Pre-salt: Geological formation, history of discoveries and evolution of production of oil and natural gas fields

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ABSTRACT
In 2006, Petrobras declared the discovery of reservoirs with significant amounts of high-grade API oil and gas located in a region below the salt layer, called the pre-salt, which extends along the southeast coast, from the state of Espírito Santo to the state of Santa Catarina. As it is a region that has not yet been explored, many doubts prevailed about what this layer would be, how the behavior of the salt works, how this system was formed and how it is possible for the oil to be trapped and be of such good quality in such an extreme and little-known environment, among other questions. This paper aims to present the geological formation of the pre-salt, the history of discoveries and the evolution of hydrocarbon production in the region in a time interval of 15 years.

Keywords: Pre-salt, Sedimentary basins, Oil production.

1 INTRODUCTION

Oil is one of the main sources of non-renewable energy for contemporary civilization, in association with natural gas and coal. Consecrated by industrialization from the final decades of the nineteenth century, the fluid was the fuel for technological advances related to logistics and transportation that revolutionized and consolidated economic development in the twentieth century.

In this context of the search for new deposits, the pre-salt deposits are inserted. In 2006, Petrobras declared the discovery of good quality oil and gas in the Santos basin, off the coast of the state of Rio de Janeiro, and production began in 2010. Currently, the pre-salt reservoirs are already responsible for about 75% of the country's production.

These discoveries were responsible, in the country's internal scenario, for the opening of new jobs, the entry of foreign companies into the country, the hiring of ships, the signing of contracts, the increase in the collection of states and municipalities through special participations *and royalties*, the creation of the Social Fund and the long-awaited self-sufficiency in terms of production.

This work aims to present the pre-salt, the environment with the main oil reserves in Brazil, highlighting its geological formation, the evolution of production and its relevance to the Brazilian economy.

2 METHODOLOGY

To achieve the purpose of the work, information was obtained from bibliographic research in articles, magazines, newspapers, books, theses and monographs on the subject.

The work presents concepts about the origin and migration of oil, reservoir rock, sealing rock and oil trapping in the country, as well as the specific conditions of the Santos basin that gave rise to the pre-salt deposits.

The aim is for the reader to understand the formation of the pre-salt petroleum system, as well as the particularities associated with the discovery of extensive oil and gas reserves on the southeast coast of Brazil (PETROBRAS, 2021).

3 PETROLEUM GEOLOGY

To form an oil reservoir, the generation, migration and trapping of the fluid are necessary, which are phenomena that occur over geological time. In addition to these phenomena, four factors are relevant: i. the existence of source rocks, from which the hydrocarbons originate, ii. reservoir rocks, to house the fluid, iii. sealing rocks to trap, and iv. traps, which store the fluid (MILANI *et al.*, 2000).

A given petroleum system in a sedimentary basin involves the existence of the four factors associated, synchronously, with the phenomena of generation, migration and trapping of hydrocarbons.

Source rocks are sedimentary rocks of clay granulometry, low permeability, rich in organic matter, and, when subjected to high pressures and temperatures, are responsible for generating hydrocarbons. Organic matter is basically composed of microorganisms and algae that have not undergone oxidation processes. (THOMAS, 2001).

Reservoir rocks are responsible for trapping oil and gas and, for this to be possible, it is necessary that it has interconnected voids (pores), which give it the characteristic of being permeable. In order for the fluid not to remain flowing, reservoir rocks must be limited by barriers, known as sealing rocks. These rocks need to have low permeability and good plasticity (THOMAS, 2001).

4 FORMATION OF THE PRE-SALT PETROLEUM SYSTEM

The pre-salt is the name of a layer of rocks, usually carbonate, located below the salt layer present in the sedimentary basins of Santos and Campos. To understand the formation of the salt layer, one must understand the formation of the Atlantic Ocean.

About 150 million years ago (BGS, 2023), the continent of Gondwana (which involved a territory composed of the union of Africa and South America), began to undergo a process of rupture or fragmentation that gave rise to the African and American continents, as well as the Atlantic Ocean. This rupture process was caused by tensile forces acting on the tectonic plate associated with the continent of Gondwana, caused by the internal dynamics of the planet.

The initial phase of separation, called the pre-rift period, began in the Cretaceous Era about 145 to 66 million years ago (BGS, 2023), in a region that currently corresponds to the east-northeast coast of Brazil and the west-southwest coast of Africa.

