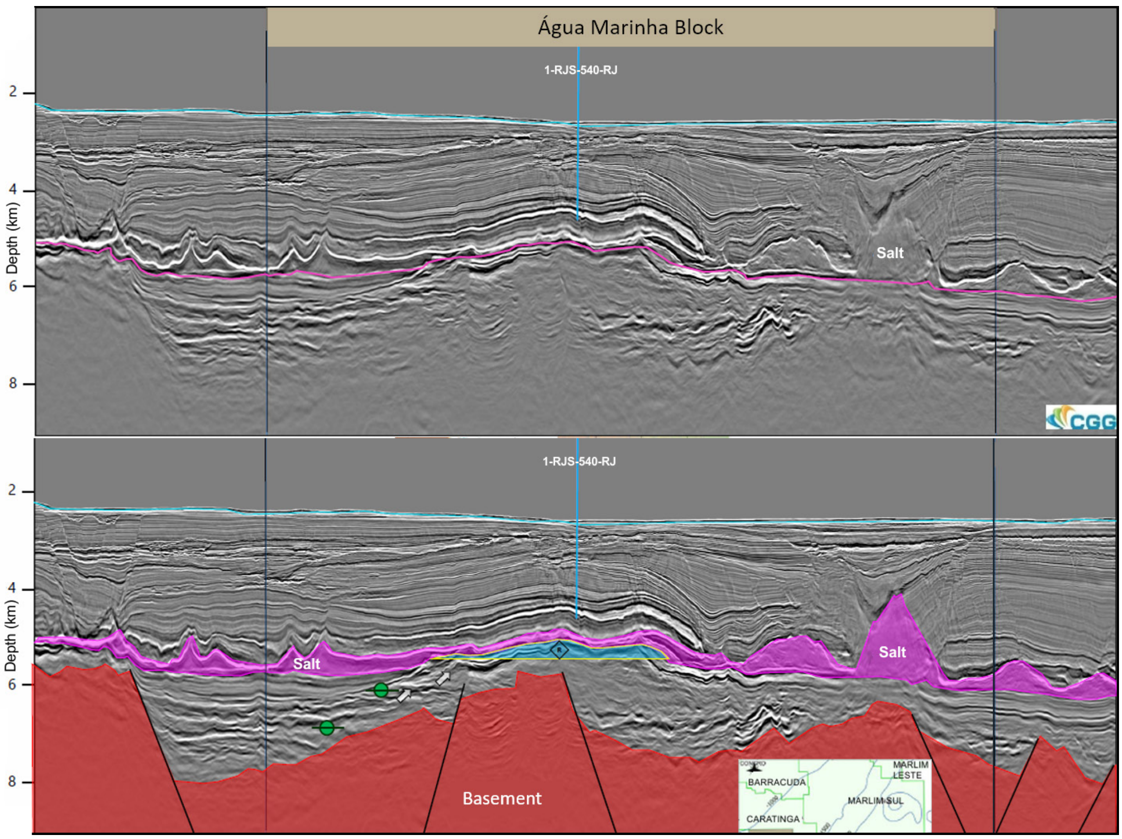

FIGURE 16 – 2D seismic section (depth) illustrating the Água Marinha prospect in the Campos Basin (ÁVILA 2022). The microbialite reservoirs (main targets) are outlined in light blue. The magenta reflector indicates the base of the salt. The thick graben to the left of the structure displays seismic facies typical of the source rocks (green circles) and could represent the hydrocarbon kitchen that sourced the prospect. The drilled well 1-RJS-540-RJ did not cross the salt interval.

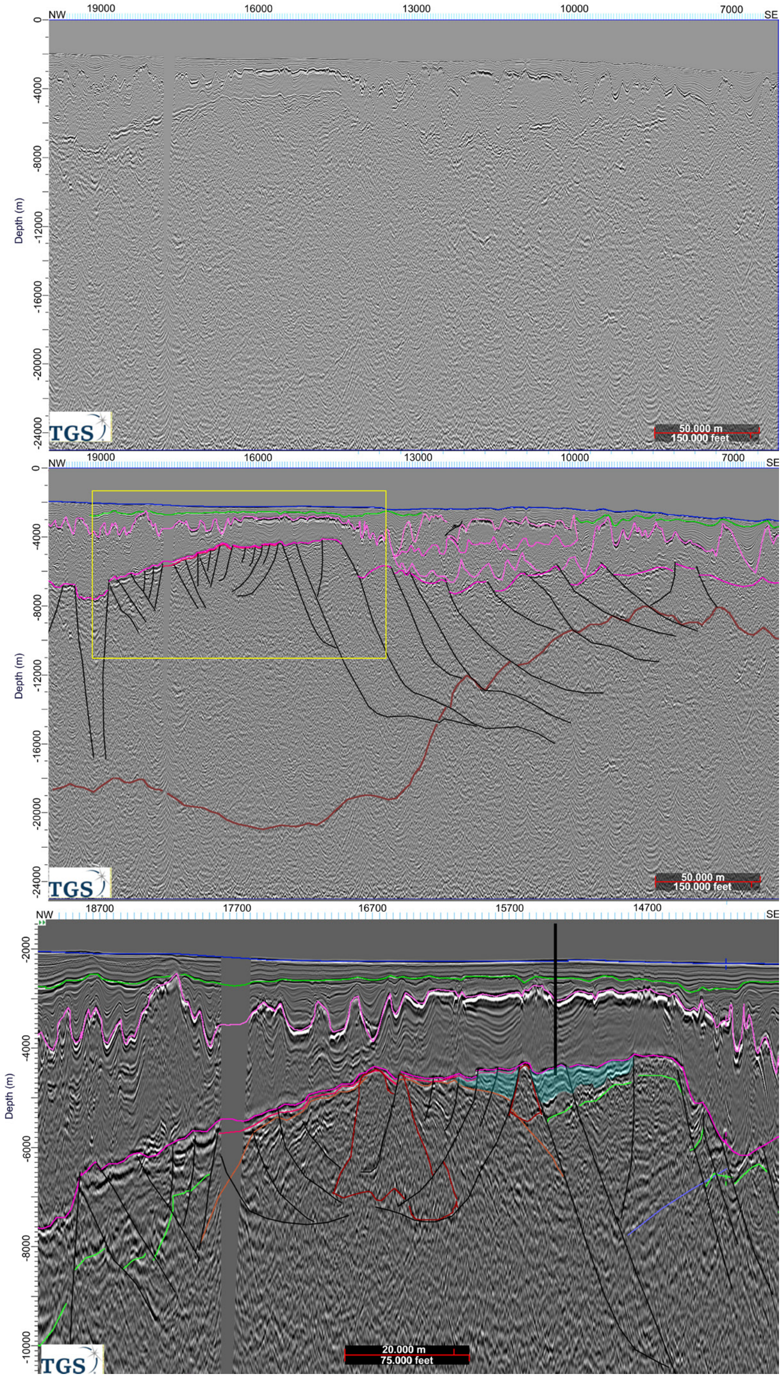

FIGURE 17 – 2D PSDM (depth) seismic section down to 25 km. Regional crustal scale section crossing transversally the External High in one of its thickest portions. (A) non-interpreted. (B) interpreted. The crest of the structure (mapped at the base of the salt, magenta reflector) corresponds to the Tupinambá prospect (see figure 13) close to its culmination. The deep brown reflector marks the MOHO. The characteristic bulging geometry of a crustal resistate is precise for the External High, with a strong necking to the left and extreme thinning (hyper-extension) to the right. (C) Zoom view of the crest of Tupinambá prospect. The typical seismic facies of the Pre-Salt microbialites are present (light blue), thus confirming the presence of reservoirs in the prospect. The black line is the updip projection of well 3-ESSO-5-SPS drilled by Exxon on the northern flank of the structure, in a structural position much lower (at the base of the salt level) than here displayed. This well found reservoirs with shows of oil. Magenta color reflectors indicate the base and top of the salt and internal sub-divisions of this evaporite package.

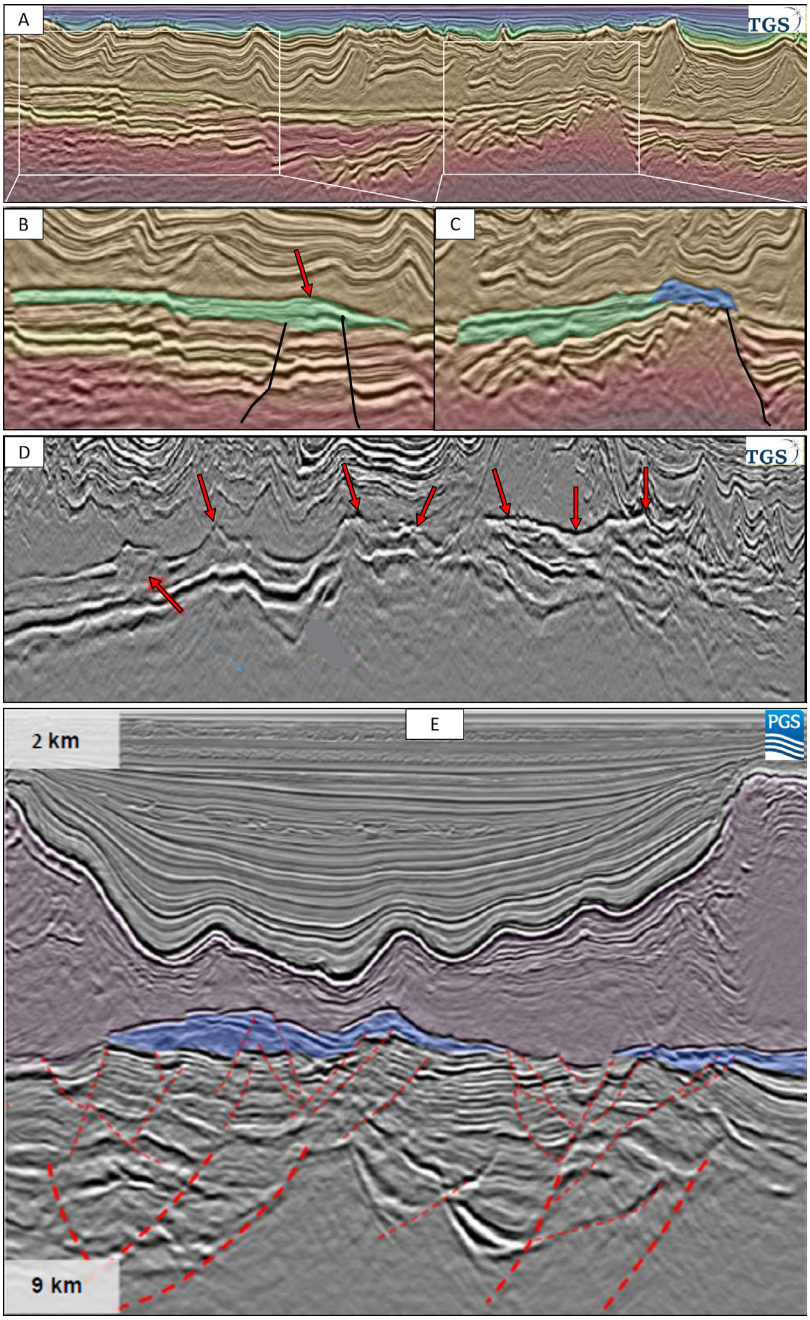

FIGURE 18 – Several seismic sections illustrate varied examples of undrilled hydrothermal buildup structures (travertines) inside the Pre-Salt Polygon. (A) Depth seismic section displaying two structures at the base of the salt (Picanha 3D survey, courtesy of geophysicist Andrew Hartwig of TGS). Different shades represent velocity fields. (B) The zoom of the structure to the left of the previous section shows tabular-shaped microbialites formed in a carbonate platform (light blue). The bulge (red arrow) above the two faults probably represents a hydrothermal buildup. (C) Zoom of the structure situated to the right of the section displayed in (A) showing the two main models of deposition of Pre-Salt carbonate reservoirs, side-by-side: the classic carbonate platform (light blue) (notice clinoforms and shelf edges) and the classic buildup seismic facies (dark blue) (hydrothermal travertines), this last one situated above a large normal fault. (D) 3D seismic section (depth), non-interpreted, exhibiting several buildups (red arrows) developed on top of a large Pre-Salt anticline (COBO et al. 2021). (E) 3D seismic section (depth) interpreted by the authors (ARASANIPALAI et al. 2019) displaying a wide Pre-Salt structure capped by the typical buildup seismic facies (dark blue). Notice intensive faulting affecting the structure, reaching up into the travertines.

carbonate terrains), intermingled with jagged peaks of probable volcanic origin, developed on top of an exhumed mantle protrusion (Figure 19). In this case, the petroleum could have been sourced by the ACT (Albian-Cenomanian-Turonian) anoxic marine shales surrounding the structure (Figure 19). This prospect is similar to the Ranger discovery by ExxonMobil in Guyana.

