MANUEL SEBASTIAN SALAZAR RUIZ

A study on well design and integrity for deepwater exploratory drilling in Brazilian Equatorial Margin

Master's thesis presented to the Graduate Program in Mining Engineering at the Escola Politécnica da Universidade de São Paulo to obtain the degree of Master of Science.

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Concentration area: Mining Engineering

Advisor:

Prof. Dr. Ronaldo Carrion

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To my parents who provided me the best education opportunities and raised me with the moral values that I carry along every day.

To my stepfather who supported me throughout the whole duration of this study and is the best example of hardworking, positive and responsible man.

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ABSTRACT

RUIZ, M. S. **A study on well design and integrity for deepwater exploratory drilling in Brazilian Equatorial Margin.** 2018. 102 p. Master's thesis – Mining and Petroleum engineering department of University of São Paulo, São Paulo, 2018.

Drilling operations in deepwater (DW) or ultra-deepwater areas, even more in exploratory frontiers, have been increasingly challenging due to the operational complexities and limited available data about the subsurface conditions. In this sense, enhancing safety and minimizing the likelihood of losing well integrity and damage to the environment is a currently essential objective relating to offshore drilling activities. Hence, deepwater well designs should advance to safely meet the challenges related to the progression of well and water depths. The safe construction of these wells requires the application of suitable well design considerations that include well integrity approaches to reduce the risk of an unintended release of formation fluids (oil, gas or water) to the environment during the deepwater drilling operations, in other words a "Blowout" occurrence. In this study it is proposed two deepwater well architectural designs, limited to drilling stage, that safely accomplish the well targets and facing several deepwater well complexities, e.g. narrow operating envelopes. Thus, well logging and geological data of two actual pioneer wells drilled in deep and ultradeep water zones in Ceará Basin are used as a basis to construct and assess the drilling operating envelopes, to define the casing shoe depths and well barrier envelope. Furthermore, it is introduced the application of at least two independent Barrier Integrated Sets (BISs) to ensure the well integrity during the 4th phase drilling of the proposed well architectures, as it has recently been required in Brazil by the National Petroleum Agency (ANP) through "Well Integrity Management System" (SGIP for its acronym in Portuguese).

Keywords: Deepwater drilling. Well design. Well integrity. Operating envelope. Casing setting. Kick tolerance. Barriers Integrated Set.

RESUMO

RUIZ, M. S. **Um estudo sobre projeto e integridade de poço para perfuração exploratória em águas profundas na Margem Equatorial Brasileira.** 2018. 102 p. Dissertação (Mestrado) – Departamento de Engenharia Mineral e de Petróleos da Universidade de São Paulo, São Paulo, 2018.

As operações de perfuração em áreas de águas profundas ou ultra profundas, ainda mais nas fronteiras exploratórias, têm sido cada vez mais desafiadoras devido às complexidades operacionais e aos limitados dados disponíveis sobre as condições do subsolo. Nesse sentido, aumentar a segurança e minimizar a probabilidade de perder a integridade do poço e os danos ao meio ambiente são objetivos essenciais atualmente relacionados às atividades de perfuração *offshore*. Portanto, os projetos de poços em águas profundas devem avançar para enfrentar com segurança os desafios associados à progressão do poço e das profundidades da água. A construção segura desses poços requer a aplicação de considerações de projeto adequadas que incluam abordagens da integridade do poço para reduzir o risco de liberação não intencional de fluidos de formação (óleo, gás ou água) para o ambiente durante as operações de perfuração em águas profundas, em outras palavras a ocorrência de "Blowout". Neste estudo, são propostos dois projetos arquiteturais de poços em águas profundas, limitados à etapa de perfuração, que cumprem com segurança os objetivos do poço e enfrentam várias complexidades de poços em águas profundas, por exemplo janelas operacionais estreitas. Assim, dados geológicos e de perfilagem de dois poços pioneiros perfurados nas zonas de águas profundas e ultra profundas da Bacia do Ceará são usados como base para a construção e avaliação da janela operacional, para definir as profundidades da sapata do revestimento e do conjunto das barreiras do poço. Além disso, é introduzida a aplicação de pelo menos dois Conjuntos Solidários de Barreiras (CSBs) independentes para garantir a integridade do poço durante a perfuração da 4ª fase das arquiteturas dos poços propostos, como tem sido recentemente exigido no Brasil pela Agência Nacional do Petróleo (ANP), através do "Sistema de Gerenciamento de integridade de Poços" (SGIP).

Palavras-Chave: Perfuração em águas profundas. Projeto de poços de petróleo. Integridade de poço. Janela operacional. Assentamento de sapata. Tolerância ao “kick”. Conjunto Solidário de Barreiras.

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LIST OF ACRONYMS

ANP	*Agência Nacional do Petróleo, Gás Natural e Biocombustíveis* (National Agency of Petroleum, Natural Gas and Biofuels, Brazil)
API	American Petroleum Institute
BDEP	*Banco de Dados de Exploração e Produção*
BEM	Brazilian Equatorial Margin
BHA	BottomHole Assembly
BIS	Barrier Integrated Set
BOE	Barrels of Oil Equivalent
BOP	BlowOut Preventer
CSB	*Conjunto Solidario de Barreiras* (Barrier Integrated Set)
DW	Deepwater
ECD	Equivalent Circulating Density
ELOT	Extended Leak-Off Test
EZZ	Brazilian Economic Exclusive Zone
E-W	East to West
FIT	Formation Integrity Test
LOT	Leak-Off Test
MPD	Managed pressure drilling
RFT	Repeated Formation Test
ROP	Ratio of Penetration
RP	Recommended Practice
SEC	South Equatorial Current
SGIP	*Sistema de Gerenciamento da Integridade de Poços* (Well Integrity Management System)

LIST OF SYMBOLS

σ_{ov}	Overburden pressure
G_{ov}	Overburden gradient
P_p	Pore pressure
G_N	Normal Pore pressure gradient
G_p	Pore pressure gradient
$G_{P\,max}$	Maximum pore pressure
G_f	Fracture gradient
$G_{f\,shoe}$	Fracture gradient at casing shoe
G_F^{kt}	Fracture gradient based on kick tolerance
K	Effective stress coefficient
P_A	Absorption pressure by LOT
P_{BOP}	BOP working pressure
$P_{H\,gas}$	Hydrostatic pressure of gas column
$P_{H\,wc}$	Pressure exerted by water column
ρ_w	Sea water density
ρ_{bi}	Formation bulk density
ρ_{kt}	Kick tolerance
ρ_{mud}	Drilling fluid density
ρ_k	Kick fluid density
$\Delta\rho_{kt}$	Differential kick tolerance (safety factor)
$\Delta\rho_{kt\,min}$	Assumed minimum differential kick tolerance
D_{fm}	Weakest formation depth
D_h	Well depth
D_{hp}	Depth of the maximum pore pressure
D_w	Water Column depth
D_{shoe}	Casing shoe depth
ΔD_i	Formation depth intervals
h_k	Kick length
a, b	Empirical constant for Gardner’s equation
c, d	Exponents for Eaton’s empirical equations
V	Sonic velocity
Δt	Travel time

Δt_N	Travel time value in trend line
Δt_o	Observed travel time
R_N	Resistivity value in the trend line
R_o	Observed resistivity

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1 INTRODUCTION

The offshore area of Brazilian Equatorial Margin (BEM) is an extensive exploratory frontier which is part along with Brazilian eastern margin of the Brazilian Economic Exclusive Zone (EEZ), also called “Amazonia Azul”. Although, it produces oil and gas in its shallow waters, the deepwater region has been slightly explored with few wells drilled. In 2012, Petrobras announced the first significant light oil discovery in deep-water Ceará basin, one of the sedimentary basins that composes BEM (FAVERA et al., 2013). In 2013, the Brazil 11^{th} bidding round offered an important amount of exploratory blocks to search commercial reserves of hydrocarbon with prospects of light oil in BEM deeper waters (ANP, 2013a, 2017a).

The drilling of offshore wells is a demanding operation, which has several inherent risks being more remarkable in lightly explored and deeper water areas such as those found in the Brazilian Equatorial Margin (BEM). These associated risks to the exploration have increased the efforts to ensure wells integrity (API RP 96, 2013). In the event the well integrity is not ensured, or/and related risks are not mitigated could lead to numerous consequences as damage to, or loss of wellbores, facilities, environment or lives. The best example for this undesirable case is the Macondo blowout (*Deepwater Horizon* oil spill), an accident where the well integrity was lost during the well construction activities (TURLEY, 2014), generating a massive unintentional marine oil spill in Gulf of Mexico approximately estimated in 3.8 MMSTB according to recent study developed by Liu et al. (2017).

The desired final success of the well, from a drilling perspective, is heavily dependent on the capacity of the well planning or design (DEVEREUX, 1998). The basis for a proper well construction is an understanding of the environment in which the well is to be drilled (local geologic structure, geo-pressures, local drilling experiences, etc.). Thus, casing design and well integrity approaches are mostly based on these interpretations (API RP 96, 2013).

As casings are running after each drilled phase into the well to protect the formations of cave-in and fracture and allow that adequate drilling fluid weight can be used in the next one, a typical project of casing shoe setting is mainly defined by the operating drilling window, which is mainly established by identifying the geopressures. Although, each oil company has their own criteria to determine the casing shoe setting, it is common to include well control considerations in this process by employing kick tolerance concept (DEVEREUX, 1998; ROCHA; AZEVEDO, 2009).

After the casing shoe depths are determined, well integrity becomes in a major concern during well design phase, mainly in the well barrier planning considerations. Well integrity can be defined as “application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well” (NORSOK, 2013).

Further, according to Mendes et al. (2016) well integrity is detailed as the capability to keep controlled the oil, gas or water flow from the reservoir into the well, avoiding spills of any type to the environment. This capability is accomplished by employing safety barriers. Thus, the safety barriers can be defined as equipment or physical separations that obstruct specific flow paths between a permeable formation and the environment.

Several international standards such as NORSOK D-010 and API RP 96 define requirements, concepts and guidelines relating to appropriate well design, well integrity and safety barriers in Deepwater (DW) drilling. Similarly, today it is being implemented in Brazil an ANP’s ordinance called “Well Integrity Management System” (SGIP for its acronym in Portuguese), to report the operational safety conditions regarding the well integrity during the whole life cycle of each well (ANP, 2016a, 2017b, 2017c).

The ANP’s ordinance requires that at least must exist two (02) Solidary Barrier Sets (CSB by its acronym in Portuguese) throughout the Well Life Cycle to ensure the well integrity (ANP, 2016b). The CSB is the same concept of the Barriers integrated set (BIS) defined by Miura (2004).

This thesis presents well architectural designs that safely achieve well objectives, including mainly well integrity approaches based on the previous cited international or local standards and regulations for drilling operations of DW exploratory wells in Ceará Basin. Several well design considerations are applied in this work, such as interpretations of local geologic structure, geo-pressures, casing designs and drilling risk derived from local drilling experiences. However, borehole instability concerns and other drilling design consideration such as casing structural features, drill string, bit and cementing, directional drilling, among others, are not deeply studied.

1.1 OBJECTIVE

The aim of the present study is to develop two well architecture proposals for the drilling stage of deep and ultra-deep water exploratory wells respectively, focusing on some critical considerations of well design based on API RP 96. Furthermore, it is introduced the application of at least two independent BISs throughout the 4^{th} drilling phase to increase reliability and well integrity, reducing risk of undesired leakage of formation fluids (oil, gas and water) to the environment.

2 LITERATURE REVIEW

2.1 BRAZILIAN EQUATORIAL MARGIN

The Brazilian Equatorial Margin (BEM) is located on North and Northeast of Brazil and along a large Oceanic fracture zone (large transform faults). It encompasses about 344.000 km^2 in shallow water[1] and 200.000 km^2 in deeper water. BEM is part along with Brazilian eastern margin of the Brazilian Economic Exclusive Zone[2] (EEZ), also called “Amazonia Azul”.

