MASTER PROGRAM IN
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DRILLING FLUID:
A STOCHASTIC ROP OPTIMIZATION APPROACH FOR THE BRAZILIAN PRE-SALT CARBONATES

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Master Thesis submitted to the Master Program in International Study in Petroleum Engineering as partial fulfillment of the requirements for the title award Diploma Engineer (Dipl.-Ing.) in International Study in Petroleum Engineering.

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...and strong we have to be,
in this necessity of knowledge…

DEDICATORY

To my family and to all that have been depositing and still deposit in myself, believe, complicity and the source for ambition.

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ABSTRACT

The oil & gas industry has improved in exploration for deeper areas and in areas of salt layers. Some years ago, much has been said in the field of exploration about the complexities related to activities in the pre-salt region, in Brazil, frequently located in regions of ultra-deepwater, yielding technologies challenges. Considering the scenario for 2030, it is expected an increase in the world oil demand of 34 Mbbd, and an increase in oil production in Brazil of about 4 Mbbd, which represents approximately 11% of the global demand increase. Initially, the thesis presents the context of the pre-salt of Brazil, emphasizing the particularities of the exploration activities undertaken. As case studies, it has been used, respectively, the wells 1-BRSA-329D-RJS (Parati), 1-BRSA-369A-RJS (Tupi), 1-BRSA-491-SPS (Carioca), for the carbonates drilling optimization approach. By analyzing the provided and reported well-logs from BDEP, including sonic wave transit time logs, gamma-ray logs and formation bulk density logs, rock mechanics properties are estimated and pore pressure extrapolated for the pre-salt carbonate layers for each specific well. In this way, different analysis converged for a minimum acceptable MW to be used on the system, taking into account possibilities of kick occurrence and limitation related to wellbore collapse prevention needs. Being the MW one of the most important drilling parameters that can be changed over the operation, its optimization directly reflects on the ROP optimization, methodology used for driving the results presented over the thesis. Further accomplished and supported by Monte Carlo simulations for an overall analysis, considered are as well other parameters that affect the ROP such as bit size, WOB, hydraulic jet impact force, etc., used through stochastic values generations. A wide range of ROP increasing could be easily achieved for the Brazilian pre-salt carbonates, mainly by making use of lighter MW, since just a one decimal decrease in them value reflected in almost 12%, 16% and 27% in ROP efficiency, respectively for each well. Stated could be as well that a minimum weighted mud for dealing with the wellbore wall withstand (15.2 ppg, 23.0 ppg and 13.8 ppg, to well in sequence) is innaplicable, since them lead the ROP to be very low, being almost zero from 18.8 ppg, 15.5 ppg and 13.7 ppg, respectively, for each well. Thus, stated was that the minimum acceptable limit for MW design should take into account the pore pressure plus a safety margin of 3%. Even that, the MW reported for the activities run in the Brazilian pre-salt carbonates have shown a usage of MW in 14.83%, 14.74% and 11.46% greater than necessary, which could be better designed for optimizing the ROP.

KEYWORDS: Brazilian pre-salt; carbonates; drilling optimization; rate of penetration; mud weight; stochastic variables.

LIST OF SYMBOLS

°:	Degree;
’:	Minute;
’’:	Second;
ºAPI:	American Petroleum Institute degree;
ºC:	Celsius degree;
ºF:	Fahrenheit degree;
ºF/km:	Fahrenheit degree per kilometer;
µD:	Micro Darcy;
bbd:	Blue barrel of oil per day;
Bboe:	Billion of blue barrels of oil equivalent;
CO2:	Carbon dioxide;
ft/hr:	Feet per hour;
Gal:	Gallon;
GAPI:	Gamma-ray API;
H2S:	Hydrogen sulphide;
in.:	Inches;
Kgf/cm2	Kilo-gram force per square centimeter;
Klbf/in.	Kilo-pound per inch;
KPa:	Kilo Pascal;
KPa/m:	Kilo Pascal per meter;
L:	Liter;
lbf/in.:	pound per liter
m:	Meter;
m/hr:	Meters per hour;
m3:	Cubic meter;
m3/day:	Cubic meter per day;
max.:	Maximum;
min.:	Minimum;
Mbbd:	Million blue barrels of oil per day;
mg/L:	Milligram per liter;
Mpa:	Mega Pascal;
mV:	Milivolt;
ohm-m:	Ohm-meter;
ppg:	Pound per gallon;
psi/ft:	Pound per square inches per foot;
rpm:	Revolution per minute;
Tboe:	Trillion blue barrel of oil equivalent;

LIST OF ABREVIATIONS

ANP:	*Agência Nacional de Petróleo, Gás Natural e Bicombustíveis*, National Agency of Oil, Natural Gas and Biofuel (Brazil);
API:	American Petroleum Institute;
BDEP:	*Banco de Dados de Exploração e Produção*, National Database of Exploration and Production (Brazil);
BHA:	Bottom-hole assembly;
BOP:	Blowout preventer;
BRSA:	*Petrobras sociedade anônima*, Petrobras anonymous society;
BM-S:	*Bacia marítima de Santos*, Santos sea basin;
CNPE:	*Conselho Nacional de Política Energética*, National council of energy policy (Brazil);
DR:	Drilling rate;
E&P:	Exploration and production;
ECD:	Equivalent circulating density;
EXCEN:	*Centro de Excelência em Eficiência Energetica*, Centre of Excellence in Energy Efficiency;
EMW:	Equivalent mud weight;
E.g.:	*Exempli gratia*, For example;
Fm.:	Formation;
GR:	Gamma-ray;
HD:	Hole diamater;
HTHP:	High temperature and high pressure;
IBP:	*Instituto Brasileiro do Petróleo, Gás Natural e Biocombustíveis*, Brazilian's Institute of Oil Natural Gas and Biofuel;
ID:	Inside diameter;
IEA:	International Energy Agency;
IPR:	Inflow performance relationship;
KOP:	Kick-off point;
LNG:	Liquefied natural gas;
LWD:	Logging-while-drilling;
MUL:	*Montanuniversität Leoben*, Mining University of Leoben;
MW:	Mud weight;

MWD:	Measurement-while-drilling;
MD:	Measured depth;
NPV:	Net present value;
OBM:	Oil based mud;
OD:	Outside diameter;
O&G:	Oil and gas;
OECD:	Organization for Economic Co-operation and Development;
ORF:	Oil recovery factor;
OPEC:	Organization of the Petroleum Exporting Countries;
PDC:	Polycrystalline diamond composite;
PRH:	*Programa de Recursos Humanos*, Human Resources Program;
RJS:	*Rio de Janeiro submarino*, Rio de Janeiro submarine;
ROI:	Return on investment;
ROP:	Rate of penetration;
RPM:	Rotary speed;
RSS:	Rotary steerable system;
RT:	True formation resistivity;
SOBM:	Synthetic oil based mud;
SPS:	*São Paulo submarino*, São Paulo submarine;
TVD:	True vertical depth;
UCS:	Ultimate compressive strength;
USD:	United States dollar;
UNESP:	*Universidade Estadual Paulista*, State University of São Paulo;
UNIFEI:	*Universidade Federal de Itajubá*, Federal University of Itajubá;
WBM:	Water based mud;
WOB:	Weight on bit.

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INTRODUCTION

It is remarkable the role that energy has been playing in the modern society, specifically oil and gas associated energy. In recent years the petroleum exploration and exploitation has valued the pre-salt layers in Brazil, located at great depths and in quite complex exploratory conditions, if taken into account the new scenarios presented.

The theme discussed in this thesis is the specific drilling techniques to be applied during the petroleum exploration regarding the pre-salt carbonates in Brazil. Emphasized are the studies focused to rate of penetration (ROP) optimization possibilities while drilling the pre-salt carbonates. As case studies, including observation and interpretation from exploration wildcat well reports, are presented ways to derive rock properties information from well-logs and the development of a drilling model by making use of Monte Carlo simulations, in order to reach possible optimization of drilling parameters, tending to drilling efficiency. For drilling efficiency, from the dependent factors to affecting it, the main focus addressed throughout the thesis is the drillability factor of influence [1]. The wells in study are the 1-Petrobras anonymous society (*Petrobras sociedade anônima*, BRSA)-329D- Rio de Janeiro submarine (*Rio de Janeiro submarine*, RJS) (Parati), 1-BRSA-369A-RJS (Tupi), 1-BRSA-491- São Paulo submarine (*São Paulo submarino*, SPS) (Carioca).

In addition, an overview about the pre-salt prospect, Brazilian business forecast and as well the pre-salt value for the country now-a-days are taken into account, being further detailed and described.

1.1 Historical development

The early modern oil industry is dated from 1859, with the discovery of a reservoir 21 m deep, by Colonel Edwin Drake Laurentine in Tittusville, Pennsylvania. With a production of about 10 blue barrels of oil per day (bbd), it was discovered that resulted derivatives from their refining could replace with great margin of profit many products used by the companies, but still originated from other processes. Thus, the era of petroleum began. With systems still precarious on that time, the petroleum industry was summed up in trial and error; search and research on accumulations of oil and gas (O&G) had been done over the years without deep analysis of more likelihood regions. The drilling rigs used the technique of percussion drilling where the drill string was hoisted by cables, enabling drilling through the impact of its weight on the ground. With the advances, the techniques have become refined, incorporating the rotary method, which allows reaching greater depths [2].

Currently, the activities are mostly conducted by the rotary method, either through rotary tables (old technology) or top-drive (most recent technology), where the entire drill string is moved and rotated, or even through a hydraulic motor located nearby the drill bit, by which only the bit of the bottom-hole assembly (BHA) rotates. Called as geosteering, the act of adjusting inclination and azimuth angle from BHA while drilling a certain borehole, has been enabling more accuracy by reaching one or more geological targets. Thus, over the years, as well with the development of new technologies, the petroleum exploration and production (E&P) has become more efficient and cheaper, spreading between countries and increasingly demanding rules, limits of production, as well as minimally established E&P models [2, 3].

As a result, petroleum became the main source of energy in the modern society. Being a natural resource unevenly distributed geographically, went on to reveal a subject of not only economic dispute but also political, exerting a strong importance internationally [3]. With the continuously increasing in energy demand, the search for O&G began to understand more and more unusual locations, deepwater and ultra deepwater regions with complex geological profiles, as by this new pattern in the worldwide energy scenarios, the pre-salt in Brazil. By Figure 1.1.1 can be observed the evolution of the activities carried out in Brazil, emphasizing chronologically the water depth reached, and the pre-salt layers, known to be mainly carbonates.

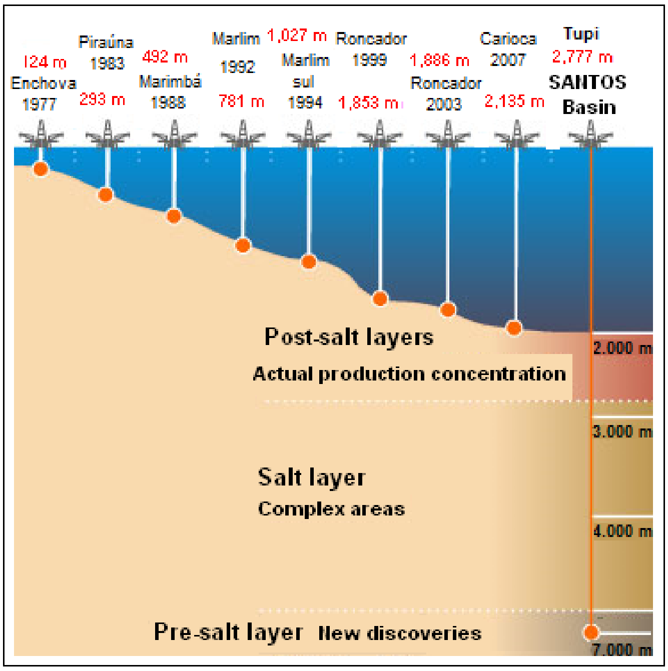


Figure 1.1.1 - Evolution of petroleum exploration in Brazil [4, 5].

1.2 Current scenario for the oil & gas industry in Brazil

The needs to meet O&G demand drive increasingly them exploration in areas with different characteristics, localities and constantly in more complex areas. Examples are the recent discovered fields in ultra-deep water exploration and exploitation, from 2,000 m to 3,000 m below sea level, and below an approximately 2,500 m layer thick of salt.

Projections done by the International Energy Agency (IEA) for 2030 show an increase in daily consumption of oil in about 34 millions of blue barrels of oil (Mbbd) from the current 86 Mbbd, to 120 Mbbd [6]. Brazil, with a current production of 2.2 Mbbd, and with its recent discovered new reserves, highlighting the pre-salt reserves, has great importance in this context. Projections for Brazilian oil production in Brazil reveal that the country might be producing in 2014, 3.6 Mbbd, and in 2030, a total of 6 Mbbd [7]. This growth in Brazil represents approximately 11% of the world oil demand increase for the same period.

Responsible for this increase in national production already predicted, are essentially the Brazilian pre-salt reserves, which mark, also because of this fact, an important moment for the petroleum industry in Brazil and its worlwide diplomatic relationship. Since mid 2005, with the first published information regarding the pre-salt region, many companies turned their attention to the Brazilian energy sector, contributing to a significant increase in the industry activities in the country. At the moment, despite already offering market opportunities for both, creation and establishment of companies on national soil, there is still a must of further development of the petroleum E&P for the pre-salt regions, so that these perspectives actually imposing, overcome some economic and technological challenge [8]. As an example, it is expected an investment, by Petrobras business plan, of about USD 224 billions by 2014, of which USD 108 billion is earmarked for E&P projects in Brazil, and USD 33 billions specifically for the pre-salt activities [9].

Furthermore, in the technological field, there are many barriers associated with the characteristics of E&P activities in these regions. Besides showing a high content of carbon dioxide (CO_2) and hydrogen sulphide (H_2S), the reserves are present in greatest abundance in locations of ultra-deepwater, high temperature and high pressure (HTHP), and below a thick layer of salt. With a thickness of about 2 km, this type of geological formation characterized by specific features in their properties, making necessary more robust and careful E&P plans. Another point to be highlighted is the fact that most of the pre-salt accumulation are concentrated in carbonates zones, known to be microbiological limestone, reason for constant developing studies and researches in the field of ROP optimization;

being brittle formations with tricky limitations in regards to applied strength and stresses, enhancing operations efficiency directly reflects in project budgets.

1.3 Objectives

The objective of this study is to identify, characterize and suggest changes in the treatment of technical exploration of hydrocarbons (oil and gas) in the pre-salt region, specifically for the Brazilian context, regarding to the drilling activity performance, ROP optimization.

This research has the following specific objectives:

- Analyze the Brazilian and world energy scene, contextualizing the pre-salt;

- Study techniques and new researches concerning drilling optimization regarding rate of penetration, and how to predict different rock parameters and properties from well-logs;

- Analyze these studies relating field operations to the Brazilian pre-salt carbonates,

- suggesting possible alternatives to ROP optimization based on Burgoyne & Young's drilling model, focusing to drilling fluid and stochastic analysis.

1.4 Thesis structure

The thesis work is structured in seven Chapters, spread out as following:

In this first Chapter - introduction - are addressed relevance to the development of the thesis, specifying its structure, purpose and a brief background of the subjects and its importance.

Chapter two presents the Brazilian and global world energy and petroleum scenarios, highlighting the importance of the pre-salt in this context.

Chapter three presents a literature review of issues relevant to the field of exploration and technological knowledge for drilling optimization engineering.

Chapter four focuses into the methodology used for the well-log data gathering, rock properties determination and drilling model estimation done through simulations.

Chapter five, the main focus of the thesis, presents analysis of different petroleum exploration activities run in specific regions of pre-salt deposits, emphasizing the characteristics of these activities in carbonate rocks. As case studies, observations and interpretations are presented based on exploratory reports of the further prospects: 1-BRSA-329D-RJS, 1-BRSA-369A-RJS and 1-BRSA-491-SPS.

Followed by Chapter seven, by which all references studied and used are listed, Chapter six presents a consolidation of results and perspectives for future researches.

2 ENERGETIC AND PETROLEUM SCENARIOS WORLD-WIDE AND IN BRAZIL

In this Chapter, characteristics concerning the actual energy sector tendencies for Brazil and worldwide are covered, correlating them to a forecast of the energetic and petroleum demand, emphasizing the importance and the reflex of the E&P activities in the pre-salt in Brazil.

2.1 Actual stand and perspectives for the petroleum industry

Although the world wide development shows an expansion of the renewable and alternatives energetic sources, the petroleum will still influence and have its importance within the worldwide energetic matrix.

Throughout projections reported by IEA, from 2006 to 2030, a growth of about 45% in the world demand is expected. Data has shown as well highlights that the petroleum will rise as primary energetic source, from 34% to 30%, worldwide, and from 36% to 27% in Brazil. Independently of this fact, an increase in the consumption of petroleum, due to the increase of the world wide energetic demand is expected [6]. For the actual scenarios, is estimated an enhance in the petroleum consumption, registering an increment from 86 Mbbd to 106 Mbbd by 2020, and to about 120 Mbbd by 2030 [10]. In Brazil, is expected an increment of the petroleum production as well, from the actual 2.2 Mbbd to about 3.6 Mbbd in 2014 (0.24 Mbbd just from new pre-salt reserves), 5.0 Mbbd in 2020 (1.2 Mbbd just from new pre-salt reserves) and 6 Mbbd projected for 2030 (Figure 2.1.1) [7, 9].

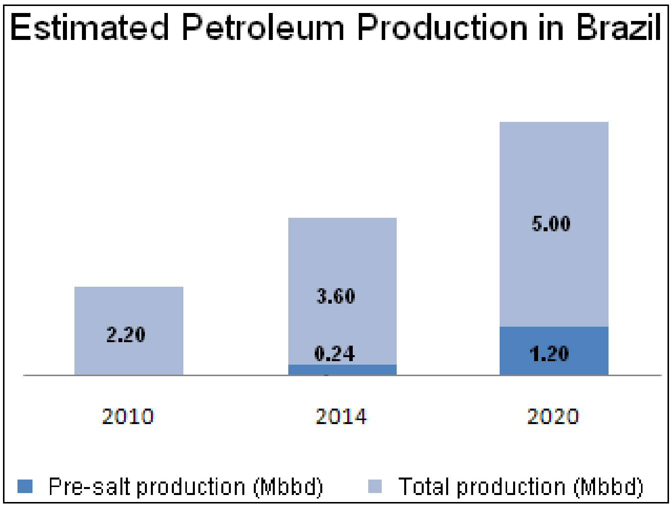


Figure 2.1.1 - Outlook of Brazilian petroleum production between 2010 and 2020.

In the global scenarios, is verified an actual petroleum production of about 80 Mbbd for 2010, projecting for 2030, approximately, 31 Mbbd, what represent a rise of about 61% in the production, if estimation still may be applicable for to date. Thus, a gap of 89 Mbbd in this energetic balance for the end of the next decade might be present [7]. This difference, a consequence of the increase in consumption and a decrease in production might have to be filled up by enhancing the oil recovery factor (ORF) of existing hydocrabonates fields, or by incorporating new discovered regions, such as these highlighted over the thesis. In the Figure 2.1.2, can be seen a natural decreasing in the production of existing fields, rating approximately 6% a year [7].

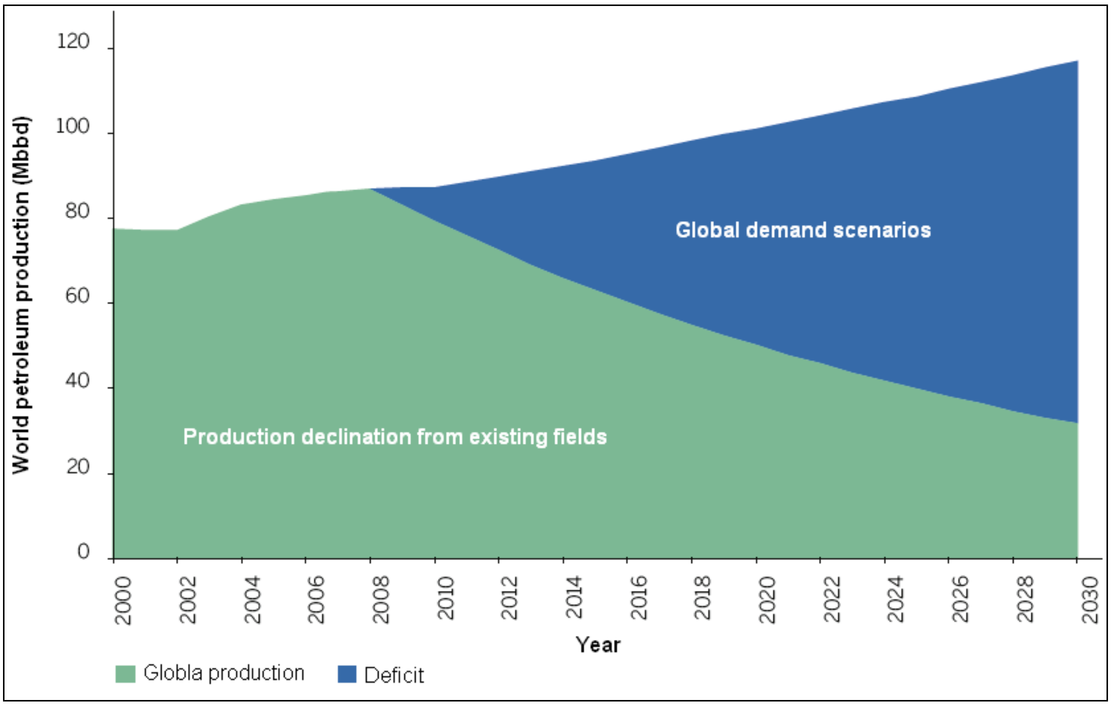


Figure 2.1.2 - Demand and world wide petroleum production [7].

Globally, the oil reserves are distributed, belonging 75% of it to the Organization of the Petroleum Exporting Countries (OPEC), which is explained in more details in the next subchapter. Of these, 65% or 1.26 trillions of blue barrels of oil equivalent (Tboe) belong to Saudi Arabia, Iran, Iraq, Kuwait, United Arab Emirates (UAE) and Venezuela, while the remaining 35% belong to Libya, Nigeria, Algeria, Angola, Qatar and Ecuador; Russia, Kazakhstan and Azerbaijan hold approximately 10% of the world reserves, and 7% belongs to the Organization for Economic Co-operation and Development (OECD), comprised of the United Kingdom (UK), United States of America (USA), Canada and Norway. The rest, about 8%, is spread around the world, including with high relevance, among other countries, Brazil and Mexico.

Thus, throughout the development of new technologies and by using new techniques, has been possible to discover new reserves with considerable accumulation and with volumes that might make possible to overcome the predicted demand gap, even in more complex areas and in locations considered to be not reachable in recent years. Due to the increasingly global energetic dependence previously presented, it is a really relevant point to mention the pre-salt discoveries, not just for Brazil, but for the globe. It can be verified that the reserves from the prospects of Tupi (5 to 8 billions of blue barrels of oil equivalent, Bboe), Iara (3 to 4 Bboe) and Guará (1 to 2 Bboe), together, summarize almost the same value of reserve as Kashagan, discovered in Kazaquistan early 2000, a giant field with a commercial potential of approximately 9 Bboe [7]. The Figure 2.1.3 summarizes the biggest discoveries in the last twelve years, for potentials greater than 3 Bboe. The Tupi and Iara field are located in Block Bacia marítima de Santos (BM-S)-11, and Guará field in Block BM-S-09, all in Santos basin.

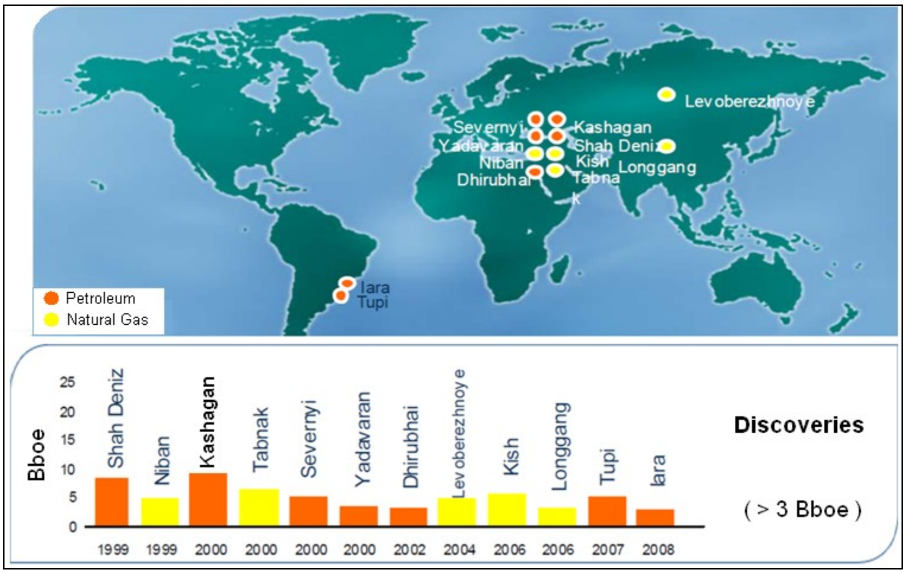


Figure 2.1.3 - Biggest relevant petroleum discoveries from the last eleven years [11].

Instead of the fact that new discoveries are showing up around the world, one is important to be highlighted, that petroleum reserves are still the major cause of crises, conflicts and international wars, and are these scenarios, of divergence of interests and needs, which promotes splits between O&G consumer and producer countries. China, although it has an oil production of around 3.8 Mbbd, due to its consumption of more than 8.3 Mbbd, more than 4.5 Mbbd has to be imported. Other consuming countries such as Japan (4.8 Mbbd), Germany (2.5 Mbbd), South Korea (2.3 Mbbd), France (1.9 Mbbd) and Italy (1.7 Mbbd) produce little expressive volumes, being importers. Russia has already a production of approximately 9.8 Mbbd, and a consumption of 2.8 Mbbd, exporting around 7.0 Mbbd [7].

2.2 The importance of pre-salt for Brazil

The new pre-salt discoveries should serve as boosting to the national development. With these discoveries, the country must remain self-sufficient for many years and may be, in the future, an important actor for the globe as an exporter of gas, crude oil and its derivatives.

2.2.1 Impact on the market and the industrial park

The pre-salt reserves are not already precisely known in its totality, but it is estimated that with the discovery of Tupi, Iara, Jubarte and Guara, Brazil could double the national production, jumping from 2.2 Mbbd (2010) to about 5.0 Mbbd in 2020, and approximately 6,0 Mbbd by mid 2030. Figure 2.2.1 shows a projection done in 2009 for Petrobras' total production by 2020, which shows to be delayed nowadays, but not concrete conclusion or definition could be further done, since information is a very critical and valuable resource at this stage. The growth rate of annual production of Petrobras was 5.5% annually between 2001 and 2008 [7].

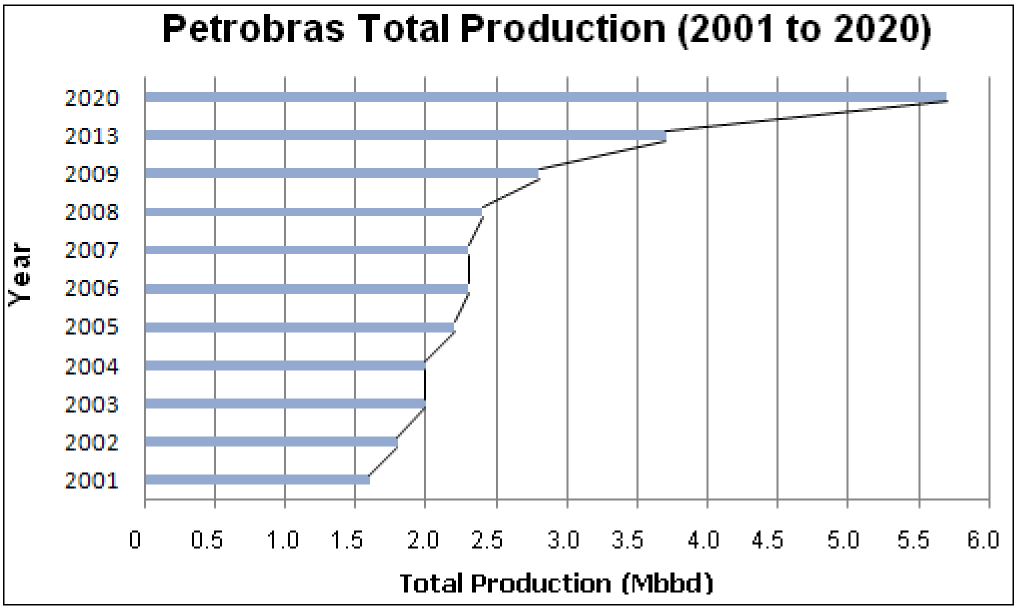


Figure 2.2.1 - Projections of Petrobras' total production from 2001 to 2020 [7].