Outside the Pre-Salt Polygon, several Pre-Salt structures have already been drilled, but none have had commercial success up to now, as described before. All major companies worldwide have acquired blocks in the External Kitchen, situated east of the Polygon. The expectations for repeating the sensational discoveries made upon the External High by Petrobras in the External Kitchen were very high. The ANP`s Bid Rounds were very competitive. Companies spent billions of dollars in bonuses in the acquisition of several blocks. Several discoveries of gas were achieved, but none of them were considered commercial, given the fluid, the water depths and the distance to shore. Some humongous structures were alarmingly disappointing, like the Peroba Prospect

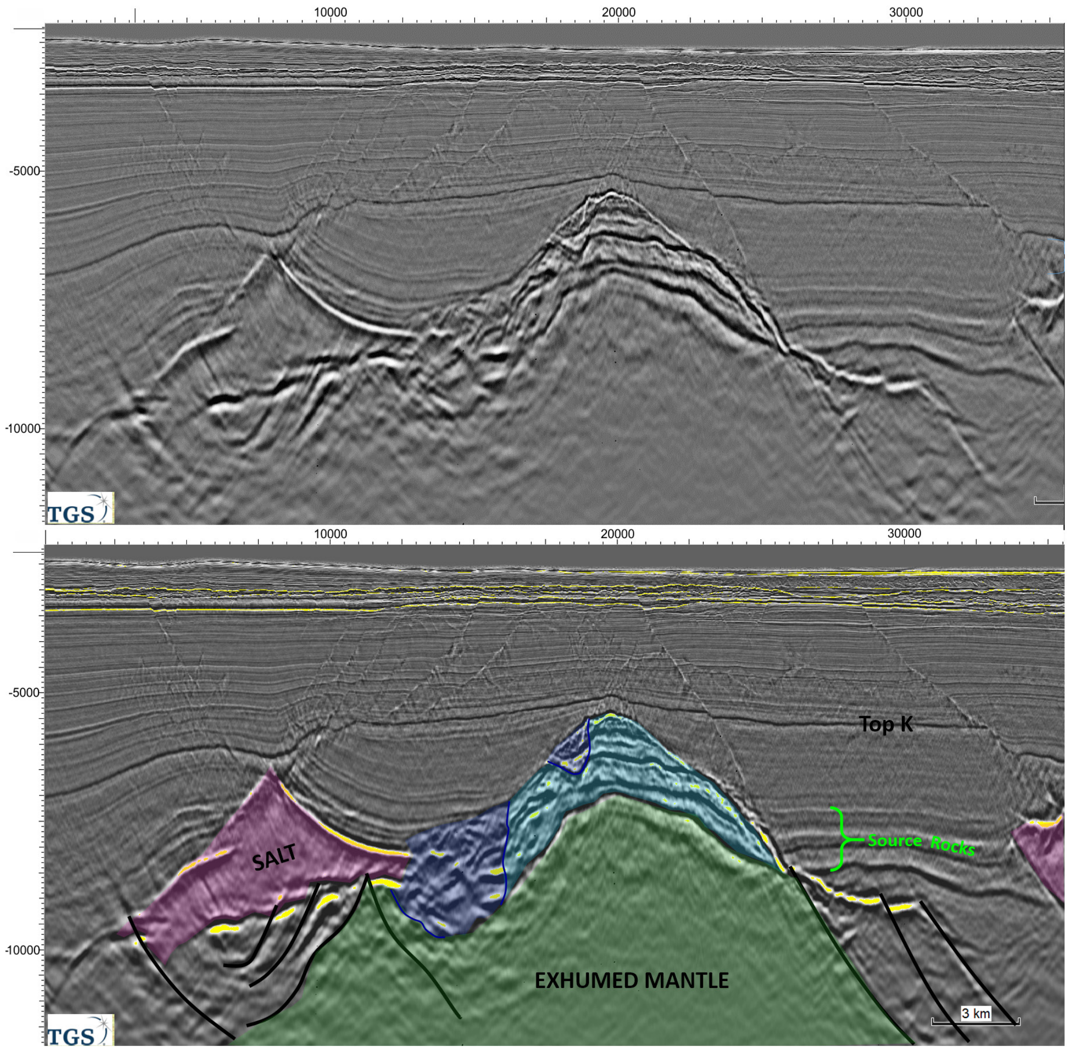

FIGURE 19 – 3D KPSDM seismic section (depth) presenting the magnificent Albian buildup named Ametista prospect in the southern Santos Basin, developed upon an protrusion of exhumed mantle. See the location of the Ametista Block in figure 20. The light blue color indicates seismic facies interpreted as a carbonate platform. The dark blue color shows seismic facies interpreted as collapsed cave breccias, a typical feature of karst topography, thus corroborating the carbonate nature of the buildup. The ACT source rocks are in direct lateral contact with the probable reservoirs.

(Figure 20). The drilling of Peroba was the first test in the External Kitchen, and it interrupted the company´s magnificent series of successful Pre-Salt discoveries. Peroba is a gigantic buildup structure. The well drilled through more than 500 m of highly porous and permeable microbialite reservoirs (possibly travertines). It is still the second thickest and most continuous microbialite reservoir found up to now. Unfortunately, they were completely saturated with CO_2 (Figure 21). Two other large structures that also did not meet expectations were Titã and Saturno, both dry. There are other buildup structures, however, that are very similar to Peroba. Their location seems to be more favorable in relation of the contaminant CO_2. Such buildups are not situated upon the trend of the Crustal Faults. Such faults mark roughly the boundary between the External High and the External Kitchen (Figure 12). They root deeply into the mantle and could be the paths for migrating this gas into the overlying Pre-Salt structures (Figures 20 and 21). One such structure is Pau-Brasil, the twin sister of Peroba, geologically speaking. Contrary to Peroba, its location is far from the Crustal Faults; thus, it presents a high probability of holding a large reserve of petroleum devoid of CO_2 (Figure 20).

There is a remote region in the distal part of the Santos Basin, beyond the Exclusive Economic Zone (EEZ), but already adjudicated to Brazil by the Commission of the Limits of the Continental Shelf (CLCS) of the United Nations, that, although being situated outside of the Pre-Salt Polygon, presents all the typical geological features of the significant Pre-Salt discoveries situated upon the External High. This area is, in fact, an extension of the External High to the southwest that bends strongly to the southeast towards the Florianópolis Oceanic Fracture Zone (Figures 12 and 20). In the seismic section of figure 22, it is possible to see a large, deep and thick Pre-Salt graben that displays all the characteristics typical of the Internal

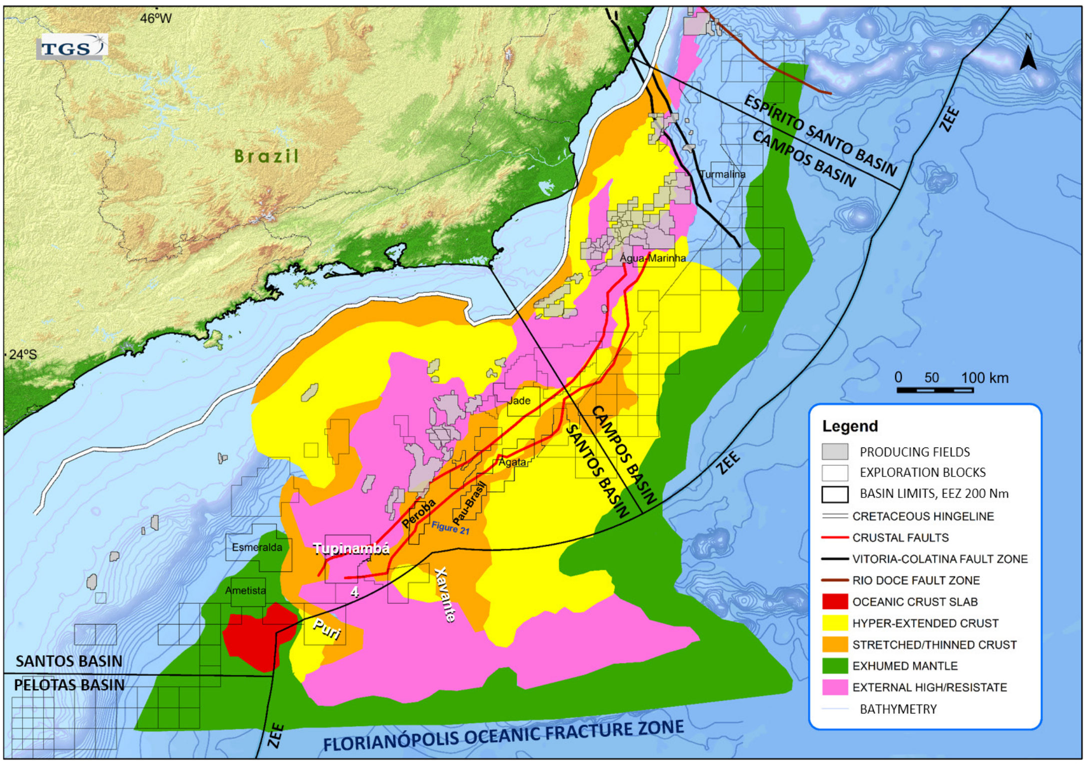

FIGURE 20 – Map of the crustal provinces of the Santos and Campos Basins (modified from ZALÁN et al. 2020b) displaying all ring fences of the Post-Salt and Pre-Salt fields and several exploratory blocks. The prospects in white represent mapped Pre-Salt structures that could hold giant petroleum accumulations in the southwest extension of the External High in the Santos Basin. The Crustal Faults possibly represent the collapse of the eastern margin of the continental resistate (External High), as explained in figure 12. Notice the different locations of Pre-Salt prospects Peroba (drilled and saturated with CO_2) and Pau-Brasil (undrilled) relative to the Crustal Faults.

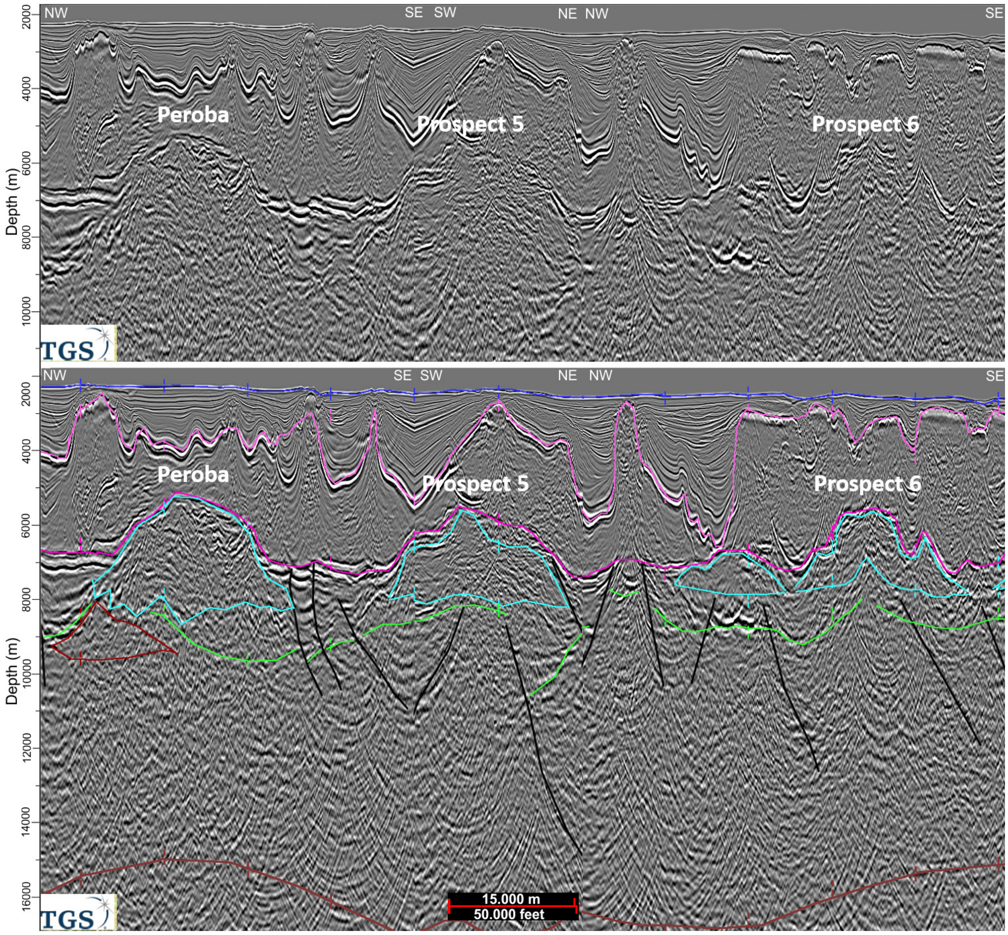

FIGURE 21 – 2D PSDM seismic line (depth) displaying three Pre-Salt buildup structures (prospects) in the Santos Basin, interpreted as hydrothermal buildups (travertines). Peroba was already drilled and confirmed > 500 m of excellent permo-porous microbialite reservoirs, saturated with CO_2. The two other undrilled prospects, located east of Peroba, are similar to drilled buildup and should contain the same reservoirs but with a higher probability of holding oil instead of CO_2. They are not inside the Crustal Faults trend (see Figure 20). From top to bottom: blue – sea bottom, light magenta – top salt, dark magenta – base salt, light blue – buildups, green – base Pre-Salt section.