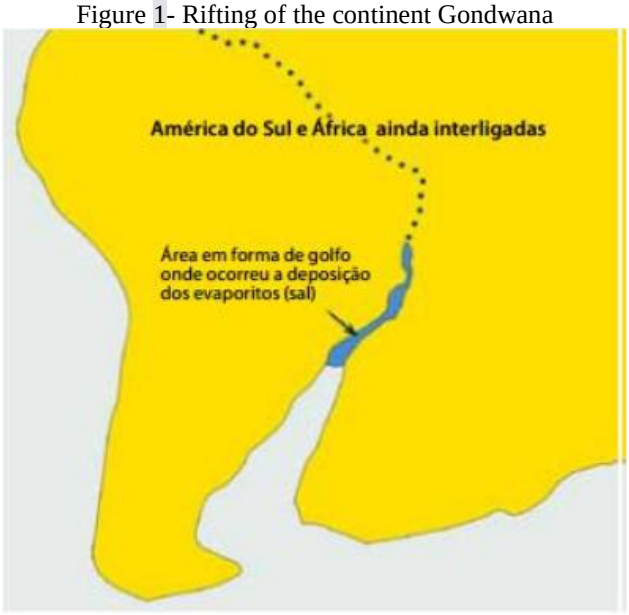
In the next phase of the separation process, called the rift phase, deep, narrow, localized fractures were formed, in which freshwater lakes were implanted. The lakes created became deeper and deeper, and in their deepest parts clayey sediments rich in organic matter (phytoplankton) and sands dragged by the currents of the rivers were deposited (PEREIRA & FEIJÓ, 1994). These sediments rich in organic matter give rise to the hydrocarbons present in the pre-salt.

Due to increased continental separation, caused by the stretching of the crust, the fracture systems connected and reached the edge of the continent, allowing seawater to penetrate the rifts. In the south of the continent Gondwana, the process of saltwater entering the rifts, such as the definitive separation of South America and Africa, occurs from south to north, as can be seen in Figure 1.

This figure represents a stage of *separation*, in which the sea reached the sedimentary basins of Santos and Campos, allowing the deposition of salt layers or evaporites. During a certain period of time, in hot climate conditions with high evaporation, a gulf-shaped saltwater lake was implanted in the region, in which salt deposits were formed that reached up to 2500 meters in thickness (CHANG *et al.*, 1990).

The salt deposits mark the transition from an environment with continental characteristics to an environment with marine characteristics in the Santos basin.

Figure 1- Rifting of the continent Gondwana



Source: Curti & Riccomini (2011)

The next phase of separation is called the post-rift, and in this phase, the Atlantic Ocean began to take shape. Marine sediment deposits are formed in sedimentary basins, the continental margins

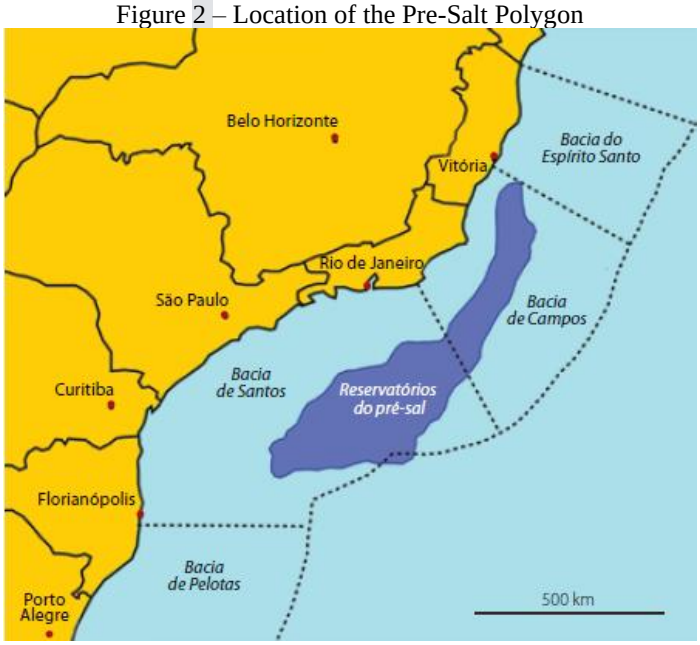
sink in part, due to the weight of the sediments. In this phase, transitional marine sediments, deep-water shales, shallow-water sandstones and turbidites are formed (PEREIRA & FEIJÓ, 1994).

In the last stage, known as *drifte*, the separation between the two continents of Africa and South America widened, and the Atlantic Ocean widened. The evaporitic deposits now belong to the Campos and Santos basins.

5 THE EVOLUTION OF OIL PRODUCTION

In 2006, Petrobras announced the discovery of oil reserves in the pre-salt layers in the Santos basin. The area covered by the pre-salt corresponds to a region of approximately 149,000 km², from the coast of the state of Santa Catarina to Espírito Santo (Figure 2).

Figure 2 – Location of the Pre-Salt Polygon



Source: Curti & Riccomini (2011)

The deposits are located at a depth of approximately 7,000 meters, with 2,000 meters of water depth, 1,000 meters of the post-salt layer, 2,000 meters of salt layer and 2,000 meters of pre-salt layer (MORAIS, 2013).