The deep-water region of BEM has been slightly explored due to the high risk associated to many mechanical problems during the drilling operations and it remains an extensive new frontier region, where geological data is poorly available, and a few wells have been drilled. However, important oil discoveries have been achieved there, e.g. the offshore Ubarana oil field in Potiguar Basin (FAVERA et al., 2013; MELLO et al., 2013).

Furthermore, Brazilian Equatorial Margin shares similar tectono-stratigraphic evolution with the equatorial west Africa margin, suggesting equivalent petroleum systems for both, e.g. a Cenomanian source rock and an Upper Cretaceous turbidite reservoir. Petroleum exploration in these two regions, which were once joined but now are separated by the Atlantic Ocean and dominant transform faults, has led to significant oil discoveries. This condition becomes BEM in a vast exploratory frontier with high exploration potential.

The Jubilee field offshore Ghana is the best example for the potential in the conjugate margin sedimentary basins. It is located in the Gulf of Guinea, has an

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[1] According to Petrobras, the water depth classification is shallow water for water column less than 350 m, deep water for water column between 350 m and 1500 m and, ultra-deep water for water columns greater than 1500 m.

[2] An exclusive economic zone (EEZ) is a sea area prescribed by the United Nations Convention on the Law of the Sea under which a state has special rights regarding the exploration and use of marine resources (UNITED NATIONS, 2011).

estimated reserve of about 600 million barrels, producing a light oil (37° API) (FAVERA et al., 2013; MELLO et al., 2013).

2.1.1 Petrobras Offshore Projects

In the last decade, Petrobras has successfully discovered and developed several fields in shallow water and it has continued to deep and ultra-deep waters within Campos Basin and Santos Basin. Mainly, an important oil fields province, named the Brazilian Pre-Salt, shown in figure 2.1. The petroleum production from only the Pre-Salt fields was approximately 1,000,000 BOE[3] per day in 2016 (MORAIS, 2013; JOHANN; MONTEIRO, 2016).

However, the exploration of new reserves to replace the depleted fields, lead to the search of new frontier areas as BEM. Nowadays, the BEM is a relative unknown basin where the petroleum companies are looking for new commercial reserves of hydrocarbon.

The existence in this region of high currents environments from south equatorial current (SEC), that range between more than 4 knots at the surface to one knot at the bottom, increase the challenges for offshore drilling operations. High currents zones in drilling sites can generate high drag forces that cause vortex-induced vibration phenomenon in riser, drill pipes and casing strings (GARDNER; COLE, 1982; SILVEIRA et al., 2000).

In 1970, it was initiated the offshore exploration activities in the Brazilian Equatorial Margin and since then approximately 490 wells have been drilled in shallow water. The first oil discovery was the offshore Ubarana oil field in 1973, located in the Potiguar basin. During the next six years, Petrobras had four small oil discoveries in the shallow water of Ceará Basin.

In 2012, Petrobras announced an important light oil discovery in Aptian (lower cretaceous) turbidite reservoirs penetrated by the 1-CES-158 (1-BRSA-1080-CES by

[3] Barrel of Oil Equivalent. BOE is used as a way of combining oil and natural gas reserves and production into a single measure.

ANP well nomenclature[4]) well in the deepwater Ceará Basin. Until 2013, about 20 deep-water wells have been drilled in BEM, nine of which were abandoned due to mechanical problems (FAVERA et al., 2013).

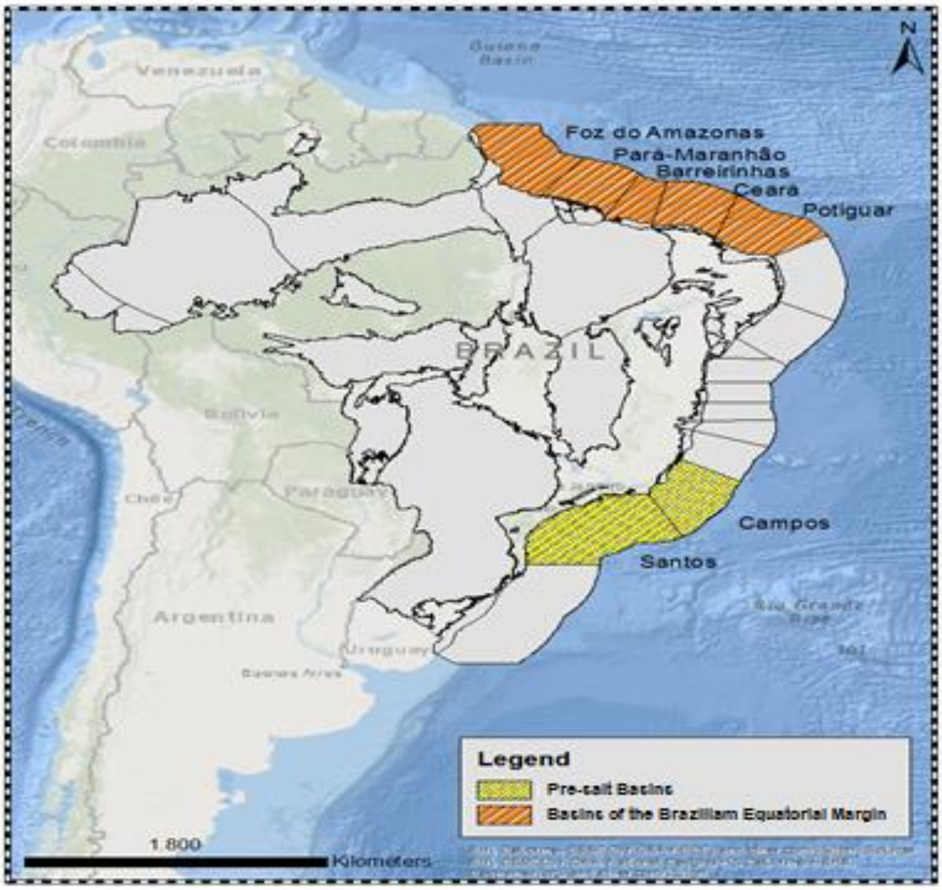

Figure 2-1 – Basins of the Brazilian Equatorial Margin and the main pre-salt province in Brazilian Eastern Margin.

According to the Brazilian Agency of Petroleum, Natural Gas and Biofuels, ANP (2017), in 2013 with the Brazil 11th bidding round was offered about 50 exploratory blocks within the five basins composing BEM, indicating an important move by the oil industry to further test of deeper water early Cretaceous turbidite play[5]. Therefore, at least 56 exploratory wells shall be drilled in BEM along the next decade.

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[4] The description of the Petrobras and ANP exploratory well nomenclature is shown in the Appendix A

[5] A Petroleum play is an area in which hydrocarbon accumulations or prospects of a given type occur.

2.1.2 Geological Setting

Brazilian sedimentary basins have been of great interest, especially the Brazilian Offshore basins located in the Eastern Margin, for the exploration and the commercial petroleum production during the last decades. It encloses 29 sedimentary basins, of which 13 are onshore basins, nine extend from onshore coastal area to the offshore and 7 are entirely placed in offshore territory of the Brazilian Atlantic Margin (FAVERA et al., 2013).

According to Mohriak (2003) and considering the present geologic frameworks, the Brazilian Atlantic margin basins can be divided in 3 segments or groups: the Northeastern margin basins; the eastern, southeastern and southern margin basins; and the Equatorial margin basins.

The sedimentary basins of the Northeastern margin are mainly characterized for the presence of the transverse shear deformation and these include the Pernambuco-Paraiba basin, the Sergipe-Alagoas basin and the Jacuipe basin. The eastern, southeastern and southern margin basins present a divergent tectono-stratigraphic framework such as the Espirito Santo basin, the Campos basin, the Santos basin, among others.

The last group, the Equatorial margin basins, shown in figure 2.1, displays complex and strong deformation shear zones mostly set up by the transform faults, like the Romanche Fracture Zone and São Paulo Fracture Zones (BACOCCOLI; BEDREGAL, 2002).

There are five sedimentary basins in the Brazilian Equatorial margin, the Foz do Amazonas Basin, the Potiguar Basin, Ceará Basin, Pará-Maranhão Basin and Barreirinhas Basin. These basins were formed and have suffered changes due to movement of tectonic plates in three periods (Rift, Transitional and Drift) and their geology and stratigraphic characteristics have been set.

During the first rifting period between South American and African continents, the Potiguar and Ceará Basins were constituted, and in the posterior rifting period, the first sedimentary layers (interbedded sandstones and shales deposited in fluvial environment) of these Basins and in addition, the other ones emerged. In the transitional and drifting sequences, the basins evolved with distinct structural and sedimentological characteristic, only in the case of Pará-Maranhão Basin and Barreirinhas Basin that have similar development and thus, similar sedimentological features.

The Brazilian Equatorial margin basins are mainly composed of shale, sandstone, calcarenite layers and in few mounts by siltstones and dolomite. In the specific case, the Ceará Basin (adjacent to Ceará state, Brazil) has a complex structural framework in its 35.000 km^2 of extension, because of its depositional system characterized by erosion, very high propagation rate, and the presence of local zones with faults interaction and guyots, e.g. Romanche Fracture Zone and Ceará Guyot (FAVERA et al., 2013). The actual wells exploited in this work were drilled in deeper water zones of this basin, what is described in more detail in section 3.1.1.

2.2 DEEP-WATER WELL DESIGN

The success or failure of a well, from a drilling perspective, is heavily dependent on the capacity of the well planning. This capacity is principally related to the quality of the data, e.g. offset and geological data, used in planning. The well design, therefore, determines casing characteristics and shoe setting points (DEVEREUX, 1998).

The drilling operations of offshore wells is a demanding operation, which has several inherent risks being more remarkable in underexplored and deeper water areas such as those found in BEM and in the specific case of Ceará basin (FAVERA et al., 2013). The complexity of DW wells has expanded over the years as measured by water depth, well depth, mud weights, geo-pressures, temperatures, and the number of casing points required to reach the objectives (API RP 96, 2013).

DW wells present a special problem: the narrow drilling operating envelope due to the low fracture gradients. Then, a better understanding of the geo-pressures such as pore, fracture and collapse gradients are necessary to establish the proper weight of the drilling fluid that ensure wellbore stability and integrity prior to setting a casing (ERIVWO; ADELEYE, 2012; ZHANG; YIN, 2017).

Independently from the well type to be drilled, either exploratory or development, the complete description of the drilling and completion phases takes great importance at the time of determining well time and cost and, consequently, for the assessment of the technical and economic feasibility. Thus, the better the well design, the greater the chances of achieving the well targets, respecting the current safety standards and maintaining the well integrity (ROCHA; AZEVEDO, 2009).

The following workflow is a common multidisciplinary scheme to elaborate a well design only for the drilling phase:

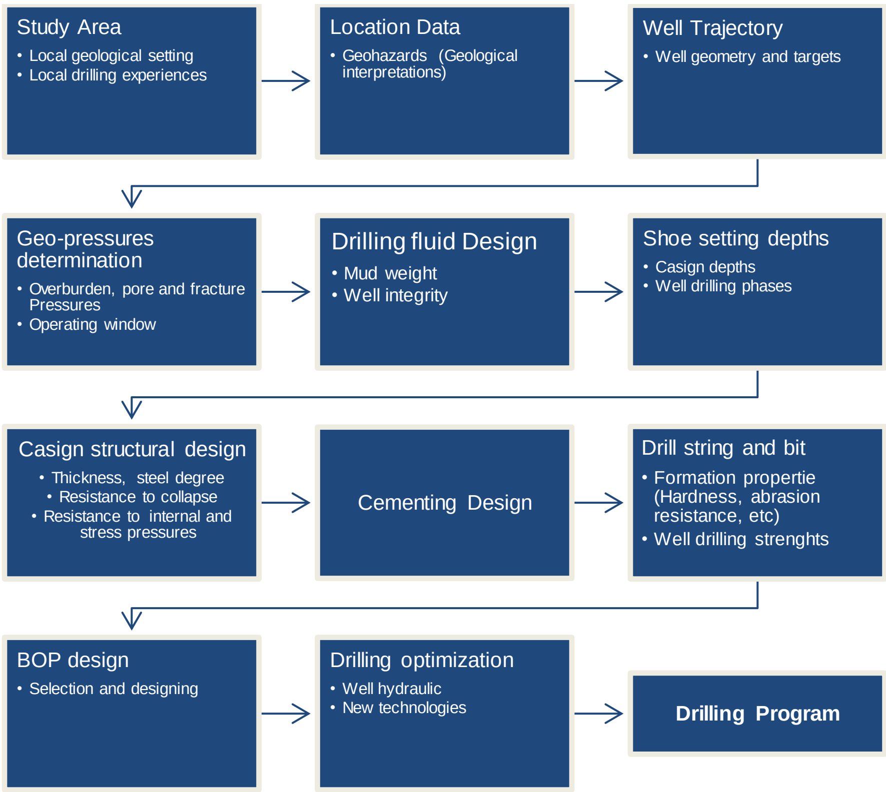

Figure 2-2 – Workflow for a well design limited to the drilling phase (Modified from Rocha and Azevedo (2009))

The first point to note is a well design or project starts with the analysis of the well area to be drilled. Clearly, a local geological interpretation and a review of the offset well data are done to identify potential geohazards or drilling risks. After that, the better well trajectory to reach the “pay zone”, can be determined knowing target depth and desired geometry of the well (ROCHA; AZEVEDO, 2009).