Kitchen. Two gigantic structures flank this graben, Puri and Xavante (see locations in figure 20), both with Pre-Salt structural closures of over 1,000 km^2. Both have high probabilities of becoming super-giant petroleum fields (Figure 22) in the future. This region was first mapped by Spectrum, nowadays TGS, after the completion of an extensive 3D survey shot entirely beyond the EEZ. The interpretation of this survey revealed to the petroleum industry the continuation of the Pre-Salt play and its gigantic structures to remote corners of the ocean never considered before as having any petroleum potential (ZALÁN & NEWMAN 2020). Besides these two structures, others are of lesser magnitude but still large enough to hold significant petroleum accumulations (Figure 20).

To summarize, the successful exploratory model of the Pre-Salt can still yield the discovery of several giant fields and a pair of super-giants. This model, presented in figure 23, can guide several companies to succeed in their exploratory campaigns soundly, especially along the External High and in the Internal Kitchen region. For the External Kitchen, we suggest the geochemical modeling of numerous but smaller and thinner grabens, as well as enriching their filling with volcanic rocks (lavas and volcaniclastic material). As for the input of past geothermal gradients, there should be extra care, taking into account their location atop the very thin hyper-extended continental crust. In doing so, the results may point to a predominance of gas over oil in future

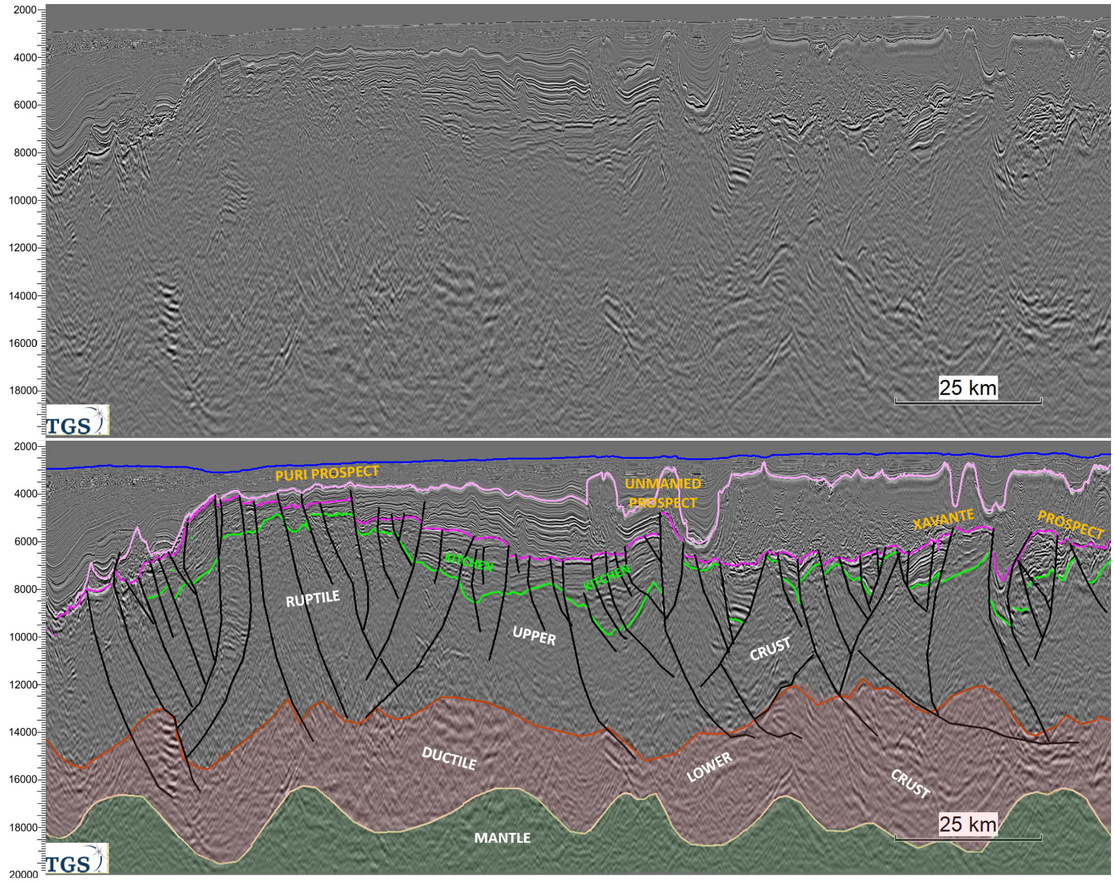

FIGURE 22 – 3D PSDM (depth) seismic section down to 20 km, illustrating the gigantic Puri Pre-Salt structure, half of the giant Xavante structure, and another prospect yet unnamed (location in figure 20). Notice the thick graben adjacent to Puri, probably a hydrocarbon kitchen, folded into a syncline, with its flanks favorably tilted upward toward Puri and the unnamed prospect. From top to bottom: blue – sea bottom, pink – top salt, magenta – base salt, green – base Pre-Salt section, brown – Conrad, beige – Moho.

discoveries in these ultra-distal regions. When exploration becomes intense in these remote regions, gas will probably be the planet´s most sought-after energy provider material.

5.2 Equatorial Margin - Pará-Maranhão, Foz do Amazonas and Barreirinhas basins

The Equatorial Margin of Brazil is usually treated by the press and laymen as a single and uniform entity. In reality, it can be divided at approximately its geographic middle region into two distinct groups regarding their geology and petroleum plays (Figure 1). The first group, constituted by the Foz do Amazonas/Pará-Maranhão/Barreirinhas Basins, developed upon Magma- Poor Passive Margins (MPPM). They display variable extensions of their continental platform, underneath which restricted and narrow sedimentary grabens can be seen. They represent the Rift Phase of the initial opening of the Equatorial Atlantic Ocean. The taper profile of the underlying continental crust varies from smooth in the Foz do Amazonas to very abrupt in the other two basins (Figure 4). Exhumation of the mantle occurs in all three. The thicknesses of their Drift Sequences in the deep and ultra-deep waters are huge, reaching 11 km in Foz do Amazonas and Barreirinhas. The main petroleum richness of these basins lies solely in the Drift Sequence. The other group, Ceará/Potiguar, developed upon Transitional Passive Margins (TPM). Their Rift Sequence grabens are larger and thicker and are petroleum producers onshore and in the shallow waters. They extend far into the deep and ultra-deep waters and constitute their main play. The Drift Sequences present moderate to thin thicknesses and are considered secondary play.

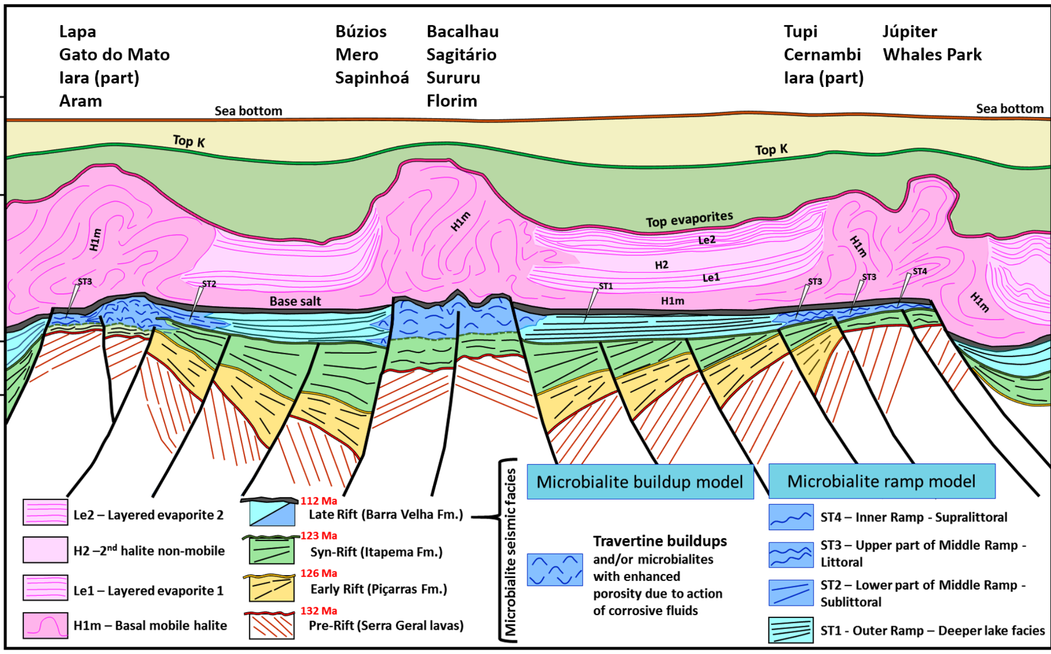

FIGURE 23 – Suggested exploratory model guide for petroleum exploration in the Pre-Salt, particularly over the External High and along the Internal Kitchen region (FONTES & ZALÁN 2014, unpublished). Two large groups of reservoir seismic facies should be sought: buildups and ramps. The buildups are usually linked to hydrothermal events linked to faulting, either as biogenic constructions by microbes due to the concentration of nutrients or as abiotic travertines. The sub-facies of the ramps are highlighted and follow the classic model of a carbonate ramp. Thick grabens should be present in the vicinities to source hydrocarbon kitchens. The names of discovered oil fields are indicated above the depositional models prevailing in their microbialite reservoirs.

The Equatorial Atlantic Ocean's continental shelves have traditionally produced modest quantities of petroleum. On the African side, Ghana and Ivory Coast have a few small fields producing oil and gas from structures in the Rift Sequence. In Brazil, Potiguar (Ubarana and Pescada Fields) and Ceará (Curimã and Xaréu Fields) also produced oil and gas from a few moderate size structures of the Rift Sequence, but also from some Late Cretaceous and Cenozoic turbidites (Espada, Xaréu and Agulha Fields) situated above the Rift Sequence fields. This scenario changed drastically in 2007 when the Jubilee Field was discovered in the deep waters of Ghana and in 2015 when the Liza Field was unveiled in Guyana. Both are giant fields in deep waters and reservoired in Late Cretaceous turbidites found inside fully stratigraphic traps. Their present productions are in the order of several hundred thousand barrels of oil daily. Uncovering these landmark fields ignited the discovery of tens of similar oil (mostly) and gas fields. In one block (Stabroek) only, in Guyana, ExxonMobil discovered 11 billion boer in more than 30 fields. In Suriname, Ghana and Ivory Coast, a few billion boer have also been discovered in each. All in the same Cretaceous Petroleum System: Late Cretaceous turbidites sourced by the ACT (Albian-Cenomanian-Turonian) marine anoxic shales in the Drift Sequences.