Between the first activity, which began on October 17, 2006, and the extraction of the first oil, on May 1, 2009, there were 30.5 months of activities involving the long-term test. Since the beginning of production, more than 20 drilling platforms, 47 support vessels, 3 ultra-deepwater pipe-laying vessels (PLSV) and 13 helicopters have been employed (PETROBRAS, 2021).

The discovery occurred through the drilling of well 1-RJS-628A, in the Santos Basin, Exploratory Block BM-S-11, in the Tupi region. Oil was found after a vertical depth of 7,021 meters, of which 2,126 meters were water depth. The oil found had an API grade between 28 and 30, considered medium to light (MORAIS, 2013).

In May 2007, a second well, 1-RJS-646, was drilled, 10 km away from the original well, in order to ascertain the economic possibility of exploring that area (MORAIS, 2013). The results confirmed the existence of a reservoir extending to the southern region of Tupi, as well as an estimate of oil recovery ranging from 5 to 8 billion barrels of oil.

Subsequently, new areas were declared. In August 2007, the Lapa Field, belonging to Block BM-S-9, was discovered through the drilling of well 1-SPS-50, finding API 24 grade oil, producing about 2,900 barrels per day and 57 thousand m³/d of gas, 270 km off the coast of the state of São Paulo.

In 2008, new reserves were discovered: Jupiter (well 1-RJS-652), Bem-te-vi (well 1-SPS-52A), Guará (well 1-SPS-55) and Iara (well 1-RJS-656). All of these reserves contained oil with API grade around 28 to 30 and were found at a depth of more than 6,000 meters.

In 2010, other reserves were discovered, including the Búzios Field, about 180 km off the coast of the city of Rio de Janeiro, through the 2-ANP-1-RJS well at a depth of 1,894 meters of water depth, with reservoirs located between 5,000 m and 6,000 m below sea level with a pressure close to 650 bar and temperature ranging from 90°C to 120°C.

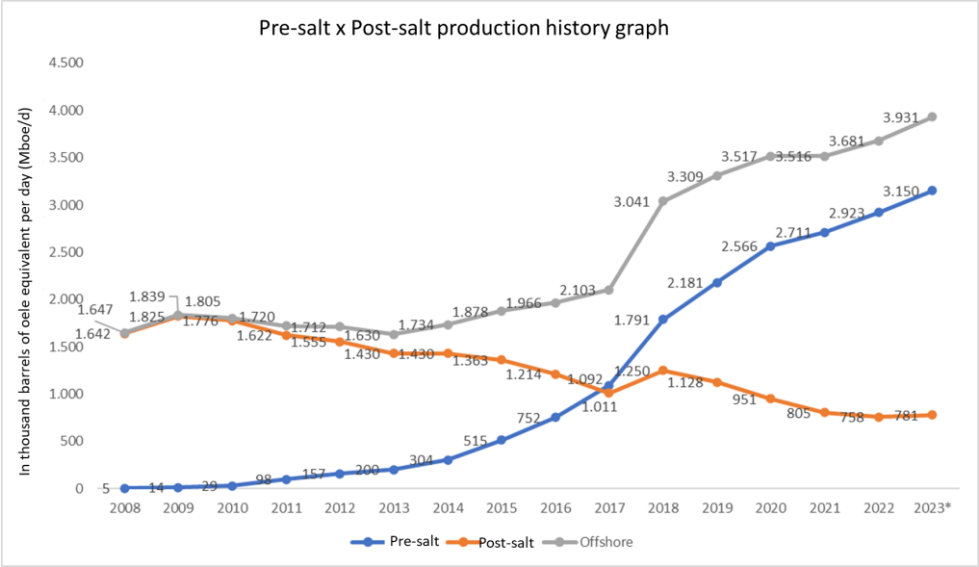
The reservoir is composed of biogenic carbonate sediments, the oil has good quality with API grade ranging between 26 and 28. (OLIVE TREE *et at.*, 2021). Búzios had its production started in April 2018 through the FPSO P-74 platform ship, followed by P-75 in November 2018, P-76 in February 2019, P-77 in March 2019 and FPSO Almirante Barroso in May 2023.

Also in 2010, the Mero field was also discovered in the northwest area of the Libra block, found through well 2-ANP-2A-RJS, at a depth of 2,100 meters of water depth. Its deposits are about 400 meters thick, the oil has an API grade of around 29, with a gas/oil ratio above 350, and the estimated total recoverable volume is 3.3 billion barrels of oil.

According to the ANP (2010), in November of that year, Petrobras broke a record in the Brazilian production of oil and natural gas, with approximately 2.089 MMbbl/d and that of natural gas, of 66.2 MMm³/d. It is noteworthy that 1MMbbl/d corresponds to one million barrels of oil per day, and one barrel is equivalent to 159 liters. and 1MMm³/d corresponds to one million cubic meters of gas per day (Figure 3).