These new discoveries may provide some advantages to Brazil such as energy security, ensuring the maintenance of self-sufficiency in oil, expansion of the national industrial park and engineering, due to the increase in equipment orders and services; accumulation of reserves, assisting a sustainability of economic growth; creation and development of technologies, comprising equipments for offshore E&P activities; natural gas production on a large scale and future possibility of exporting liquefied natural gas (LNG); possibility to become one of the ten largest petroleum producers and increase the energetic and economic importance worldwide [9].

All expectations related to the pre-salt are linked to high investments, limiting the possibility and speed of activities development in these fields. Projections for 2014 reveal investments for the pre-salt, just by Petrobras, of about USD 33 billions (14.7% of total investment in the period), being USD 18.6 billion specifically for the Santos basin, comprising approximately 56% of the investments directed to pre-salt regions in this period. And for enabling E&P activities and making it possible, a huge number of specific equipment are required, such as rigs, platforms, ships, refinery, transportation etc. These tend to boost the industry, as well as the Brazilian engineering, encouraging training for the sector [7, 9].

Another relevant issue to future of Brazil is the possibility to integrate into OPEC, regardless of the controversies presented in relation to positive or negative impact it can generate. Headquartered in Vienna, Austria, and raised on September 14th, 1960, is an organization composed of countries that not only have considerable petroleum production, but also qualify themselves as potential exporters. Thus, tend to control prices and volumes of worldwide petroleum production. Currently the twelve member countries (Angola, Algeria, Libya, Nigeria, Venezuela, Ecuador, Saudi Arabia, UAE, Iran, Iraq, Kuwait and Qatar) summarize an annual production of approximately 30 Mbbd, representing 35% of the 80 Mbbd world production (2010) [12].

2.2.2 Changes in the regulatory framework

Defined as a set of laws, rules and guidelines that governs the activities related to the sector and that establishes bodies and processes of supervision and control of these activities, the regulatory framework in the petroleum sector is characterized mainly in three systems, the concession, production sharing agreement and the services contracts. In this context, the pre-salt prospect discoveries have been a perfect occasion for discussions about the Brazilian national regulatory framework, since the choice of best system to fit is usually linked to needs and particularities of each country.

The concession system is often used by countries that represent risk for investments. In this model, activities are carried out by the dealer, without interference or government control in the E&P projects, respecting the regulation in force. If there is a discovery, after the extraction of hydrocarbon, it might belong to the dealers, however, only after payment of royalties and other government taxes [13].

The production sharing agreement system is often used by countries with reserves that include low exploratory risks. In these contracts, the company or consortium is responsible for performing activities and assumes the risk. On success, the production is divided between the government and the company or consortium, and the investment repaid in equivalent produced hydrocarbon [13].

In the services contracts systems, a company is hired to carry out the E&P activities and get paid for the services. In this model, all production is usually owned by the Union [13].

By Figure 2.2.2 can be seen the regulatory system adopted by some countries. Attention should be given to Brazil, country that started using instead of just concession system, the production sharing agreement system as well, but just valid for the new discoveries from pre-salt blocks have not yet been auctioned.

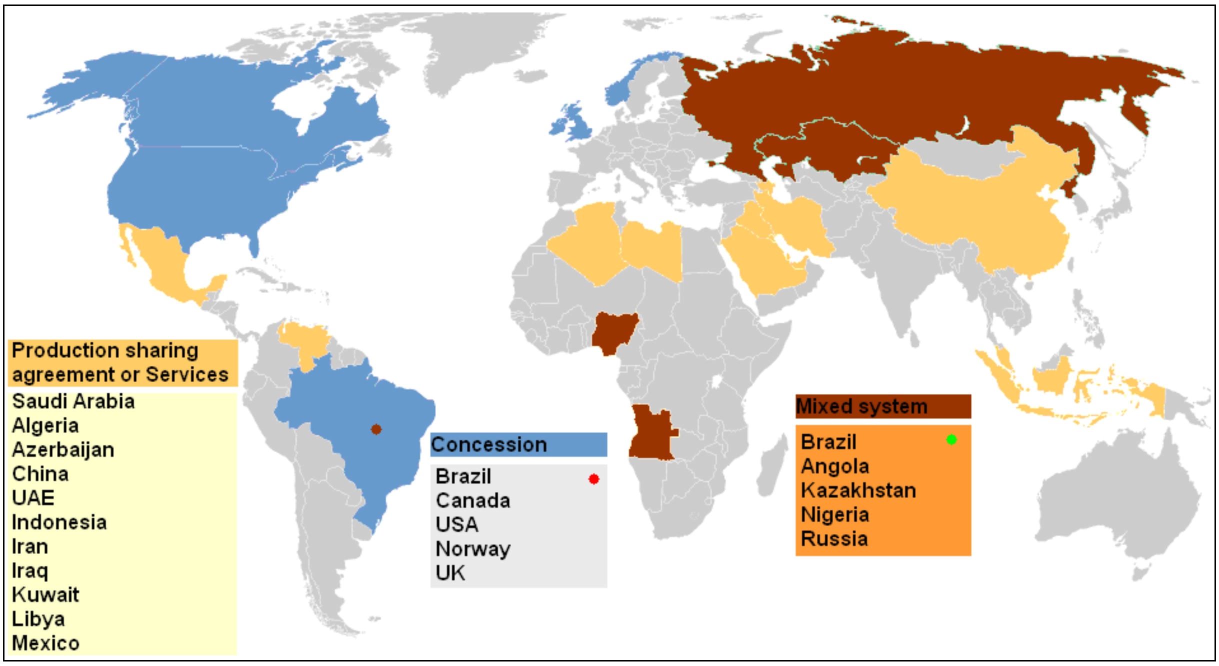


Figure 2.2.2 - Regulatory system adopted by some countries, highlighting Brazil [7, 14].

Currently, the main E&P activities in Brazil are governed by federal law 9.478/97, which adopts the concession system. Thus, to allow E&P activities, the ANP promotes public auction through bidding rounds, which are open to the public and to the private companies, aiming signatures of concession contracts. The company or consortium wins depending on which one receives a highest score, based on three factors: a) signing bonus (cash value offered to the Union for the right to sign the concession contract), b) nationalization index of equipment to be purchased and services for the activities to be performed, and c) minimum estimate time for developing the field. Since 1999, it was awarded a total of 500 exploration blocks throughout bidding rounds [15, 16].

At the time this legislation was created for regulating the oil industry in Brazil in 1977, the price of a barrel of oil was at a low value, around USD 20, and as well exploration blocks had some risks added by low profitability prospects, many other factors, as well as those presented, influenced by 70's, even as oil importing country, driven for this system. But nowadays, the scenario is slightly different; Brazil is self-sufficient regarding to oil, the price per barrel was in recent times with a considerable value, with an average of about USD 95 a barrel (2011) and the reserves of pre-salt, according to tests already carried out, ensure a not very high risk. These facts, as well as charges of Petrobras, had been influencing the Brazilian government in 2009, which proposed a change in the regulatory framework, validating for the pre-salt regions had not been auctioned and strategic areas to be defined by the National Council of Energy Policy (*Conselho Nacional de Política Energética*, CNPE). These changes include the addition of the production sharing agreement system to the

Brazilian regulatory framework, and the creation of a new state company called Pre-salt Petroleum SA (federal law 12.304/2010) [17]. The formation of a social fund and the determination of onerous assignments to Petrobras (the situation where 100% of the block might belong to Petrobras), are also part of these changes [7, 18].

With this new regulatory system, the production sharing agreement system, the Union, represented by Petrobras, may enter into contracts in two different ways, straightly by receiving 100% or even by normally participating throughout auctions. In the case of bidding, Petrobras is the operator and owns 30% of the block. And, if it wishes to increase its participation, must usually compete with the other companies [7].

Independently of all these information, there are still many controversies about changing the regulatory framework in Brazil. While some believe the changes can benefit the country and the society, others believe to be a hasty decision, without the need to have done such as sudden action.

2.3 Summary

As can be seen over the Chapter description about the relationship between Brazil and the global energetic market, the nation is slowly showing up its importance worldwide, as well because of the potential its new discovered reserves are weighting on the global petroleum market. Thus, a study relating its importance with technical cases studies has a recognized relevance, from a technical and from an economical point of view. All the further exploratory five wells in study are located in the Santos basin, in the pre-salt area, having as target the carbonates from the Formation Guaratiba, scenario that drives the particularity of this thesis. Since the penetration rate achieved by the drilling operations in these prospect are quite limited, most of the time below 5 m/hr, a study is developed in order to analyses the rate of penetration particularity in those cases, what shows its importance once being directly related to operations performance, reflecting in efficiency, resuming in positive economical approaches.

3 DRILLING OPTIMIZATION ENGINEERING

This Chapter covers relevant topics concerning drilling engineering and drilling optimization regarding to the rate of penetration. Examples are shown and specifically attention are given to parameters might be changeable to achieve an optimum in optimization of drilling rate.

3.1 Drilling operations

The drilling process or activity conducted throughout a specific wellbore is done by using different machineries, as well called as drill rig in a summary, which consists of a combination of numerous systems working together. From the whole drill string, which is composed mainly by the drill pipe, drill collar, Bottom-hole assembly (BHA) and bit, is the drill collar the ultimate responsible one for providing the necessary weight on bit (WOB), and also prevent possible buckling of the drill pipes above them, by placing the neutral point (the point on a string dividing the region of tension and compression, non having neither ones present by itself) in the right location. Depending on the technology applied by the rig, the rotational motion provided to the drill string comes from the rotary table and the kelly or the top-drive. A fluid-tight rotary joint, the swivel, is located at the top of the kelly or integrated with the top-drive, and provides a connection between the mud pump discharge line and the inside of the drill string. From all these, a robust hoisting system is required to support the weight of the drill string, lower it into the hole and pull it out. This is the function of the derrick, the travelling block, the hook and the draw works, followed by the crown block and drilling line. Since during a drilling operation the drilling fluid has to be cleaned for reuse or disposal, all rigs are as well equipped with facilities to treat the drilling fluid when back to the surface, a storage area for tubular goods, shelters and offices on site. Figure 3.1.1 summarizes an onshore basic drilling rig with its main components, from which can be seen as well some basic equipments and components that make up all hardware systems: power generation system, hoisting system, drilling fluid circulation system, rotary system, well blowout control system, and drilling data acquisition system and monitoring system.

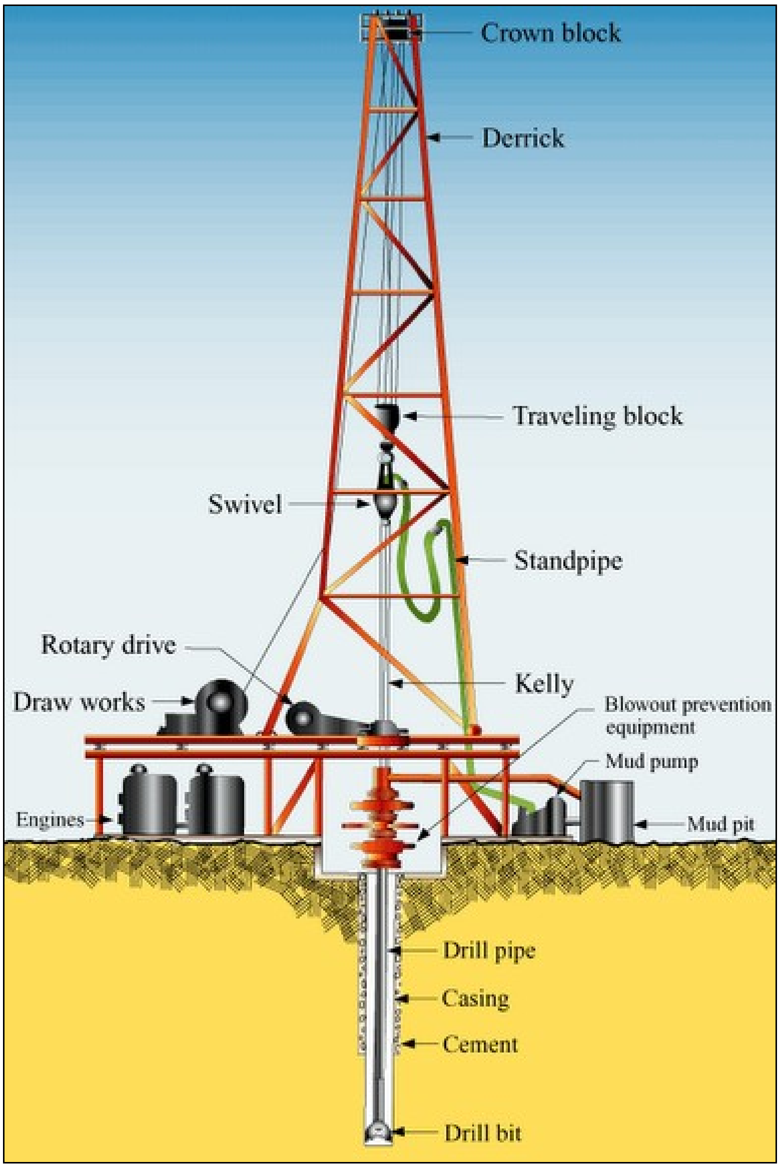


Figure 3.1.1 - Basic onshore drill rig and main components [19].

In addition, when a well is being drilled, it is regularly cased after each drilled section. Lined with steel pipe, as well denominated casing, it is lowered into the hole by its own weight or kindly pushed if in highly deviated environment, in smaller and smaller diameters as the hole gets deeper, being each step called as section, accomplishing one or more run per interval or section, depending on necessity of change the bit due to wear, BHA measuring tools due to failure or operations limitations, such as overpressure zones, etc. The first length of casing is run in as soon as the bit has drilled the surface formation and is then cemented in the hole. All the following lengths of casing, its diameter and the diameter of the drill bit for the next run are used in accordance to previously selection specifically determined and described in the drilling program for a specific well. The deeper the borehole gets and the more casings are set in the well, the smaller is the diameter of the bit that must be used.

Figure 3.1.2 summarizes a well schematic with five sections, by which the gray paint part represents well casing cementation.

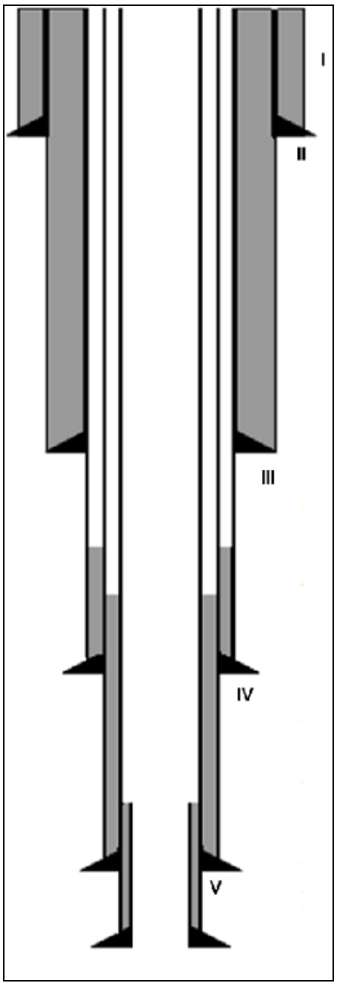


Figure 3.1.2 - General well schematic example [19].

Essentially to all operations in order to be able to recover underground O&G, is a process which requires two major constituents; man-power and hardware systems, previously described. The man power includes and is mainly related to the drilling engineering and rig operations group, also called crew. The first provides engineering support for optimum drilling operations, including rig selection, design of mud or drilling fluid program, casing and cement programs, hydraulic program, drill bit program, drill string program and well control program. After the drilling operation begins, the daily activities are handled by a rig operator group which can be consisted of a tool pusher and several drilling crews.

3.2 Drilling parameters optimization

During all drilling operations, there are always essential parameters that have to be designed and monitored in order to prevent eventual unexpected problems and as well, to permit optimizing as much as possible the performance of well operations, driving all step programs previously listed. Thus, the most important approach in real time operations are the monitoring of certain drilling parameters and them changeability in the lowest possible space of time, in order to provide continuously optimized operations and updates to fit any difference and necessity being experienced in real scenarios in relation to the predicted one. All these factors weight leading for reducing operations time, and most important reducing overall cost, directly reflecting to the economical value of projects.

Also, for drilling a well, optimizations have to be in accordance with three main factors one have to apply while drilling, simultaneously; 1) a certain load has to be applied on the bit, WOB 2) the bit has to be rotated, what is measured in revolution per minute (rpm) and 3) a drilling fluid has to be circulated within the well bore, mud weight (MW). These three main factors have a huge impact in how fast a well is drilled, drilling rate of penetration (ROP), and are covered in the Chapters four.

3.2.1 Effects on rate of penetration

There are many known factors to be effectively affecting the penetration rate in a certain operation. And since it is affected, once can be improved for a given field until it reaches its technical limits. This would be the maximum achievable ROP without compromising the operation safety or activities integrity. But, this is true and achievable just by carefully selecting all critical drilling parameters in place [20].

From those parameters directly related to the performance in how fast a well can be drilled, one can be put in two main categories regarding the operation, those controllable and those some uncontrollable variables. As the first one, mentioned can be the formation properties, such as rock properties, formation matrix, pore pressure, permeability, compaction, in-situ stresses, and mineral content. On the other hand, several drilling controllable variables, when selected carefully, can improve ROP, such as bit type, hydraulic parameters, MW, WOB and RPM (Table 3.2.1) [20].

Table 3.2.1 - Summary of main parameters related to ROP [20, 21].

Uncontrollable	Controllable
Rock properties	Bit type
Formation matrix	Hydraulic parameters
Pore pressure	MW
Permeability	WOB
Compaction	RPM
In-situ stresses	
Mineral content	

3.2.2 Formation characteristics

Formations (Fm.) characteristic, as an uncontrollable factor regarding drilling parameters, highly affect the penetration rate. Depending on where it is located, much different kind of formations present different rock properties, matrix, mineral content, permeability, pore pressure, in-situ stresses, etc. And none of them can be released to the side while designing drilling operations. Not directly related, formation characteristic influences decision on type of bit to be used, the boundaries for the mud weight selection, as well the applicable WOB and RPM for a specific scenario, in order to accomplish with the hydraulic program selected [20].

From the presented Fm. parameters, those that have more impact are the elastic limit and ultimate strength. Elastic limit of a rock means the greatest stress that can be applied to an elastic body without causing permanent deformation (plastic strain), remaining at a recoverable deformation stage (elastic strain). Depending on the confining stress and temperature as plastic deformations occur, the rock can either fail in a brittle manner (fractures propagates through the material by low confining stresses and high strain rates) or deform itself in a ductile manner (mostly happened at high confining stresses, low strain rates and high temperatures).

The ultimate strength of a rock is the capacity to withstand axially pushing forces. By reaching the compressive strength limit, materials are crushed apart. The shear strength is also very important since it is related to the threshold force required to initiate the drilling in a given rock. Thus, crater volume or rock cuttings particles produced beneath the bit or more precisely beneath the bit teeth is inversely proportional to the compressive and shear strength of the rock.

The permeability of the formation also has as well its effect on penetration rate. Since in permeable rocks, the drilling fluid can easily filtrate and flow into the rock ahead of the bit, leading for faster pressure differential equalization beneath the bit, proportionally relating itself to the accumulation and cuttings removal. Since the pressure equalization relates itself to the type of pore fluid phase, for instance, the presence of liquid or gas might have it influence in ROP as well, since for gas, more filtration may be required for equalization [20].

Concerning rock mineral content, hard and abrasive minerals can cause rapid dulling of the bit teeth, decreasing the effectiveness by the drilling process, and rocks containing plastic clay minerals can cause the bit to ball up, starting drilling inefficiently. Figure 3.2.1 represents a generic rock crushing apart mechanism acting by a bit tooth while drilling.

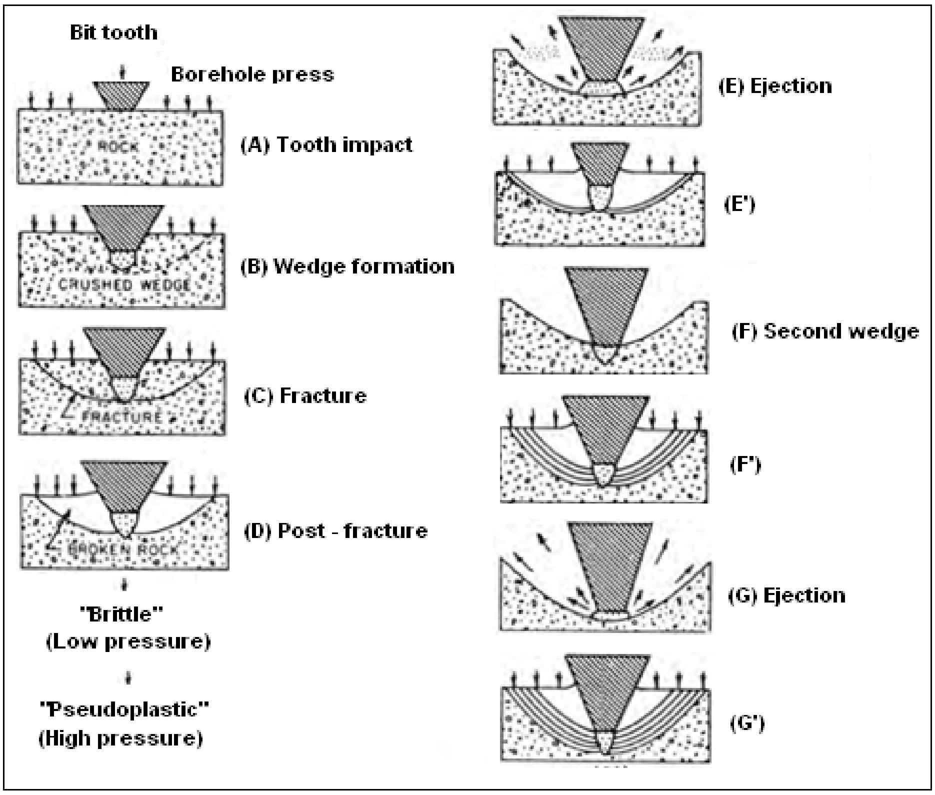


Figure 3.2.1 - Generic crater mechanism acting to a bit tooth while drilling [20].

3.2.3 Bit type and hydraulics

Designing the most appropriated bit type for an operation has as well a huge impact on ROP. For shallow depths, where soft formation might be present, rolling cutter bits with long teeth and a large cone offset angle let achieve higher performance. But, since a rapid tooth wear is a characteristic of this type of bit, it is applicable just for soft formations [20]. The diamond and polycrystalline diamond composited (PDC) bits, designed by the selection of the size and number of diamonds or PDC blanks, are most applicable for soft, firm, and medium-hard, non-abrasive formations. Most bits tend to drill slower by tooth wear, and, the impact is higher for milled tooth bits than insert bits. The teeth of tungsten carbide insert-type rolling cutter bits and PDC bits fail by breaking rather than by abrasion, and often, the entire tooth is lost when breakage occurs.

Significant improvements in penetration rate could be achieved by a proper jetting action at the bit, which drives better cleaning of the bit face as well as the bottom of the borehole. Parameters such as bit hydraulic horsepower, jet impact force, Reynolds number, etc., are commonly known influences to ROP. But not only a simply selection, sometimes those parameters, especially flow rate, has to be in accordance with the BHA measuring tools to be used. Most of the time it is strict well parameters, but can be changed in order to permit the tool to be used and optimized in terms of telemetry signal for the environmental scenarios in place.

Directly dependent on bit selection, the lowest cost per foot drilled can be obtained when using an optimum in operating conditions regarding the longest bit tooth or bit itself life.

3.2.4 Operating conditions: WOB & RPM

While drilling, two main controllable parameters are the WOB and RPM applied during the operation. Not just as wishes, the measurement equipment used, measurement-while-drilling (MWD) and logging-while-drilling (LWD) have to be respected in regarding its operation limitations. Since they have limitations, in special stick/slip (the irregular movement of a logging tool up a well due to it being stuck at some point and then being released), those parameters have first to attend its requirement in order to be able to continuously provide the required measurements, and in a second step, can be optimized according to the expected ROP [20].

A typical and general plot of ROP versus WOB can be seen by Figure 3.2.2, by which all the others drilling parameters were held constant. No significant penetration rate is obtained until the threshold bit weight is applied (point a). By segment a-b, the penetration rate increases with increasing WOB, and continually, as it values are more increased, a higher increase in ROP is observed (segment b-c), and, up to a certain value, a subsequent increase may cause only slight improvements in ROP (segment c-d). In some cases, by reaching the WOB optimum limit, a decrease in penetration rate is observed, but makeable just at extremely high WOB values (segment d-e), known as bit floundering a the petroleum industry, and should be avoided. The poor response of penetration rate at high values of bit weight is attributed to less efficient bottom-hole cleaning, since cuttings might start to inappropriately accumulate beneath the bit and around the BHA.

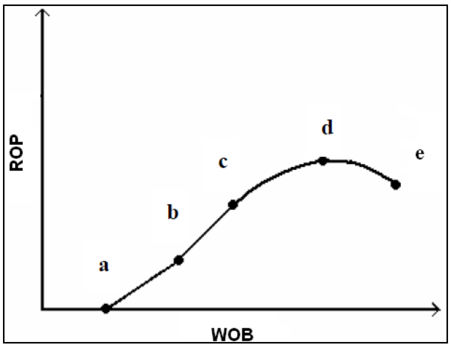


Figure 3.2.2 - Typical response of penetration rate versus bit weight increase [20].

A typical plot of ROP versus RPM can be seen in Figure 3.2.3, by which plot was obtained with all other drilling variables held constant. On the beginning, penetration rate respond linearly with rotary speed increase (segment a-b), and after a certain value, the ROP increase rate decelerates (segment b-c). After point-c, RPM starts to have a very slight influence on ROP, so that the poor response of ROP at high values of RPM attributed to less wellbore stability and enlargement of the well bore (most of the cases).

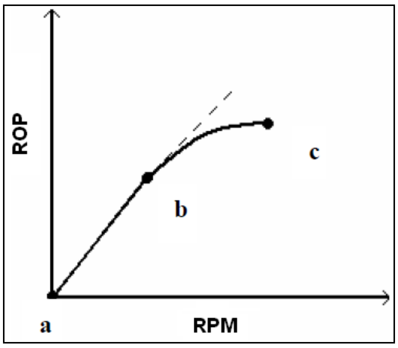


Figure 3.2.3 - Typical response of penetration rate versus rotary speed increase [20].

3.2.5 Drilling fluids properties

The drilling fluid or drilling mud directly affects the penetration rate, being some of its properties most important than others, such as mud density or MW, rheological properties, filtration characteristics, solids content and size distribution, and chemical composition. The higher the fluid density, viscosity and solid content may be present, the lower the penetration rate becomes to be; and the higher the filtration rate, higher the penetration rate becomes to be. The density, solids content, and filtration characteristics of the mud control the pressure differential across the zone of crushed rock beneath the bit. The fluid viscosity controls the parasitic frictional losses in the drill string and, thus, the hydraulic energy available at the bit jets for cleaning. From these, the drilling fluid density plays a big role in ROP, since this is the responsible characteristic to permit and drive the pressure equalization beneath the bit, previously explained, driving how string would be the chips or cutting hold against the borehole wall, what can lead to difficulties in getting them free, and consequently, decrease drilling rate (DR) performance [20]. Figure 3.2.4 shows a general example of a ROP response due to drilling fluid MW property, by which all other parameters were hold constant.

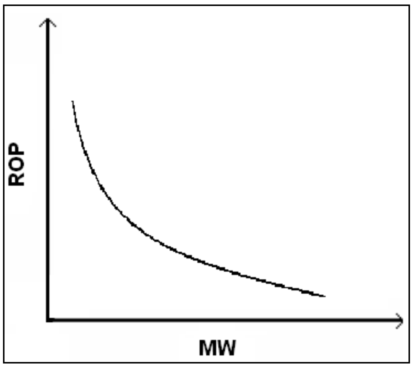


Figure 3.2.4 - ROP response accordingly to MW changes [21].