The Foz do Amazonas / Pará-Maranhão / Barreirinhas Basins present all the necessary features to replicate the exploratory success in these adjacent and homologous basins (ZALÁN et al. 2019b). We stress that not only they will be capable of replicating these successes but in much larger volumes. Modern 2D seismic surveys cover were shot over these basins, and they display thick Drift Sequences in the deep and ultra-deep waters presenting the same seismic facies of the source rocks and reservoirs, the same stratigraphic traps and the same DHI (Direct Hydrocarbon Indicators). In a recent mapping performed by TGS in the Foz do Amazonas/Pará-Maranhão Basins, 100 prospects having similar geological/geophysical characteristics to those discovered in the mentioned countries were delineated. Figure 24 shows how the gigantic Amazon Cone contributed to create a powerful hydrocarbon kitchen underneath it. The

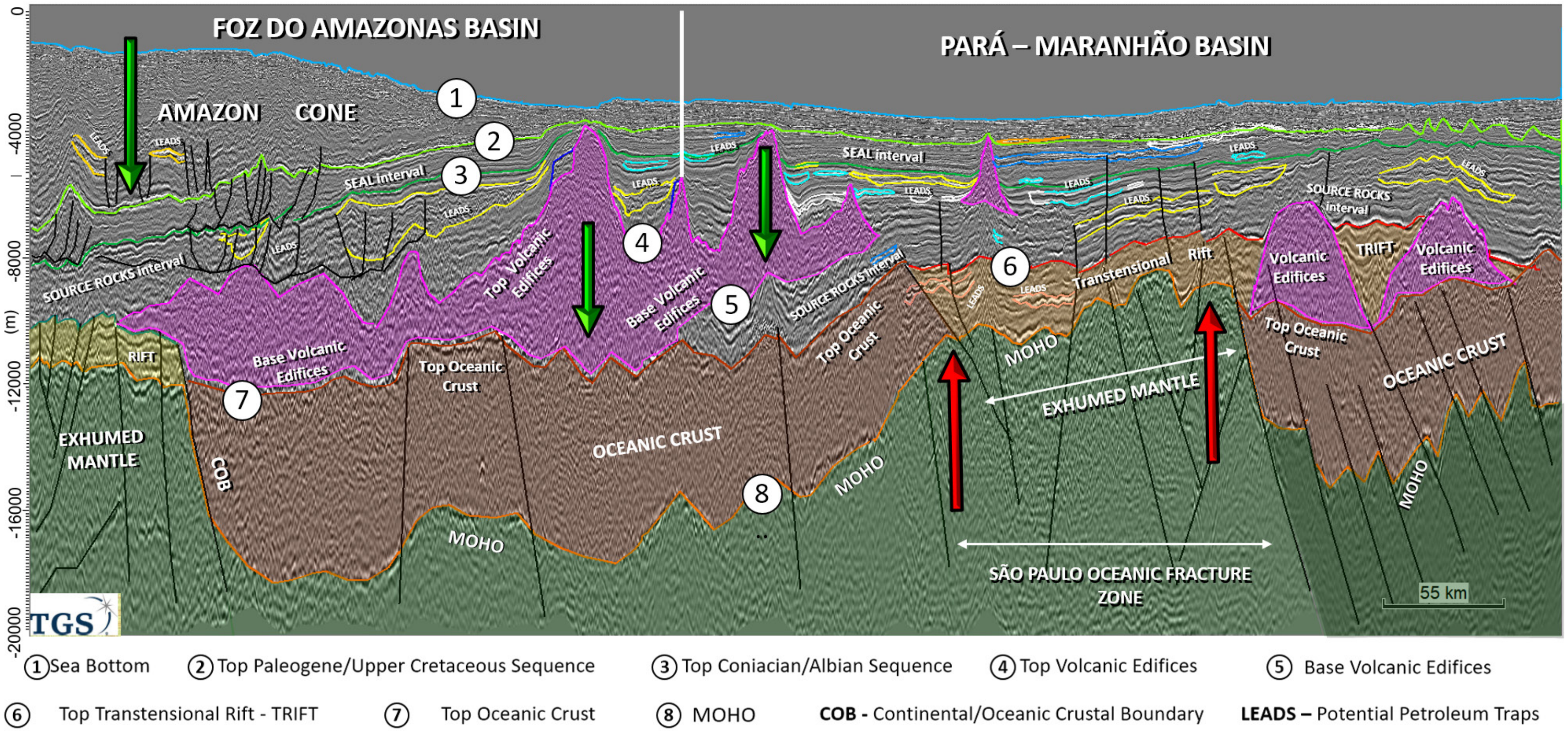

FIGURE 24- 2D PSDM (depth) seismic section down to 20 km, crossing the southern part of the Foz do Amazonas and Pará-Maranhão Basins, illustrating the functioning of the prevailing petroleum system. The load of the Amazon Cone and the load of the volcanic edifices (green arrow) bend the crust downward, pushing the ACT source rocks into depths of gas and oil generation windows (kitchens). Mechanical compensation bends the crust underneath the Pará-Maranhão Basin upward (red arrows), transforming it into a powerful focusing structural high, favorably located to collect the fluids generated in the kitchen. Turbidite bodies in this migration route constitute potential stratigraphic leads/prospects (irregularly shaped outlines of diverse shades). In this basin, local hydrocarbon kitchens also develop underneath the volcanic edifices (see next to number 5); they add petroleum volumes to the overall potential.

hydrocarbons were expelled from this kitchen both radially to its fringes in the Foz do Amazonas (south) and Pará-Maranhão Basins and vertically into its filling. Beautiful examples of turbidites in stratigraphic traps displaying DHI, similar to the Liza Field, are presented in figure 25, allowing a preview of the petroleum potential expected from the Pará-Maranhão Basin. There are also prospects similar to the Ranger discovery by ExxonMobil in Guyana. Figure 26 shows a well-defined and strongly stratified sedimentary platform, rigid and of probable carbonate nature, developed on top of an older volcano. This carbonate construction is surrounded by seismic facies closely resembling the ACT marine anoxic shales. It is an additional play that could be explored in this basin, different from the classic Cretaceous Petroleum System.

It is here considered that the Pará-Maranhão Basin, among all others in the Brazilian Equatorial Margin, is the basin with the greatest probability of yielding discoveries of giant fields, second only to the Pre-Salt play. A recent technical/economic study (BARROS FILHO et al. 2021) concluded that its petroleum potential in risked prospective resources is in the order of 20-30 billion barrels of oil recoverable. We truly believe that there is an excellent probability that these numbers can really happen in the Pará-Maranhão Basin. We would just add a correction/modification in the volume unit used. Using billion barrels of oil equivalent recoverable would be more appropriate. Given the great depths and overburden of the envisaged source rocks, a significant portion of these discoveries will likely contain high contents of gas. The same reasoning is valid for the Foz do Amazonas and Barreirinhas Basins, where we can predict discoveries with slightly lower overall volumes of petroleum, in the order of billions barrels of oil equivalent each.

5.3 Pelotas Basin

The Pelotas Basin is the next Brazilian basin to repeat the fable of the ugly duckling that will turn into a beautiful swan. Disregarded since the beginning of offshore petroleum exploration in Brazil, the Pelotas Basin may be keeping big surprises for the industry. Initial 2D surveys over its shallow waters displayed an awkward geology, consisting of a shallow “basement” with few and small grabens within it and a very thin Drift Sequence. The classical rift and drift plays of the nearby Campos and Santos Basin were absent. Things just got worse when deepwater seismic lines began to unveil huge packages of SDR, known to be totally composed of volcanic and volcaniclastic rocks worldwide. No sedimentary rifts were present. The classic source rock of the Campos and Santos Basins could not exist in such an environment. There was no salt and absolutely no deformation in the Drift Sequence. The Pelotas Basin was really ugly duckling from the 1970s to the 2000s. In the last decade, the acquisition of a regular grid of modern 2D seismic sections in deep and ultra-deep waters (Figure 27) and state-of-the-art processing and reprocessing started to unveil the riches of the basin. These surveys displayed the existence of a very thick Drift Sequence on top of the volcanic rifts (SDR). By then, the world already knew about the discoveries of great volumes of petroleum stratigraphically trapped in Late Cretaceous turbidites, sourced by Cretaceous anoxic marine source rocks (Cretaceous Petroleum System), in Ghana/Ivory Coast, Equatorial Guinea, Sergipe-Alagoas and Guyana. The similarity of the Pelotas Basin Drift Sequence stratigraphy and structural geology to those in these basins started to be noticed. The Pelotas Basin Drift Sequence is nearly a copy of the Foz do Amazonas Basin. There is no need to repeat the geological reasons for our belief in its great potential here. They are the same for the Equatorial Margin Basins. The only and significant difference to those basins, in favor of the Pelotas Basin, is the existence of an additional source rock to the classic ACT organic-rich packages. An Aptian marine anoxic shale may probably exist at the base of the Drift Sequence in the Pelotas Basin. Such source rock is the main contributor to the large discoveries made in Namibia, the counterpart basin of Pelotas in West Africa.

ZALÁN (2017c) presented a paper pointing out the promising potential of the Pelotas Basin, highlighting the advice to drill deeper into the basal portion of the Drift Sequence. Because of the lack of tectonic features in the Drift Sequence, the closer the targets are to the source rocks, the greater the probability of the turbidites being charged. However, only after the discoveries of the giant gas fields of Brulpadda-Luiperd (2019-2020) in South Africa and of the giant oil field of Venus (and Graff) in the Orange Basin in Namibia (in 2022) did the petroleum industry look to the other side of the southern South Atlantic looking for the homologous basins. There was the Pelotas Basin, straddling the entire southern offshore of Brazil and the entire offshore of Uruguay and northern Argentina. The great advantage of the Brazilian

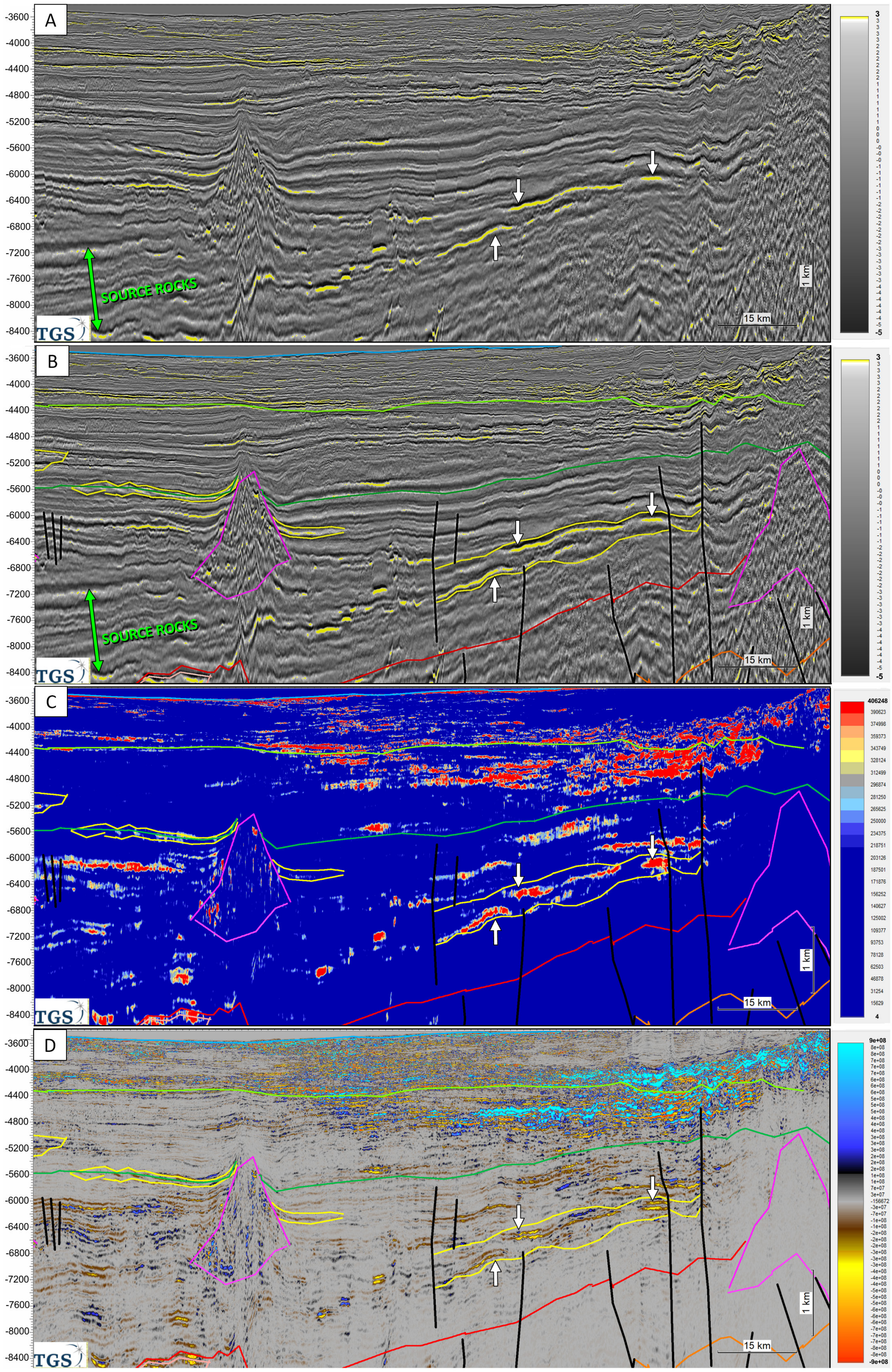

FIGURE 25 – 2D PSDM (depth) seismic section in the Pará-Maranhão Basin presenting (A) and (B) one prospect constituted by a lens-shaped turbidite body, thinning and pinching updip (between white arrows) and presenting bright spots. (C) Sweetness seismic attribute presents positive anomalies (red), indicating strata with anomalous low seismic velocities. (D) (F-N)*F seismic attribute presents AVO Tipo IV (yellow and brown), thus confirming the DHI (Direct Hydrocarbon Indicator) character of the amplitude bright spot displayed in (A) and (B). The prospect is located updip from the source rocks package (A) and (B), which is in a very favorable position for direct migration of fluids into it. The area of this prospect is circa 2,000 km^2. The similarity with the giant Liza field in Guyana is very strong and indicates an excellent probability of discovering a large petroleum field.