The next stage is the calculation of the geo-pressures, e.g. overburden, pore and fracture pressure, with the aims to construct the operating envelope or window that represents the allowed mud weight range that ensure the well integrity.

Subsequently, the casing shoe setting project defines the casing setting depths, establishing the drilling well phases. Several criteria based on operating envelope and kick tolerance approach are employed in the oil industry to determine the casing setting depths. Furthermore, casing structural properties and cementing requirements shall be also specified to the casing supports mechanical stresses and to avoid the fluid migration outside settled casing respectively (DEVEREUX, 1998) .

The last stage is represented by bit, drill string and BOP design. The first one is planned according to formation characteristics, e.g. hardness, strength and abrasion. The second one is projected to withstand the drilling induced stresses. The last one, the Blowout Preventer (BOP) is designed by considering pore pressure gradient and a possible "kick" density (ROCHA; AZEVEDO, 2009). Clearly, BOP is an important well barrier installed in the well during drilling phase, as is shown in well integrity section of this work.

Despite the previous workflow covers all the necessary stages to develop a proper well architecture, it requires the participation of experienced multidisciplinary engineers. Hence, this work focuses on simplified basis for a well planning defined by API RP 96 (2013), which targets mainly in providing well design and operational considerations in order to safely design and construct any deepwater well drilled with subsea riser system and blowout preventers (BOPs). This simplified basis of well planning, in a drilling phase, is described by the below fundamental considerations.

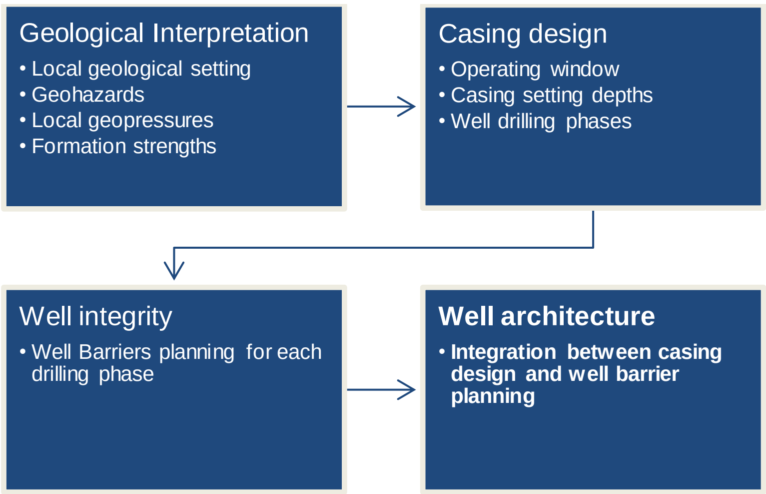

Figure 2-3 – Main well design considerations (API RP 96 (2013))

Initially, a well design must be based on an understanding of the environment in which the well is to be drilled. Later, the developing and integration of casing design and well integrity approaches must be derived from the previous interpretations, local drilling experiences and critical factors, taking into account the guide of some international/local well integrity standards such as ***NORSOK D-010 and API RP 96,*** *besides the new* ***ANP resolution, SGIP*** (ANP, 2017c). In this point, well integrity becomes in a final goal and consequently in a major concern during the well design phase, principally in the barrier planning considerations, providing a well architecture that aims to safely achieve well objectives.

So, in the next sections, it is detailed the literature review about the definition and determination of the geo-pressures that define the boundaries of the well-known safe mud weight operating envelope. Then, it is shown singularities of DW well architecture and the methods to calculate casing shoe setting depths. Finally, the well barrier and integrity approaches are introduced according to the above cited standards.

2.2.1 Mud Weight Operating Window

In drilling operation, the selecting of a safe range of mud weight to prevent undesired formation fluid influx (kick), wellbore instability, and loss of circulation it is usually made by the knowledge about how the geo-pressures are expected to change with depth (DEVEREUX, 1998).

The geo-pressures term can be defined like all pressures and stresses that exist in subsurface, and all of those that are imposed to the formations, which could be lead to the rock breakout or well integrity failure while drilling. Then, the estimation of the geo-pressures such as pore, fracture and collapse pressures are necessary to establish the appropriate weights of the drilling fluid (mud) prior to setting and cementing a casing (ROCHA; AZEVEDO, 2009; ZHANG, 2011). Thus, geo-pressures define the limits of the mud weight operating envelope or window (LESAGE et al., 1991). Figure 2.4 represents an example of an offshore operating window, where can be noted mud weight and geo-pressure curves.

In a typical operating envelope versus depth plot, the pore pressure gradient (i.e. pore pressure divided by the depth) of rock layers defines lower limit, indicating the minimum mud weight that one can use during an overbalanced fluid drilling (ZHANG, 2011; ZHANG; YIN, 2017). That is, in the case of the mud weight was lower than local pore pressure gradient in a very permeable rock, then a kick would occur; if it happens in a soft and impermeable rock, the well could collapse. However, in many cases drillers could develop an underbalanced drilling to increase rate of penetration (ROP), where the used mud weights are lower than pore pressure gradient (LESAGE et al., 1991).

Similarly, the fracture gradient (i.e. fracture pressure divided by the depth) defines the upper limit, which indicates the maximum allowable mud weight where the wellbore will not fracture, causing losses of drilling mud into the fracture formation (ZHANG, 2011; ZHANG; YIN, 2017). Moreover, with loss of circulation, the fracture could propagate in case of mud weight overpass the minimum horizontal earth stress (LESAGE et al., 1991).

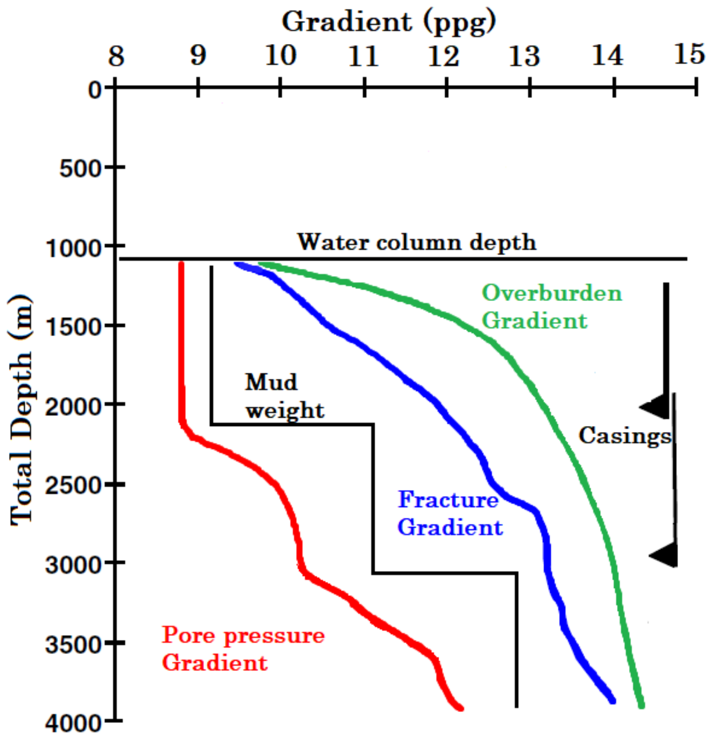

Figure 2.4 – Example of an offshore operating envelope: Pore pressure gradient, fracture gradient, overburden gradient, mud weight, and casing shoes with depth.

Consequently, the relationship between the rock properties and principal in-situ subsurface stresses shall be also considered when it is established the pressure limits of drilling fluid that ensure the wellbore stability to be maintained. Thus, to avoid excessive breakout development, whether the collapse pressure is greater than pore pressure, it should be selected as the lower limit of the mud operating envelope (ROCHA; AZEVEDO, 2009).

Despite wellbore stability analysis makes possible to reduce drilling costs by maintaining lost time low and by planning wells just cautiously enough to minimize geo-mechanical issues without extra cost, it is not deeply addressed in this research due to very little data available (i.e. geo-mechanical parameters) to construct a complete geo-mechanical model. Note that in this work, it is not discussed the collapse gradient and it is assumed the pore gradient as the lower limit of the mud weight envelope.

Figure 2.5. displays a brief workflow for the construction of the operating envelope. It begins with the determination of overburden gradient (overburden pressure divided by the depth) by using pre-existing surrounding density or sonic log data. After that, pore pressure gradient can be determined by employing direct and indirect methods that work with resistivity and sonic logs, and the previous calculated overburden gradient. In addition, one can estimate the pore pressure gradient with other pre-existent well parameters such as drilling fluid weight, penetration rate, formation tests and even seismic data when no correlation wells are available (ROCHA; AZEVEDO, 2009).

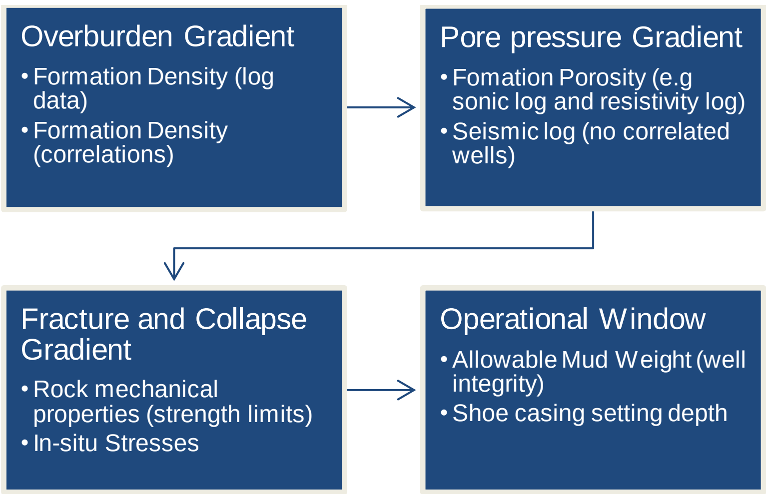

Figure 2-5 – Workflow for operating envelope determination (Modified from Rocha and Azevedo (2009))

Finally, for the prediction of fracture gradient, one shall examine both stress regime around the wellbore (i.e. vertical stress and maximum and minimum horizontal stresses) and rock strength parameters (i.e. tensile strength, Poisson’s ratio, etc.).

2.2.1.1 Overburden Gradient

The overburden (lithostatic) pressure over a subsurface rock element in a certain depth is the sum of all overlapping layers weight to this element, i.e. the stress caused by the weight of all the components above a depth of interest (DEVEREUX, 1998). In this way to offshore wells, considering the water layer, the overburden pressure can be calculated with the following eq. (2.1) (ROCHA; AZEVEDO, 2009):

$$\sigma_{ov} = 1{,}422\left(\rho_w D_w + \sum_{0}^{n} \rho_{bi} \Delta D_i\right), psi \qquad (2.1)$$

Where, ρ_{bi} and ρ_w are each formation layer bulk density (g/cm^3) and the seawater density (g/cm^3) respectively, D_w is water column depth (meters) and ΔD_i are the depth ranges. The total density of the formation or bulk density is an average between of the density of the rock matrix and fluid within the pores. A typical value for seawater density may be 1.03 g/cm^3.