3.3 Quantitative relationships between drilling rate and drilling parameters.

It has long been observed that the DR generally increases with increasing flow rate, WOB, RPM, but, on the other hand, it decreases with increasing drilling fluid viscosity and MW, as highlighted in the previous Chapters. And a normal consequence of parameters effect, some variables may have significant whereas others might have marginal effects on MW [20-23].

Several authors have been proposing mathematical relationships between ROP and the major drilling variables among which the most complete mathematical drilling model being used nowadays is the one presented by Burgoyne & Young's model [20-23].

The drilling model selected for predicting the ROP response, considering the effect of many various drilling parameters is described by Equation 3.3.1, which accomplish Burgoyne & Young's model. The function $f_1^{'}$ represents the drillability identity of a certain formation, the functions $f_2^{'}$ and $f_3^{'}$, respond to uncontrollable variables and the functions from $f_4^{'}$ through $f_8^{'}$, variables that might be controllable and that have as well effect on ROP.

$$ROP \approx f_1^{'})(f_2^{'})(f_3^{'})(f_4^{'})(f_5^{'})(f_6^{'})(f_7^{'})(f_8^{'}) \qquad (3.3.1)$$

where:

ROP: rate of penetration (ft/hr);

$f_1^{'} \ldots f_8^{'}$: functional relations between penetration rate and different drilling parameters.

The Equation 3.3.2 represents the effects of formation strength and bit type on the penetration rate. It is expressed in the same units as penetration rate, called as formation drillability. Thus, drillability is numerically equal to the ROP that would be observed in a specific formation when operating with a PDC or a new bit (Equation 3.3.8) at zero overbalance (Equation 3.3.5), a TVD (Equations 3.3.3), WOB (Equations 3.3.6), RPM (Equation 3.3.7) and hydraulic jet force (Equation 3.3.9) equally valuable as the normalization values specified for each respective sub-functions. The drillability of the various formations can be computed using drilling data obtained from previous wells in the area, and it is effectively the function $f_1^{'}$, varying accordingly to the in-situ scenarios through the functions $f_2^{'} \ldots f_8^{'}$.

$$f_1^{'} = e^{a_1} \qquad (3.3.2)$$

Where:

$f_1^{'}$: drillability function accounted for formation strength and bit type (ft/hr);

e: Euler constant (approximately 2.718282);

a_1: coefficient for formation strength effect function.

The Equations 3.3.3 and 3.3.4 relate the effect of compaction of a determined formation, being the first one accountable for the rock strength increase due to the normal compaction with depth, and the second one for the effect of pore pressure gradient change due to depth. As by Burgoyne & Young's, the normalization value for depth is can be defined as 10,000.0 ft.

$$f_2^{'} = e^{a_2(TVD_N - TVD)} \qquad (3.3.3)$$

Where:

$f_2^{'}$: function accounted for rock strength;

e: Euler constant (approximately 2.718282);

a_2: coefficient for formation compaction and rock strength effect function;

TVD_N: chosen true vertical depth for normalization (ft);

TVD: true vertical depth (ft).

$$f_3^{'} = e^{a_3 TVD^{0.69}(g_p - \ )} \tag{3.3.4}$$

Where:

$f_3^{'}$: function accounted for pore pressure gradient;

e: Euler constant (approximately 2.718282);

a_3: coefficient for formation compaction and pore pressure gradient effect function;

TVD: true vertical depth (ft);

g_p: pore pressure gradient (ppg).

The Equation 3.3.5 models the effect of in-situ pressure differential, specifically the effects of overbalance operation on ROP, and thus, assumes an exponential decrease in penetration rate as a consequence of excessive bottom-hole pressure. For the model development the ECD is considered to be the EMW at the bottom of interval.

$$f_4^{'} = e^{a_4 TVD(g_p - ECD)} \tag{3.3.5}$$

Where:

$f_4^{'}$: function accounted for overbalance pressure differential effect;

e: Euler constant (approximately 2.718282);

a_4: coefficient for pressure differential effect function;

TVD: true vertical depth (ft);

g_p: pore pressure gradient (ppg);

ECD: equivalent circulating density or MW at section bottom (ppg).

The Equation 3.3.6 models the effect of bit diameter and WOB. As by Burgoyne & Young's drilling model, the threshold by which the rock begins to be crushed apart is considered to be 100.0 lbf/in., and the normalization value, 4.0 Klbf/in.., further applied in the thesis [22].

$$f_5' = \left(\frac{\frac{WOB}{d_b} - \left.\frac{WOB}{d_b}\right|_t}{\left.\frac{WOB}{d_b}\right|_N - \left.\frac{WOB}{d_b}\right|_t} \right)^{5} \tag{3.3.6}$$

Where:

f_5': function accounted for the effects of bit diameter and bit weight;
WOB: weight on bit (Klbf);
d_b: drill bit diameter (in.);
a_5: coefficient for bit effect function;
t: threshold;
N: normalization.

The Equation 3.3.7 shows the effect of RPM on ROP. Even having some limited proportional relationship, the critical RPM, however, must be estimated by considering the drill string properties, bit type and field data. As per Burgoyne & Young's drilling model, the normalization value is considered to be 100.0 rpm, further applied in the thesis.

$$f_6' = \left(\frac{N}{N_N} \right)^{6} \tag{3.3.7}$$

Where:

f_6': function accounted for RPM effects;
a_6: coefficient for RPM function effect;
N: rotary speed (rpm);
N_N: normalization rotary speed (rpm).

The Equation 3.3.8 summarizes the tooth wear effect on ROP, by which h might vary from 0.2 up to 1.0, unit less. And for totally new tungsten carbide insert bits and PDC, f_7' is considered to be equal to 1.0, having no effect on ROP [22]. As per demonstrating the simulation, its stochastic variations are as well generated in Chapter four, but its influence is not applied on the final drilling model development.

$$f_7' = e^{a_7(- \quad)} \tag{3.3.8}$$

Where:

f_7': function accounted for the tooth wear effects.

e: Euler constant (approximately 2.718282);

a_7: coefficient for tooth wear function effect;

h: fractional tooth dullness, ranging.

The Equation 3.3.9 summarizes the bit hydraulic effect on penetration rate. The normalization value is assumed to be 1,000.0 lbf as by Burgoyne & Young's drilling model [22].

$$f_8' = \left(\frac{F_j}{F_{jN}} \right)^{8} \tag{3.3.9}$$

Where:

f_8': function accounted for the bit hydraulic effects;

a_8: coefficient for bit hydraulic function effect;

F_j: hydraulic impact force beneath the bit (lbf);

F_{jN}: normalization of hydraulic impact force beneath the bit (lbf).

Over the years, from the mentioned and presented coefficients, as well with a characteristic to vary continuously within a specific range, could be stated more precisely an upper and lower limit for some of them. The coefficient a_5 might vary from 0.5 to 2.0, a_6 from 0.4 to 1.0, a_7 from 0.3 to 1.5, and a_8 from 0.3 to 0.6 [20, 22].

3.4 Summary

As described over the Chapter, many parameters have influence on the ROP, and each parameter that have influences can be seen by the mathematical drilling model developed by Burgoyne & Young's. In many cases, there is necessary to have a consistent database with operation parameters recorded from activities run in similar areas and conditions in order to be able to predict exactly behaviours throughout this model. Due to the fact that the pre-salt activities are a new approach in study in different research centre, the field data provided to be analysed has its limitation, and thus, for further analysis and scenario boundary determination, the five well in study are the only ones used for needed variables determination. As well, according to the parameters that influence the ROP, the thesis concentrates itself on MW versus drilling performance relationship, being its limitations and optimum value determined over well-logs analysis and empirical calculation. As a first step, by knowing that function $f_4^{'}$ accounts the effect of overbalance on penetration, assuming an exponential decrease in penetration rate with excessive bottom-hole pressure, further analysis have been developed relating specifically the MW, after stochastic assumptions for the unknown variables for the drilling model built, further used to relate the MW to each specific well.

4 METHODOLOGY FOR RATE OF PENETRATION TECHNICAL LIMIT APPROACH

As previously described in Chapter three presented, there are some drilling parameters applicable to be changed during the drilling operations that might help increasing the rate of penetration, providing an optimum in terms of field activity. In the specific case of this thesis, since it mostly approaches the effects of drilling fluid, and as well correlates it to different wells over the carbonates of Brazilian pre-salt, the following Chapter details the methodology to come out with the quantitative values presented for analysing how far the ROP, through a drilling model development, are affected by the MW in specific scenarios.

4.1 Mud weight particularities

It has been stated over the years that the drilling fluid and the hydraulics are the most important variables regarding DR optimization. It has been as well observed that the DR generally increases with decreasing the ECD, achieved by reducing some drilling fluid parameters such as MW and viscosity [21, 24].

Thus, a definition of a minimum acceptable MW for some a specific scenario, so that the well integrity and stability could be maintained, without any risky or dangerous situation, is what drives the further presented explanation in the thesis. A good approach is the investigation of possible problems that can arise due to insufficient MW, such as the following two situations:

- 1: Formation fluids might flow into the well, what can develop and lead to a kick;
- 2: Formation may collapse become instable, what can develop and lead to borehole collapse.

These two issues usually appear at two different MWs, stating that it should be at least sufficiently higher to prevent the borehole to collapse, addressed by the wellbore stability gained with the in-situ hydrostatic pressure applied by the mud over the entire section, and stating that it should be at least sufficiently higher to prevent any influx of fluid from the formation to the wellbore, achieved by the overbalanced drilling stability gained with the in-situ hydrostatic pressure applied resulting, what results in a positive pressure difference. Therefore, the lowest acceptable drilling fluid density or MW to be used in a specific well scenario would be the highest one of the two boundaries variables already pointed out, them avoidance [21].

While drilling a permeable formation, formation fluids may flow into the borehole if the drilling mud hydrostatic pressure falls below the formation fluid pressure. In such a case, the lower limit of drilling fluid density is selected in a way that the hydrostatic pressure of the mud column is slightly higher that the formation fluid pressure, in a safety margin of 3% [24].

The lowest acceptable limit for the MW in order to prevent a kick to occur is determined by the Equation 4.1.1.

$$MW = \frac{(1+S_f)P_f}{(1{,}176.27)TVD} \qquad (4.1.1)$$

Where:

MW: mud weight (ppg);

S_f: safety margin (%);

TVD: true vertical depth (m);

P_f: pore pressure (Pa).

The lowest acceptable MW, in order to prevent the wellbore collapse, is related to the stresses state [20, 24]. Defined by two variables, basically the octahedral shear stress and effective confining pressure, it has to be compared with an experimentally envelope of rock failure (Figure 4.1.1). If the stress state at the borehole wall falls below the rock strength curve (point b and point c), a compressive failure will not occur since the system is stable, and, if it remains above (point a), due to the instability, borehole collapse may occur. For the assumed condition of no flow, vertical well and normally stressed formation, the stresses at the borehole wall can be given in polar coordinates, an written per Equations 4.1.2, 4.1.3 and 4.1.4;

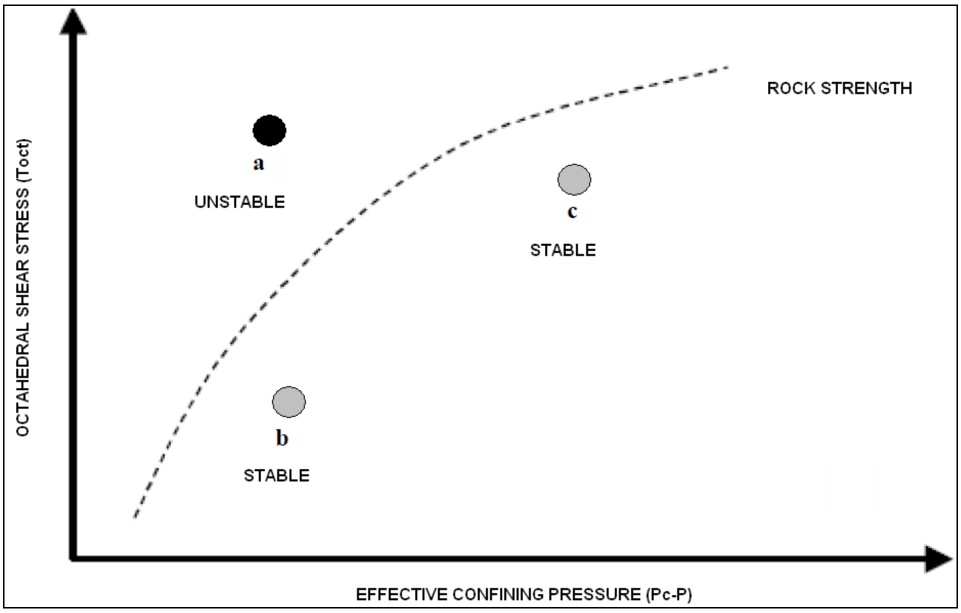


Figure 4.1.1 - General example of stress versus effective confining pressure [21].

$$\sigma = \int_0^z \rho \, d_z \qquad (4.1.2)$$

$$\sigma = P_m = MW \qquad (4.1.3)$$

$$\sigma_\theta = 2\sigma - P_m = 2\sigma \left(\frac{\upsilon}{1-\upsilon} \right) - MW \qquad (4.1.4)$$

In terms of σ, σ and σ, the effective confining pressure and the octahedral shear stress are given by Equations 5.1.5 and 5.1.6.

$$P_c - P_f = \frac{\sigma_\theta \, \sigma \, \sigma}{3} - P_f \qquad (4.1.5)$$

$$\tau_{oct} = \sqrt{\frac{(\sigma_\theta - \sigma)^2 + \sigma_\theta - \sigma)^2 + \sigma - \sigma)^2}{6}} \qquad (4.1.6)$$

Once a failure envelope of a specific rock is obtained, for a given effective confining pressure, the minimum acceptable MW can be determined, following the flowchart presented by Figure 4.1.2.

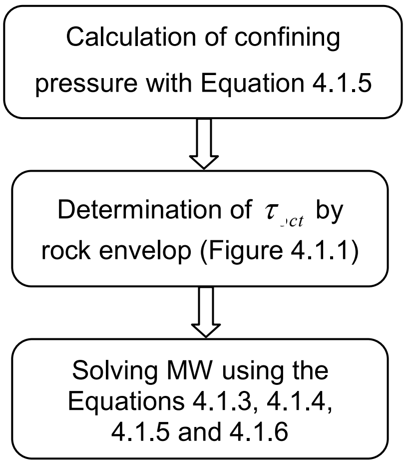


Figure 4.1.2 - Sequence for minimum MW determination [22].

But, since by many situations, such as the one presented throughout this thesis, no field data for the exact failure envelop determination is available, empirical equations (and equation that is created based on different test for a specific scenario, in order to substitute any quantitative behaviour expressed in a draw or chart) might be used. Since no laboratory studies for the octahedral stresses versus confining pressure of the pre-salt carbonates are available, the empirical correlation shown by Equation 4.7 have been used in order to compute the in-situ uniaxial compressive strength or ultimate compressive strength (UCS), leading to know the minimum preventive MW in order to avoid instability, or borehole collapse.

Ultimate compressive strength (UCS):

It is defined as the capacity of a material to withstand axially directed pushing forces. When the limit of compressive strength is reached, materials are crushed and can be empirically calculated with the Equation 4.1.7 [20, 21, 25].

$$C_o = \frac{(1-\upsilon\ \rho^{2}\cos\theta}{5.355(1-\sin\theta\ 10^{-11}}\left(\frac{1}{\Delta^{2}\Delta^{2}}-\frac{1}{\Delta^{4}}\right)\left[V_{shl}+4.5\left(-{}_{shl}\right)\right] \quad (4.1.7)$$

Where:

C_o: ultimate compressive strength (Pa);

V_{shl}: percentage of shale/clay volume;

ρ : formation bulk density (kg/m^3);

Δ : compression sonic travel time (µs/m);

Δ : shear sonic travel time (µs/m);

θ: friction angle (~30°, for most rocks).

Once the value of C_o is empirically determined, it is introduced into Coulomb's criterion, determining for the present borehole stresses, if the rock failure occur or not (Equation 4.1.8).

$$C_o = \left(\sigma_{max} - p_f\right) - \left(\sqrt{\upsilon^2 + 1} + \upsilon\right)^2 \left(\sigma_{min} - p_f\right) \quad (4.1.8)$$

Where:

C_o: ultimate compressive strength (Pa);

σ_{max}: maximum in-situ stress (Pa);

σ_{min}: minimum in-situ stress (Pa);

p_f: fluid pore pressure (Pa);

υ: Poisson´s ratio.

In a normally stressed, and considerable tectonically inactive formation, by which the maximum and minimum horizontal stresses can be considered to have the same value, one can assume $\sigma_{max} = \sigma_H$ and $\sigma_{min} = \sigma_z$. And, by combining Equations 4.1.2 and Equation 4.1.4, the lowest MW gradient that satisfies the mechanical borehole stability criteria can be determined by Equation 4.1.9.

$$MW = \frac{1}{D}\left[2\left(\sigma_H - p_f\right) - \frac{\sigma_z - p_f - C_o}{\left(\sqrt{\upsilon^2 + 1} + \upsilon\right)^2}\right] \quad (4.1.9)$$

Where:

MW: mud weight gradient (Pa/m);

D: true vertical depth (m);

σ_H: maximum in-situ horizontal stress (Pa);

σ_z: overburden pressure/stress (Pa);

p_f: fluid pore pressure (Pa);

C_o: ultimate compressive strength (Pa);

υ: Poisson´s ratio.

As can be seen, for the calculations, specific parameters might be necessary, such as sonic wave transit time, formation bulk density, formation shale content, etc. Since them availability makes true by gathering information from well-logs, these processes will be further explained.

4.2 Rock properties determination

Much have been studied over the years about how to determination petrophysics properties of formations throughout well-logs. And from consistent research, stated are models for gathering the Poisson’s ratio and as well other dependent properties, such as Young modulus, shear modulus and bulk modulus.

Poisson’s ratio:

It is defined as the ratio of transverse contraction strain to longitudinal extension strain in the direction of stretching force (Equation 4.2.1) [26, 27].

$$\upsilon = \frac{\frac{1}{2}\left(\frac{\Delta t_s}{\Delta t_c}\right)^{-} -}{\left(\frac{\Delta t_s}{\Delta t_c}\right)^{-} -} \qquad (4.2.1)$$

Where:

υ: Poisson’s ratio;

Δ : transit time of compressional waves (μs/m);

Δ : transit time of shear waves (μs/m).

Shear modulus:

It is defined and a material's response to shearing strains (Equation 4.2.2) [26, 27].

$$G_d = \rho \frac{1}{\Delta^{2}} \qquad (4.2.2)$$

Where:

G_d: shear modulus (Pa);

ρ: formation bulk density (kg/m^3);

Δ : transit time of shear waves (μs/m).

Young modulus:

Known as well as tensile modulus, it is a measurement of the stiffness of an isotropic elastic material (Equation 4.2.3). It is defined as the ratio of the uniaxial stress over the uniaxial strain in the range of stress [26, 27].

$$E_d = 2G_d(1+\upsilon) \tag{4.2.3}$$

Where:

E_d: Young modulus (Pa);

G_d: shear modulus (Pa);

υ: Poisson's ratio.

Bulk modulus:

It is the measurement of the resistance to uniform compression in a certain material. It can be defined as the necessary pressure increases to cause a given relative decrease in volume (Equation 4.2.4) [26, 27].

$$B_d = \frac{E_d}{3(1-2\upsilon)} \tag{4.2.4}$$

Where:

B_d: bulk modulus (Pa);

E_d: Young modulus (Pa);

υ: Poisson's ratio.

There are others variable essentials, which concerns the rock properties but that does not should be taken into account for the specific case in study through the thesis. For the shale content determinations and as well for the formation bulk density, the data could be directly read from the logs provided from the wells in study (e.g. Equation 4.2.5 and Figure 4.2.1). Besides this, in the case formation bulk density is not provided (Figure 4.2.2), it could be well determined from the neutron porosity tool, by assuming the formation to be microbial limestone, as they represent mostly the Brazilian pre-salt carbonates, Fm. Guaratiba, as is the case, and calculated using the Equation 4.2.6.

$$V_{sh}(V_{cl}) = \frac{GR_{\log} - GR_{\min}}{GR_{\max} - GR_{\min}} \tag{4.2.5}$$

Where:

$V_{sh}(V_{cl})$: shale volume content (%);

$GR_{\log}$: gamma-ray log pointed reference (GAPI unit);

$GR_{\max}$: gamma-ray maximum read in the interval (GAPI unit);

$GR_{\min}$: gamma-ray minimum read in the interval (GAPI unit).

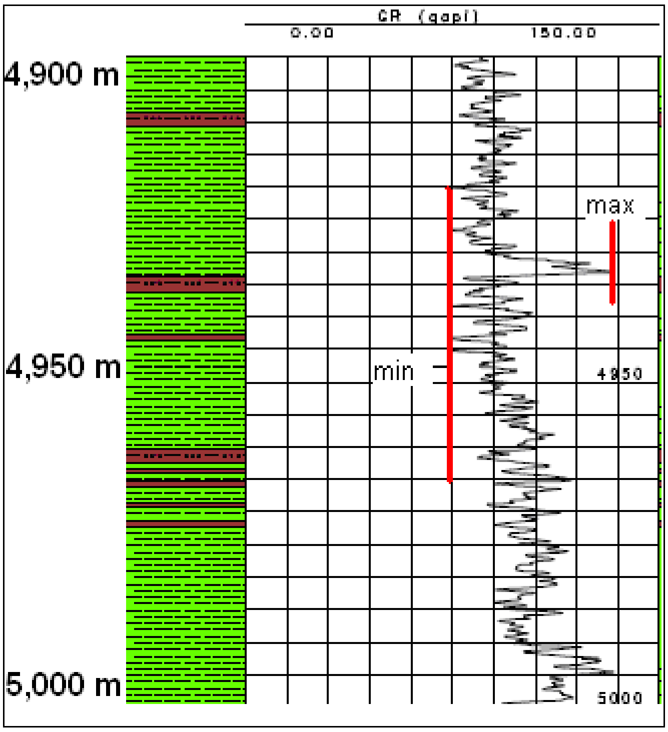


Figure 4.2.1 - E.g. of a GR logs highlighting the max. and min. occurrence of GR [28].

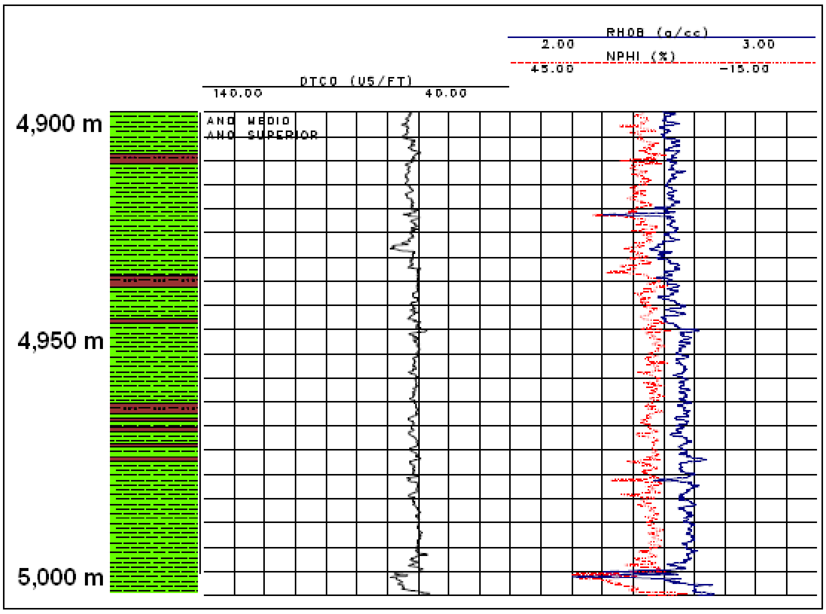


Figure 4.2.2 - E.g. of a Sonic log plus Neutron porosity index and formation bulk density [28].

As previously mentioned, in situations where no formation bulk density were provided, the formation matrix is assumed to be mostly limestone with a density of 2.71 kg/m^3, and calculated as per Equation 4.2.6 [29].

$$\rho_b = \rho_{ma} - \phi(\rho_{ma} - \rho_f) \qquad (4.2.6)$$

Where:

ρ_b: formation bulk density (kg/m^3);

ρ_{ma}: formation matrix density (kg/m^3);

ρ_f: formation fluid density (kg/m^3);

ϕ: formation porosity (kg/m^3).

4.3 Unknown drilling variables determination and Monte Carlo simulation

For the developed drilling model shown in Chapter three, it is necessary to have field data available, in order to accurate the determination of the coefficients responsible for driving the identity of a certain region. In some cases, some drilling parameters, such as RPM, WOB, hydraulic jet force, etc., are unknown in its totality, so that some estimative approach might be used in order to develop a minimally acceptable drilling model.

Thus, faced day-by-day with uncertainty, ambiguity, and variability, the risk attributed to each decision, due to unknown variables, can be as well applied to the industry and furthermore, for studying and approaching optimization in specific processes, as is the case of this research. Monte Carlo simulations, as well known as the Monte Carlo method, provides possibilities to outcome decision and assess the impact of these risks, allowing for better decision making under uncertainties, approaching considerable results if unknown variables are present. The technique was first used by scientists working on the atom bomb, by the Second World War, and since them, simulation has been used to model a variety of physical and conceptual systems [29-31].

Specifically a computerized mathematical technique, is used by professionals in many different industrial fields, such as finance, project management, energy, manufacturing, engineering, research and development, insurance, transportation and is as well applied to the O&G industry. Concerning this thesis, an approach for drilling optimization model determination has been developed. The Monte Carlo simulation performs possible results by substituting a range of values by a probability distribution, for any factor that has inherent uncertainty. It then calculates results interactively, using different sets of random values from the probability functions, or unknown variables. Depending upon the number of uncertainties and the ranges specified for them, the simulation can involve from thousands up to, if it is the case, up to tens of thousands of recalculations before is completed, producing distributions of possible outcome values [29-31]. These probability distributions can be defined to have specific outcome behaviors, such as [29-31]:

- Normal: a mean or expected value and a standard deviation describe the variation about the mean values are determined. Symmetric, values in the mid near the mean are most likely to occur, and describes many natural phenomena such as people's heights. Examples include inflation rates and energy prices;
- Lognormal: values are positively skewed, not symmetric like a normal distribution. It is used to represent values that do not go below zero but can have unlimited positive potential. Examples include stock prices, and oil reserves;
- Uniform: all values have equal chance of occurrence within a defined minimum and maximum within a range. Examples include manufacturing costs, future sales revenues for new products, and, in the case of this thesis, bit fractional tooth dullness, or tooth wear;
- Triangular: are defined the minimum, the most likely, and the maximum values of a specific range, so that the most probable outcome stays near the likely value. Examples include past sales history per unit of time, inventory levels, and in the case of this thesis, WOB, RPM, and as well hydraulic jet force while developing an operation.

Some particularities that might be positive and defend the successful in using Monte Carlo simulation for these studies, can be stated as following [29-31]:

- Probabilistic results. Shows not only what could happen, but how likely each outcome is;
- Graphical results. Creation of graphs of different outcomes and their chances of occurrence;
- Sensitivity analysis. Analyses of inputs have the biggest effect on bottom-line results. In the thesis, help analyzing which unknown variable has more impact on the ROP final value;

- Scenario analysis. Determination of inputs with different values and the impacts on final value;
- Correlation of inputs. Possibility to model interdependent relationships between input variables. In the thesis, them might show when some factors go up, others go up or down accordingly, resulting in final value changing.

As example, functions such as $z = xy$ can be evaluated n times. The variables x and y are called assumptions and have a defined probability distribution. In this case, z is called the forecast and is calculated n times, using random numbers to generate pairs of x and y values. The result is also a range of values of z with varying probability. In the thesis study, this approach is automatically put together with the drilling model coefficient determinations, by each unknown variables in the process.