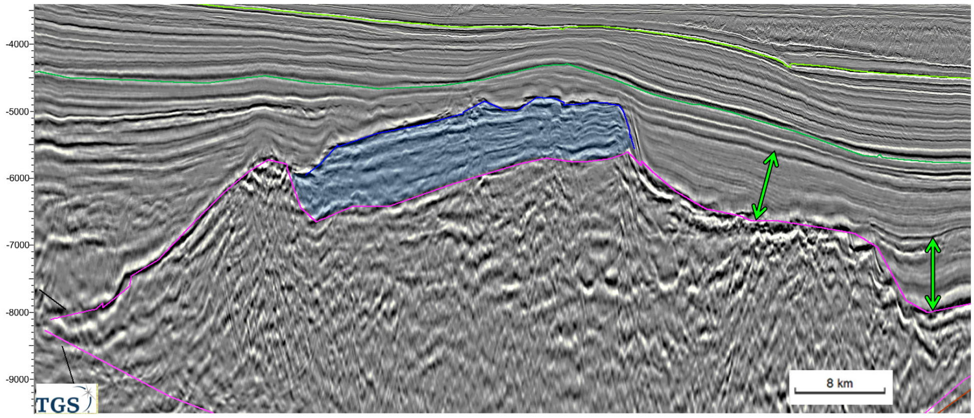

FIGURE 26 – 2D PSDM (depth) seismic section in the Pará-Maranhão Basin presents a prospect very similar to the Ranger discovery in Guyana. A stratified and rigid platform (in blue) developed on top of a large volcano sitting upon oceanic crust. This body is here interpreted as an Albian (?) carbonate platform, presenting great prospectivity since it is in direct lateral contact with the package of ACT source rocks (green arrows).

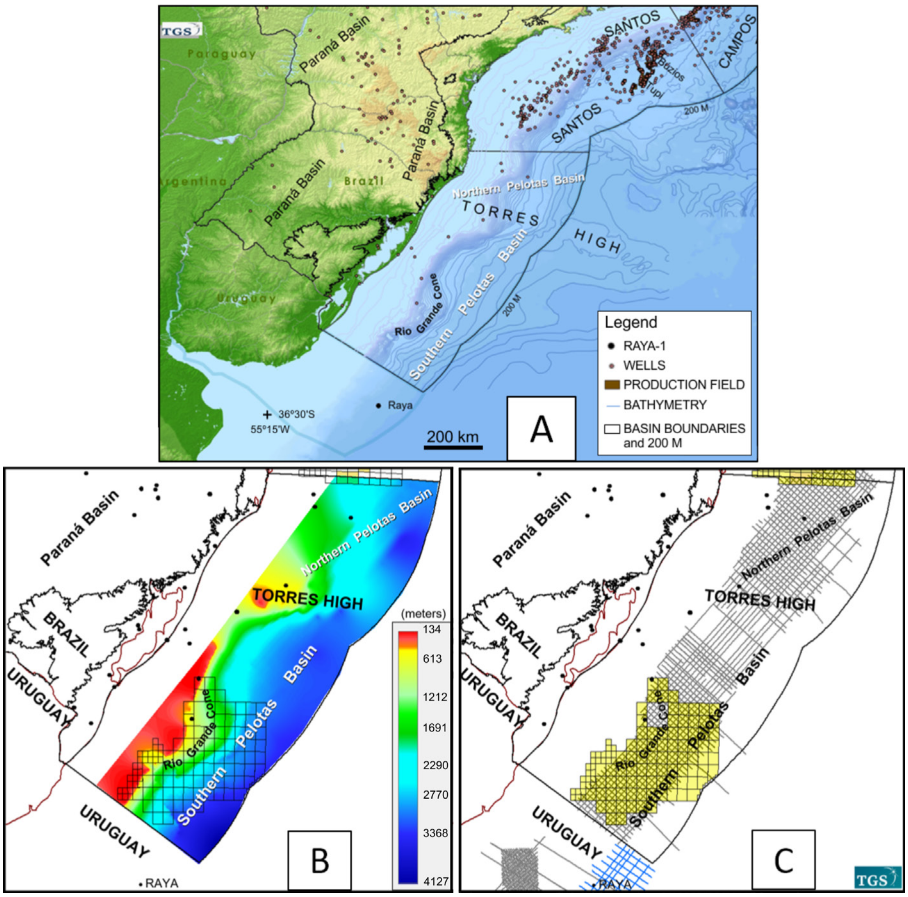

FIGURE 27 – (A) Regional context of the Pelotas Basin. Bathymetry, wells, basin boundaries and the EEZ line (200 NM) are displayed. (B) Detailed bathymetric map of the basin where two important features stand out: Torres High and Rio Grande Cone. The Torres High is a deep-rooted structure (thick continental crustal block) that divides the basin into two sub-basins: Northern Pelotas and Southern Pelotas. The Rio Grande Cone is a sedimentary cone similar to the Amazonas Cone. (C) The existing 2D grid of modern seismic sections allowed the present interpretation that indicated the excellent petroleum potential of the basin. Yellow blocks were open to the industry in ANP`s Permanent Offer mode. Most of these blocks were acquired by Petrobras/Shell and Chevron at the end of 2023 in ANP`s Fourth Permanent Concession Cycle.

portion of the Pelotas Basin is that it contains the thickest depocenter of all these margins, asides from being the largest portion. Just north of the maritime boundary between Brazil and Uruguay lies the great hydrocarbon kitchen of the basin, which probably sourced the riches of the Brazilian portion of the Pelotas Basin.

The Pelotas Basin is too large to be considered a single entity. Sub-divisions exist. The Torres High, an important volcanic high and a possible focusing high for hydrocarbon migration, divides the Pelotas Basin into two sub-basins: Northern Pelotas and Southern Pelotas (Figure 27). The first is the uninterrupted continuation of the southern part of the Santos Basin, exception the Pre-Salt section, which ends much further north of the basins boundary. The geology of Northern Pelotas is very similar to the internal/proximal portion of the Santos Basin, where several fields hosted in Cretaceous/Cenozoic turbidites and Albian carbonates have been producing oil/gas/condensate for decades. As pointed out in the above chapters, these fields produce petroleum sourced by the ACT anoxic marine shales. The seismic resolution in Northern Pelotas is excellent, and several prospects have already been mapped. We predict that there is an excelent probability that several discoveries in turbidites, similar to Mexilhão, Merluza, Baúna, Neon, Patola, Echidna and Kangaroo, will be made. The individual reserves of such discoveries should be in the order of several tens to a few hundred million of boer. In the case of Albian carbonates, there is medium probability for the discovery of a giant gas field on the crest of the Torres High, where an extensive carbonate platform developed above the uplifted volcanic rocks. Beneath this carbonate platform, on the apical region of the Torres High, the fracturing/faulting of the volcanic rocks is intense, and seismic anomalies such as bright spots, are strong and numerous. There, we estimate a great probability of discovering a super-giant gas field in fractured volcanic rocks of this immense structural high.

In our opinion, the Southern Pelotas sub-basin has a high probability of containing several light oil and gas fields, reservoired in Cretaceous/Paleogene turbidites, several of them of giant sizes. Individual reserves should be in order of several hundred million boer. Cumulatively, several billion boer could probably be achieved, eventually a few tens of billion boer. Its great advantage is the enormous thickness of the Drift Sequence (up to 11,000 m). The overburden zoning of the source rocks indicates the existence of parallel belts of oil, light oil and gas windows. The geology observed in this sub-basin is exactly the same as described in the Pará-Maranhão Basin. The analogy with the Orange Basin in Namibia is extraordinary (ZALÁN et al. 2022a, b). Figures 28 and 29 display examples of prospects with great petroleum potential in the Southern Pelotas sub-basin.

Note: At the end of 2023, Petrobras, Shell and Chevron acquired 44 blocks in the Pelotas Basin in ANP`s Fourth Permanent Concession Cycle. That emphasizes the importance that major companies are giving to Pelotas nowadays. In early 2024, Galp announced the discovery of another oil giant field in Namibia (Mopane).

5.4 Post-Salt - Campos-Santos-Espírito Santo basins

The deep and ultra-deep waters of the Campos, Santos and Espírito Santo Basins have been producing oil and gas for decades from turbidites and carbonates situated above the Late Aptian/Early Albian evaporites. Giant turbidite fields of different ages occur in Campos (e.g., Marlim, Marlim Sul, Albacora, Barracuda, Caratinga and Roncador) and Santos (e.g., Mexilhão and complexes of Eocene turbidites holding billions boip of very heavy oil). Large oil fields in Albian carbonates are producers in Campos (e.g., Garoupa, Enchova, Pampo) and in Santos (e.g., Coral, Caravela, Estrela do Mar). Espírito Santo has production and discoveries of oil and gas in tens of turbidite fields whose ages vary from Santonian to Miocene (e.g., Cangoá, Peroá, Golfinho, Canapu, Camarupim, Parque do Doces, Parque do Cachorros). None of these turbidite and carbonate plays is exhausted! In any of the three basins!

Turbidites from these three basins will still yield many riches for petroleum companies. In the northern part of the Campos Basin, we forecast the discovery of turbidite oil fields of the most diverse ages. They will probably be similar to Shell`s fields in the Parque das Conchas (Argonauta, Ostra, Abalone) (in the order of several tens of million boer). In its central/southern part, Campos Basin could deliver few but significant discoveries (giant fields) of heavy oil in Late Cretaceous turbidites, similar to the Xerelete field. Such discoveries will probably be located on the eastern border of the External High. Further offshore to the east, over the External Kitchen area, the chances of discoveries