The density profile is normally utilized with the aims to assess the formations porosity by the direct measurements of their bulk densities (ρ_b). Thus, knowing the formation density from the density log, can determine the overburden gradient by the simple application of eq. (2.1). However, the formation is commonly subdivided in segments where only a few of them contain available formation density data obtained from well logging.

Hence, the overburden gradient for the remaining segments (without available logging data) could be estimated by assuming a typical value of rock density between 1.90 and 2.50 g/cm^3. In the specific case of the shallowest segments, more porosity sediments, generally the typical density values can be varied between 1.5 and 1.95 g/cm^3 (ROCHA; AZEVEDO, 2009).

Some other methods to determine formation density are explored when the density log data is not available or reliable, such as sonic profile data and rock core data. One of them, Bellotti's correlation, associate formation densities with the travel time (sonic log) of the formation and the rock matrix in two expression for consolidate and unconsolidated formations (BOWERS, 1999). A similar method but one of the most used in the petroleum industry, due to the simplicity and reliability, is Gardner's relation.

This method correlates the formation density with the travel time or the sonic velocity according to the following equations (GARDNER; GARDNER; GREGORY, 1974; ROCHA; AZEVEDO, 2009):

$$\rho_b = a(V)^a \tag{2.2}$$

$$\rho_b = a(\frac{10^6}{\Delta t})^b \tag{2.3}$$

Where, ρ_b is formation bulk density (g/cm^3), a is an empirical constant (its usual value is equal to 0.23, defined to Gulf of Mexico), b is an empirical constant (its usual value is equal to 0.25, defined to Gulf of Mexico), V is the sonic velocity (ft/s) and Δt is the travel time (μs/ft) given by sonic profile.

The parameters $a = 0{,}23$ and $b = 0{,}25$ were estimated from laboratory tests and observations of field data, in the Gulf of Mexico, for several types of rocks, except for evaporates. The use of these estimated values for the empirical constant could underestimate the formation densities in offshore wells, and must be corrected with other density profiles from the studied area (ROCHA; AZEVEDO, 2009).

2.2.1.2 Pore pressure Gradient

Pore pressure is one of the most important parameters for drilling planning, because it directly influences the design of the drilling fluid to be used during each drilling phase. Pore pressures can be defined as the fluid pressures (water, oil or gas) in the pore spaces of porous formations.

It is very common in the oil industry to use the pore pressure gradient term instead of pore pressure, in the sense that the drilling parameters are obtained as a function of the drilling fluid density, so it is convenient to work with these terms in the same unit. Gradients are generally obtained in psi/ft and can be easily converted to ppg or g/cm^3. Thus, a normal pore pressure gradient varies between 8.5 and 9.0 ppg (pound per gallon), which is equivalent to the specific gravity of 1.02 and 1.08 g/cm^3 (ROCHA; AZEVEDO, 2009; ZHANG, 2011).

Pore pressure can vary from hydrostatic pressure (normal pressure) to harshly abnormal pore pressure. Abnormal pore pressure occurs when the pore pressure is lower or higher than the normal pore pressure. So, in the case that pore pressure exceeds the normal pressure, it is called overpressure. The presence of this type of pressures can be determined by studying the drive mechanism of high pressures, e.g. fluid expansion, in-situ stresses, Buoyancy, lateral transfer (ZHANG, 2011).

The imbalance between pore pressure gradient and drilling fluid gradient can generate unwanted occurrences. One of the most relevant occurrences is in the presence of permeable formation, an influx of formation fluids to the well, called well kick, could occur whether the pore pressure exceed the drilling fluid pressure (e.g. overpressure zones). In case this kick is not safely controlled before reaching the surface, called Blowout, could be taken place terrible consequences as damage to, or loss of wellbores, facilities, environment or lives (ROCHA; AZEVEDO, 2009; ZHANG, 2011).

The pore pressure gradient can be predicted by applying two methods: Direct and Indirect. One the one hand, direct measurements of pore pressure are performed by employing well tests in permeable formations, in other words, in potential producing zones. These measures are normally applied to calibrate the indirect methods of pore pressure estimation because although the tests results are useful for well designers and are assumed like the absolute truth, generally their main objective is the reservoir evaluation. Therefore, an important disadvantage of these methods is the fact that they are punctual registers, meaning they are not give a pore pressure curve of whole well. The most common test applied in the oil industry are the formation test, the repeated formation test (RFT) and the formation pressure while drilling.

One the other hand, the indirect methods are only based in sub compaction mechanisms. For this reason, these methods were developed to the application in shales that are clay and low permeability rocks. Shales shows the constancy of the porosity reduction along the depth due to the rock compaction. Hence, porosity data obtained from sonic or resistivity logs are exploited for the identification of a normal compaction trend. In the literature there are various indirect methods (e.g. Bowers' method, Miller's method and Eaton's Method), nevertheless in this work is only addressed one of the most used in the petroleum industry, Eaton's method (LAREDO; DA FONTOURA, 2007; ROCHA; AZEVEDO, 2009; ZHANG, 2011)

The Eaton's Method is extensively applied in some oil basins around the world. Especially in the Gulf of Mexico, because it was in this region that Eaton carried out the study that gave rise to this method (EATON, 1972, 1975). The method is based on the work of Hottmann and Johnson (1965), which states that the porosity decreases with increasing depth by analyzing acoustic travel time in Miocene and Oligocene shales in Upper Texas and Southern Louisiana Gulf Coast. This trend represents the “normal compaction trend” as a function of burial depth, and fluid pressure exhibited within this normal trend is the hydrostatic.

Plotting of normal compaction curves is utilized to evaluate abnormal pressures in the compaction process and consist in drawing of a trend line by using the observed segment where the compaction is normal. The clay formations are used to determine this relationship because, theoretically, must present a unique normal compaction trend line. For this reason, the porosity profile points associated to shales must be employed to plot this trend line. Usually, the function that represents the trend line is approximate to a straight or curve in a semi logarithmic graphic. An example of a trend line plotting is shown in figure 2.6 (ROCHA; AZEVEDO, 2009; ZHANG, 2011).

The Eaton´s empirical equations (2.4) and (2.5) show the estimation of pore pressure gradient by using sonic profiles and resistivity profiles respectively. The pore pressure gradient in a determined depth is function of the overburden gradient, normal pore pressure gradient, the ratio between the observed parameter value and the value of the trend line of normal compaction, and a chosen exponent. The exponent value depends on the study area and the parameter (log data) that is being implemented. For instance, values of 1.2 for resistivity profile and 3.0 for sonic profile were defined in the Gulf of Mexico (EATON, 1972, 1975; ROCHA; AZEVEDO, 2009; ZHANG, 2011)

$$G_p = G_{ov} - \left[(G_{ov} - G_N) \times (\frac{\Delta t_N}{\Delta t_o})^c\right] \tag{2.4}$$

$$G_p = G_{ov} - \left[(G_{ov} - G_N) \times (\frac{R_o}{R_N})^d\right] \tag{2.5}$$

Where, G_p is pore pressure gradient (ppg), G_{ov} is the overburden gradient (ppg), G_N is the assumed normal pore pressure gradient, Δt_o is the observed travel time (sonic log), Δt_N is the travel time value in trend line, R_o is observed resistivity (resistivity log), R_N is the resistivity value in the trend line, c is exponent for sonic log data and d is exponent for resistivity log.

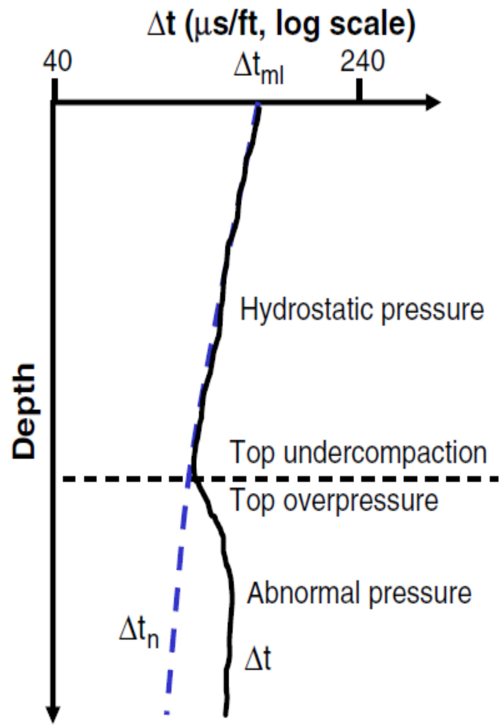

Figure 2-6 – Schematic plot showing sonic travel time (Δt) measured in shale and the normal compaction trend line of the travel time (Δt_N) in the normal pressure condition (Modified from Zhang (2011))

2.2.1.3 Fracture Gradient

Fracture pressure is an important parameter for mud weight and casing design, in both drilling planning stage and while drilling. Fracture pressure can be defined as the pressure necessary to lead the formation fracture and generate mud loss from wellbore into the induced fracture. This pressure can be divided by true vertical depth to obtain the fracture gradient. Therefore, fracture gradient is the maximum allowable mud weight where the wellbore will not be fractured, causing losses of drilling mud, i.e. lost-circulation problems (ZHANG, 2011; ZHANG; YIN, 2017).

Eventually, a loss circulation of mud can cause the reduction of the fluid level in the well as the consequent declining of the hydrostatic pressure, generating an increment in the probability of a well kick occurrence (ROCHA; AZEVEDO, 2009).

For the prediction of fracture gradient, it shall examine stresses around the wellbore. As previously discussed, the overburden (vertical stress) gradient can be calculated by utilizing density logs data (ZHANG; YIN, 2017). The maximum and minimum horizontal stresses, which are functions of the vertical stress and elastic properties can calculate through a constitutive model such as linear pore-elasticity stress model (LE; RASOULI, 2012).

There are several approaches to obtain fracture gradient, however, the petroleum industry usually does it by applying two types of approach: direct and indirect. The first one, the direct measurements are performed by formation integrity test (FIT), leak-Off test (LOT), extended leak-Off test (ELOT) and mini-frac test. The second one, indirect estimation methods based on theoretical or empirical models such as Hoop stress method, minimum stress method, specific correlations or tensile failure method (ZHANG; YIN, 2017).

Fracture pressure can be measured directly from downhole pressure integrity tests, where the drilling fluid is pressurized in a regulated way into the well. Although, the values provided by these tests are real and reliable, these values are punctual and generally, performed in specific formations like shales. Thus, the results of these downhole tests are applied to calibrate the curves of fracture gradient developed by the indirect methods. The best common example of these methods is the leak-off test (LOT), which consists in the determination of the pressure where the rock breakdown occurs, called formation absorption pressure. LOT is normally performed after the casing running and cementing with the objective of identifying the maximum pressure gradient that can support the weakest formation, i.e. just below of the last casing shoe, without loss of circulation (ROCHA et al., 2004; ZHANG; YIN, 2017)

The standardization of the LOT results in function of the water column is a convenient tool when is necessary to compare or correlate data from wells with different water depth in order to predict the fracture gradient. In general, this standardizing is accomplished calculating the sediment pressure of the offset well by the difference between the absorption pressure and the water column pressure. Afterward, this resulting pressure is added to water column pressure of the study, obtaining the standardized absorption pressure. In addition, the absorption pressure can be expressed in gradient terms (ppg) by dividing by the total depth (ROCHA; AZEVEDO, 2009).

The indirect methods such as Hoop stress method, minimum stress method, specific correlations or rock methods and tensile failure method, are other possible ways to estimate the fracture gradient along the well. However, according to the available data, simplicity and because it is widely employed in the oil industry to determine fracture gradient in vertical wells, only will be explored the minimum stress method (LESAGE et al., 1991; ROCHA et al., 2004; ROCHA; AZEVEDO, 2009; ZHANG, 2011)

The minimum stress method assumed that it does not exist any tensile strength of the rock and that the pressure required for opening and extending a pre-existing fracture in the formation is the in-situ minimum stress. Hence, determining the in-situ minimum stress by using a correlation based on pore pressure and introducing the effective stress coefficient can be used to calculate the fracture gradient by the following expressions:

$$G_f = G_p + K\left(G_{ov} - G_p\right) \tag{2.6}$$

Where, G_f represents the fracture gradient, K is the effective stress coefficient, G_{ov} is the overburden gradient and G_p is the pore gradient.