An enhancement to Monte Carlo simulation is the Latin Hypercube sampling, which samples more accurately from the entire range of distribution functions, but what is not be taken into account within this research. Since the emphasis of this thesis is de determination of the optimum ROP for a given scenario, through a drilling model determination (Chapter three), Monte Carlos simulation will be released throughout all variables, accordingly to Equation 3.3.1. Since this equation can be used only, if all the parameters truly represent their average values throughout the drilling operations, to fit this research, another approach has been developed. The uncertainties driven by the unknown variables involved are taken into account by estimating the probability of them occurrence, by using specific probabilistic model followed by most likely values determination. As many Easy-to-use software's, for supporting in its approach, as an add-in for Microsoft Excel 2007, Oracle Crystal Ball version 11.1, has been used [31-33].

By rearranging Equation 3.3.1 with the Equations from 3.3.2 up to Equations 3.3.9, the Equation 4.3.1 and 4.3.2 can be developed, in order to apply the unknown variables to the Monte Carlo simulation.

$$ROP = e^{a_1} e^{a_2(TVD_N - TVD)} e^{a_3 TVD^{0.69}(g_p - \;)} e^{a_4 TVD(g_p - \;CD)} \left(\frac{\frac{WOB}{d_b} - \left.\frac{WOB}{d_b}\right|_t}{\left.\frac{WOB}{d_b}\right|_N - \left.\frac{WOB}{d_b}\right|_t} \right)^{5} \left(\frac{N}{N_N} \right)^{6} e^{a_7(- \;)} \left(\frac{F_j}{F_{jN}} \right)^{8} \qquad (4.3.1)$$

$$ROP = {}^{a_1} e^{a_2(10{,}000- \; VD)} e^{a_3 TVD^{0.69}(g_p - \;)} e^{a_4 TVD(g_p - \; CD)} \left(\frac{\frac{WOB}{d_b} - \;.1}{4 - \;.1} \right)^{5} \left(\frac{N}{\;00} \right)^{6} e^{a_7(- \;)} \left(\frac{F_j}{\;,000} \right)^{8} \qquad (4.3.2)$$

By applying the natural logarithms to both sides, the Equation 4.3.2 can be rewritten as shown by Equation 4.3.3.

$$\ln(ROP) = a_1 + a_2(10{,}000 - TVD) + a_3 TVD^{0.69}(g_p - 9) + a_4 TVD(g_p - ECD) + a_5 \ln\left(\frac{\frac{WOB}{d_b} - 0.1}{3.9} \right) + a_6 \ln\left(\frac{N}{100} \right) + a_7(-h) + a_8 \ln\left(\frac{F_j}{1{,}000} \right) \qquad (4.3.3)$$

From Equation 4.3.3, the variables WOB (weight on bit), N (rotary speed), h (fractional tooth dullness), and F_j (hydraulic impact force beneath the bit) are unknown, and by applying the Monte Carlo method, which is also embedded into Crystal Ball, stochastic assumption/generation (Table 4.3.1) values for this variables are used while applying a multi-regression for the drilling model coefficients ($a_1 .. a_8$) determination [33-34]. This topic is detailed in Chapter five, section by which the simulations is developed, summarizing and accomplishing all wells in study, ending up with an model identity for the Brazilian pre-salt carbonates, emphasizing the ROP response due to MW changes.

Table 4.3.1 - Unknown variables characteristics.

Variable	**Model**	**Maximum**	**Minimum**	**Likeliest value**
WOB (Klbf)	Triangular	50.0	10.0	40.0
N (rpm)	Triangular	250.0	60.0	100.0
h	Uniform	1.0	0.2	-
F_j (lbf)	Triangular	1,200.0	600.0	1,000.0

5 CASE STUDIES

In order to properly analyze all the aspects described in the Chapters four, case studies with three different exploratory wells from Santos basin has been performed, addressing some possibilities one might have for optimizing the drilling activities concerning the pre-salt carbonates, as well defined by the Brazilian ANP nomenclature as Fm. Guaratiba, by which most of the pre-salt hydrocarbon accumulation are situated. Also by using different empirically equations, developed over the years, throughout experiments and researches, well-logs such as sonic log, gamma-ray log, neutron-porosity log and density log are used for rock properties estimation. Formation pressure tests are extrapolated for pore pressure estimation over the entire carbonates layers and for its specific comprehended sections, ending up with results covering the minimum acceptable MW for the drilled interval. From stochastic generated values for the unknown drilling variable, a drilling model is generated, accomplishing some identity of drillability for the pre-salt. Thus, further analysis and graphs of MW and its performance are generated, accomplishing as well ROP response and drillability for these the pre-salt carbonates, presented over this Chapter.

5.1 Well 1-BRSA-329D-RJS

On this subchapter, general information, drilling performance graphs and a cross-study about the estimated and calculated properties of the Parati prospect are described.

5.1.1 General Information

The well 1-BRSA-329D-RJS is located in the Block BM-S-10, on the state of Rio de Janeiro, in the Santos basin (Table 5.1.1). This exploratory activity was conducted in the Parati prospect (known as the pioneer and responsible for the developed activities in the pre-salt region in Brazil), having as spud date 1st January 2005 and ending up on 28th October 2006, approximately 22 months of operation, comprehending a gas/condensates and oil reservoir [28].

In Table 5.1.1 and 5.1.2 are shown main information about the respective well, as part of the well operation final report.

Table 5.1.1 - 1-BRSA-329D-RJS operators and contract information [28].

Event	Description
Country	Brazil
State	Rio de Janeiro
Operation	Offshore
Block	BM-S-10
Operator	Petrobras
Operator’s well name	1-RJS-617-D
Identification synonym	Parati
ANP’s well name	1-BRSA-329D-RJS
ANP’s registration code	74316021189
Well type	Directional
Coordinates	Latitude: 25:03:42.047 S Longitude: 43:22:00.813 W
Datum	SAD – 69

Table 5.1.2 - 1-BRSA-329D-RJS operations and drilling activity information [28].

Event	Description
Spud date	01/01/2005
End drilling date	30/03/2006
Well conclusion	28/10/2006
Final depth	7,628.0 m
Rotary table	14.0 m
Water depth	2.038,0 m
Contract number	48610.003885/2000
Rig’s operator	TRANSOCEAN
Rig’s code	NS-20
Rig’s unit	Deep water expedition

Figure 5.1.2 shows the well location and the Block BM-S-10 referring to the coast.

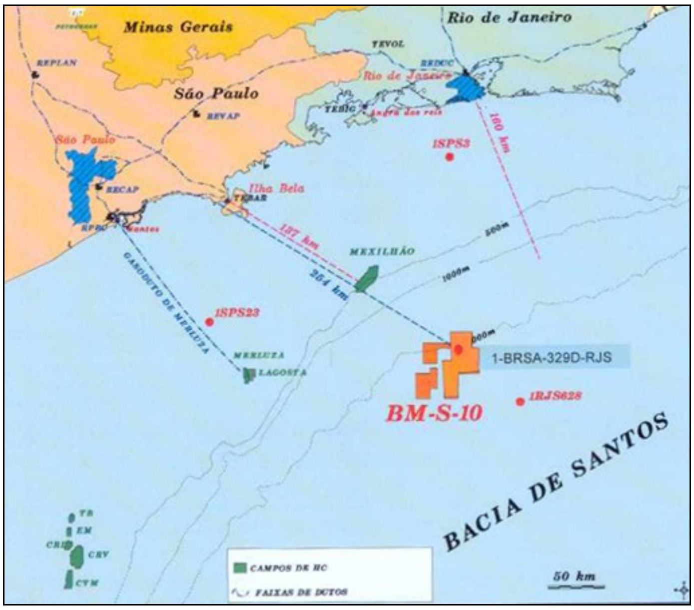


Figure 5.1.1 - Map of 1-BRSA-329D-RJS location [28].

Furthermore, Table 5.1.3 provides information regarding the predicted and measured stratigraphic layers depth.

Table 5.1.3 - 1-BRSA-329D-RJS predicted versus measured stratigraphic layers depth [28].

Stratigraphic	Predicted depth (m)	True depth (m)
Fm. Marambaia	2,052.0	2,052.0
Fm. Itajaí-açu	2,430.0	3,349.0
Fm. Itanhaém	5,172.0	5,464.0
Fm. Ariri	5,872.0	6,186.0
Fm. Guaratiba	5,900.0	6,208.0
Fm. Camboriú	-	7,639.0

Table 5.1.4 provides information about the well section description.

Table 5.1.4 - 1-BRSA-329D-RJS well sections description [28].

Well section	Bit size (in.)	Casing OD (in.)	MD (m)	Mud type	EMW (ppg)
I	36	30	2,101.0	Sea water	9.8
II	26	20	2,524.0	Sea water	8.5 / 9.7
III	22	16	3,256.0	Cationic	9.2/ 9.4
IV	16 ½	13 ⅜	4,463.0	Cationic	9.4/ 9.9
V	12 ¼	9 ⅝	6,104.0	Cationic	10.1/ 10.5
VI	8 ½	7	7,015.0	Cationic	10.4/ 12.0
VII	6 ¼	-	7,628.0	-	-

5.1.2 Drilling performance

Table 5.1.5 provides information about the well operations performance according to the productive, unproductive and lost time as well. From these, further analyses are developed, estimating for each section, the ROP over the operations run.

Table 5.1.5 - 1-BRSA-329D-RJS well operation performance [28].

Well section	Drilling time (hours)				Depth (m)	
	Productive	Unproductive	Lost	Total	MD	TVD
I	2.0	50.0	0.5	52.5	2,101.0	2,101.0
II	22.0	155.0	82.5	259.5	2,524.0	2,524.0
III	53.0	440.5	161.5	655.0	3,256.0	3,256.0
IV	105.5	744.0	1,006.0	1,855.5	4,463.0	4,463.0
V	526.0	650.0	333.5	1,509.5	6,104.0	5,815.0
VI	370.5	1,010.0	3,621.5	5,002.0	7,015.0	6,478.0
VII	598.0	574.0	368.5	1,540.5	7,628.0	6,952.0
Total	1,677.0	3,623.5	5,574.0	10,874.5	-	-

By Figure 5.1.3 can be seen a graphical representation of the productive, unproductive and lost time related to each drilled section. Since there were some limitations regarding to the mud logging reported with the exploration reports, information such as WOB, RPM and exact ROP per drilled section were unknown. Thus, for the case studies, an estimation of the ROP is calculated taking into account the productive time of the drilling operations per each section, considering a water depth of 2,038.0 m for this specific prospect, coming out with an overall ROP of approximately 3.3 m/hr (Figure 5.1.4).

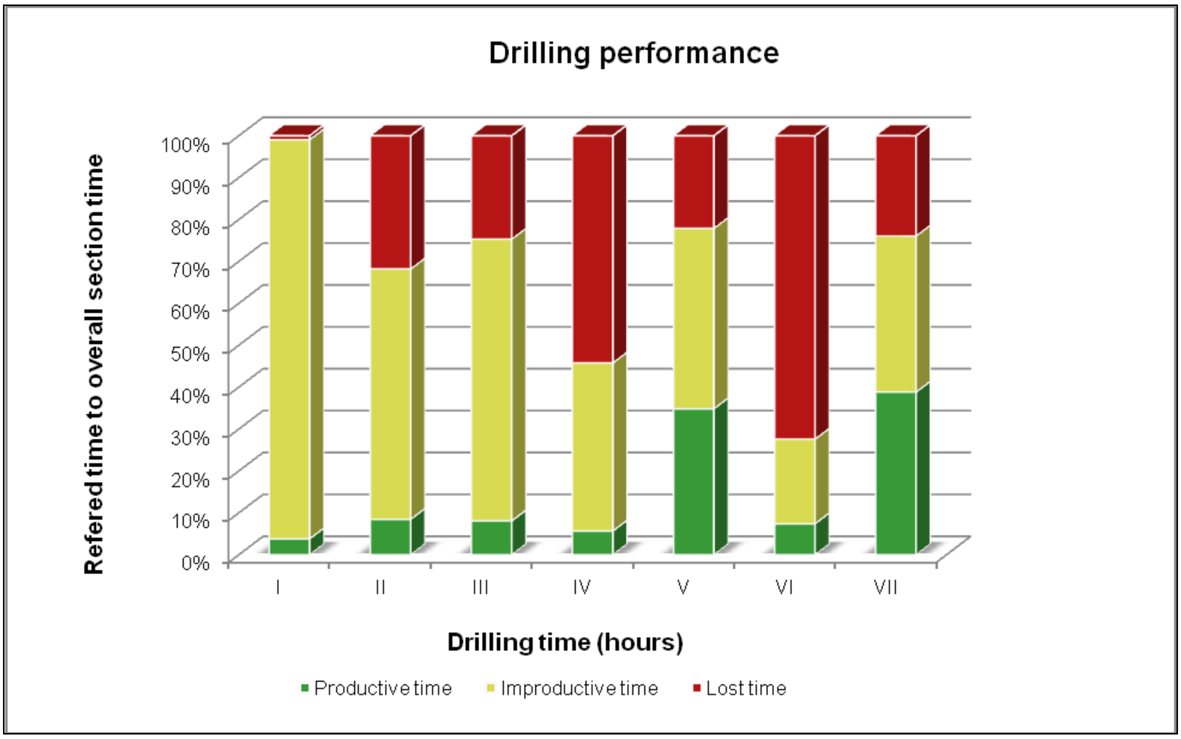


Figure 5.1.3 - 1-BRSA-329D-RJS drilling performance over well operations [28].

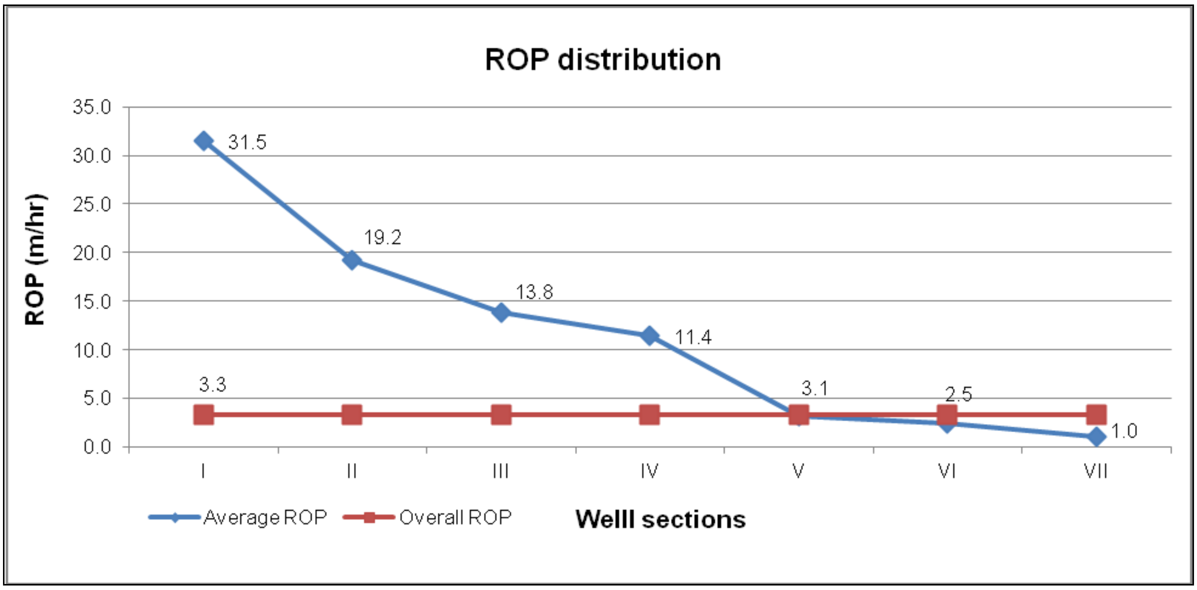


Figure 5.1.4 - 1-BRSA-329D-RJS ROP distributions over well operations [28].

5.1.3 Well-log analysis

From the well-logs, basically from formation gamma-ray and sonic wave transit time response, rock mechanics properties are estimated, taking into account all the equations and assumption previously discussed in Chapter four. Also, for all further analysis, taken into account are specific parts by which portions represented by the logs by which pre-salt carbonates, Fm. Guaratiba, may be present.

For the well 1-BRSA-329D-RJS, the carbonates are mostly present over the section VI, from 5,815,0 m to 6,478.0 m TVD (Tables 5.1.3 and 5.1.5). And for the reported logs, for this section, the data provided were limited between 5,900.0 m to 6,317.0 m TVD.

Thus, Figure 5.1.5 highlights the natural gamma-ray detection and the formation bulk density over the TVD.

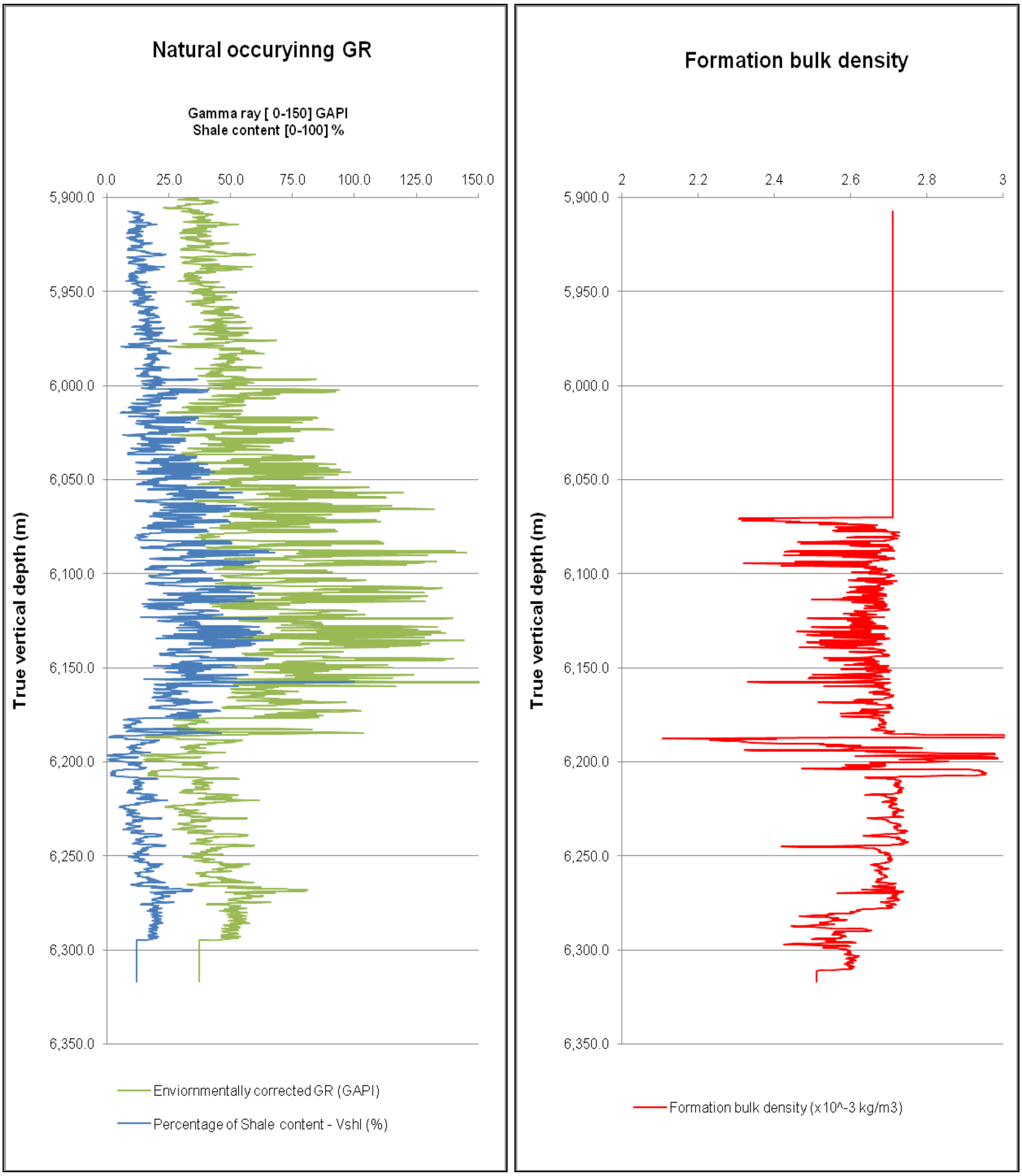


Figure 5.1.5 - 1-BRSA-329D-RJS section VI natural occurring gamma-ray (left) and formation bulk density (right) [28].

Figure 5.1.6 (left) shows the detected sonic wave transit time for the referred layers, which are further used for the rock mechanics properties estimation, shown by Figure 5.1.6 (right).

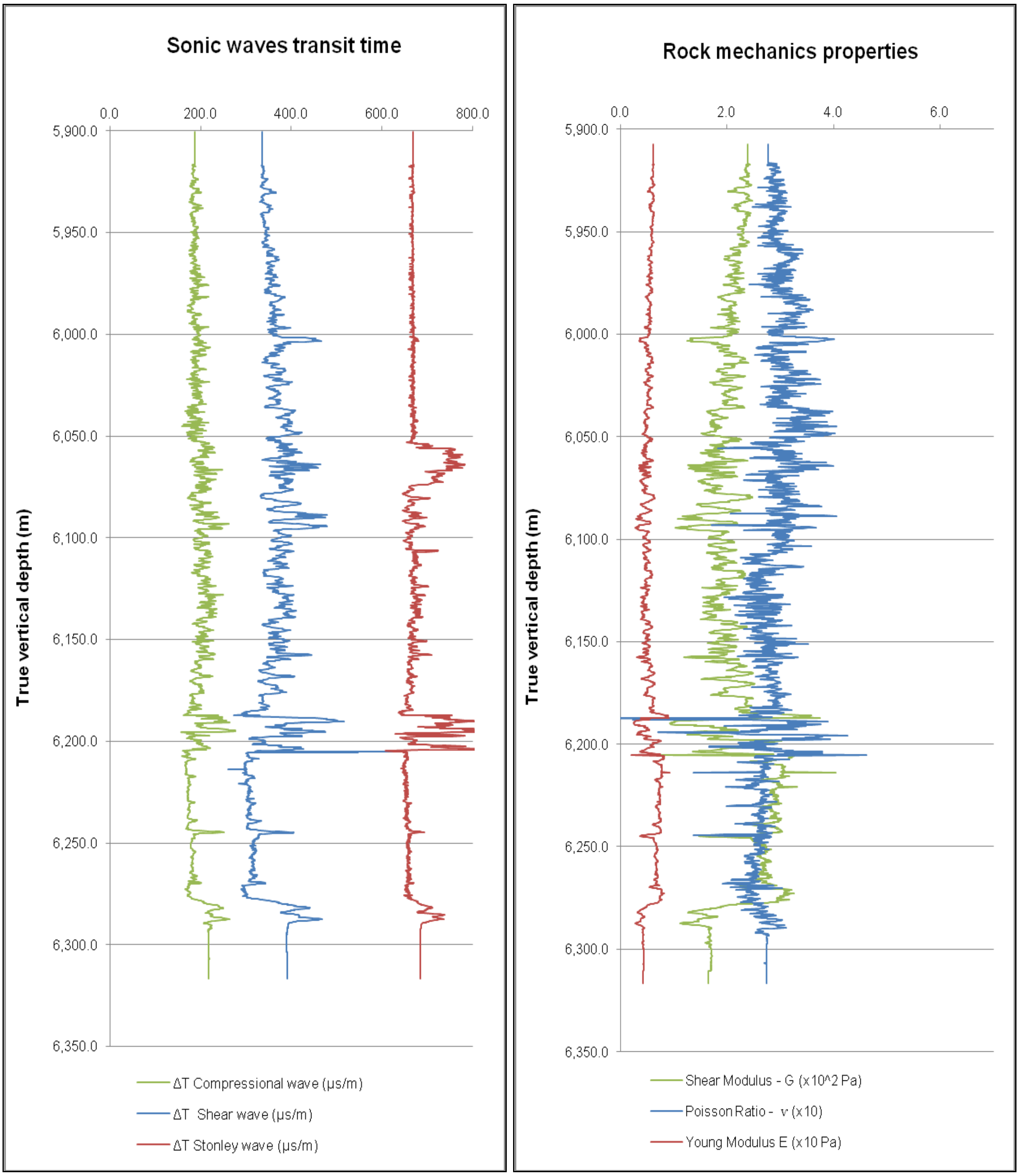


Figure 5.1.6 - 1-BRSA-329D-RJS section VI sonic wave transit time (left) and rock mechanics properties estimation (right) [28].

For the final determination of the minimum acceptable MW to be used for this section, in order to avoid kick and as well wellbore collapse, the vertical and horizontal stress and the in-situ pore pressure are determined, by calculations done throughout approximations and empirically equations, and by extrapolating the static fluid pressure data reported by the formation fluid pressure test, respectively.

Figure 5.1.7 shows the pore pressure data points and the extrapolated curve developed after applying the power-law approximation. Driven by Equation 5.1.1, the carbonates section pressure are determined as 38.70 KPa.

$$P_o = {}'(10^{-3})TVD^{3.6877} \qquad (5.1.1)$$

Where:

P_o: pore pressure (MPa);

TVD: true vertical depth (m).

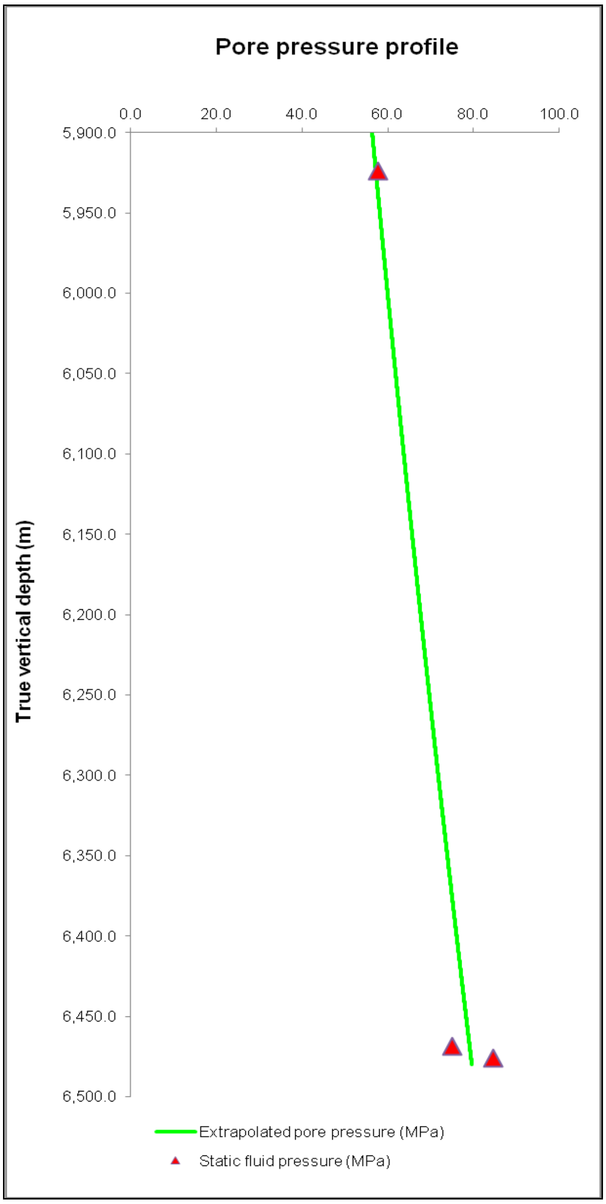


Figure 5.1.7 - 1-BRSA-329D-RJS section VI pore pressure estimation [28].

Figure 5.1.8 shows the minimum acceptable MW to be used for the carbonate section, in order to prevent either a kick or a wellbore collapse, being them respectively, 9.7 ppg and 15.2 ppg.