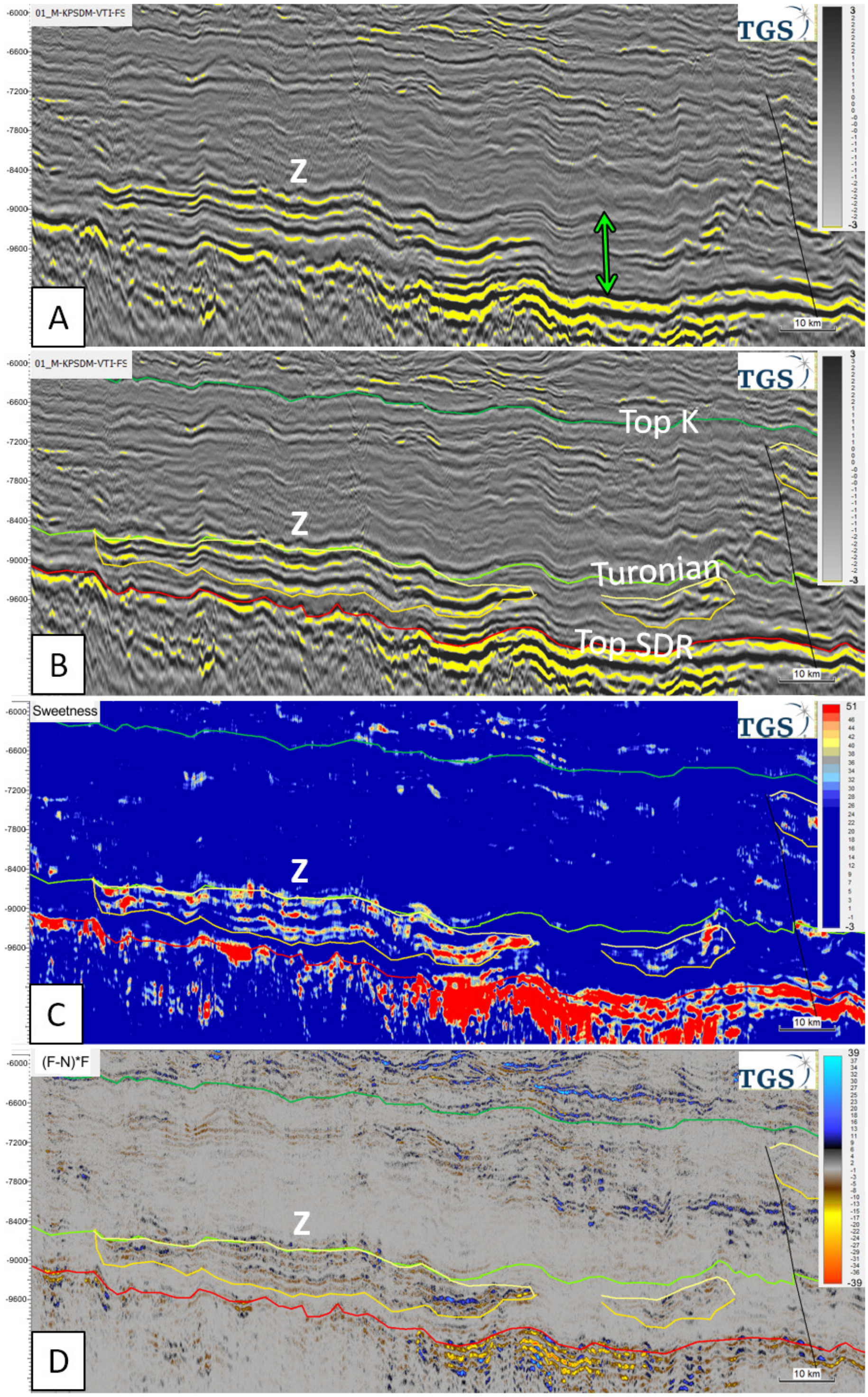

FIGURE 28 – 2D PSDM (depth) seismic section in the Pelotas Basin displaying a bright large lenticular package of strata that thins and ends updip (modified from ZALÁN 2022b). (A) A non-interpreted section highlighting a bright spot in Prospect Z. Another important feature is its insertion into the package of source rocks (green arrow). (B) Interpreted section. (C) Sweetness seismic attribute shows a positive anomaly (in red) in Prospect Z, indicating the existence of rocks with very low seismic velocities. (D) AVO Type III (in blue) in the (F-N)*F seismic attribute confirms that the bright spot is a DHI. We can estimate that there is a great probability that Prospect Z is a package of turbidite sandstones with anomalously low velocities containing large volumes of light hydrocarbons.

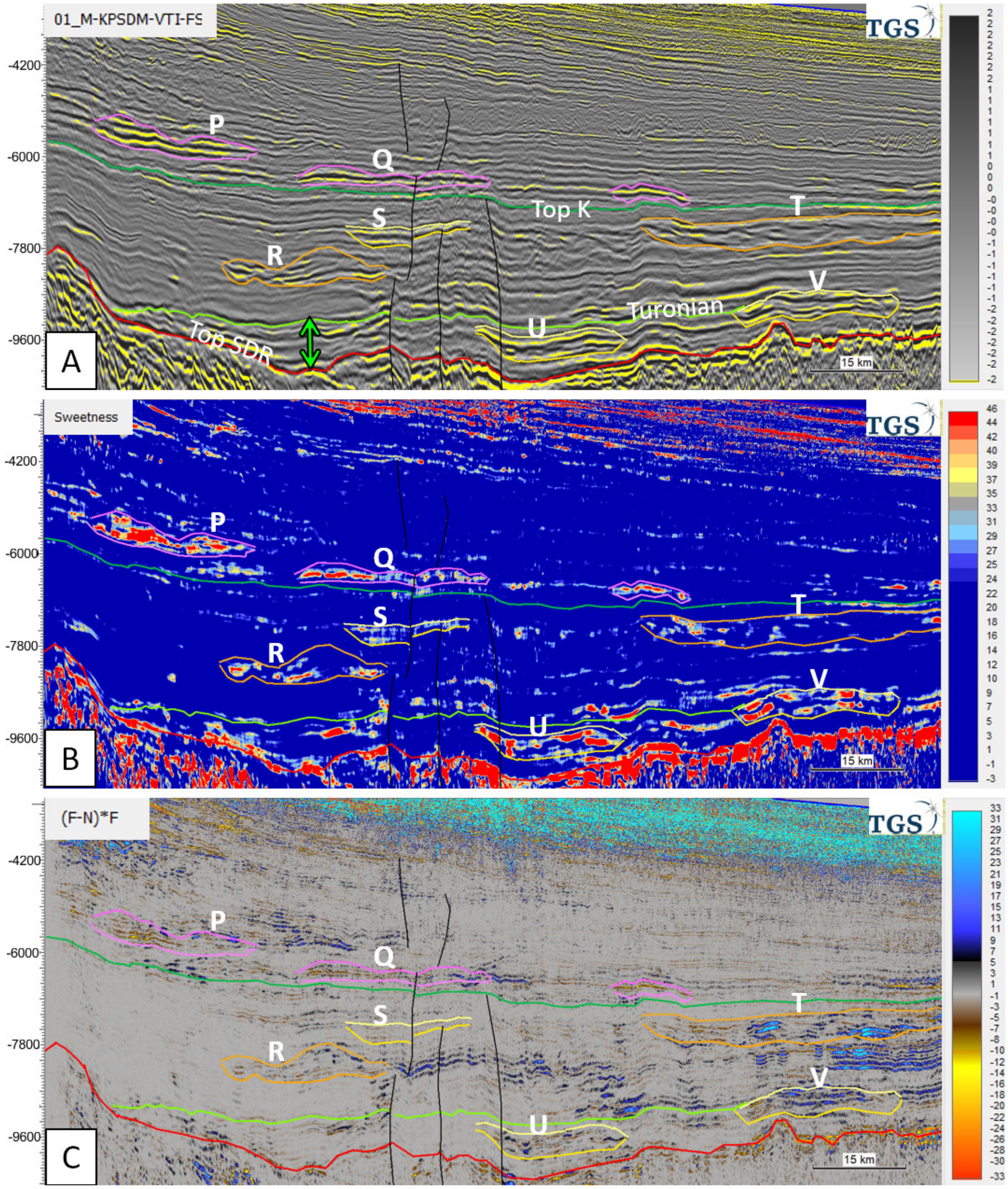

FIGURE 29 – 2D PSDM (depth) seismic section in the Pelotas Basin exhibiting several Cenozoic and Cretaceous prospects presenting lenticular (channels) and tabular (submarine fans) shapes, most of them with bright spots (ZALÁN 2022b). (A) The interpreted section indicates that Prospects U and V are inserted into the source rocks package (green arrow). Prospect T presents lateral progradational surfaces typical of submarine meandering channels. (B) Sweetness seismic attribute indicates anomalously low velocities in the younger Prospects P, Q, and the older U and V. (C) Strong Type III AVOs (in blue) can be found in Prospects U, V and T ((F-N)*F seismic attribute). Prospects P, Q and R present moderate Type IV AVOs (in brown and yellow). The Cretaceous Prospects U and V are the most promising, followed by Prospect T and Cenozoic Prospects Q and P. Notice the presence of faults that link the source rock section (green arrow in (A) to Prospect Q, allowing a long migration vertical route into Prospects Q and P.

in turbidites are slim. There is too much salt and very little Drift Sequence over it. In the proximal part of the Campos Basin, over the Internal Kitchen, there are moderate chances for repetitions of discoveries of heavy oil accumulations, such as those already made in Cenozoic turbidites (Atlanta and Oliva fields, unnamed complexes of Eocene turbidites) in the nearby Santos Basin. These discoveries were abandoned or partially developed either because of the reservoirs' petrophysical problems or the very heavy oil nature of some of them. It is emphasized here that this kind of play should not be disregarded since the overall reserves discovered up to now are in the order of a few billion boip. The industry should look to Equinor´s outstanding performance in the development of the Peregrino field. This accumulation consists of heavy oil in Late Cretaceous turbidites. For some time, it was a disregarded accumulation because of the nature of the oil and the complexity of the reservoirs. From 2004 on, the Norwegian company was able to develop the field and raise its status to the 10th most oil-producing field in Brazil by the end of 2022 (83,000 bopd) (Boletim da Produção de Petróleo e Gás Natural, ANP, December 2022). With a cumulative production of 210 million barrels of oil since 2011, the forecasted ultimate production will certainly surpass 500 million barrels of oil (EQUINOR 2022), making Peregrino another giant turbidite oil field in the Campos Basin.

In the Santos Basin, the search for hydrocarbons in turbidite reservoirs will be concentrated in the proximal/internal area of the basin, notably in its southwestern and southern regions. The exploration will focus on the extensive NE/SW-trending cluster of fields/discoveries such as Mexilhão, Merluza/Lagosta, Guaiamá, Piracucá, a complex of several discoveries by Karoon (Neon and others) and Baúna/Patola/Piracaba. All these had their hydrocarbons sourced from the ACT organic rich shales. We predict a high probability of several small to medium discoveries (a few tens of million boer each) in turbidites ranging in age from Santonian to Oligocene-Miocene, mostly of light oil and gas. Such a prediction can soon come true. Total and Shell are chasing a massive Maastrichtian bright spot inside several recently acquired blocks (ANP's Third Round of Permanent Offer Blocks, 2022) close to the boundary with the Pelotas Basin.

We consider that the chances of discovering turbidite fields sourced from the Pre-Salt Barremian/Early Aptian organic-rich lacustrine shales above or around Pre-Salt fields are slim. In these locales, the salt cover is extensive and thick, precluding the migration of hydrocarbons from the Pre-Salt source rocks. Salt windows in highly stretched and torn-up regions, individualized salt bodies, are more favorable for oil accumulations in Post-Salt turbidites. Excellent examples are the complex of Eocene turbidite accumulations (unnamed yet) holding several billion boip of heavy oil, plus Atlanta/Oliva, in northern Santos. Except for Atlanta, these fields have not yet been developed. The quality of the oil may prevent their commercial exploitation.

As for the Albian carbonates, we predict several medium-sized discoveries (tens to a few hundred million boer) for the specific play "Wandering Albian Turtles" in the deep waters of the Campos Basin. Such discoveries will take place inside the turbidite fields' ring fences or separately in less explored areas. In the ultra-deep waters, one or two such accumulations are possible but not probable. Another depositional model seems to prevail in the ultra-deep waters. The Catuá field is a carbonate syn-tectonic buildup developed on top of a salt foldbelt (compression due to gravitational sliding). In this case, the volumes in similar accumulations should be giant to be economical, because of operational matters. Catuá is at the limit of economic; thus, it was returned by Petrobras. In shallower waters, shallow to deep transition, inside the ring fences of classic exhausted turbidite fields, small discoveries (a few tens of million boer) in Albian carbonate reservoirs, folded into classic rollover structures, shall occur. Similarly, in the Santos Basin, we predict that a few minor discoveries (a few tens of million boer), also hosted in classic rollover structures, will take place at the extension of the producing string of pearls oil fields (Tubarão-Estrela do Mar-Coral-Caravela-Cavalo Marinho). We also forecast a high probability of discovering a giant oil field in the Ametista Prospect (Figure 19). There, an Albian carbonate buildup developed on top of a protrusion of the exhumed mantle. This buildup is constituted by two seismic facies that strongly resemble a regular carbonate platform topped in part by a massive structureless buildup, tentatively interpreted as a (rudists?) reef. The association of carbonate deposition side-by-side with volcanos is very similar to the modern atolls located in the Pacific Ocean.

In the deep and ultra-deep waters of the Espírito Santo Basin, we predict a high probability for the continuation of oil and gas discoveries (several tens of million boer) in turbidite reservoirs similar to the discoveries made by Petrobras in the Parque dos Doces (Quindim e Brigadeiro) and Parque dos Cachorros (São Bernardo, Dálmata, Labrador). As for the discovery of petroleum in Albian carbonates, we consider it close to nil, given the very restricted occurrence of individualized carbonate rollover structures at these profound depths of the margin.

5.5 Sergipe-Alagoas and Bahia Sul basins

The offshore portion of the Sergipe-Alagoas Basin regained the industry´s attention after another very efficient exploratory campaign carried out by Petrobras after discovering the first commercial field in the deep waters of the basin (Piranema). A very competent exploratory team, under the guidance of geologist João Claudio Conceição, discovered the fields named Barra, Cumbe, Farfan, Muriú, Moita Bonita and Poço Verde in the ultra-deep waters of the basin (a few billion boer cumulative). This same team of geologists and geophysicists was responsible for developing the victorious “Wandering Albian Turtles” play in the Campos Basin (as described above). The success rate of the exploratory wells drilled turned out close to 100%. These discoveries consist of purely stratigraphic traps of Maastrichtian-Campanian turbidites, rich in gas and light oil and sourced by the ACT marine anoxic shales. It is the same play that is already a producer in Equatorial Guinea (homologous margin), Ghana/Ivory Coast and Guyana/Suriname. ExxonMobil and partners acquired nine blocks surrounding these Petrobras discoveries to the east and southeast. ExxonMobil was trying to replicate its successful experience in Guyana. The drilling of the first well (Cutthroat), in water depths of 3,094 m, came out a great disappointment because, although the reservoirs were found, there was no sign of hydrocarbons in the well. A warning yellow signal lit up. After all, the operator that found 11 billion boer in a similar play in Guyana managed the “feat” of drilling a duster adjacent to blocks with a 100% success rate in exploratory wells. This might indicate that, once again, as happened in the Pre-Salt history, Petrobras invested in the basin when nobody else believed in it. It was highly successful in a creative exploratory drive, and after screening the rest of the basin, it acquired the best blocks available. After this one-well campaign, ExxonMobil quit and returned all the blocks in its possession (mid-2022). In my opinion, it is a very premature and emotional decision. It seems that ExxonMobil forgot that the second well drilled by it in Guyana (Skipjack) resulted in a sound duster, followed by a string of fantastic discoveries.