Additionally, it can use eq. (2.7) to estimate locally the value of K for a unique well when any minimum stress data exist. In addition, it is possible to stablish correlations K versus sediments depth by plotting a curve using LOT test data obtained from correlation well in the surrounding area. The results are employed to extrapolate the local K value for an entire area, allowing the prediction of the fracture gradient for other wells to be drilled in the same region (ROCHA et al., 2004; ROCHA; AZEVEDO, 2009; ZHANG, 2011).

$$K = \frac{P_A - P_p}{\sigma_{ov} - P_p} \tag{2.7}$$

Where, P_A is the absorption pressure using as an approximation of the horizontal minimum stress and σ_{ov} is the overburden pressure.

2.2.2 Deep-Water Well Architecture

As water depths for exploratory DW wells started to increase over the years, it also increased the challenges for drilling operators to design mud weights and the number of casing required to reach the objectives. Some complexities that directly affects the well architectural designs in DW environments are detailed by API RP 96 (2013):

- Subsurface geological hazards, e.g. shallow water/gas flow.
- Low fracture pressures relative to pore pressures (narrow operating window)
- Salt and subsalt zones
- Abnormal pore pressures
- BOP limitations

The identification of the offshore geohazards such as sea floor irregular topography, sea floor erosion, landslides, gas hydrates, weak under consolidated shallow formation and shallow water/gas zones is an important concern for the well construction (CUNHA, 2004). *Geohazard* term can be defined as a geologic or hydrological process on surface and subsurface that can be a risk to drilling/production platform. In this sense, shallow hazards are related to shallow depth problems because pressurized and poorly consolidated formations that can lead to a fluid influx (gas or water) into well, where conventional well control procedures could not be effective and allowing a blowout occurrence. Shallow gas/water are generally located above of superficial casing setting point (ROCHA; AZEVEDO, 2009).

Other relevant technical challenge presented in DW environments is the narrowing of the operating envelope. One of the main reasons for narrow margin is the water depth itself and how it affects the pore pressure and fracture gradient relationship. Normally, fracture gradient at a given depth is directly conditioned by the overburden gradient. Therefore, in DW zones the hydrostatic pressure exerted by the sea water column substitutes a pressure amount that would be exerted by the overburden. That is, a lower resulting overburden gradient (Rocks and water column weight) than for a comparable onshore area. As a result, a reduction in fracture gradient and consequently, a narrower margin. Then, deeper water drilling operations requires the installation of multiple casing string to protect narrow margin zones (ERIVWO; ADELEYE, 2012).

Exposure to difficult kicks and lost-circulation incidents can be primarily derivate problems of narrow operating envelops in deepwater while drilling, running casing, and cementing. However, the drilling in salt and subsalt rubble zones are also associated with the previously mentioned problems (POWER; IVAN; BROOKS, 2003; ROCHA; AZEVEDO, 2009). The challenge shown by salt rock drilling is due to its singular property of flow plasticity, i.e. it tends to flow as a fluid. This plastic deformation or creep can lead to quickly close around the drillstring.

Whether the salt rock has a lower density and higher creep than other surrounding rocks, as in case of evaporites, it could deform and move until upper layers to form saline dome structures that compresses the overlapping formations. This compression can develop overpressure zones with potential to kick occurrence in the presence of oil, gas, brine or H_2S accumulation. Furthermore, these abnormally pressurized zones immediately below the salt are either mechanically weaker or fractured (i.e. overburden stress is not more than the main stress), presenting a greater risk of lost circulation during drilling operations. These thief zones are commonly called rubble zones (POWER; IVAN; BROOKS, 2003).

To summarize, lost-circulation zones, salt zones and additionally zones with presence of H_2S or CO_2 could be considered drilling hazards because their existence can cause risk to drilling operation.

As previously discussed in the section 2.2.1.2 (pore pressure gradient), kicks and blowouts can be caused in the abnormally high pore pressure zones. Therefore, to identify where the abnormal pore pressures may occur is of crucial significance for the well construction to reduce wellbore trouble time and avoid drilling incidents (ZHANG, 2011).

The last considered complexity in DW well architectural design, is the BOP (Blowout Preventer) restraints. BOP can be described as a valve set installed on the wellhead, which can be closed in case of an influx of formation fluid take place into the well (kick), allowing to shut in the well for further well control procedures (ROCHA; AZEVEDO, 2009; API RP 96, 2013). Thus, the selection of BOP is one of the critical phases in the developing of a well design, and it is explored in a next section.

Then, a variety of DW well architectural (casing) designs have appeared to safely meet the above cited challenges associated with the deeper water wells. Figure 2.7 shows two examples of DW casing well design that can be used to safely achieve well objectives in diverse wellbore conditions.

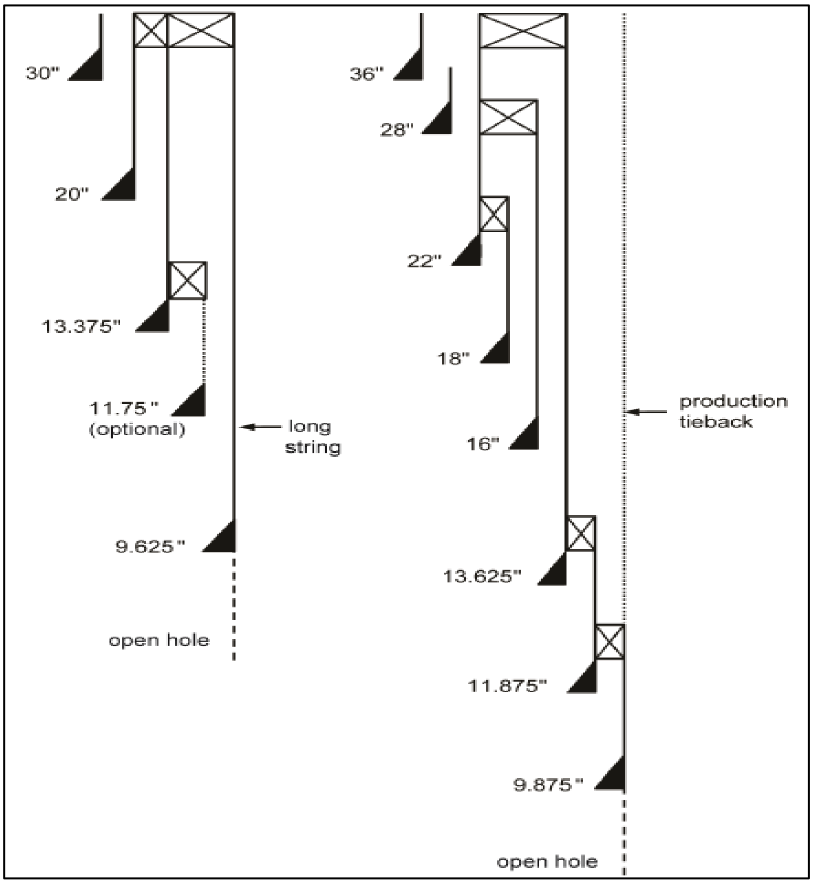

Figure 2-7 – Well architecture examples: in the left side a normal-clearance design and in the right side a tight-clearance design (Modified from API RP 96 (2013)).

The first one, a normal-clearance casing well architecture employed in areas with low pore pressure relative to fracture gradients, demanding few casing points to reach well total depth. The other one is tight-clearance well architecture to face narrow operating envelope conditions but increasing the amount of casing string set in the well. Remarkable characteristics of a tight-clearance architecture are the use of shallow intermediate liners hung in the surface casing and a large diameter intermediate casing landed in the subsea wellhead to supply additional shoe integrity and low load ratings from more liners below it (API RP 96, 2013).

Cunha (2004) introduces the evolution of DW exploratory well architectures in offshore Brazil since 1990s. The reduction of the number of casing sections was successfully done on exploratory wells where only three casing were set, because the well casings constitute one of the biggest parts of the well cost. Figure 2.8 presents a common design that includes a 30” conductor casing, 20” surface casing, 13 3/8” intermediate casing and 9 5/8” production casing. In contrast, a slender architecture without a 20” surface casing instead of a 13 3/8” intermediate casing and a longer final 12 ¼” section with a 9 5/8” production casing until the well total depth. This well configuration is frequently used in developments wells because they imply lower unknown risk when drilling.

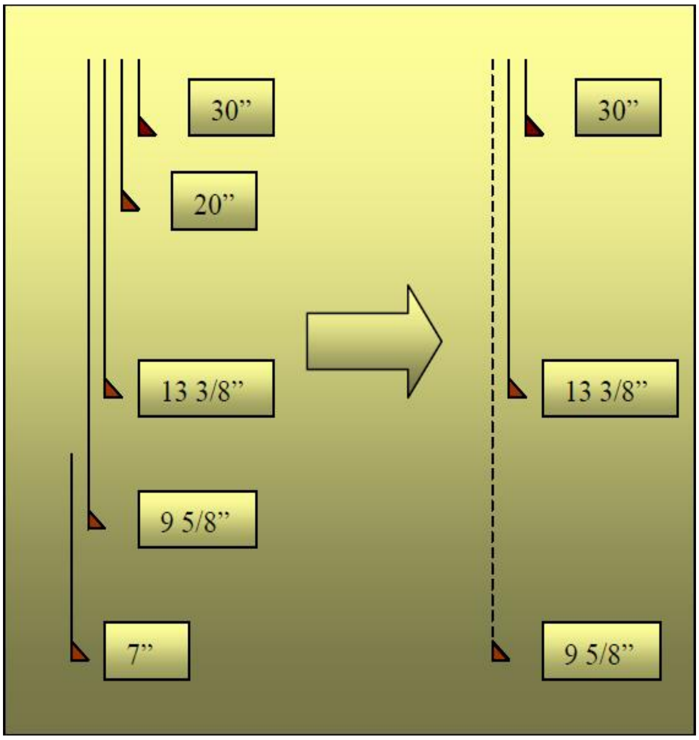

Figure 2-8 – Evolution of deepwater exploratory well design (CUNHA, 2004)

Moreover, some others typical DW well architectures largely used in the oil industry are presented in Figure 2.9, specifically in ultra-deep water wells (ROCHA; AZEVEDO, 2009).

As casings are running after each drilled phase into the well to protect the formation of breakdown, allowing that appropriate mud weight can be used in the next hole section, a conventional casing setting design is determined principally by pore pressure and fracture gradient profiles which define the bounds of the mud operating window. Despite, each oil company have their own criteria to determinate the casing shoe setting, it is common to include well control considerations to choose casing points that allow kick tolerance to be maintained (DEVEREUX, 1998; ROCHA; AZEVEDO, 2009).

Furthermore, casings shall be also designed taking into account other considerations such as the behavior of casing steel mechanical properties expected when a tensile loads are applied (stress) and the resulting strain, and other safety factors (e.g. burst, collapse, tension, compression and Buoyancy effects)(DEVEREUX, 1998; NORSOK, 2013), nevertheless in this thesis, for practical purposes, are not addressed.