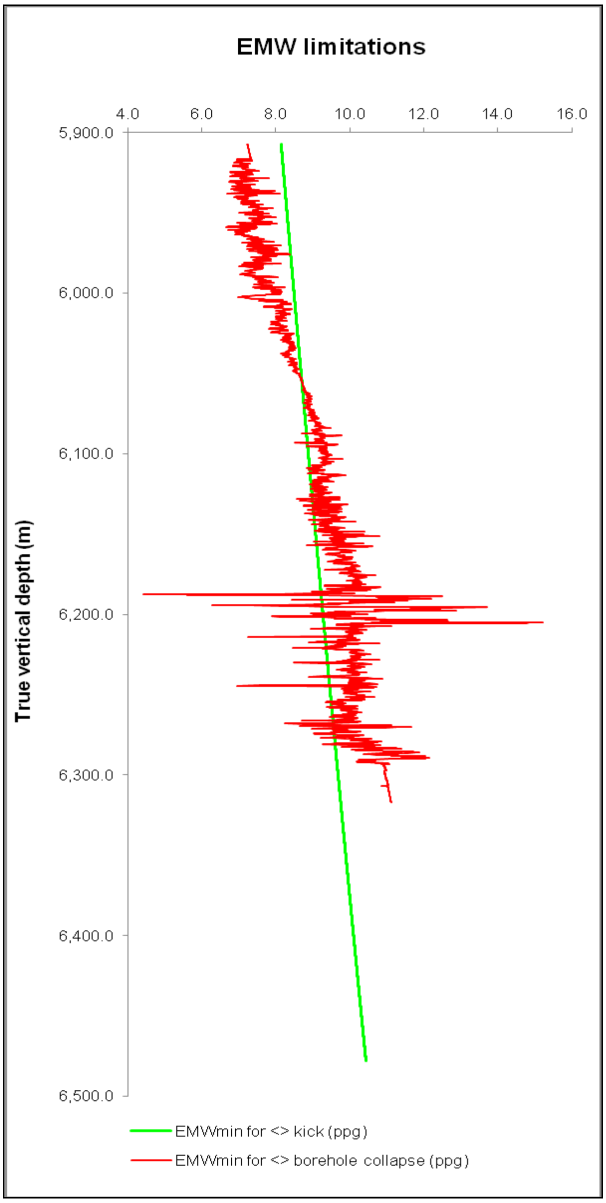


Figure 5.1.8 - 1-BRSA-329D-RJS section VI EMW limitations [28].

5.1.4 Summary

Since the boundaries of the analysis are the pre-salt carbonates, the layer studied concentrates itself into section VI, 8 ½ in., and more specifically, just from TVD 5,815.0 m to 6,478.0 m, due to data limitations. For the activity run, it was reported a utilization of cationic mud with an EMW ranging from 10.4 ppg to 12.0 ppg. Furthermore, for kick and wellbore collapse prevention, a MW with minimally 9.7 ppg and 15.2 ppg, respectively, may be used.

5.2 Well 1-BRSA-369A-RJS

On this subchapter, general information, drilling performance graphs and a cross-study about the estimated and calculated properties of the Tupi prospect are described.

5.2.1 General information

The well 1-BRSA-369A-RJS is located in the Block BM-S-11, on the state of Rio de Janeiro, in the Santos basin (Table 5.2.1). This exploratory activity was conducted in the Tupi prospect (known as the giant new discovered pre-salt reservoir in Brazil), having as spud date 1th October 2005, ending up on 12th October 2006, almost 1 year of operation (376 days), in a water depth of about 2,126.0 m, up to a final TVD of 5,957.0 m (Table 5.2.2). The goal of this exploratory well had been to achieve and test the structural traps of the carbonates and sandstones, from Fm. Guaratiba and Fm. Camboriu, respectively [28].

Table 5.2.1 - 1-BRSA-369A-RJS operators and contract information [28].

Event	Description
Country	Brazil
State	Rio de Janeiro
Operation	Offshore
Block	BM-S-11
Operator	Petrobras
Operator's well name	1-RJS-628A
Identification synonym	Tupi
ANP's well name	1-BRSA-369A-RJS
ANP's registration code	74316021508
Well type	Pioneer/ Vertical
Coordination	Latitude: 25:28:54.200 S, Longitude: 42:49:37.669 W
Datum	SAD – 69

Table 5.2.2 - 1-BRSA-369A-RJS operations and drilling activity information [28].

Event	Description
Spud date	1/10/2005
End drilling date	13/08/2006
End Well operations	12/10/2006
Final depth	5,957.0 m
Rotary table	25.0 m
Water depth	2,126.0 m
Contract number	48610.003886/2000
Rig's operator	Noble Drilling
Rig's code	SS-53
Rig's unit	Paul Wolf

The Figure 5.2.1 highlights the Block BM-S-11 by which the referred prospect well is located.

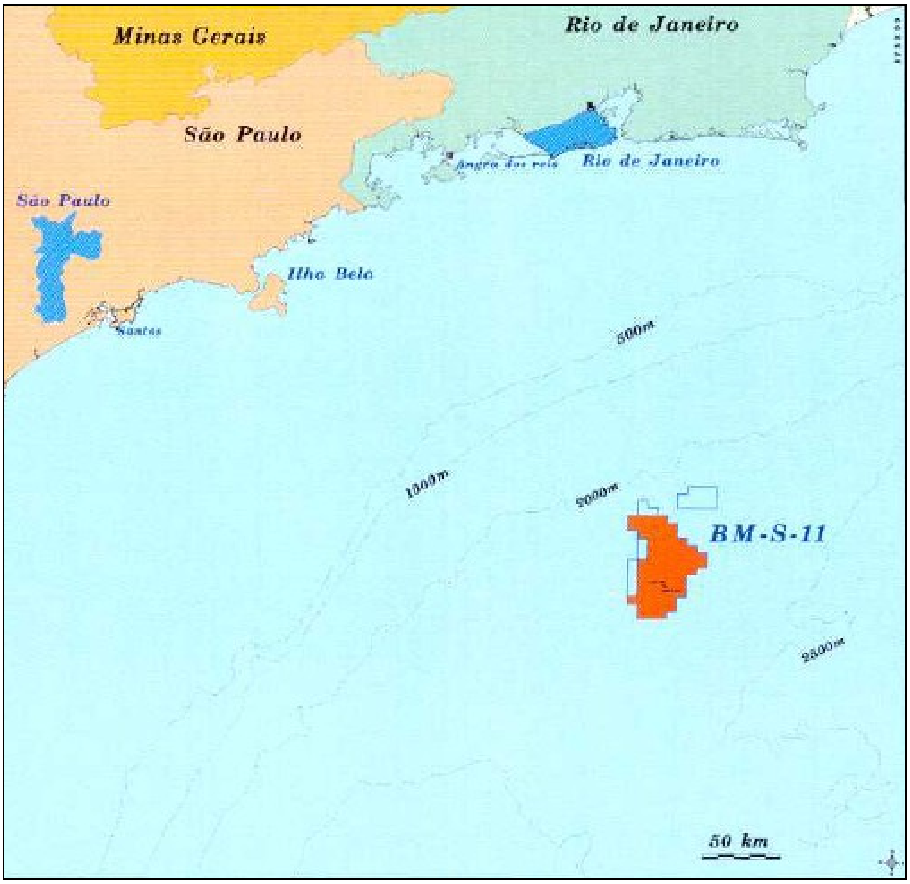


Figure 5.2.1 - Map of Block BM-S-11 location [28].

Furthermore, Table 5.2.3 provides information regarding to predicted and measured stratigraphic layers depth.

Table 5.2.3 - 1-BRSA-369A-RJS predicted versus measured stratigraphic layers depth [28].

Stratigraphic	Predicted depth (m)	True depth (m)
Fm. Marambaia	2,165.0	2,159.0
Fm. Itajaí-açu	2,515.0	2,447.0
Fm. Itanhaém/ Fm Guarujá	2,869.0	2,867.0
Fm. Ariri	3,009.0	3,005.0
Fm. Guaratiba	4,965.0	4,949.0
Fm. Camboriú	5,225.0	5,448.0

Table 5.2.4 - 1-BRSA-369A-RJS well section description [28].

Section	Bit size (in.)	Casing OD (in.)	MD (m)	Mud type	EMW (ppg)
I	36	30	2,214.0	Conventional	8.7
II	26	20	3,117.0	Conventional	10.5
III	17 ½	14	4,900.0	Synthetic Oil Based Mud (SOBM)	11.6
IV	12 ¼	10 ¾	5,130.0	SOBM type Petrobras BR-MUL	10.9
V	8 ½	-	5,957.0	-	11.0

5.2.2 Drilling performance

Table 5.2.5 provides information about the well operations performance according to the productive, unproductive and as well lost time. From these, further analyses are developed, estimating the ROP for each section.

Table 5.2.5 - 1-BRSA-369A-RJS well operation performance [28].

Sections	Drilling time (hours)				Depth (m)	
	Productive	Unproductive	Lost	Total	TVD	MD
I	3.0	12.0	0	15.0	2,214.0	2,214.0
II	67.5	48.5	41.5	157.5	3,117.0	3,117.0
III	389.5	209.5	3.5	602.5	4,900.0	4,900.0
IV	174.0	176.5	114.5	465.0	5,130.0	5,130.0
V	397.0	139.5	45.5	582.0	5,957.0	5,957.0
Total	1,031.0	586.0	205.0	1,822.0	-	-

By Figure 5.2.2 can be seen a graphical representation of the productive, unproductive and lost time related to each drilled section during this exploration. Due to limitation of WOB, RPM and ROP average tracked over the operation, the ROP are calculated taking into account the productive time of the drilling operations per each section, considering a water depth of 2,126.0 m, resulting in an overall ROP of approximately 3.7 m/hr (Figure 5.2.3).

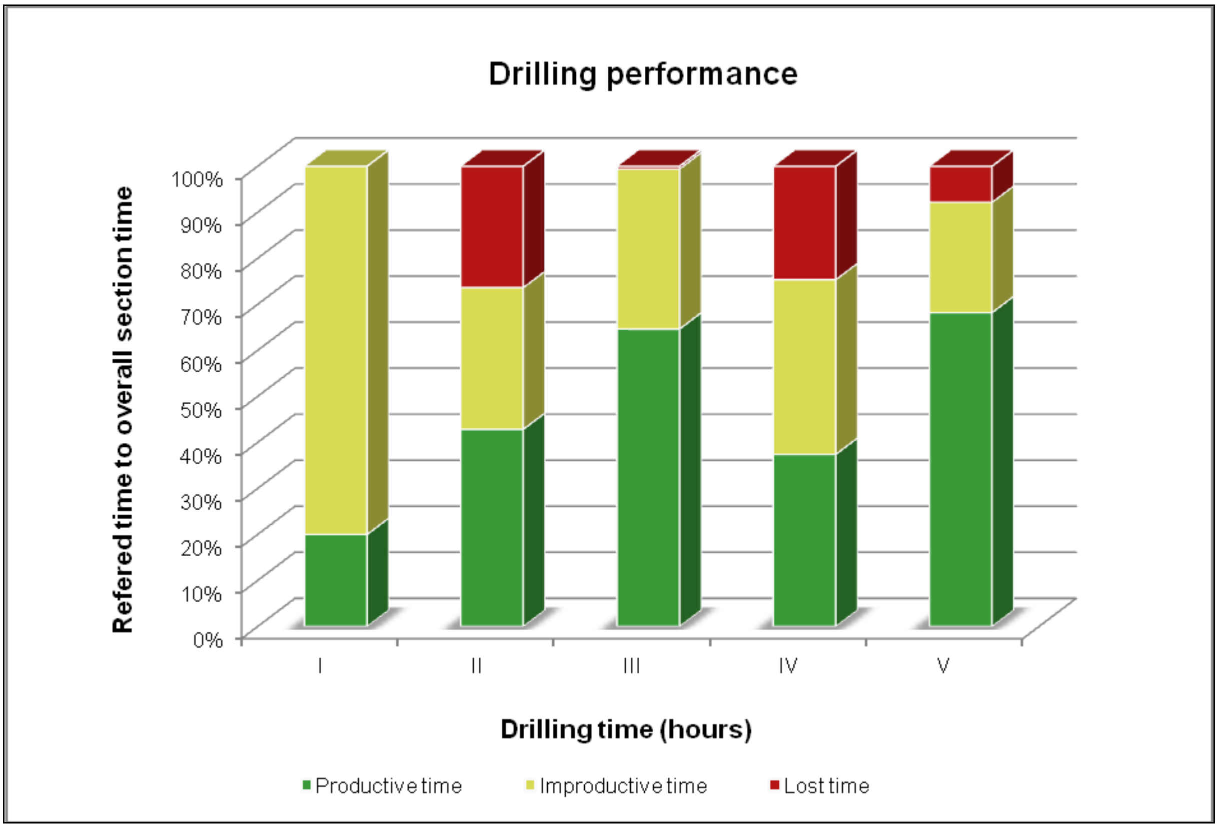


Figure 5.2.2 - 1-BRSA-369A-RJS drilling performance over well operations [28].

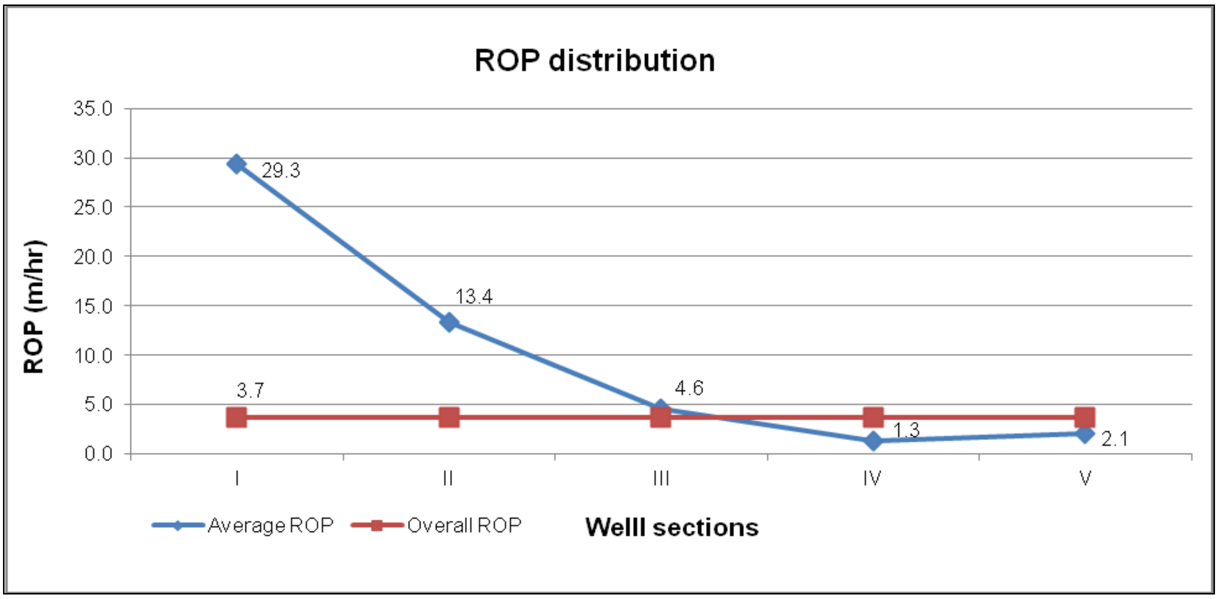


Figure 5.2.3 - 1-BRSA-369A-RJS ROP distributions over well operations [28].

5.2.3 Well-log analysis

From the well-logs, basically from formation gamma-ray and sonic wave transit time response, rock mechanics properties are estimated, taking into account all the equations and assumption previously discussed in Chapter four. Also for all further analysis, taken into account are portions representing by the logs which specifically refers to the pre-salt carbonates (Fm. Guaratiba). For the well 1-BRSA-369A-RJS, the carbonates are mostly present over the section IV, from 4,900.0 m to 5,130.0 m TVD (Tables 5.2.3 and 5.2.5). And for the reported logs, for this section, the data shows some not normal response between 4,987.0 m and 5,028.0 m TVD. Figure 5.2.5 highlights the natural detection of gamma-ray and the formation bulk density over the TVD.

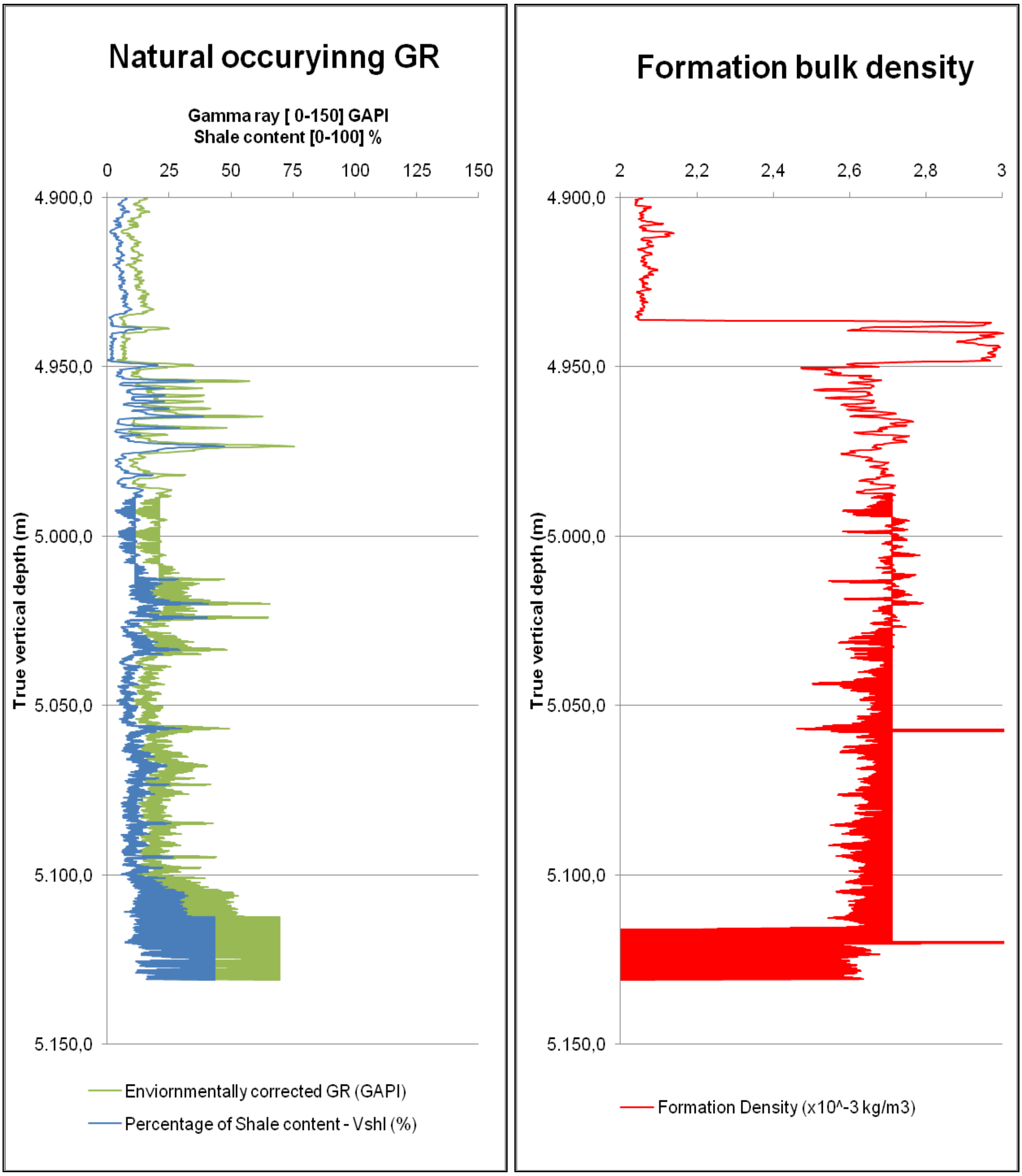


Figure 5.2.5 - 1-BRSA-369A-RJS section IV natural occurring gamma-ray (left) and formation bulk density (right) [28].

Figure 5.2.6 (left) shows the detected sonic wave transit time for the referred layers, which are further used for the rock mechanics properties estimation, shown by Figure 5.2.6 (right).

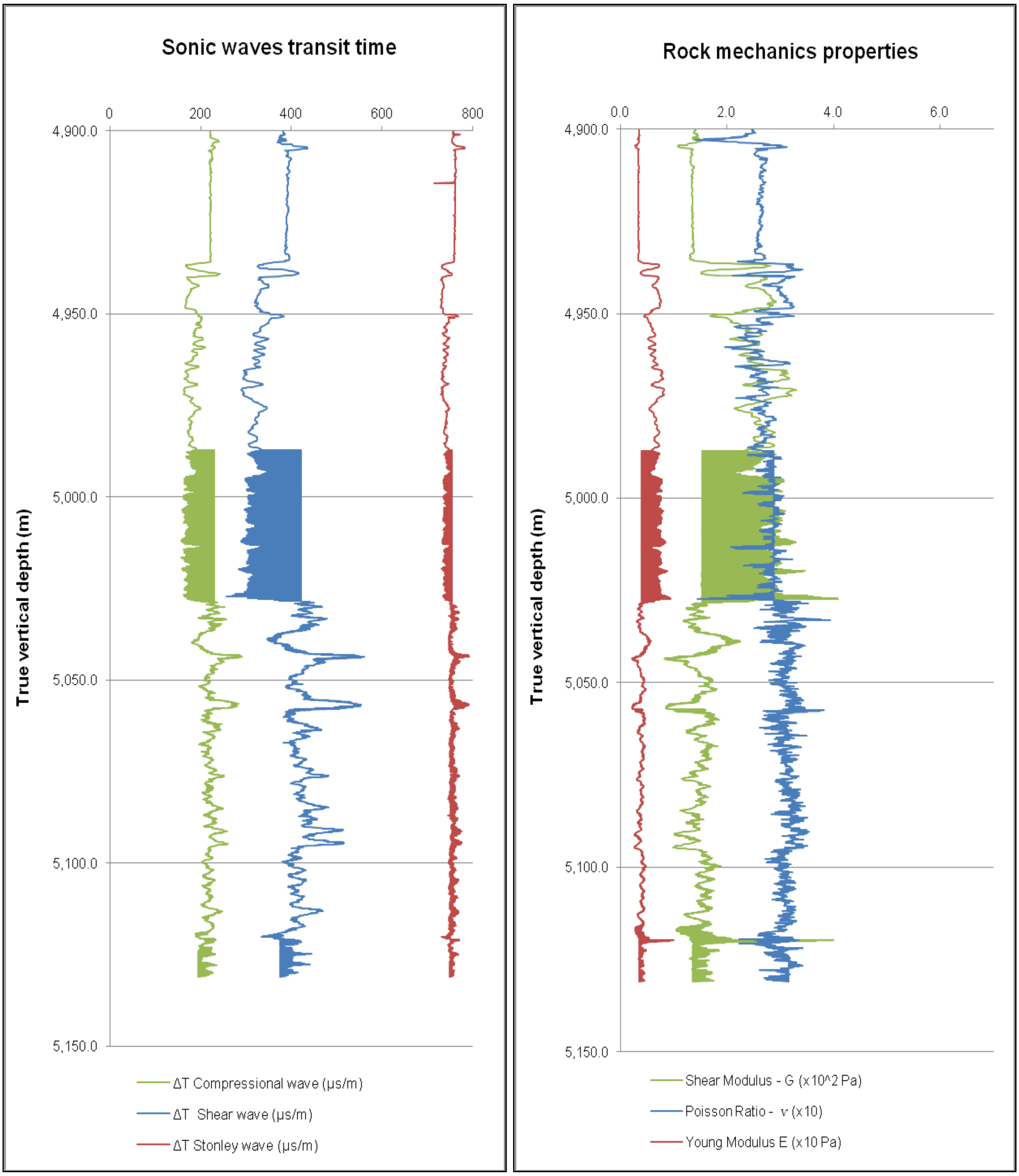


Figure 5.2.6 - 1-BRSA-369A-RJS section IV sonic wave transit time (left) and rock mechanics properties estimation (right) [28].

For the final determination of the minimum acceptable MW to be used for this section, in order to avoid kick and as well wellbore collapse, the vertical and horizontal stress and the in-situ pore pressure are determined, by calculations done throughout approximation and empirically equations, and by extrapolating the static fluid pressure data reported by the formation fluid pressure test, respectively. Figure 5.2.7 shows the pore pressure data points and the extrapolated curve developed after applying the power-law approximation, driven the Equation 5.2.1. The pressure is determined to be 11.62 kPa, over the carbonate section.

$$P_o = 7.5(10^{-})TVD^{1.046} \tag{5.2.1}$$

Where:

P_o: pore pressure (MPa);

TVD: true vertical depth (m).

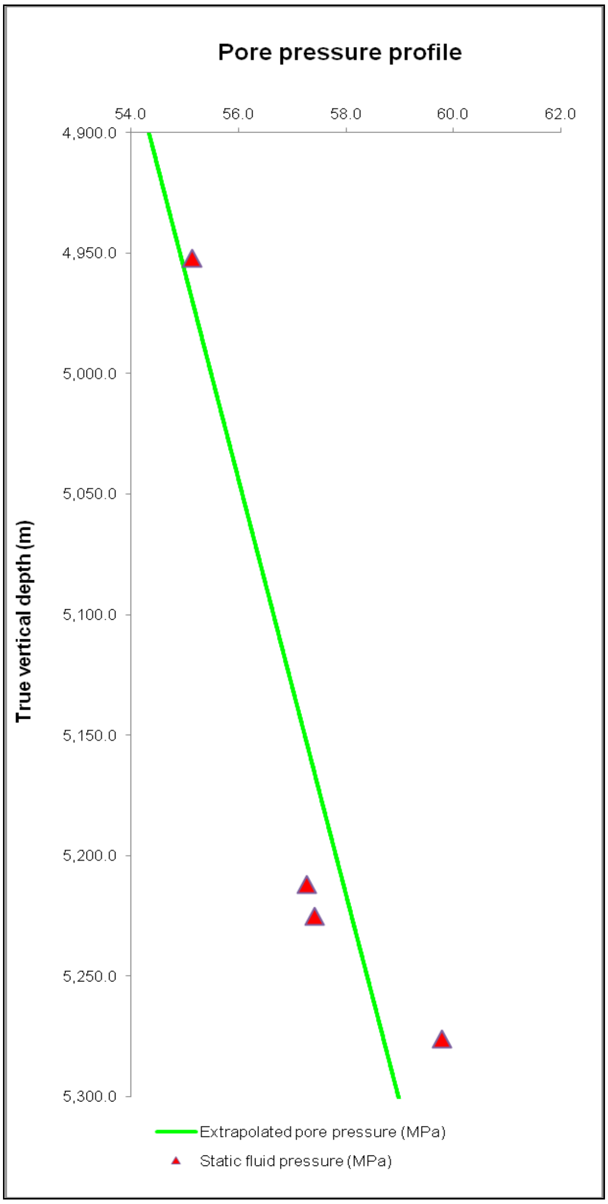


Figure 5.2.7 - 1-BRSA-369A-RJS section IV pore pressure estimation [28].

Figure 5.2.8 shows the minimum acceptable MW to be used in this section, in order to prevent kick and wellbore collapse, being, respectively 9.5 ppg and 18.0/23.0 ppg.

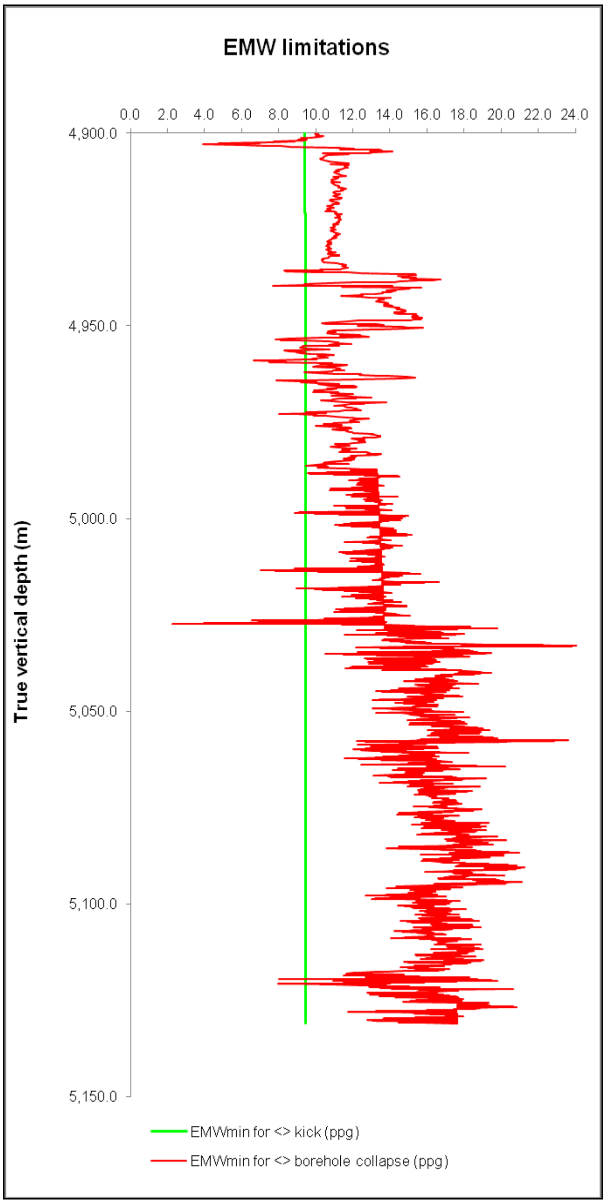


Figure 5.2.8 - 1-BRSA-369A-RJS section IV EMW limitations [28].