Over the years, the company has been breaking records and, in 2014, reached the production mark of 412 Mbbl/d in a single day in the pre-salt region, a result obtained with only 21 producing wells. That same year, the first buoy to support *risers* - pipelines that connect the flowlines - to the production platforms in the Sapinhoá field was implemented, a technology that allowed an increase of 36 Mbbl/d (PETROBRAS, 2014).

Figure 3 - Graph of the History of Pre-salt x Post-salt Production



Source: Prepared by the authors based on data from the ANP's Oil and Natural Gas Production Bulletins
*Until June/2023

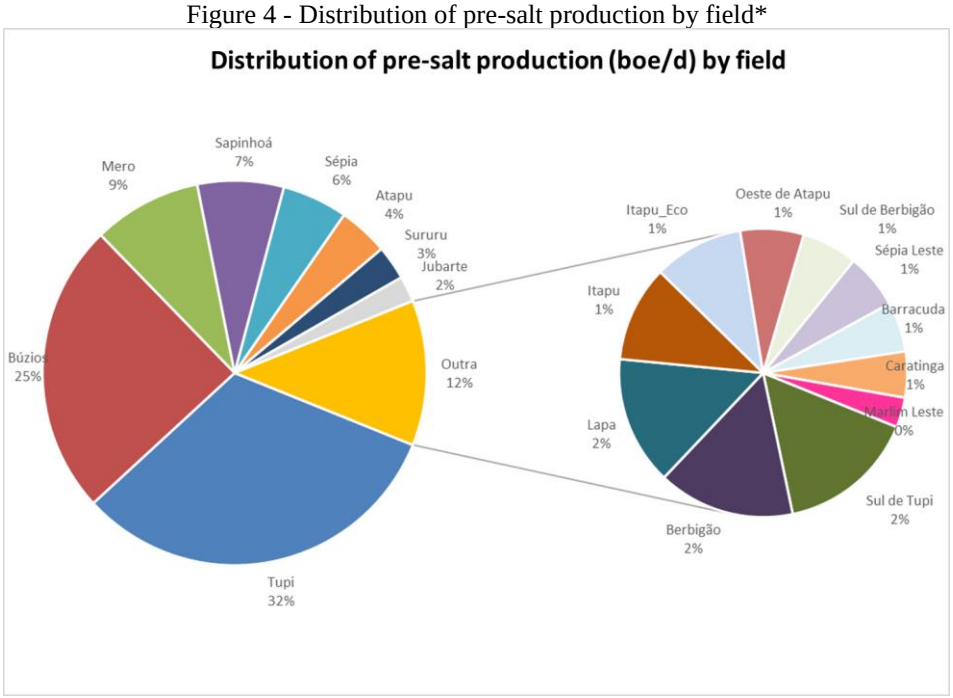
In June 2016, pre-salt production reached the mark of 1,000 Mbbl/d. During 2017, pre-salt oil production continues to rise and surpasses the production of other *post-salt* offshore fields.In June of this year, total production in the pre-salt was 1,688 Mbbl/d, while that of the post-salt was 1,686 Mbbl/d (PETROBRAS, 2017).

As of 2018, post-salt oil production declining and stabilizes in a range between 750 and 800 Mbbl/d. To deal with this situation of falling production, Petrobras is launching initiatives and projects for the revitalization of the Campos basin.

As of 2020, total oil production in the country exceeds 3,500 Mbbl/d and continues to rise, breaking new records, thanks to the contribution of the pre-salt.

Figure 4 shows the distribution of the pre-salt by fields and consequently the importance of each one in terms of production. The Tupi and Búzios fields stand out, representing more than 50% of total production. The production of these two fields, added to the production of the Sapinhoá, Mero and Sépia fields, corresponds to 78% of the current production in the pre-salt.

Figure 4 - Distribution of pre-salt production by field*



Source: Prepared by the authors based on data from the ANP's Oil and Natural Gas Production Bulletins
*Until June/2023

6 CONCLUSIONS

The present work presented a synthesis of the oil deposits of the pre-salt polygon in the Campos and Santos basins, the most important hydrocarbon asset in the country today.

The concepts about the genesis and formation of the pre-salt petroleum system were addressed, with the objective of clarifying for the reader the difference between the pre and post-salt layers, in addition to pointing out challenges associated with depths, pressures and the salt layer.

The work presented the successful results of the activities developed, such as the discoveries of deposits and oil fields, and the increase in production over the years. The pre-salt reservoirs are responsible for most of the Brazilian production of oil and natural gas, contribute to the country's self-sufficiency, and allow the Brazilian industry and economy to be boosted.

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