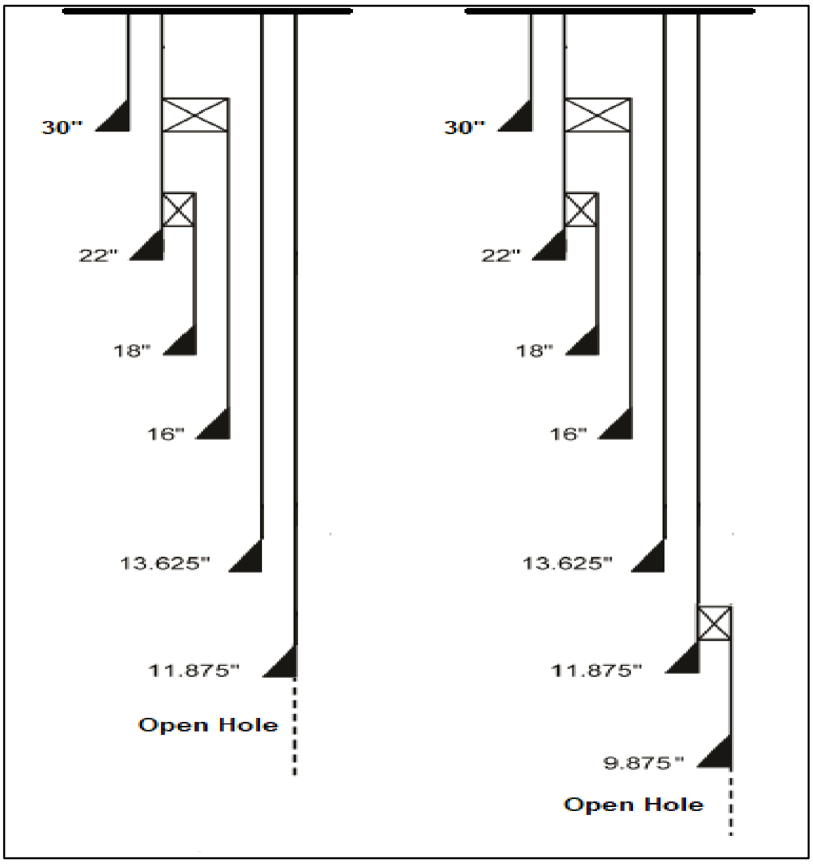

Figure 2-9 – Typical casing projects commonly used in ultra-deep water wells (Drawn based on Rocha and Azevedo (2009)).

2.2.2.1 Casing shoe depth criteria

In the stage of well drilling, the casing strings are one of the most expensive portion of the total well cost, with a participation of 15% to 20% in offshore areas. The casing strings can be commonly divided according to their purposes in following: conductor casing, superficial casing, intermediate casing, production casing and liner (ROCHA; AZEVEDO, 2009).

Conductor and surface casing are structural casings running with the manly aim to isolate shallow gas or water migration zones and in case of the presence of a kick with fractured formation, to prevent an underground blowout. Shallow gas zones with pore pressure greater than the wellbore pressure could cause kicks leading to blowouts (SANDLIN, 1986). In the specific case of superficial casing, it has also as objective to support the BOP weight and the other casings strings.

Some essential functions are performed by the intermediate casing such as protect lost-circulation zones, isolate abnormally pressurized zones and unstable hole sections, and confine production zones. The next one is the production casing, which allows the hydrocarbons can be led to surface in a safely and economically way. The last one is the liner, it is a short casing that is hung in the last casing shoe set and its main purpose is protect the open hole. It also can run as an drilling liner or production liner instead an intermediate casing or production casing respectively (DEVEREUX, 1998; ROCHA; AZEVEDO, 2009).

The choice of casing setting depth is one of the most critical tasks in preparing the well architecture design. In this selection many factors should be considered such as geological setting, abnormally pressured formations, shallow gases, lost circulation zones, wellbore pressures, troublesome zones and regulations (SANTOS et al., 1995; DEVEREUX, 1998). In addition, casings must be set with the aim of accomplishing several well design objectives such as well target, safety to crew and platform, preservation of environment and the construction of an operable and economical well.

The methods for predicting the casing setting depth are applied into two separated segments: shallow zones where conductor and surface casings are set, and deeper zones for intermediate and production casings. Clearly, in the first zone the depths are relatively shallow, therefore the setting depths are regularity defined based on the local area experience. Generally, it is assumed setting depth ranges of 10-50 m and 400-500 m for the conductor and surface casing, respectively (ROCHA; AZEVEDO, 2009).

Although, Aadnoy et al. (1991) performed an attempt to define the optimum seat depth to shallow casing string (i.e. conductor and surface casing), apparently there is not a defined method in the oil industry to stablish it. However, in a recent study, it is estimated a setting depth value of 58 m for the conductor casing by using methods based on probability statistics (XU; GUAN; SU, 2014).

In the deeper zones is common determine casing points based on two casing setting criteria: based on mud operating envelope and based on kick tolerance approach. Sometimes, it is normally considered some security margins in the limits, e.g. the riser margin (ROCHA; AZEVEDO, 2009).

2.2.2.1.1 Casing shoe depth based on the operating envelope

This criterion takes into account the pore pressure gradient curve as a lower limit and the fracture gradient curve as higher limit; hence it does not consider the probability of a kick occurrence. Furthermore, it is independent from the well geometry and it could contemplate the use of a safety factor added to the both limits of the operating envelope. Safety factor value is usually assumed as 0,5 ppg for both pore pressure and fracture gradient.

The shoe setting approach for development wells, in this case, works only from bottom to top. It means, as shown in Figure 2.10, that from the final depth of the well, one must draw a vertical arrow of mud weight until it reaches the fracture gradient curve (minus safety factor). At this depth, one must set a casing shoe. For the other casing depths is repeated the above procedure starting from the last seated shoe depth and its related pore pressure gradient (plus safety factor) (ROCHA; AZEVEDO, 2009).

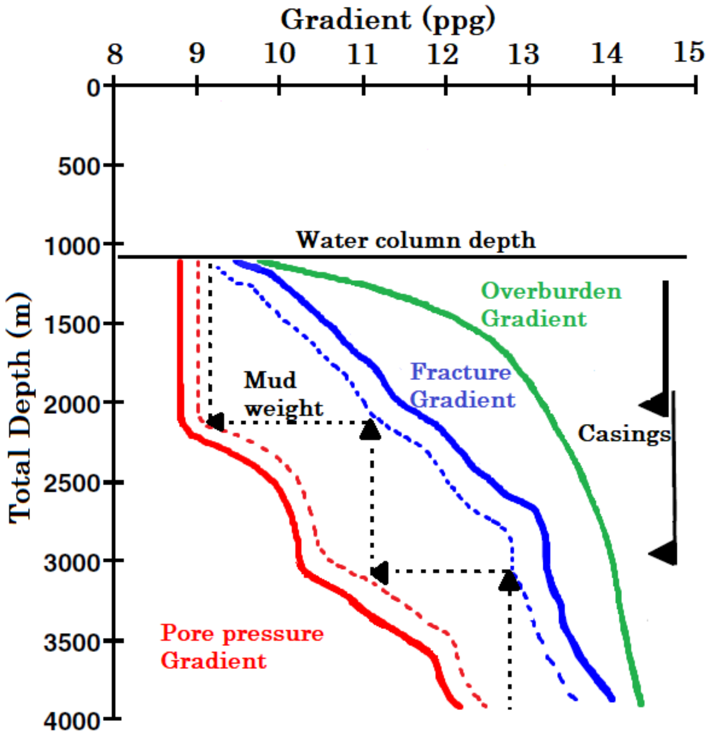

Figure 2-10 – Casing setting criterion based on pore pressure and fracture gradients with safety factors (shown as the red and blue dotted lines).

2.2.2.1.2 Casing shoe depth based on Kick tolerance

Kick tolerance can be defined as the maximum allowed pore pressure, so that in the event of a kick, the well can be closed without fracturing the weakest formation, commonly considered at the last casing shoe set (SANTOS et al., 1995; AVELAR; RIBEIRO, 2005). In fact, kick tolerance is an essential parameter to indicate the maximum volume of a given type of influx (normally gas), which can be controlled and circulated out of well allowing safe shut-in and suitable well control procedure, i.e. well killing (ZHANG, 2011; ZHANG; YIN, 2017).

The casing shoes setting criterion based on kick tolerance concept normally consider the state of pressure inside the wellbore just after the well has been shut in, meaning in static conditions. Hence, kick tolerance (ρ_{kt}) is given by the following equation (SANTOS et al., 1995; AVELAR; RIBEIRO, 2005; ROCHA; AZEVEDO, 2009):

$$\rho_{kt} = \frac{D_{fm}}{D_h}\left(G_f - \rho_{mud}\right) - \frac{h_k}{D_h}(\rho_{mud} - \rho_k) + \rho_{mud} \tag{2.8}$$

Where ρ_{kt} is kick tolerance pressure (ppg), D_{fm} is the weakest formation depth (m), D_h is well depth (m), G_F is fracture gradient of weakest formation (ppg), ρ_{mud} is drilling mud density (ppg), h_k is the kick height (m) in the annular portion and ρ_k is the invasive fluid density (ppg).

Additionally, it must be considered the “differential kick tolerance concept” that is defined as the difference value between the estimated pore gradient and kick tolerance. That is, a safety margin added to pore pressure gradient, so that in the case of a kick, there is not fracture in the weakest formation. Differential kick tolerance ($\Delta\rho_{kt}$) can be determined by using the below equation (ROCHA; AZEVEDO, 2009):

$$\Delta\rho_{kt} = \frac{D_{fm}}{D_h}\left(G_f - \rho_{mud}\right) - \frac{h_k}{D_h}(\rho_{mud} - \rho_k) + \rho_{mud} - G_P \tag{2.9}$$

Where $\Delta\rho_{kt}$ is the safety margin (ppg) and G_P is the pore pressure gradient (ppg).

The previously noted casing shoe set criterion can be applied from the surface towards the bottom of the well, i.e. from top to bottom, or from the maximum depth expected for the well to the surface, i.e. from bottom to top (SANTOS et al., 1995).

On the one hand, in the top to bottom method, the setting of casing shoe must be done when the difference between of the predicted pore gradient and kick tolerance is a value less than the minimum differential kick tolerance (i.e. safety factor), which is arbitrary stablish by each oil company. Although, the minimum safety factor is determined according to the desired level of safety, some oil companies typically establish it as 0,5 ppg. Clearly, the assumption of a kick adds an implicit safety margin for the method, but it may still use other ones.

On the other hand, the methodology from bottom to top employed a fracture gradient based on the kick tolerance and derives from eq. (2.9). This fracture gradient can calculate with eq. (2.10). So, a casing must be set when the fracture gradient based on kick tolerance (G_F^{kt}) exceed the fracture gradient estimated in operating envelope (AVELAR; RIBEIRO, 2005; ROCHA; AZEVEDO, 2009).

$$G_F^{kt} = \frac{D_h}{D_{fm}}(\Delta\rho_{kt\,min} - \rho_{mud} + G_P) - \frac{h_k}{D_h}(\rho_{mud} - \rho_k) + \rho_{mud} \quad (2.10)$$

Where G_F^{kt} is fracture gradient (ppg) based on kick tolerance and $\Delta\rho_{kt\,min}$ is the assumed minimum differential kick tolerance (ppg).

Setting from top to bottom generally tends to increase the length of the initial well phases. Therefore, this setting criterion is often applied to exploratory wells, ensuring that its final depth is reached (i.e. flexibility to deepen the well) (ROCHA; AZEVEDO, 2009).

2.2.2.2 BOP working pressure

Afterward the setting of superficial casing, the BOP (Blowout Preventer) is set and installed on the seabed by using drilling marine riser, which is a large-dimensioned column with high mechanical strength. Thus, the BOP and the drilling riser make up the connection between the well and drilling platform, granting that drilling fluid (mud) returns to surface. A typical BOP stack is composed of annular preventer in the upper part and ram-type elements (e.g. pipe, blind and shear rams) at the base (ROCHA; AZEVEDO, 2009; API RP 96, 2013).

The selection of the BOP aims to ensure that if primary well control (i.e. hydrostatic pressure from mud weight) is lost, the well can be closed and subsequently it can return back to the primary control after well killing (DEVEREUX, 1998; API RP 96, 2013). Despite, each oil company has its own criterion to choose the BOP, in some cases the BOP selection is based on the expected maximum pore pressure, considering or not water column effect. Generally, in DW drilling operations, standard BOP's present pressure ratings of 5 000, 10 000 and 15 000 psi.