5.2.4 Summary

Since the boundaries of the analysis are the pre-salt carbonates, the layer studied concentrates itself into section IV, 12 ¼ in., and more specifically from TVD 4,900.0 to 5,130.0 m. For the activity run, it was reported a utilization of BR MUL/ synthetic mud with an EMW of about 10.9 ppg. The minimum acceptable MW values are 9.5 ppg and 18.0/23.0 ppg, for kick and wellbore collapse prevention, respectively.

5.3 Well 1-BRSA-491-SPS

On this subchapter, general information, drilling performance graphs and a cross-study about the estimated and calculated properties of the Carioca prospect are described.

5.3.1 General information

The well 1-BRSA-491-SPS is located in the Block BM-S-09, on the state of São Paulo, in the Santos basin (Table 5.3.1). This exploratory activity was conducted in the Carioca prospect, having as spud date 04th April 2007, ending up on 15th September 2007, almost 5.5 months of operation (164 days), in a water depth of about 2,135.0 m. The final depth achieved was 5,718.0 m (Table 5.3.2) and the main goal of this exploratory well had been to achieve the carbonates of the Fm. Guaratiba.

Table 5.3.1 - 1-BRSA-491-SPS operators and contract information [28].

Event	Description
Country	Brazil
State	São Paulo
Operation	Offshore
Block	BM-S-09
Operator/ Consortium	Petrobras BG e Repsol YPF
Operator's well name	1-SPS-50
Identification synonym	Carioca
ANP's well name	1-BRSA-491-SPS
ANP's registration code	86316022285
Well type	Pioneer/ Vertical
Coordination	Latitude: 25:34: 47.17 S, Longitude: 43:30:24.47 W
Datum	SAD-69

Table 5.3.2 - 1-BRSA-491-SPS operation and drilling activity information [28].

Event	Description
Spud date	04/04/2007
End drilling date	18/07/2007
End Well operation	15/09/2007
Final depth	5,718.0 m
Rotary table	18.0 m
Water depth	2,135.0 m
Contract number	48610.003884/2000
Rig's operator	Brasdrill
Rig's code	NS-21
Rig's unit	Ocean Clipper

Figure 5.3.1 highlights the prospect well and it's respectively Block location regarding the Rio de Janeiro coast.

Figure 5.3.1 - Map of 1-BRSA-491-SPS location [28].

Furthermore, Table 5.3.3 provides information regarding to predicted and measured stratigraphic depth.

Table 5.3.3 - 1-BRSA-491-SPS predicted versus measured stratigraphic layers depth [28].

Stratigraphic	Predicted depth (m)	True Depth (m)
Fm. Marambaia	2,158.00	2,153.00
Fm. Itajaí-açu	2,713.00	2,732.00
Fm. Itajaí-açu / Mb. Ilha Bela	-	2,751.00
Fm. Itajaí-açu	-	2,787.00
Fm. Ariri	2,870.00	2,877.00
Fm. Guaratiba	5,268.00	5,207.00

Table 5.3.4 provides information about the well section description.

Table 5.3.4 - 1-BRSA-491-SPS well section description [28].

Section	**Bit size (in.)**	**Casing OD (in.)**	**MD (m)**	**Mud type**	**EMW (ppg)**
I	36	30	2,215.0	Conventional	8.8
II	26	20	2,905.0	Conventional/ SOBM/ Water based mud (WBM) type Petrobras STA	11.0
III	17 ½	13 ⅝	5,203.0	Paraffin / SOBM	11.0
IV	12 ¼	9 ⅝	5,718.0	SOBM	10.5

5.3.2 Drilling performance

Table 5.3.5 provides information about the well operations performance according to the productive, unproductive and as well lost time. From these, further analyses are developed estimating for each section, the ROP over the operations run.

Table 5.3.5 - 1-BRSA-491-SPS well operation performance [28].

Well sections	**Drilling time (hours)**				**Depth (m)**	
	Productive	**Unproductive**	**Lost**	**Total**	**TVD**	**MD**
I	3.0	51.0	0	54.0	2,215.0	2,215.0
II	60.5	233.5	183.5	477.5	2,905.0	2,905.0
III	524.5	385.0	112.5	1,022.0	5,203.0	5,203.0
IV	564.5	371.0	18.0	953.5	5,717.7	5,718.0
Total	1,152.5	1,040.5	314.0	2,507.0	-	-

By Figure 5.3.2 can be seen a graphical representation of the productive, unproductive and lost time related to each drilled section. Since there are some limitations regarding the data provided by the exploratory reports, such as WOB, RPM and exactly ROP, an estimation of the ROP has been calculated taking into account the productive time of the drilling operations spent per section, resulting with an overall ROP of approximately 3.1 m/hr (Figure 5.3.3).

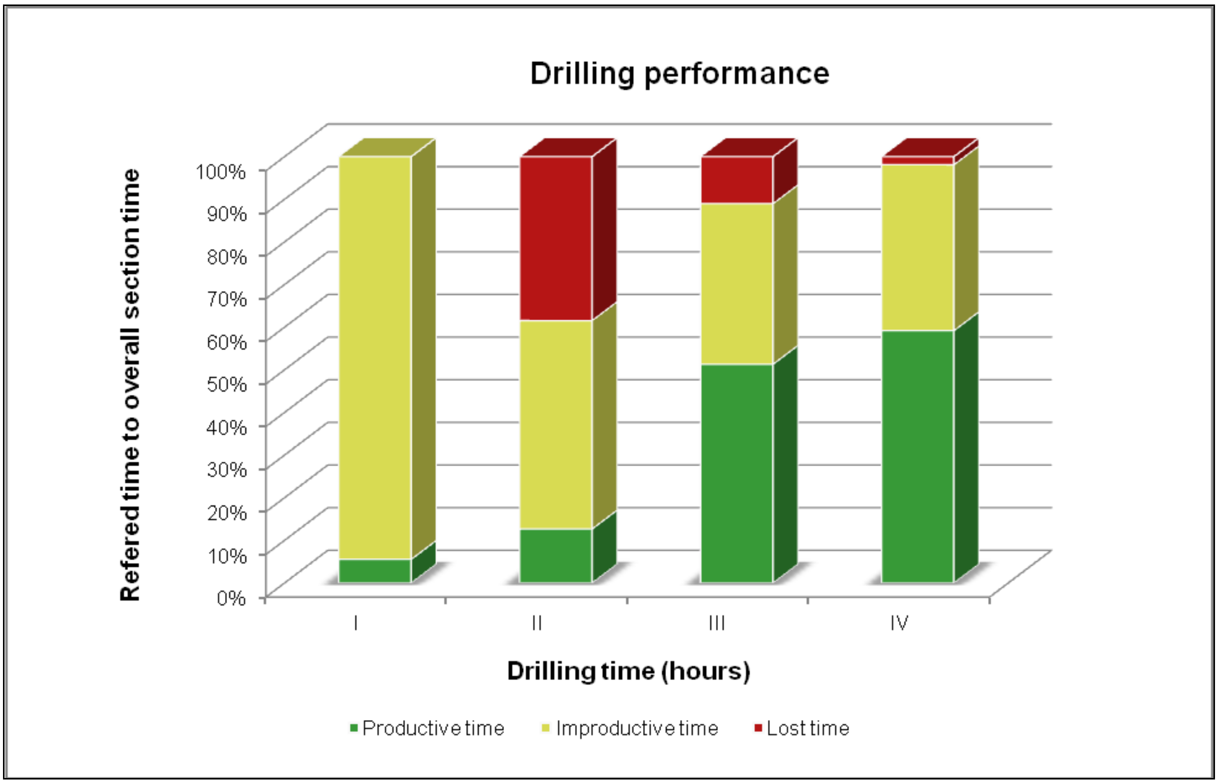


Figure 5.3.2 - 1-BRSA-491-SPS drilling performance over well operations [28].

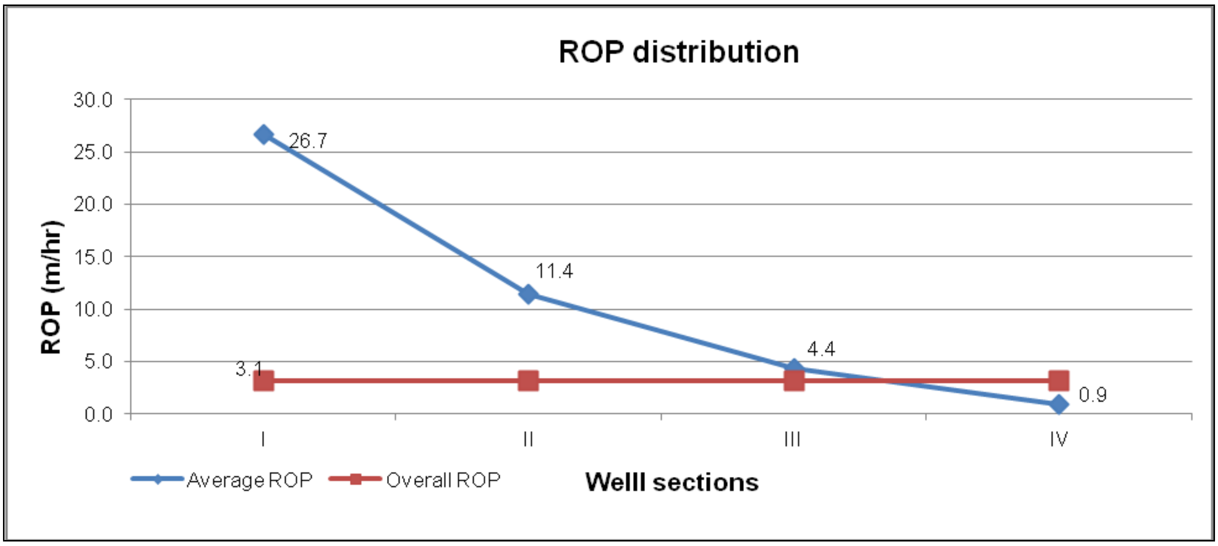


Figure 5.3.3 - 1-BRSA-491-SPS ROP distribution over well operation [28].

5.3.3 Well-log analysis

From the well-logs, basically from formation gamma-ray and sonic wave transit time response, rock mechanics properties are estimated, taking into account all the equations and assumption previously discussed in Chapter four. Also for all further analysis, taken into account are portions of the logs by which the pre-salt carbonates Fm. Guaratiba are referred. For the well 1-BRSA-491-SPS, the carbonates are mostly present over the section IV, from 5,203.0 m to 5,718.0 m TVD (Tables 5.3.3 and 5.3.5).

Thus, Figure 5.3.5 highlights the natural detection of gamma-ray and the formation bulk density over the TVD, respectively.

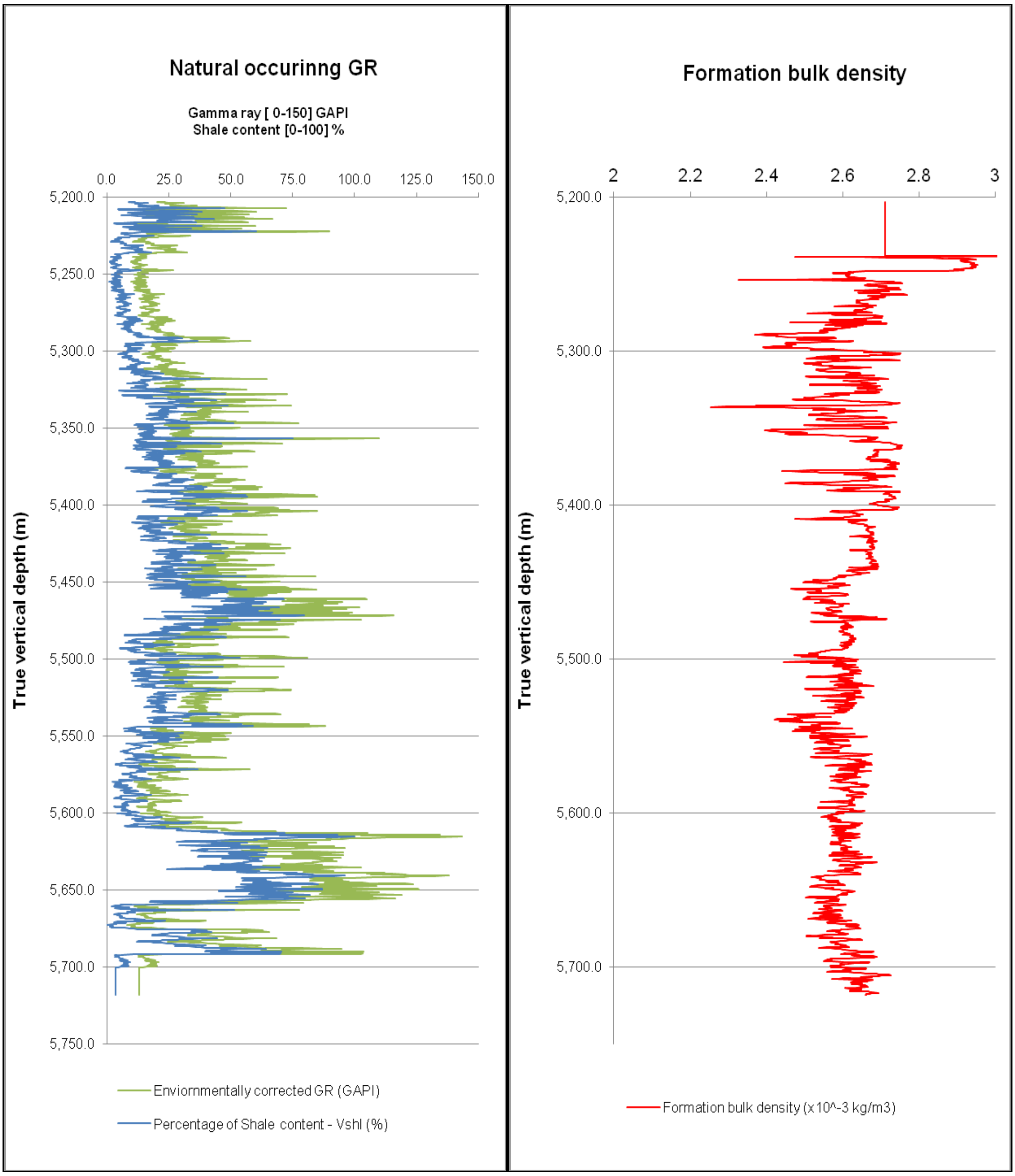


Figure 5.3.5 - 1-BRSA-491-SPS section IV natural occurring gamma-ray (left) and formation bulk density (right) [28].

Figure 5.2.6 (left) shows the detected sonic wave transit time for the referred layers, which are further used for the rock mechanics properties estimation, shown by Figure 5.2.6 (right).

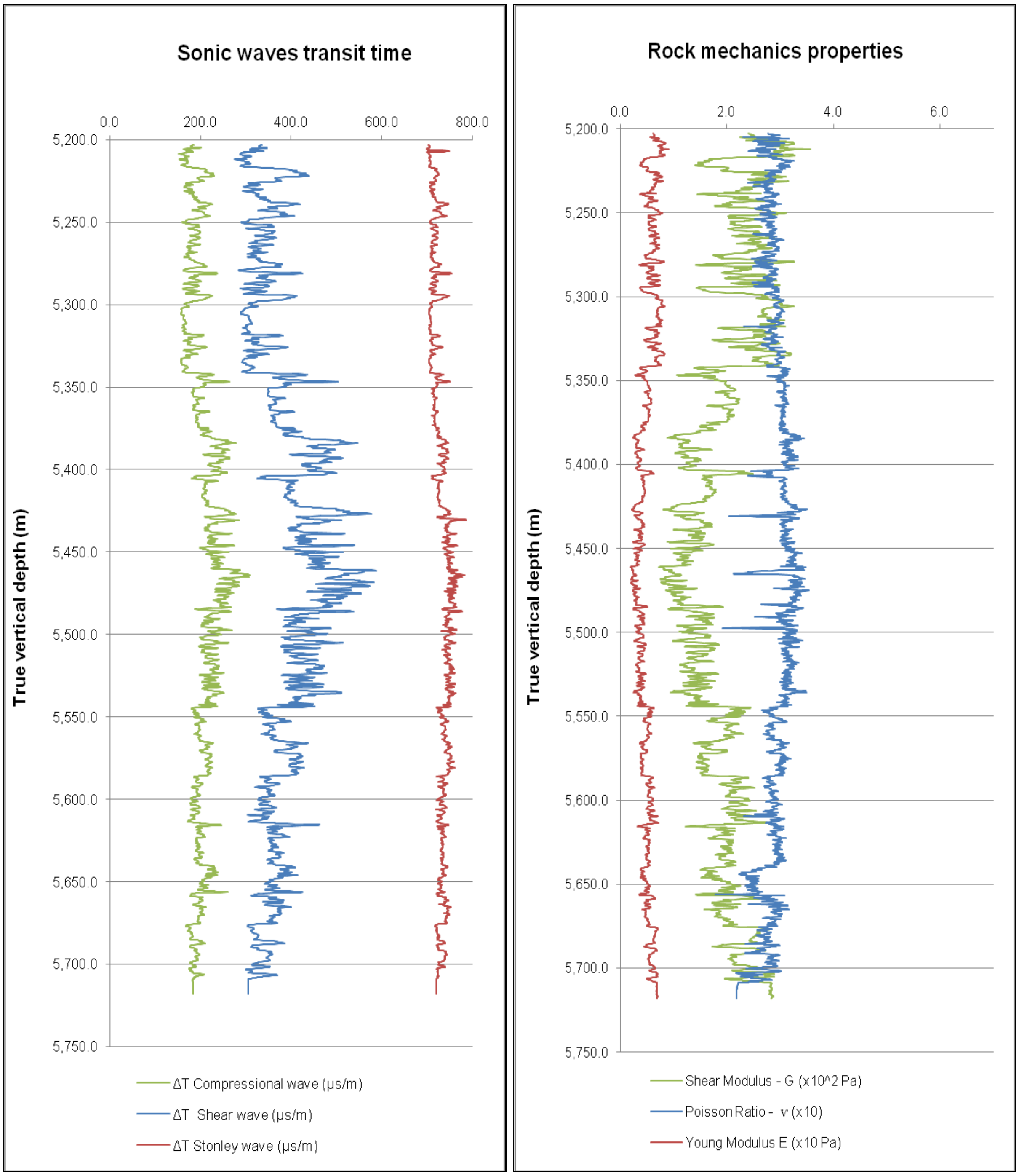


Figure 5.3.6 - 1-BRSA-491-SPS section IV sonic wave transit time (left) and rock mechanics properties estimation (right) [28].

For the final determination of the minimum acceptable MW to be used for this section, in order to avoid kick and as well wellbore collapse, the vertical stress, horizontal stresses and the in-situ pore pressure were determined, by calculation throughout empirically equations and approximations, and by extrapolating the static fluid pressure data reported by the formation fluid pressure test, respectively.

Figure 5.3.7 shows the pore pressure data points and the extrapolated curve developed after applying the power-law approximation, driven the Equation 5.3.1, and after applying the intervals to it, the pressure is determined as 0.99 kPa.

$$P_o = 2.6(10^{-}\ )TVD^{0.9003} \qquad (5.3.1)$$

Where:

P_o: pore pressure (MPa);

TVD: true vertical depth (m).

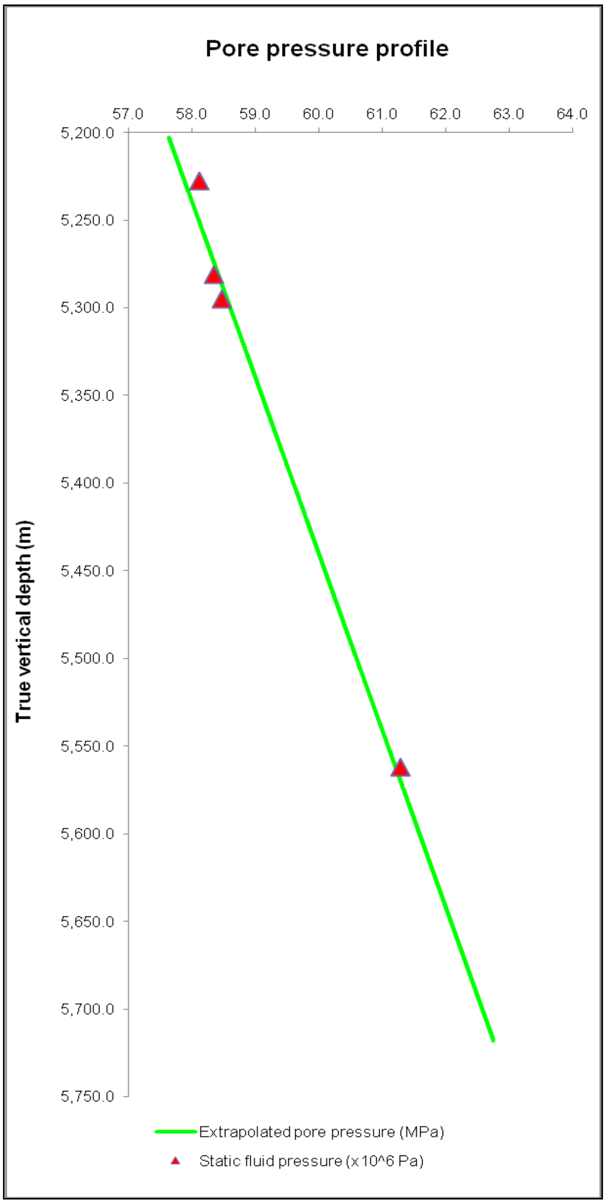


Figure 5.3.7 - 1-BRSA-491-SPS section IV pore pressure estimation [28].

Figure 5.3.8 shows the minimum acceptable MW to be used for this section, in order to prevent kick and wellbore collapse, being them respectively, 9.4 ppg and 13.8 ppg.

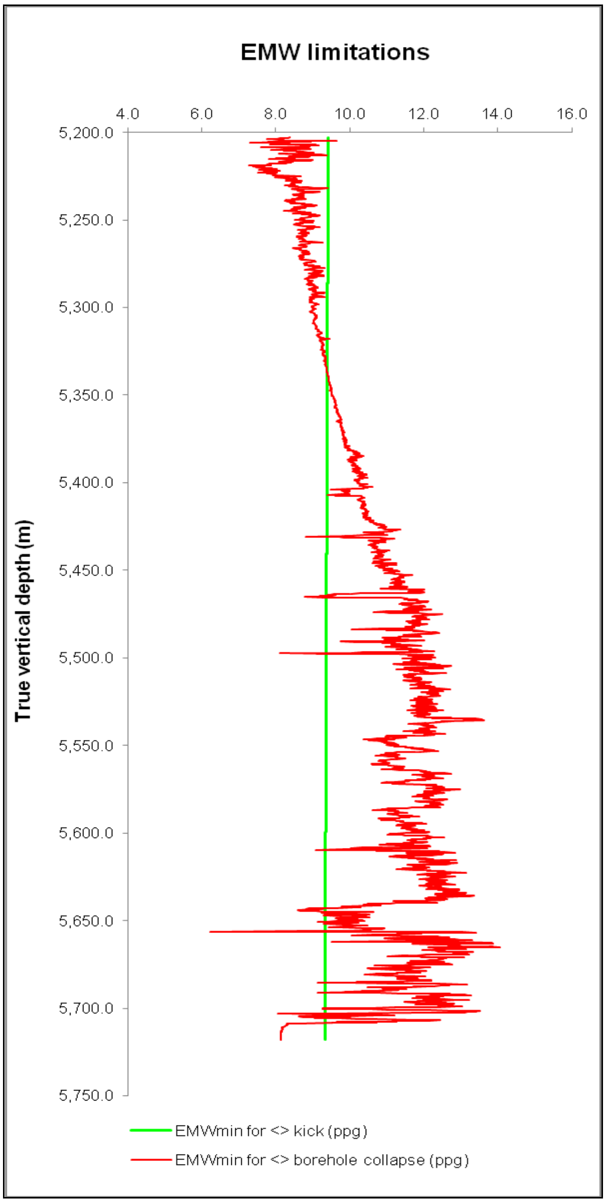


Figure 5.3.8 - 1-BRSA-491-SPS section IV EMW limitations [28].

5.3.4 Summary

Since the boundaries of the analysis are the pre-salt carbonates, the layer studied concentrates itself into section IV, 12 ¼ in., and more specifically from TVD 5,203.0 m 5,718.0 m. For the activity run, it was reported a utilization of Synthetic mud with an EMW of about 10.5 ppg. For prevention of kick and wellbore collapse, the minimum acceptable MW is 9.4 ppg and 13.8 ppg, respectively.

5.4 Simulation: drilling model determination and analysis

As described in Chapter four, a Microsoft Excel 2007 add-in Oracle Crystal Ball version 11.1 was is for the development of all simulations. Important to highlight is the fact that the drilling model in use has been developed according to field oil industry units. For this reason, also for this Chapter English unit system, oil field system, may be present in order to guarantee accuracy for the results [33].

As from the Equation 3.3.1, many variables have to be taken into account to build up the drilling model. But, since some of them are unknown, as already covered in previously Chapters, stochastic values, being precisely governed by an acceptable and right behavior probabilistic model, can be used. These values are generated randomly, accomplishing to final value which a degree of certainty to occur.

From many experienced field values of real operations, an acceptable range for the unknown variables can be determined, in order to apply the Monte Carlo simulation to a minimum acceptable interval that approaches more closely how weighty these values can be.

Table 5.4.1 shows the unknown variables and distribution model, followed by the ranges and likeliest values.

Table 5.4.1 - Unknown variables acceptable range.

Variable	Model	Maximum	Minimum	likeliest
WOB (Klbf)	Triangular	50.0	10.0	40.0
N (rpm)	Triangular	250.0	60.0	100.0
h (1)	Uniform	1.0	0.2	-
F_j (lbf)	Triangular	1,200.0	600.0	1,000.0

For the results, 10,000 trials and respective 1,000 simulation was performed, by which the values shown in Table 5.4.1 was defined as stochastic variables, and the coefficients from, as continuous and decision variables, as per Table 5.4.2. Note that for final results shown, f_7' has been considered to be 1 (one), so that h values have no effect on ROP, for the carbonate section in the Brazilian pre-salt regions, the usage of PDC bits are being common [20].

Figures 5.4.1, 5.4.2, 5.4.3 and 5.4.4 show the stochastic distribution for the unknown variables. Table 5.4.2 shows the range for the deterministic variables, from within which the drilling model coefficients are determined; for each specific well, the coefficients determination is mandatory in order to let the drilling model properly govern a ROP response for a specific scenario.

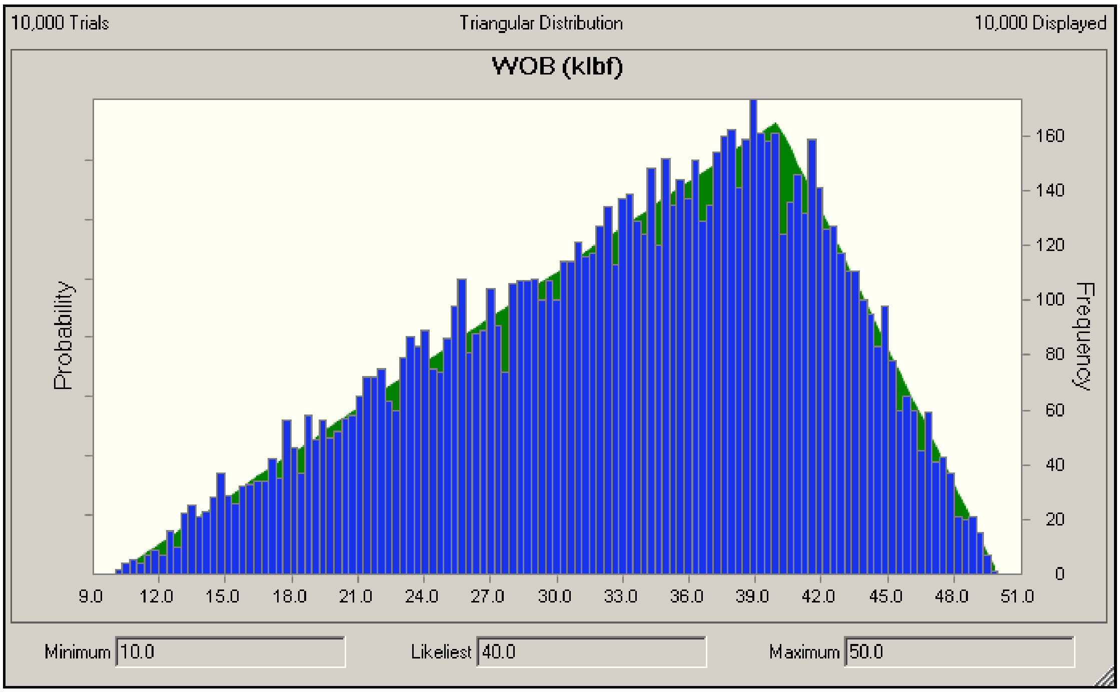


Figure 5.4.1 - Stochastic generated values for WOB [33].