Does that mean there are no hopes for further discoveries in the basin? No! It is just a matter of re-finding the pathways of the turbidite bodies that had access to the migration of fluids expelled from the ACT source rocks. In the deep and ultra-deep waters of Sergipe-Alagoas, we predict a high probability for the repetition of discoveries very similar to those achieved by Petrobras in volume (tens to hundred million boer). Seismic sections in these areas always display several opportunities for stratigraphic traps suitable for exploratory drilling (Figure 30). Some turbidite bodies will contain hydrocarbons and others will not. Not all turbidites in the basin are in the vertical migration pathway of the petroleum expelled from the underlying source rocks. The Drift Sequence of the Sergipe-Alagoas Basin is devoid of tectonism. There is no salt in the distal areas and no gravitational deformation. Migration pathways in these situations are not visible in seismic sections and they occur along sub-seismic fractures/faults. Geophysicists will have to study and apply sophisticated seismic attributes that would allow the differentiation between the seismic responses of reservoirs with oil/gas from water-bearing reservoirs. There is still a large area with no wells drilled in it. Since the petroleum system in the basin is a proved system, and turbidite reservoirs are plentiful in seismic sections, it is predictable that the former exploratory model that led Petrobras to those discoveries, aided by improved versions of seismic attributes, could lead to new successful wells. Similar discoveries will probably happen in the future.

The same geological scenario is visible in seismic sections in the deep and ultra-deep waters of the Bahia Sul Basins (Camamu, Almada and Jequitinhonha). The same petroleum system occurs. Practically no exploratory well had tested the successful exploratory model of Sergipe-Alagoas offshore in the State of Bahia. There is a difference in the economic basement in both areas. In Sergipe-Alagoas, the substratum of the Drift Sequence in deep and ultra-deep waters is dominantly volcanic, sometimes SDR, and sometimes mega-volcanos. In Bahia, the substratum of the Drift Sequence consists of sedimentary rifts above hiper-extended continental crust and exhumed mantle. This difference may have had an impact on the maturation of source rocks. A larger geothermal

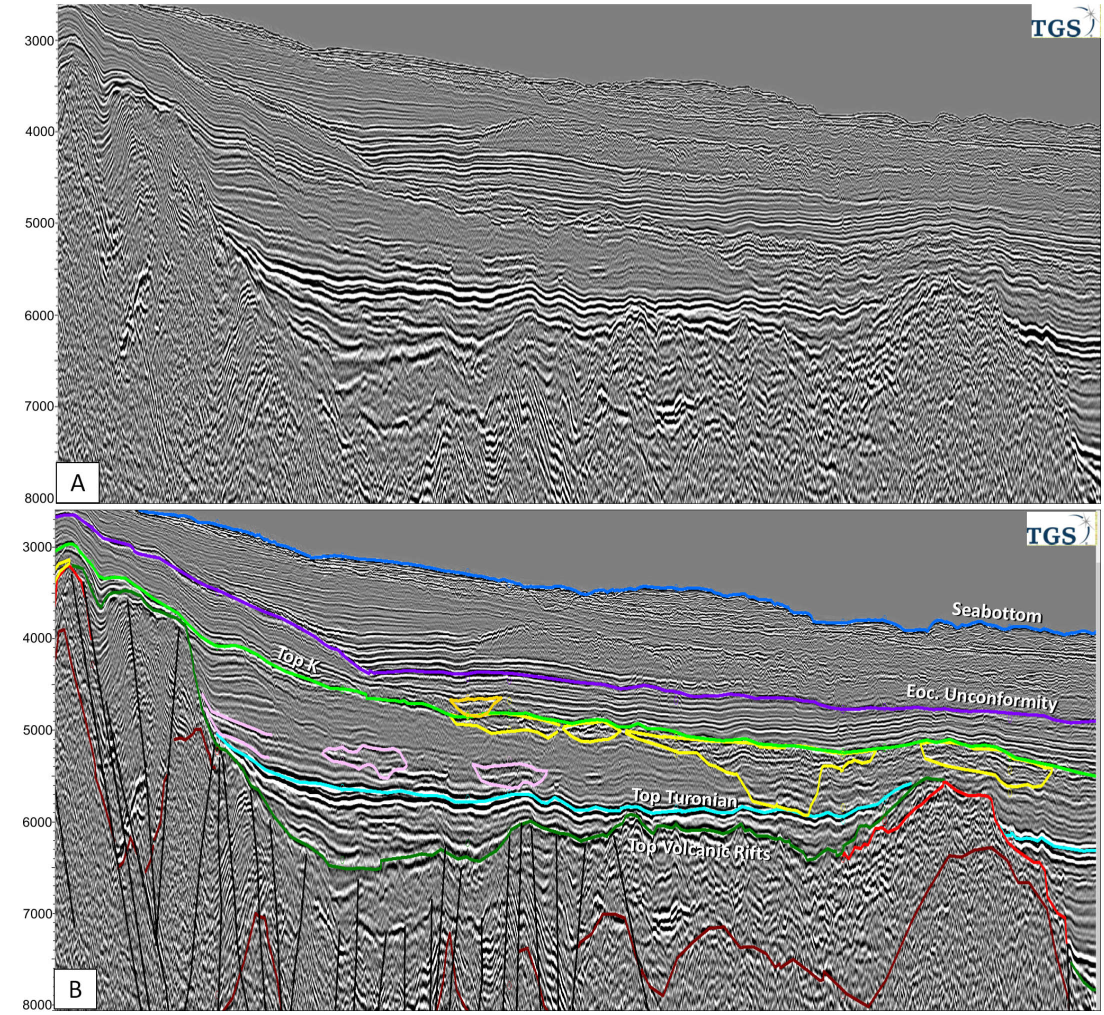

FIGURE 30 – 2D PSDM (depth) seismic section in the Sergipe-Alagoas Basin. (A) Non-interpreted section. (B) The interpreted section displays the main reflectors mapped and several leads of Santonian (pink) and Maastrichtian-Campanian (yellow) ages. The ACT source rock package is between the light blue and green reflectors. It is very thick and deeply buried in the center of the section, thus characterizing a hydrocarbon kitchen. Interpretation by geologist Maria Pessoa (unpublished). Prospects similar to these guided Petrobras to 6 large discoveries of light oil/condensate/gas in the ultra-deep waters of Sergipe.

gradient upon volcanic substratum induces a higher gas and light oil occurrence probability. Lesser geothermal gradients on continental basement rocks mostly favor the presence of oil. We predict for these three basins in the offshore State of Bahia a high probability for the repetition of discoveries very similar to those of Petrobras in Sergipe-Alagoas, in volumes as well (tens to several hundred million boer).

5.6 Equatorial Margin - Potiguar and Ceará basins

As mentioned before, although the Potiguar and Ceará Basins are situated in the Equatorial Margin, their deep and ultra-deep waters have a different geology than those of the Foz do Amazonas/Pará-Maranhão/Barreirinhas Basins. The substratum of their Drift Sequences is a wide strip of sedimentary rifts, followed by volcanic rifts (SDR) further offshore. They are basins situated upon Transitional Passive Margins, similar to Sergipe-Alagoas. Consequently, the Drift Sequence is much thinner than in the other three basins of the Equatorial Margin. The petroleum potential of the Drift Sequences of the Potiguar and Ceará Basins is not high; exceptions are made to the more distal regions where these sequences may be slightly thicker. For this type of play, we estimate a low probability of a few discoveries similar to those in the Sergipe-Alagoas. The most important play to be investigated is the subjacent rifts, which have already provided two discoveries (Pecém in Ceará and Pitu in Potiguar). The existing seismic lines display several leads typical of Rift Sequences, constituted by faulted and rotated blocks, with structural closures provided by arching and faulting, similar to Pecém and Pitu. For this play, we forecast a high probability of repeating discoveries very similar to these two fields in volumes (tens to few hundred million boer).

Additionally, a new play appeared in the recent 3D survey of TGS in Potiguar ultra-deep waters. The very northern part of Potiguar offshore is located under the tectonic influence of the Chain Oceanic Fracture Zone. Divergent strike-slip movements along this fault zone created strong transtensional deformation in the Drift Sequence. As a result, faulted and rotated blocks similar to the classic rift traps developed, affecting the Drift Sequence (Figure 31). Testing this unusual type of structural play in the Drift Sequence will be an interesting option. Eventually, Late Cretaceous turbidites will hold petroleum in conventional structural traps instead of the prevalent stratigraphic traps on Drift Sequences of both sides of the Equatorial Atlantic Ocean. We estimate a low probability of success for discovering medium-sized accumulations in this novel play (tens to few hundred million boer).

6 FINAL CONCLUSIONS AND RECOMMENDATIONS

Figure 32 summarizes the predictions outlined here, a result of knowledge accumulated through 83 years of exploration history in Brazil, and descriptions, explanations and geologic reasoning presented in this work. The map shows the sedimentary basins colored according to 4 levels: (i) *basins and areas of high potential* (with high probabilities of yielding discoveries that, individually or cumulatively, could hold volumes in the order of several hundred million to several billion boer), (ii) *basins and areas of medium potential* (with high probabilities of yielding discoveries that, individually or cumulatively, could hold volumes in the order of several tens of million to few hundred million boer), (iii) *basins and areas of low potential* (with high probabilities of yielding discoveries that, individually or cumulatively could hold volumes in the order of few million to few tens of million boer) and (iv) *basins without potential to yield economically viable discoveries of petroleum*.

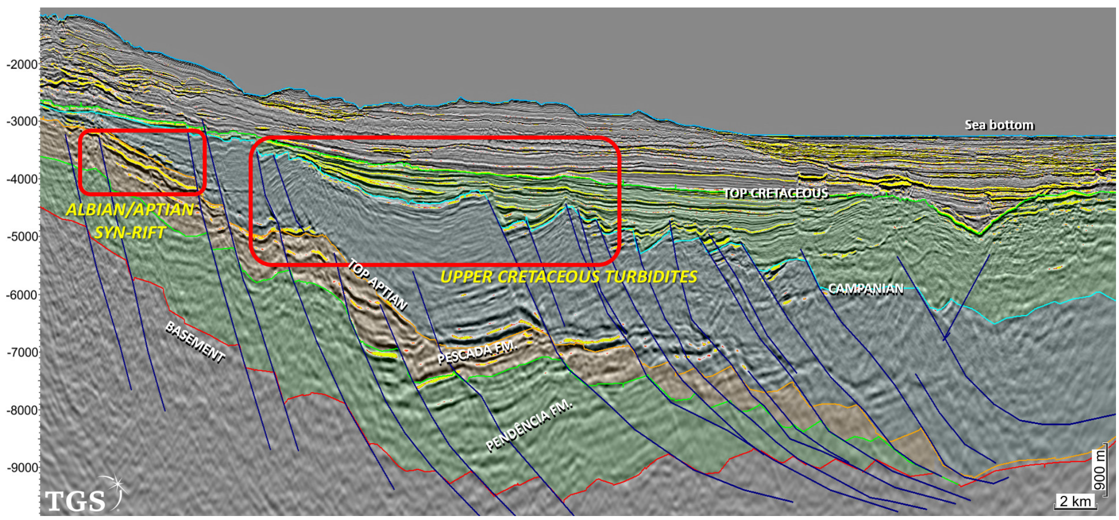

FIGURE 31 - 3D PSDM (depth) seismic section in the most distal portion of the Potiguar Basin displaying strata in the Drift Sequence rotated by intensive normal faulting, similar to structural styles found in Rift Sequences. This late deformation is of Campanian/Maastrichtian age and transtensional origin, related to strike-slip movements along the Chain Oceanic Fracture Zone. Red rectangles indicate prospects to be tested: fault blocks containing Late Cretaceous turbidites and Albian-Aptian sandstones of the Pescada Rift Sequence. Interpretation by geophysicist Randall Etherington from TGS/Houston (unpublished).