Assuming that a kick occurs and a full evacuation of fluid into the well is done, and also the wellbore is completely fulfilled of gas, the maximum allowable pressure in the BOP is defined by eq. (2.11), taking into account the maximum pore pressure obtained from operating envelope and the hydrostatic pressure of the gas inside the well. Additionally, if it is contemplated water column effects in the previous criterion, BOP working pressure is given by eq. (2.12) (ROCHA; AZEVEDO, 2009).

$$P_{BOP} = 0.1704 * D_{hp} * G_{P\,max} - P_{H\,gas} \qquad (2.11)$$

$$P_{BOP} = 0.1704 * D_{hp} * G_{P\,max} - P_{H\,gas} - P_{H\,wc} \qquad (2.12)$$

Where P_{BOP} is BOP working pressure (psi), $G_{P\,max}$ and D_{hp} are maximum pore pressure (ppg) and its respective depth (m), $P_{H\,gas}$ is the hydrostatic pressure (psi) of gas column, and $P_{H\,wc}$ is the pressure (psi) exerted by water column.

With the same well conditions above mentioned, the pressure in the BOP can be restricted by fracture gradient at last casing shoe depth, where an eventual fracture of formation could lead to a reduction in wellbore pressure. Thus, the BOP working pressure can calculate with the following eq. (2.13) (ROCHA; AZEVEDO, 2009):

$$P_{BOP} = 0.1704 * D_{shoe} * G_{f\,shoe} - P_{H\,gas} \qquad (2.13)$$

Where $G_{f\,shoe}$ and D_{shoe} are fracture gradient at casing shoe and its respective depth.

Other criterion to stablish the maximum allowable pressure in BOP is the casing working pressure, i.e. the strength to internal pressure. Therefore, the BOP working pressure must be similar to internal pressure strength of casing, where the string is not going to leak and reduce pressure into the wellbore (ROCHA; AZEVEDO, 2009).

2.2.3 Well integrity

As explained in Introduction section, the well integrity can be defined as the capability to keep the control on the oil, gas or water flow from the reservoir, avoiding spills of any type to the environment. This capability is accomplished by employing safety barriers (MENDES; DA FONSECA; MIURA, 2016). Thus, barrier is one of the most relevant approaches when evaluating operational safety (PETERSEN et al., 2011). In addition, the integration of casing design with barrier envelope contributes to increased well integrity (API RP 96, 2013).

2.2.3.1 Well Barrier and Barrier Envelope

There are two main concepts about well barriers in the literature. On one hand, NORSOK Standard D-010 (2013) defines well barriers as “envelope of one or several well barrier elements preventing fluids from flowing unintentionally from the formation into the wellbore, into another formation or to the external environment”. On the other hand, API RP 96 (2013) defines physical barrier as "material object or set of objects intended to prevent the transmission of pressure and fluid flow from one side of the barrier to the other side". In other words, while NORSOK D-010 (2013) defines barrier as envelope for all pathways, the API RP 96 (2013) defines barrier as single element for one path.

In conventional drilling based on NORSOK Standard D-010 (2013), the well barriers are subdivided in primary well barrier and secondary well barrier. The primary well barrier is the hydrostatic pressure of the mud column in the annular, in overbalanced conditions, and it can be maintained with lower ECD (Equivalent Circulating Density) than the fracture gradient, according to the determined mud weight operating envelope. The secondary safety well barrier is the BOP, but certainly it is an envelope of several barrier elements, such as well head, casing string, casing cement, casing packer, among others as shown by Figure 2.11.

Miura (2004) and Miura et al. (2006) presented the concept of safety barriers and the formal definition of BIS adopted in this thesis. Thus, the safety barriers are defined as “physical separation capable to block unexpected fluid flow, from a permeable formation to the environment, along specific paths”. Instead of the two possible leakage pathways (string and string annulus inside wellbore) considered in the API RP 96 (2013), the BIS concept considers four principal paths (PETERSEN et al., 2011).

Figure 2.12 shows the four main potential leakage pathways between permeable formation and the surface or environment around the well. Permeable or fractured rock layers crossed by the well become in a lithological path (rock path) between the reservoir and the environment. The outside casing annulus between the last landed and cemented casing becomes a well annulus path. The wellbore or annular space between string and wellbore become a well path. And any string inside the well becomes the string path (PETERSEN et al., 2011; MENDES; DA FONSECA; MIURA, 2016)

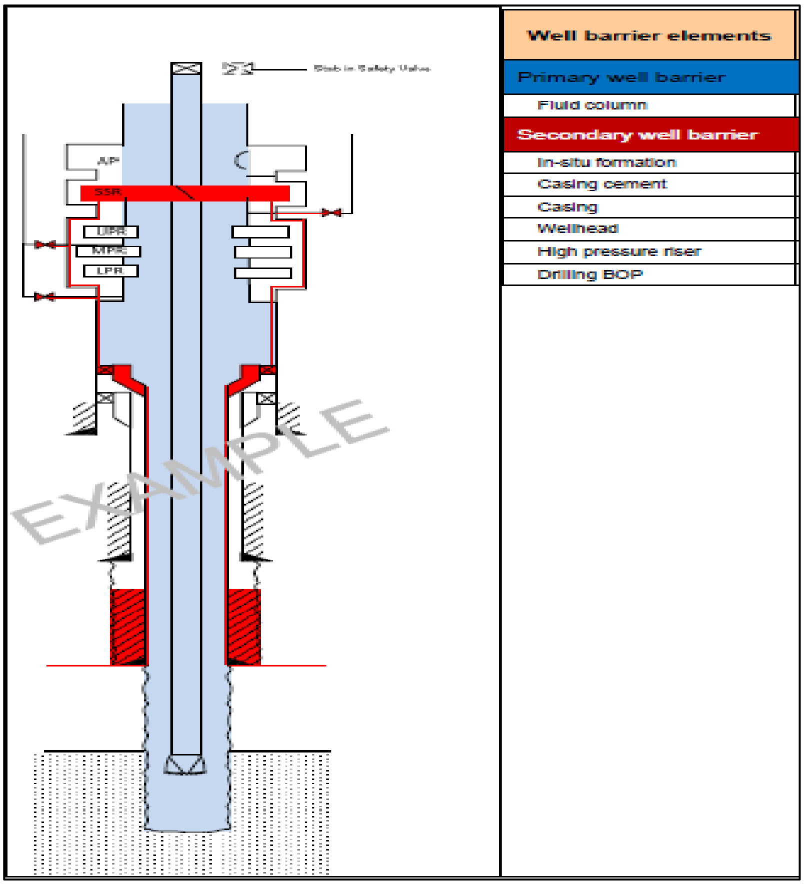

Figure 2-11 – Example of primary and secondary well barrier (Modified from NORSOK Standard D-010 (2013))

“A set composed by one or more barriers and the interfaces that interconnect these barriers, capable of preventing unintended flow of fluids from a permeable interval (formation) to external environment, considering all possible pathways" is defined as Barriers integrated set (BIS). The interface components are singular type of barrier, as well are physical separations capable to prevent unexpected flow of fluid between two adjacent paths. The definition of BIS is likely equivalent to well barrier concept described in NORSOK D-10 (PETERSEN et al., 2011).

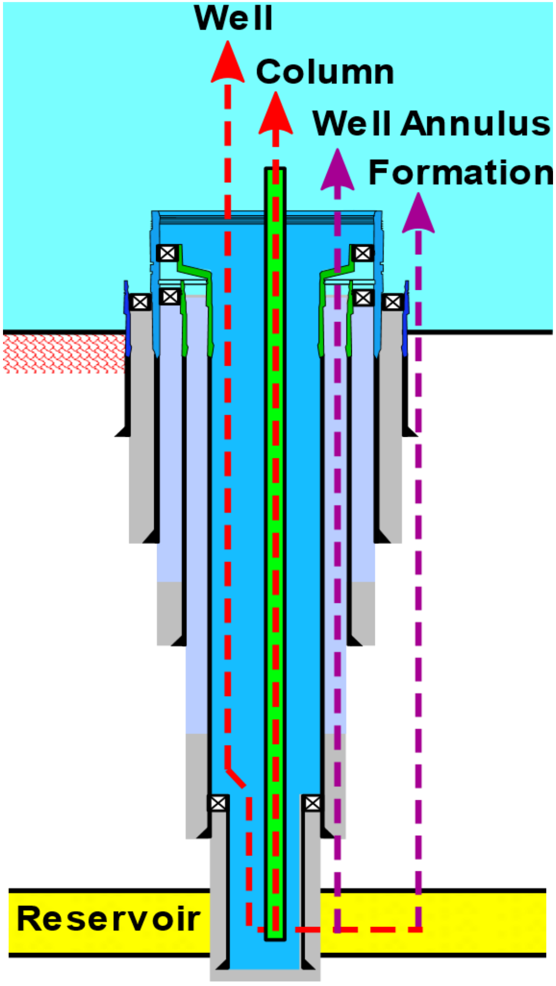

Figure 2-12 – Paths for hydrocarbon leakage from the reservoir to environment (Modified from Mendes et al. (2016)).

As is detailed in Figure 2.13, there are two BISs (Primary and Secondary) that work in the main stablished leakage pathways. However, to identify one set from another, these BISs must be mutually independent, meaning the components, i.e., barriers, of these sets do not intersect or do not belong to another one. The existence of two independent and verified BIS in the well is an acceptable criterion to diagnose a suitable condition about the well integrity (MIURA et al., 2006).

Nowadays, ANP is implementing in Brazilian oil industry the SGIP, which consists in the application of techniques, operational and organizational methods to prevent and mitigate the unintentional flow of fluids to the surface or between subsurface formations during all Life Cycle Stages of the Well (ANP, 2017c).

The ANP's statements also requires that at least must exist two (02) Solidary Barrier Sets (CSB by its acronym in Portuguese) throughout the Well Life Cycle to ensure the well integrity (ANP, 2016b). The CSB is the same definition of Barriers integrated set (BIS) defined previously.

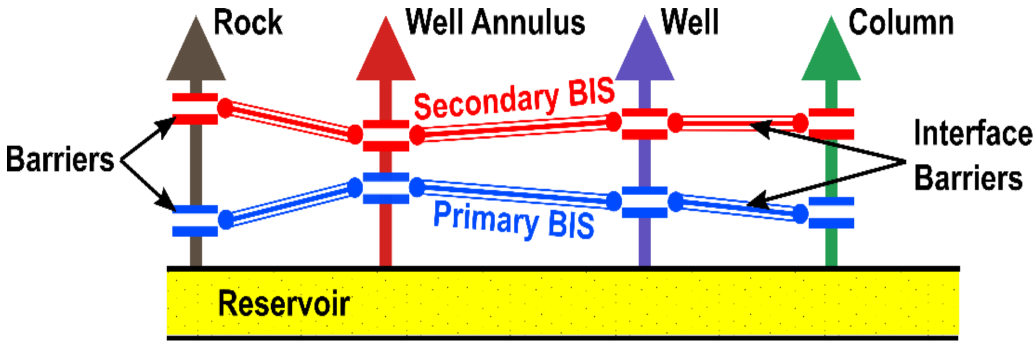

Figure 2-13 – Schematic of two independent BIS. Each BIS is composed by barriers connected through interface barrier (Modified from Mendes et al. (2016)).

Other recently view point of well barriers is related to the implementation of Managed pressure drilling systems (MPD) in regions with narrow operating window formations, e.g. fractured formations, depleted reservoirs, and DW formations. Where the safety barriers can vary according to MPD pressure control equipment and provide additional risks. Therefore, the safety well barrier can be considered like a risk reducing measures and it also plays a fundamental roll in the risk management and the risk analysis. Functions trees, fault trees and hierarchies can be used to determine the safety critical equipment for the redefinition of the safety well barrier management based on recommended industrial standard for operation on the Norwegian Continental Shelf (NORSOK, 2013). Although, these approaches are specifically related to the well control, these also can be extended for the comprehension of multiples environmental hazard events and environmental hazard sources, which affect the entire offshore drilling operation (HANDAL; OIE, 2013).

3 MATERIALS AND METHODS

The development of a well design just for the drilling phase should include the participation of a large amount of petroleum professionals to cover all the stages shown in figure 2.3, which implies a higher level of complexity. However, in this research project will be only addressed the main considerations and complexities described by the international standard API RP 96 (2013) with the purpose of simplifying the construction process of the well architectures for the drilling phase. Then, the methods and materials adopted in this study will be described in the following sections.