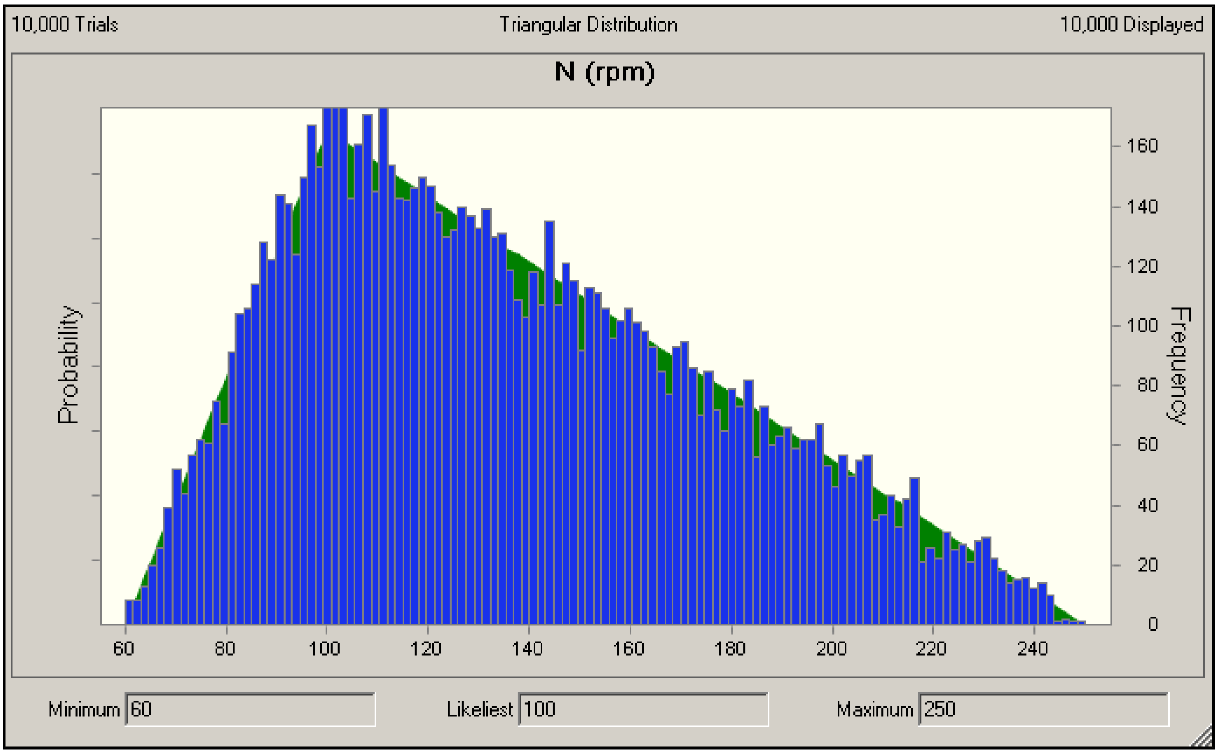
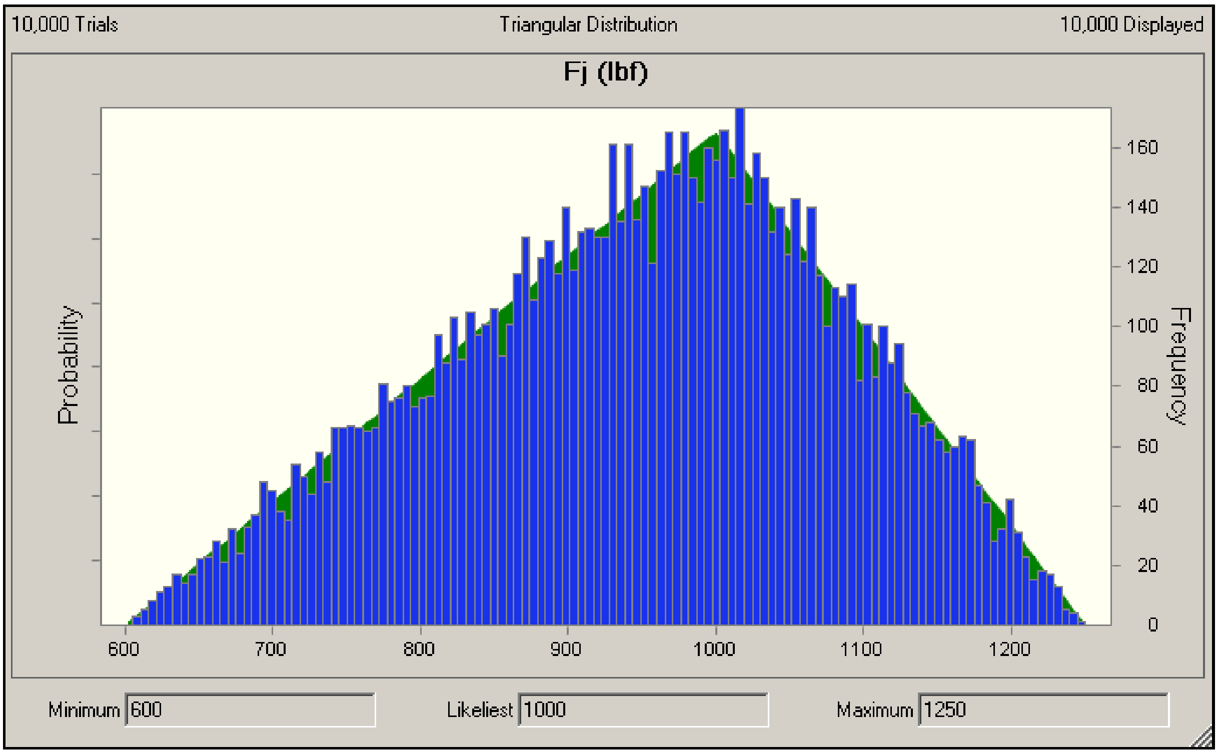


Figure 5.4.2 - Stochastic generated values for N [33].

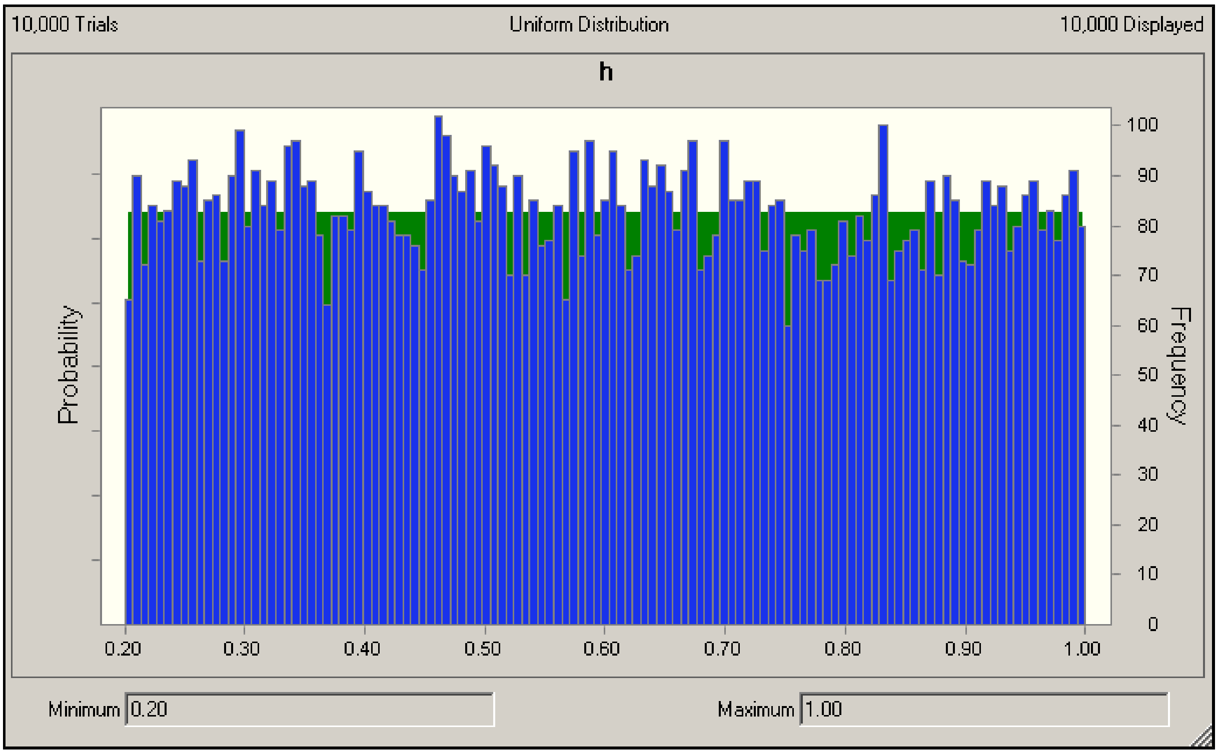


Minimum 600

Likeliest 1000

Maximum 1250

Figure 5.4.3 - Stochastic generated values for Fj [33].



Minimum 0.20

Maximum 1.00

Figure 5.4.4 - E.g. of stochastic values would have been generated for h, if applicable for simulation [33].

Table 5.4.2 - Range limits for drilling model coefficients determination [20].

Coefficient	Lower limit	Upper limit
a_1	0	4.000000
a_2	0.000001	0.001000
a_3	0.000001	0.001000
a_4	0.000001	0.001000
a_5	0.500000	2.000000
a_6	0.000100	1.000000
a_7	0.300000	1.500000
a_8	0.300000	0.600000

As per Reservoir Engineering, many have been studied in order to determine how possible, probable and proven a reserve is for a certain basin or prospect. In the same way, throughout these studies, the variables used for further calculation, etc., has converged to some degree of certainty, further shown.

Per each well presented over this Chapter, a simulation has been developed, in order to account for a drilling model not just for a certain interval of a specific well, but for the Brazilian pre-salt carbonates, around the radius comprehending the respective wells.

Table 5.4.2 shows the necessary variables for drawing the particularities of each studied well. Also highlighted are the ROP values, differing from those presented previously, due to the accountability of time spent over the operation for connections. The range considered varies from 80 seconds up to 180 seconds per make-up connection. Even that, considerations such as time spent by changing driller or operator (normal procedure by following the rules of work schedule and work shift), what may take place if operations parameters may differ from those performed by the previous one. It leads for hidden unproductive time, wrongly enhancing the productive time if not correctly considered, what false reflects negatively in the calculations developed, since by taken them into account, the ROP final value is decreased. But, since the worst case may be these mentioned, without knowing or taking into account hidden unproductive time, them may do not really affect the results.

Table 5.4.3 - List of known variables for the Drilling model determination [28].

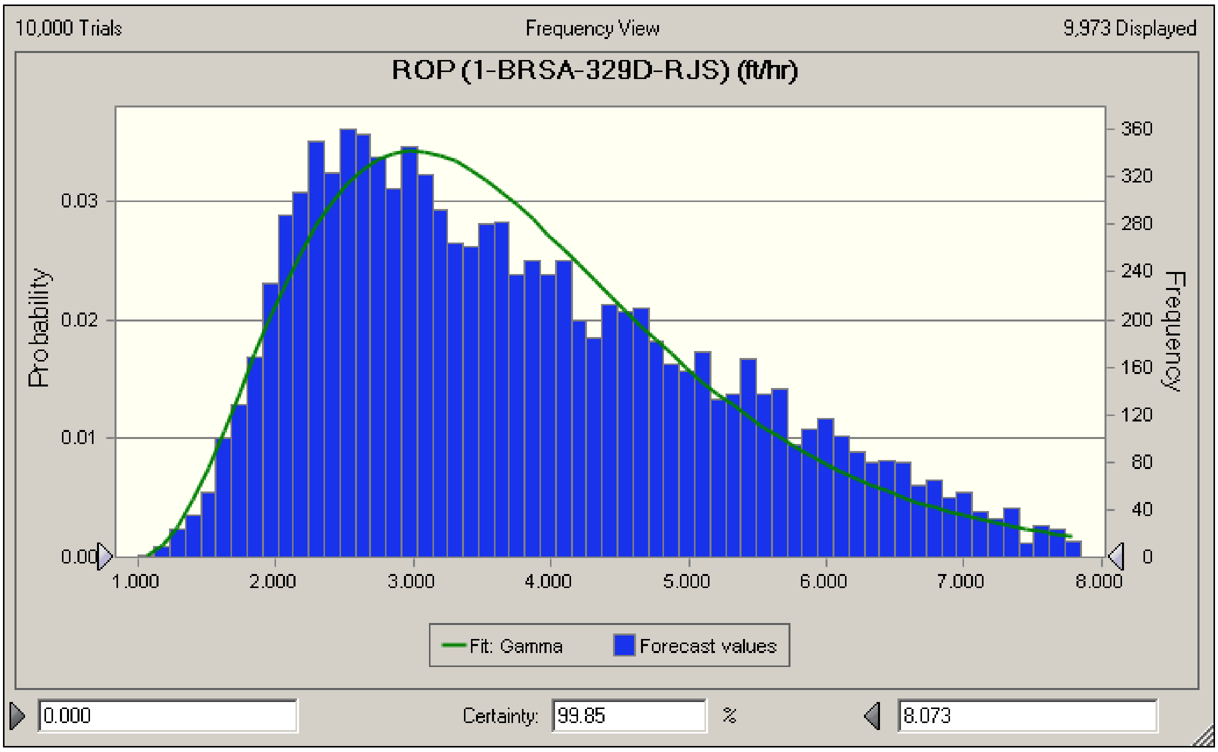
Variables/ Well	**1-BRSA-329D-RJS**	**1-RSA-369A-RJS**	**1-BRSA-491-SPS**
Section	VI	IV	IV
Section interval TVD Initial (m); Final (m)	5,815.0; 6,478.0	4,900.0; 5,130.0	5,203.0; 5,718.0
Productive time (h)	370.5	174,0	564.5
Average ROP range (m/hr);(ft/hr)	2.461; 8.073	1.323; 4.340	0.912; 2.995
Reported MW (ppg)	10.40 to 12.00	10.90	10.50
Min. estimated MW for section <> kick (ppg)	10.44 @ 6,478 m TDV	9.45 @ 5,130 m TDV	9.42 @ 5,718 m TDV
Min. estimated MW for section <> collapse (ppg)	15.20 @ 6,317 m TVD	18.00 to 23.00 @ 5,130 m TVD	13.80 @ 5,718 m TVD
Max. section pore pressure (ppg)	10.44	9.45	9.42
Bit size (in.)	8 ½	12 ¼	12 ¼

From Table 5.4.3, the coefficients shown in Table 5.4.4 are determined throughout a multi-regression mathematical calculation, also embedded in Crystal Ball, straight followed and linked to stochastic values generation by Monte Carlo, as previously shown and described.

Table 5.4.4 - Coefficient values of developed drilling model [33].

Coefficient	**1-BRSA-329D-RJS**	**1-BRSA-369A-RJS**	**1-BRSA-491-SPS**
a_1	3.899645	3.899439	3.900000
a_2	0.000001	0.000001	0.000001
a_3	0.000024	0.000075	0.000384
a_4	0.000051	0.000088	0.000128
a_5	0.500000	0.500000	0.539035
a_6	0.500000	0.000100	0.000151
a_7	1.493908	1.488238	1.500000
a_8	0.584997	0.597524	0.60000

The ROP response for each respective well can be seen in Figures 5.4.5, 5.4.6 and 5.4.7, which show to fit a Gamma distribution.



10,000 Trials

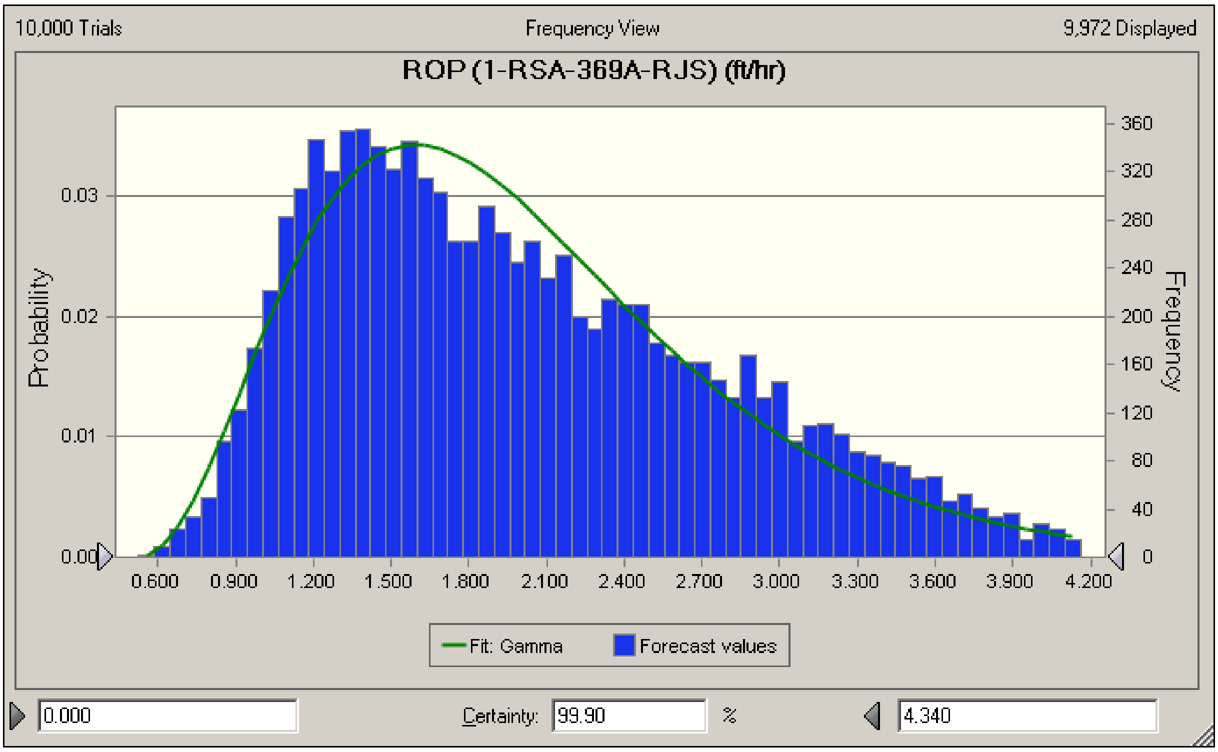
9,973 Displayed

0.000

Certainty: 99.85 %

8.073

Figure 5.4.5 - Well 1-BRSA-329D-RJS ROP response [33].



10,000 Trials

9,972 Displayed

0.000

Certainty: 99.90 %

4.340

Figure 5.4.6 - Well 1-BRSA-369A-RJS ROP response [33].

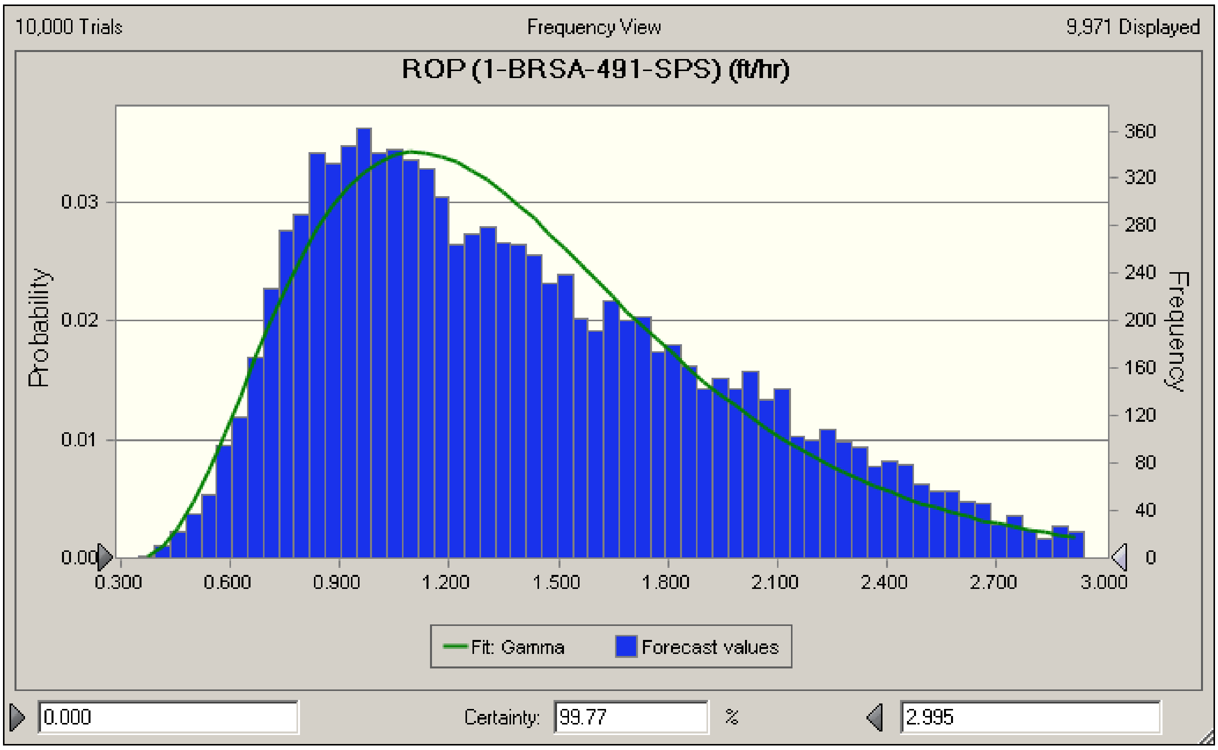


Figure 5.4.7 - Well 1-BRSA-491-SPS ROP response [33].

As per sequential analysis, the maximum and minimum range from the stochastic variables defined and given in Table 5.4.1 are used as discrete and unknown output variables for the Equation 3.3.1 properly filled up with the right coefficients (Table 5.4.4) and ROP (Table 5.4.3) for each respective well.

Table 5.4.5 – Max. and min. values for main unknown variables of drilling model [33].

Combination	Type	WOB (klbf)	N (rpm)	Fj (lbf)
1	- - -	10.0	60.0	600.0
2	- - +	10.0	60.0	1,200.0
3	- + -	10.0	250.0	600.0
4	- + +	10.0	250.0	1,200.0
5	+- -	50.0	60.0	600.0
6	+ - +	50.0	60.0	1,200.0
7	+ + -	50.0	250.0	600.0
8	+ + +	50.0	250.0	1,200.0

From the data presented in Table 5.4.5, a straight discrete analysis with Crystal Ball's algorithms is used in order to end up with some possible values for the unknown variables presented, determining how far the Equation 3.3.1, with them respective coefficients determined per each well in analysis, does represent a realistic scenarios, and may fit to each specific well operation. Some of these values can be seen on Table 5.4.6.

Table 5.4.6 - Defined values for Drilling model unknown variables for each analysed well [33].

	1-BRSA-329D-RJS			1-RSA-369A-RJS			1-BRSA-491-SPS		
	WOB (klbf)	N(rpm)	Fj (lbf)	WOB (klbf)	N(rpm)	Fj (lbf)	WOB (Klbf)	N(rpm)	Fj (lbf)
1	45,0	154.0	624.0	49.0	88.0	600.0	32.0	184.0	842.0
2	30,0	60.0	890.0	30.0	156.0	917.0	26.0	86.0	1,023.0
3	39,0	144.0	707.0	46.0	106.0	633.0	42.0	62.0	601.0
4	45,0	146.0	624.0	34.0	144.0	823.0	27.0	85.0	987.0
5	25,0	106.0	1,045.0	32.0	200.0	867.0	29.0	135.0	923.0

The Figures 5.4.8, 5.4.9, 5.4.10, 5.4.11, 5.4.12 and 5.4.13 represent the generated graphs after applying the values from Table 5.4.5 and Table 5.4.6, respectively for well 1-BRSA-329D-RJS, 1-RSA-369A-RJS and 1-BRSA-491-SPS. As can be seen and interpreted, the models developed do represent real behaviour and response to ROP regarding MW changes. All of them are focused to the mud window limitations, which in this thesis, is under-limited by the equivalent formation pore pressure and as well by the minimum necessary of pressure to withstand an eventual borehole wall collapse. But, as interpretation, can be observed how inapplicable it becomes to be as the MW increases nearly to the minimum acceptable one regarding to the withstanders of borehole collapse, since the ROP decreases too much, not representing an economically realistic operations run, due to very slow ROP. For the wells Parati, Tupi, and Carioca, and respectively limits of 15.2 ppg, 23.0 ppg and 13.8 ppg, the ROP is valuable as 0.24 ft/hr, and zero for the other two wells, Tupi and Carioca. For these, the ROP may start to draw zero in efficiency from approximately 18.8 ppg, 15.5 ppg and 13.7 ppg, respectively.

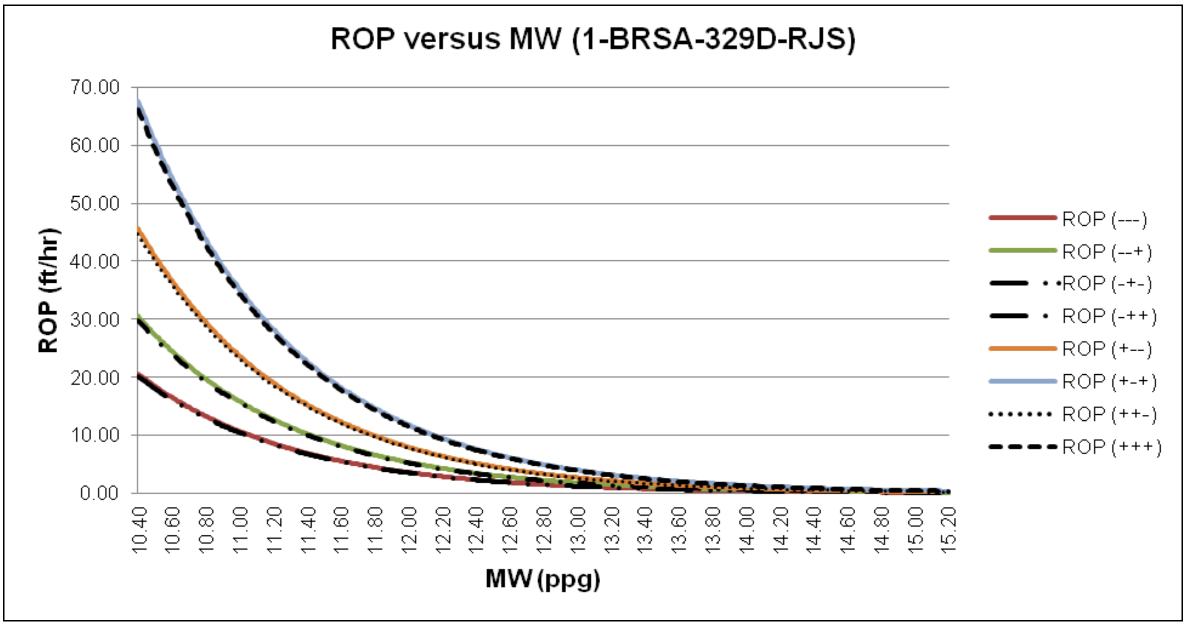


Figure 5.4.8 - Well 1-BRSA-329D-RJS ROP response due to WOB, Fj and N max. and min. variations.