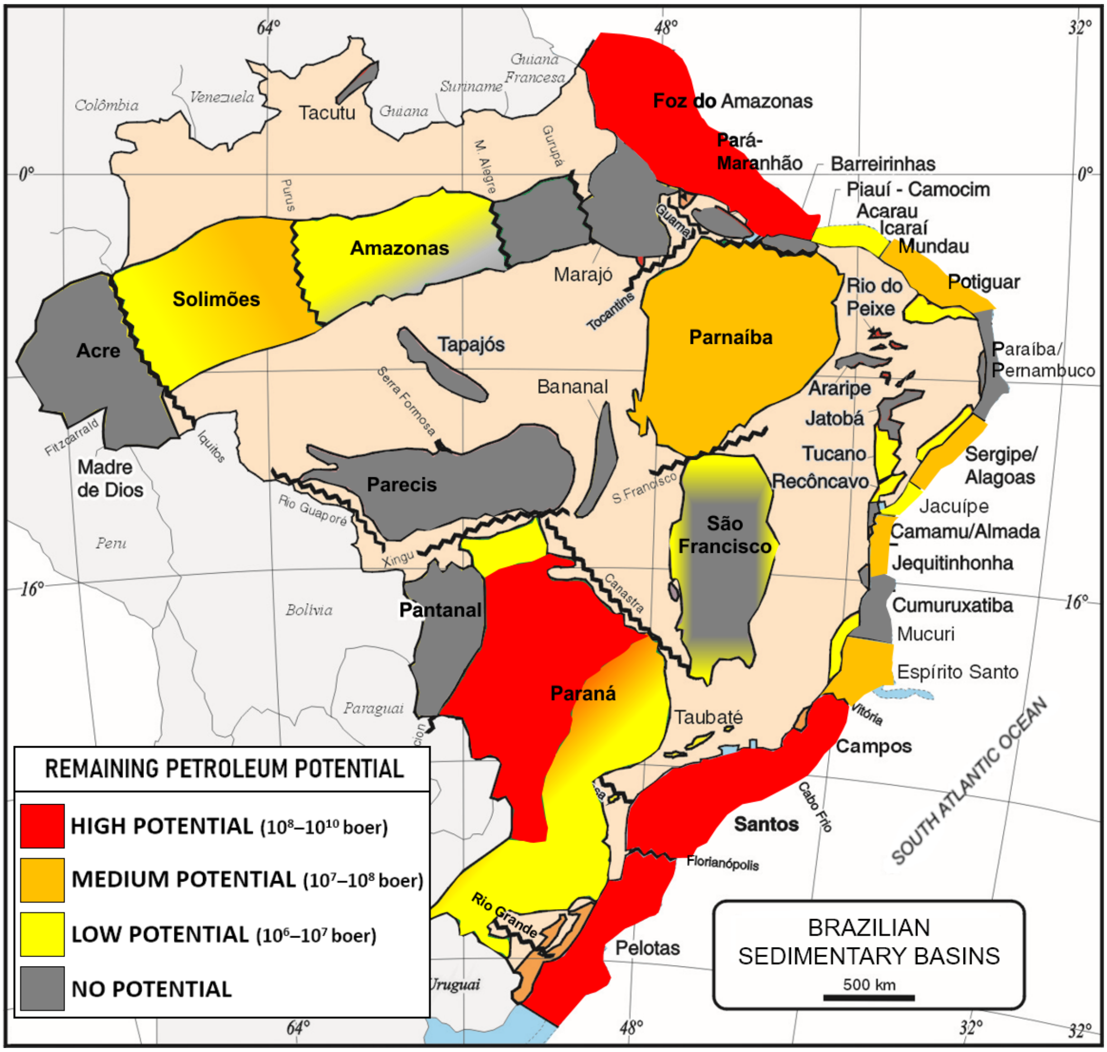

FIGURE 32 – Map summarizing the remaining petroleum potential of the Brazilian sedimentary basins, according to 4 levels: (i) *basins and areas of high potential* (volumes in the order of several hundred million to several billion boer), (ii) *basins and areas of medium potential* (volumes in the order of several tens of million to few hundred million boer), (iii) *basins and areas of low potential* (volumes in the order of few million to few tens of million boer, and (iv) *basins without potential for economic discoveries*. This last classification takes into account, besides the petroleum potential, environmental restrictions such as protected specific biomass and national parks/forests, technological restrictions, operational and logistical difficulties, remote localizations, etc. It is expected that this map can be used as a guide for the Brazilian authorities to plan the offering of blocks for future exploration; and also, for investors to decide the best areas to allocate financial resources for the rewarding activity of petroleum exploration and production.

I am fully aware that several of the predictions here stated will not come true. Probably, there will be more failed forecasts than correct ones. Maybe there will not be a single right prediction. That does not matter so much to me. The science of Geology constantly surprises us. The main objective of this article was not to issue infallible predictions. The main objective of this work was simply...*to make predictions*. But *not mere vague and groundless predictions*. Our forecasts were based on the science of petroleum geology, the cumulative knowledge acquired in the Brazilian sedimentary basins, and, most importantly, on my experience. After 34 years of hard work at Petrobras, most of them functioning as an explorationist, and 12 years as an exploration consultant for more than 30 companies and entities of the petroleum industry, domestic and international, I believe I have accumulated a large experience. I guess I have earned the right to make predictions that I believe could be useful in the future, especially about Brazilian basins. It would be a waste not to pass on to present and future generations this experience acquired, and one of the utilities of knowledge and experience is…to make predictions. If the knowledge/experience I accumulated were faulty, the future will judge that. One of the comforting things about making predictions, particularly at my age, is that if one day they come out wrong, the forecaster will probably be already dead.

The core of this work lies in the strategy that, through formulating predictions, we should instigate/stimulate teams of geologists/geophysicists to analyze, improve and prove them right or wrong. If wrong, to think "out of the box" and conceptualize creative alternative hypotheses. It is expected that, in this way, we will help Brazil to realize its true petroleum potential by the end of the century, hopefully. Through the narratives upon which our forecasts are based, it is also wished that medium and small Brazilian companies will be stimulated to risk their luck in the probabilistic world of petroleum exploration.

Since probabilities rule it, this activity could be roughly compared to casino gambling, where the chances of success of the "gamblers" (discovery of petroleum) are in the order of 10% - 30%. In contrast, the chances of the "house" (the unknown factors of geology) are between 90% - 70%. To start with, the chances of the "gamblers" here are much higher than in casinos. Immensely higher. However, petroleum exploration is not a game; instead, it is a scientific investigation. As such, the more and better data you have, the more brilliant minds work with those data, the greater the chances of beating the "house" advantage. Contrary to what happens in a casino, the more you play (acquiring data and drilling wells), the more your chances of economic success increase. The "gamblers" can significantly increase their odds by increasing their spending on data acquisition and the use of modern technology. The more you play in a casino, the more the math works against you. Moreover, in the case of success (discovery of petroleum), the premiums are highly rewarding, more than in any other type of enterprise.

Petroleum will remain humankind's main energy source for at least 50 years. This is the current opinion that serious specialists/analysts and petroleum companies state in 2023. I believe in a much longer life/usefulness for fossil fuels, especially considering the importance of petrochemicals in our everyday lives. This number is closer to 80-100 years (roughly till the end of the 21st century). Brazil is presently, and certainly will be in the future, a vital petroleum provider for the world for decades to come. It has several basins of great potential that are still unexplored. Several areas already have reserves/production and underexplored tracts. Our *final forecast* for the remaining petroleum potential (in terms of *prospective resources*, identified or conceptual, but not discovered yet) of all Brazilian sedimentary basins is in the order of 50-100 billion boer. With that in mind, petroleum companies and their exploration teams of explorationists cannot watch the opportunity passively go by. Hands to work and good luck in the search for more petroleum in the Brazilian sedimentary basins.

At this point, we will focus on a very important warning/recommendation. The realization of this richness is not only a matter of geology or engineering. The following paragraphs indicate to Brazil what is mandatory for all this probable/possible wealth to become a reality someday, generating significant benefits for the Brazilian people. Five situations are absolutely essential to exist in Brazil for this to happen:

(i) *Stable*, *clear* and *favorable* legislation to investments by the private sector, encompassing legal and fiscal matters. No businessperson or investor, domestic or foreign, is going to apply his(her) money in a high-risk activity of long-term maturation unless he(she) is fully aware of what laws and to what taxes/royalties his(her) enterprise will be subject to for 25-30 years ahead. CEOs and investors must be sure that the existing legislation at the time of the nurturing of the enterprise will not change with time and will not be modified by every new incoming government. They need the peace of mind that no new taxes will be created and that the original signed contract will be fully enforced till its end. Legal security is essential for incrementing and maintaining investments in the country.

(ii) Serious and specific environmental management in the country. The issuing of environmental licenses for several activities in the petroleum upstream sector must take into consideration, besides the environmental risks, the specific necessities of a Second/Third World country like Brazil. Brazil needs to improve its population's quality of life by creating new wealth. Its entrepreneurs cannot be at the mercy of the ideological influences of NGOs and governments from the First World countries. These supposed environmental guardians cannot dictate Brazil's pace of development.

(iii) Political non-interference in Petrobras. The technical staff of Petrobras is a Brazil's technological and competence treasure; renowned and honored worldwide several times. They are perfectly capable of competing, planning, discovering and producing the hydrocarbon reserves and their derivatives necessary for the development and well-being of the country. Being a mixed economy company listed in the São Paulo and New York stock markets, Petrobras must be profitable and reward its stockholders by distributing dividends. The company's largest stockholder is the Brazilian government, so the more the company profits, the more the government takes. Political interferences in the company, with the nomination of technically incapacitated people to high management ranks, had ended in wide-open corruption, plundering of its financial resources, and a series of faulty decisions that recently led Petrobras to become the most indebted company in the world. It took circa six years to reverse this situation. Therefore, Petrobras management must necessarily be of technical and economically oriented.

(iv) A *firm*, *immutable*, *generous*, *specific* and *swift* calendar of exploratory block offerings (rounds) in the basins/areas here appointed as most promising. It should be *firm* regarding its guidelines to allow the companies to adequately plan their data acquisition and interpretation without the fear of unexpected changes that could lead to losing the money invested two or three years down the road. *Immutable* in time (quinquennial preferred), so the companies could adequately allocate expenditures five years down the road. *Generous* in the number of rounds per year (one to two) and blocks per round (several tens to few hundreds). *Generous* also in terms of quality (high to medium potential, as defined above) of the blocks offered. *Generous* also in terms of the variety of exploratory plays offered. *Specific* in terms of adjustment of the sizes and shapes of the blocks to the type of the basins, to the degree of past exploratory activities, and to the kind of play(s) that should be present within them. The Agência Nacional de Petróleo, Gás Natural e Biocombustíveis (ANP) and the Conselho Nacional de Política Energética (CNPE), which regulate the availability of exploratory blocks to the industry, should be flexible in their specification. For instance, blocks located in areas of new and ultra-frontier basins, with scant data and practically nill exploratory activity, should be much larger, sometimes much much larger, than blocks situated in producing basins. Their geometries should also be specific and adapted to the underlying geology of the basin. Finally, the offering of exploratory blocks should be *swift* to allow Brazil to have a decent grip on the petroleum wealth it holds (or not) in a time adequate to avoid becoming an importer of petroleum and to accelerate the upgrade of the quality of life of its population.

(v) This last requirement is, maybe, the most important of the five listed here. It goes in the sense of the famous saying "*The Stone Age did not end because the world ran out of stones, and the Oil Age will not end because we run out of oil"*. We do not want the Oil Age to end, maybe in the next century, with Brazil holding a huge volume of unused petroleum in its subsurface. A well-planned calendar of block offerings should allow a long-term vision of the future and be *swift*/agile in promoting the unraveling of the hidden wealth of Brazil's subsurface. It cannot change every time a new government is sworn in. CEOs, managers and entrepreneurs need a clear and reliable view of the future to be comfortable planning their investments. In this aspect, the present mode of exploratory block offerings (rounds) employed by ANP (Permanent Offer mode) is certainly NOT the most adequate to fulfill these five requirements. We strongly recommend that such a regime should be quickly modified.

We finally arrived at *The End*. I repeat the conclamation expressed above: "Hands to work and *Good Luck* in the search for more petroleum in the Brazilian sedimentary basins". Illustrious politicians and respected government employees, please help create and *maintain* the necessary incentives for such a search. Let us unravel, exploit and use our petroleum richness in order to catapult our country into the restricted club of First World nations!

And a last note...I have mentioned swans twice in this article, once writing about the Parnaíba Basin and once about the Pelotas Basin. I will mention this beautiful bird again in this last paragraph...this work is my Swan Song.

7 ACKNOWLEDGEMENTS

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