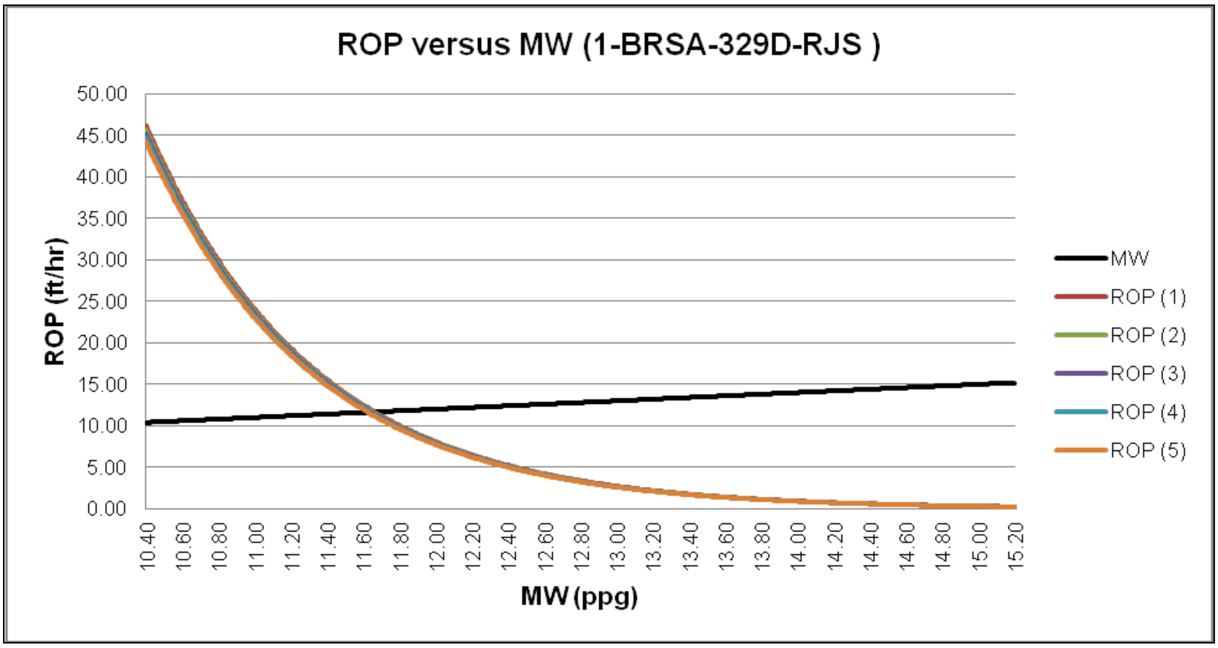


Figure 5.4.9 - Well 1-BRSA-329D-RJS Drilling model curve response regarding MW variations.

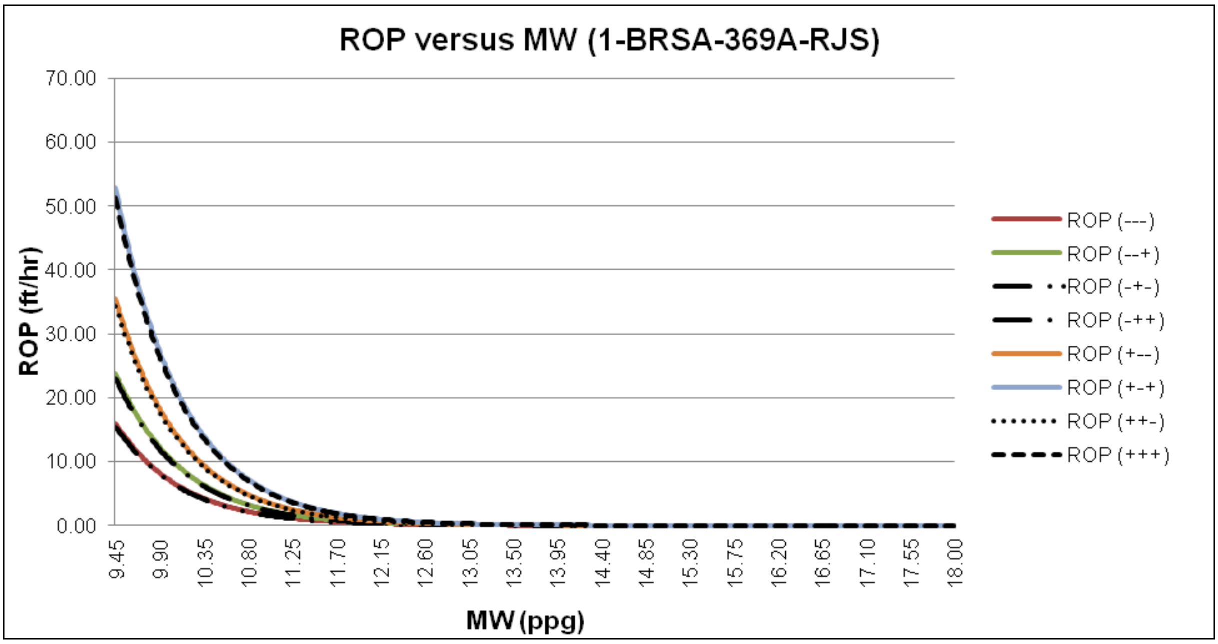


Figure 5.4.10 - Well 1-BRSA-369A-RJS ROP response due to WOB, Fj and N max. and min. variations.

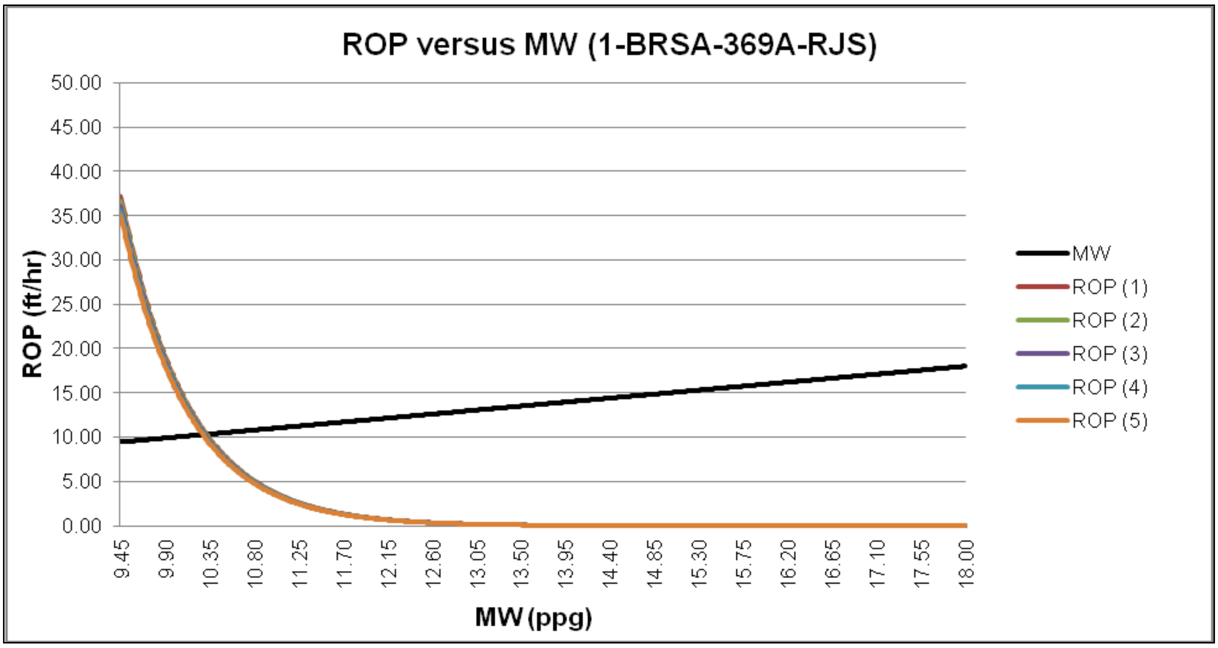


Figure 5.4.11 - Well 1-BRSA-369A-RJS Drilling model curve response regarding MW variations.

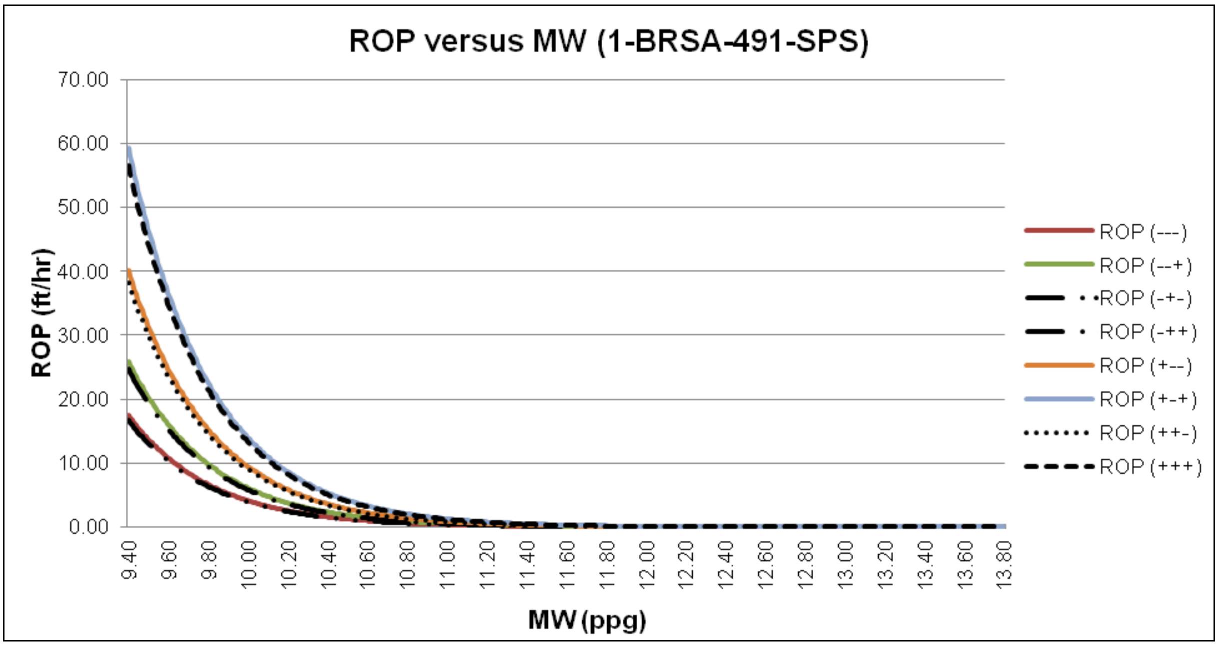


Figure 5.4.12 - Well 1-BRSA-491-SPS ROP versus MW response due to WOB, Fj and N max. and min. variations.

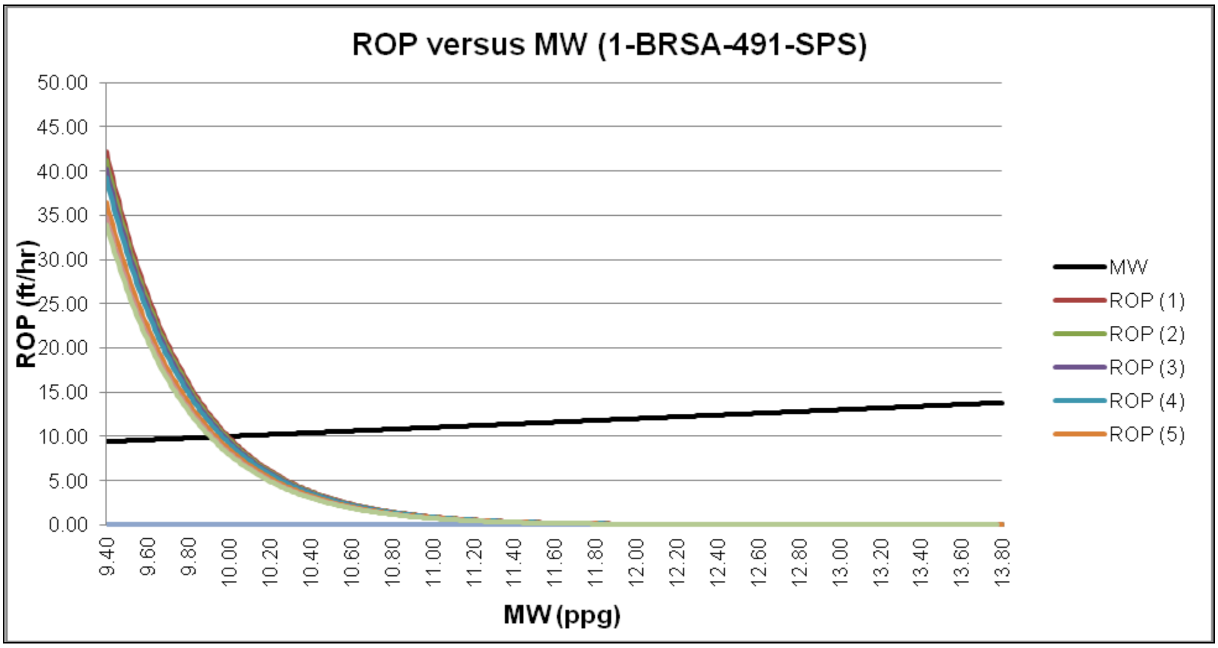


Figure 5.4.13 - Well 1-BRSA-491-SPS Drilling model curve response regarding MW variations.

As can be seen by the previously presented graphs, a decrease in MW directly reflects in a higher ROP, being very critical for drilling operations. The graphs represented by Figures 5.4.14, 5.4.15 and 5.4.16 show respectively the weighted percentage of ROP increase in regarding to MW decrease, ranging from the used one in the respectively operations until the minimum acceptable one concerning the equivalent pore pressure.

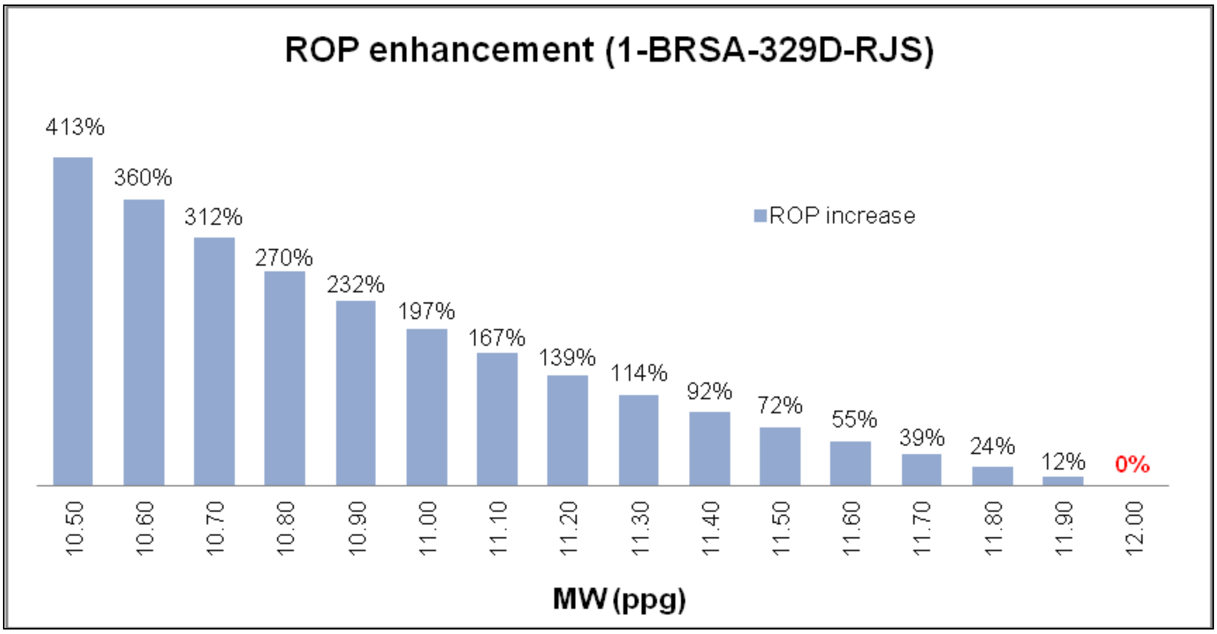


Figure 5.4.14 - Well 1-BRSA-329D-RJS ROP enhancement regarding to MW decrease.

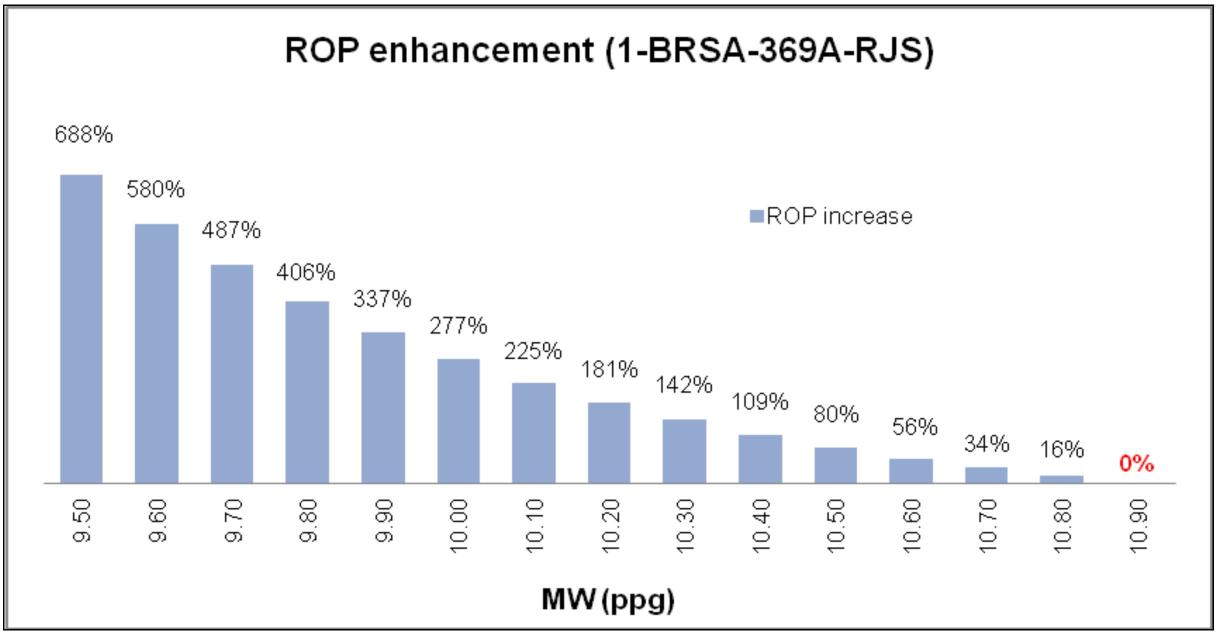


Figure 5.4.15 - Well 1-BRSA-369A-RJS ROP enhancement regarding to MW decrease.

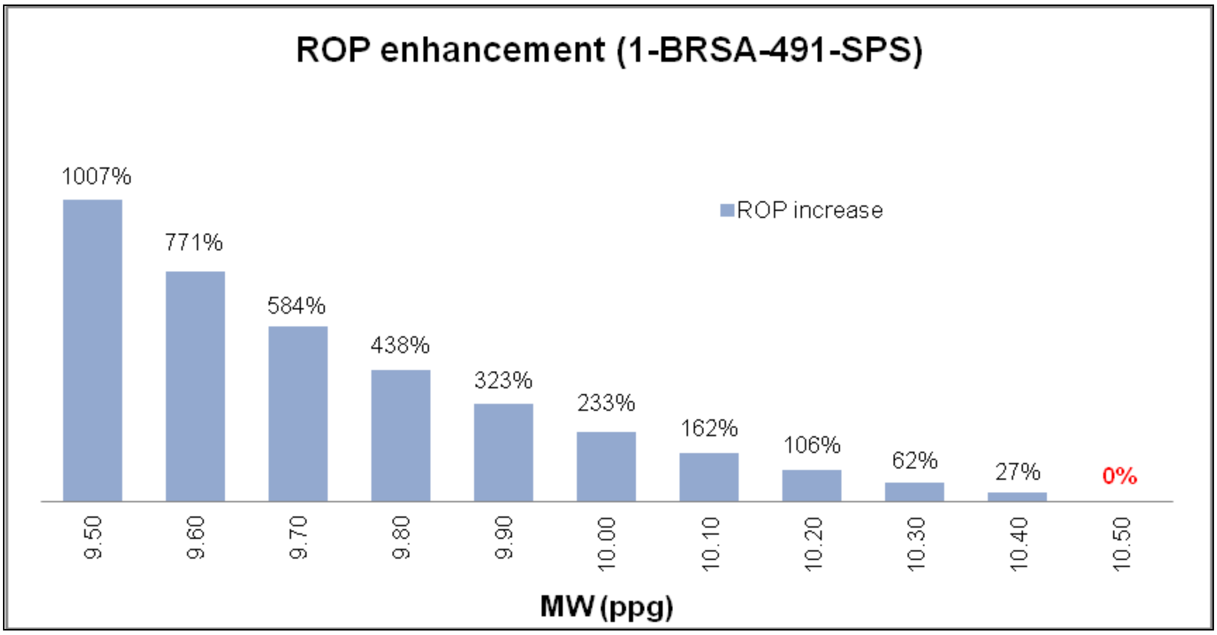


Figure 5.4.16 - Well 1-BRSA-491-SPS ROP enhancement regarding to MW decrease.

As can be observed in the privously graphs shown, a little decrease in MW does reflect positively in ROP enhancement. Just with one decimal decrease in MW, a gain of 12%, 16% and 27% respectively, for wells 1-BRSA-329D-RJS, 1-RSA-369A-RJS and 1-BRSA-491-SPS can be achieved.

How far the MW for the operations could be used in with a less dense final value, it is directly related in how far one does must respect the minimum acceptable limit of weighty mud for wellbore stability ensuranse. Since the operation are run in ultra-deep water and in a considerable deep location in its totalitty, just the overburden pressure might guratantee a stability by itself, due to the compaction of the in-situ formation. From this, for the three wells presented, the operations could be run with a lighter mud. For a safe operation, from the pore pressure, the MW should have a safety margin of about 3%, representing that as per Table 5.4.7, the operations were run with a margin of 14.83%, 14.74% and 11.46% greater than necessary, instead of just 3%, as mentioned. Specific reason for that could be previously operations run in smiliar regions, and action taken in order to avoid unexpected overpressured zones. But, from the data presented by the exploraty report, none information contextualizing this topic can be seen, so that further analysis converg themselves for a under-limit for mud windows as per pore pressure plus its accounted safety margin.

Table 5.4.7 - MW values reported and calculated and its limitation.

Description	**1-BRSA-329D-RJS**	**1-RSA-369A-RJS**	**1-BRSA-491-SPS**
Pore pressure (ppg)	10.45	9.50	9.42
Min. MW with 3% safety margin (ppg)	10.76	9.79	9.70
Max. used and reported MW (ppg)	12.00	10.90	10.50
Min. MW for <> wellbore collapse (ppg)	15.20	23.00	13.80
MW might slower ROP to zero (ppg)	18.80	15.50	13.70

6 DISCUSSION & CONCLUSION

From the beginning up to the final result of this thesis, grateful understanding about the importance of the pre-salt for the worldwide petroleum scenarios and as well for Brazil could be built. As well, specific knowledge concerning drilling rate of penetration, how and which factors do affect most its optimization and development, and a specific approach regarding the pre-salt carbonates could be stated.

Considering the scenario for 2030, it is expected an increase in the world oil demand of 34 Mbbd, and an increase in oil production in Brazil of about 4 Mbbd, which represents approximately 11% global demand increase. In this way, the study undertaking the exploratory wells 1-BRSA-329D-RJS (Parati), 1-BRSA-369A-RJS (Tupi), 1-BRSA-491-SPS (Carioca), located in ultra-deep water from pre-salt region, summarized a good approach to it.

For the rate of penetration drilling model development, due to some lack of information from the wells in study, stochastic approach making use of Monte Carlo knowledge and Oracle Crystal Ball software was used, defining a considerable acceptable model, and new approach for drilling model developments. While covering the thesis, shown had been as well the importance to define a minimum weighted mud for the operations in order to overcome the equivalent pore pressure, for kick preventing, and as well to withstand eventual borehole collapse may show up. And, as one of the most important factor affecting ROP, analysis were developed focusing to of MW in ROP response specifically.

The carbonate sections of the Brazilian pre-salt had been showing a necessary MW for borehole collapse withstand greater than the ones for kick prevention. Furthermore, the minimum MW for these wall collapses withstand had been presenting itself to be inapplicable for the operations, since were reflecting a very low ROP response, close to zero, representing a stand-by for the operation. The MW shown for Parati, Tupi, and Carioca prospects so that from them the ROP dropped close to zero were, respectively, 18.8 ppg, 15.5 ppg and 13.7 ppg.

In this way, can be stated that an operation with a MW minimally weighted to withstand the carbonates formation borehole to collapse are inapplicable, what determines as well that the most important minimum reference does still is the formation pore pressure. It also determines that if an activity is developed in a certain higher depth, the compaction due to the overlaying formation may guarantee somehow a wellbore stability by itself, since from the exploratory reports presented for the wells analysed, one had been making use of a MW much lighter than the minimum weight necessary if an avoidance of wall collapse would have been taken into account. Thus, with a MW just above the calculated pore pressure, the exploratory reports had been showing that the minimum acceptable values for the MW chosen in the operations were enough to guarantee a safety operation, but, as could be as well stated over the thesis, it does not mean and are not optimum values regarding ROP optimization and efficiency.

Specifically for each well, and taking into account the explanation and interpretation of the results, can be said that MW used for the operations could be less weighted, reflecting in a ROP optimization. For the wells 1-BRSA-329D-RJS, 1-BRSA-369A-RJS and 1-BRSA-491-SPS, respectively, a ROP increasing could be easily achieved mainly if a more carefully MW would have been designed, since by shorting it in just one decimal, started reflecting in almost 12%, 16% and 27% ROP enhancement, respectively. This is simply noted, once for these respective wells, the MW used and reported were calculated to be greater than necessary in aproximately 4.83%, 14.74% and 11.46%.

Thus, the conclusion consideration can be stated as following:

- The Brazilian pre-salt reserves do represent an important actor globally, and the forecast concerning the national production is that Brazil may fill up 11% of the worldwide demand increase;
- Since the pre-salt reservoirs are mainly composed by carbonates rocks, and since the average ROP on these operations are being considerable low, drilling optimization are reinforced as an really important topic for future researches;
- One of many parameters that drives ROP optimization is the MW selection, so that the less dense it is, the higher ROP efficiency can be achieved;
- A minimum necessary MW for avoiding wellbore collapse might be inapplicable, being to weighty, since it brings the ROP to draw responses close to zero;
- The operations previously run and reported, as per used on the thesis, show that avoidance of wellbore collapse through MW design might not be that necessary, since the MW reported to have been selected for the exploratory wells operations studied were slightly heavier than the pore pressure and far lighter than the one for collapse avoidance, and these facts did not represent any problem or issues for the operations, as per exploratory reports;

- In the activities analysed, just the pore pressure is respected as lower limit for the minimum necessary MW, and possibility of wellbore collapse is not taken into account;
- Since the activities in study are run in a region that vary from TVD 5,130 m up to TVD 6,478 m, just the overburden pressure may guarantee a certain integrity for the operation, as can be seen, again, since none problem had been reported according to it up to wells finalization;
- There were found out a wide range for the MW to be chosen so that the ROP enhancement for the Brazilian pre-salt carbonates could be achieved, if taken into account, as is the case, just the necessity of having MW slightly heavier as the pore pressure, as per safety margin of 3%;
- In the Brazilian pre-salt carbonate sections analysed, the MW used were in average 13.68% heavier than the necessary, leading to the conclusion that for the entire operation, an ROP optimization could be well achieved.
- Even that, it is necessary to emphasize how strong can and effectively is the effect of the learning curves over operations. The more operations are run, the more knowledge can be developed, helping guaranteeing efforts on future activities in similar locations, regions, Block or Basins, what nevertheless also has its influence on drilling efficiency.

As future works and researches, a good approach would be an more detailed analysis taking into account the morning report for each well in study, having the real in-situ drilling parameters for the entire section in study, and as well laboratory experiments for a more close analysis in how far the minimum MW for wellbore collapse withstand does must be respected, and for each wide range of difference in value it would have to take place.

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