3.1 GEOLOGICAL INTERPRETATION OF BEM

The complexity of DW operations demands an in-depth understanding of the DW environment, thus, the first consideration to start designing a well architecture is the local geological interpretation. Therefore, the main objective of this section is the determination of possible geohazards present in the region of BEM, and the identification of drilling risk associated to drilling operation in this region by reviewing of documented occurrences and geological features in this zone.

To reduce the study area, one representative basin of BEM is considered: Ceará basin. This basin is a big region with high exploratory opportunities in DW zones. Its geological setting and petroleum systems are addressed in the following section 3.1.1. In addition, another basin of BEM, Potiguar basin, is taken into account to complement and correlate drilling risks. It can be done due to Potiguar basin shares similar evolution process and geological features with Ceará basin.

With the aim to obtain geological information closest to the features present in deeper water areas, it is mainly chosen the pioneers wells that were drilled in water depths greater than 350 m (i.e. deep-water areas according to Petrobras classification) to be analyzed. Using the BDEP's[6] web maps is determined the drilled well locations

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[6] The Exploration and Production Database (BDEP by acronym in Portuguese) of the National Agency of Petroleum, Natural Gas and Biofuels (ANP by its acronym in Portuguese).

and it is required the following data from the BDEP: well folder, digital well-logging data and composite well logging[7].

The selected exploratory DW wells were drilled between the years 1993 and 2013 in front of the shore area of the state of Ceará, of which four are in the Ceará basin and five in the Potiguar basin as shown in figure 3.1. Furthermore, four of them in deep waters and the rest in ultra-deep waters. Appendix B displays well architectural designs and the geological formations crossed by these wells.

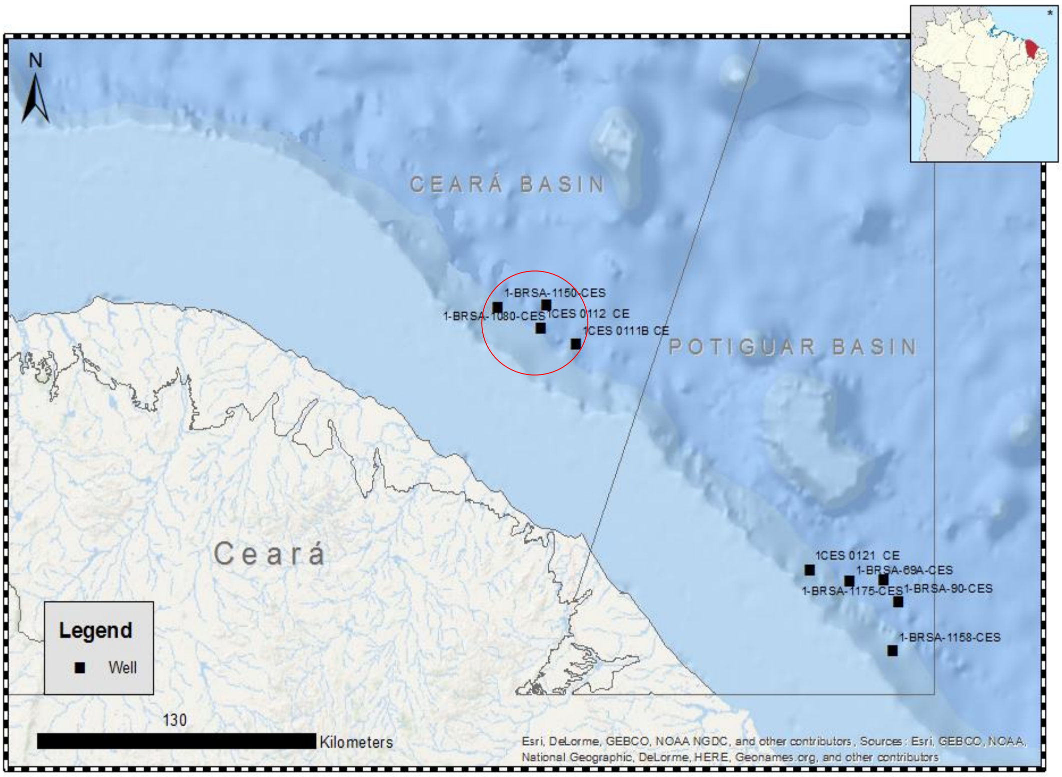


Figure 3-1 – Location of the studied wells in Ceará basin and Potiguar Basin, in the Brazilian Equatorial Margin.

The main objective of the drilling operation of these wells was to find commercially viable hydrocarbon accumulations in reservoir rocks such as the turbidite sandstones of Ubarana formation, Cretaceous rocks in Paracuru and Mundaú formation in the Ceará basin, and Ubarana, Pendência, Alagamar and Pescada formations in the Potiguar basin.

[7] This data was provided in DVD media (BDEP - ANP/STD, 2016a).

Finally, drilling reports of these wells are analyzed to identify the mainly drilling risks, e.g. lost-circulation events, that could require setting casing prematurely at that depth.

3.1.1 Ceará Basin

Ceará basin encompasses the oceanic portion in front of the state of the same name, with area of approximately 49.753 km^2. To-date, 117 wells have been drilled in this basin, 101 of which were drilled in the Mundaú sub-basin. Only 58 wells indicated presence of hydrocarbons, most of which are distributed in four shallow water fields: Atum (32° API), Curimã (27° API), Espada (35° API) and Xaréu (39° API) (ANP, 2013a, 2017d).

The drilling activities in the offshore portion began in 1971, and the first discovery took place in 1977 in Xeréu Field's shallow waters. In 1993, the first deep-water well was drilled, 1-CES-112 (water depth: 1.290m) and later in 2012 was made the first discovery in ultra-deep waters, 1-CES-158 (Water depth: 2.129m).

In 2013, the Brazil 11th bidding round offered 11 exploratory blocks, with different formation targets and exploratory opportunities in the Ceará basin, specifically in Mundaú sub-basin. The offered block is divided in deep (4 blocks) and ultra-deep (7 blocks) waters (ANP, 2013a, 2013b, 2017a). Recently, in the Brazil 15th bidding round has been offered 12 exploratory blocks located in deepwater areas (water depths >1000 m) of the Acaraú, Icaraí and Mundaú sub-basins (ANP, 2017d).

3.1.1.1 Geological setting

Three segments are recognized in the Ceará basin according to the peculiarities in structural and stratigraphic styles: from west to east, the sub-basins of Piauí-Camocim, Acaraú-Icaraí and Mundaú. These are characterized by different complex structural areas separated by major positive transverse features, corresponding to the high basement, large igneous bodies or large-scale anticline structures produced by syn-sedimentary inversion. Seamounts and guyots comprises this basin (MILANI et al., 2000; FAVERA et al., 2013)

Western Ceará Basin involves the sub-basins of Piauí-Camocim and Acaraú-Icaraí in front of the coast of Piauí and Ceará states. According to Bacoccoli and Bedregal (2002), it extends over about 29.090 km^2 of the offshore region, being divided into 50% of deepwater area and 50% of shallow water area. The Piauí-Camocim sub-basin is a complex segment owing to the transpressional inversion zones (MILANI et al., 2000).

The first of the stratigraphic mega-sequences that occurred in these basin is the rift (Lower Aptian) that represents to Mundaú Formation, comprised of continental lacustrine facies and shallow marine sediments like coarse clastics that grade into interbedded sandstones and shales (BELOPOLSKY et al., 2015). The transitional sequence (Upper Aptian) corresponds of the Paracuru Formation containing carbonates and evaporites, which also grades into interbedded shales and sandstones. Here is marked the transition from the continental environment to marine environment (FAVERA et al., 2013). The last sequence, the drift (Albian to recent), involves the Ubarana Formation composed by siliciclastic sediments. In the Tertiary, a thick sequence of sandstones occurs in the Tibau formation in the adjacent position and grades into carbonates (calcarenite) of Guamaré formation, and volcanic intrusions in the Macau Formation.

Eastern Ceará Basin, the Mundaú sub-basin, has a tectonic evolution less complex than the other basins and covers an area of 10.000 km^2 of depth water upper of 100 m. It has borders on the north with the transform fault (Romanche Fracture Zone) of Ceará in E-W direction and on the east with the Fortaleza high of the Potiguar basin. In this sense, many author associate this sub-basin to the Potiguar basin to calculate the total offshore area (BACOCCOLI; BEDREGAL, 2002). Figure 3.2 displays the stratigraphic framework of the Mundaú sub-basin.

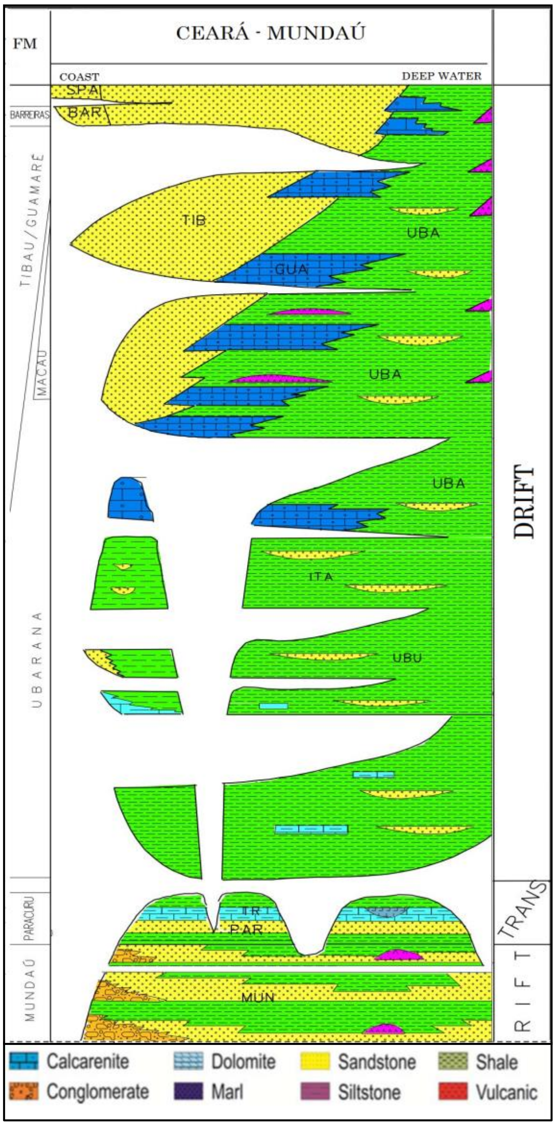


Figure 3-2 – Stratigraphic framework of Mundaú sub-basin (Modified from ANP, 2002).

The development of the normal faults and the thick sedimentary layers of continental shales and sandstones that comprises the Mundaú formation characterize the rift sequence (Neocomian to Aptian) of this basin. The transitional sequence (upper Aptian to Albian) is represented by the deposition of fluvial-lacustrine sandstones and limestone of the Paracurú formation. The drift sequence (Albian to recent) begins with the thermal subsidence of the basins, and posterior carbonates and shales of the Ponta do Mel and Ubarana formations respectively. Besides of clastic marine sediments of the Barreiras formation (MOHRIAK, 2003).

3.1.1.2 Petroleum Systems

An active petroleum system addresses the presence and the synchronized work of elements and geologic events: A mature source rock to generate and expulse hydrocarbons, a network of pathway and hydrocarbon migration event, a porous reservoir rock to storage and a seal area or rock to trap the hydrocarbons. All of these must take place in a proper time sequence to form a petroleum play (MILANI et al., 2000).

According to ANP (2017b), there are mainly three plays in the Ceará basin: Upper-Cretaceous turbiditic sandstone (Ubarama formation), Neo-Aptian fluvial-deltaic sandstone (Paracuru formation), and Aptian fluvial-deltaic sandstone (Mundaú formation).

In the last years, Petrobras discovered an Aptian deposit of light oil in the deepwater region of Ceará basin through well 1-CES-158. The Aptian-and-Albian-aged shales deposited in rift and transitional sequences in the basins of BEM are the main known source rocks. Although, the deep water of the Ceará basin is relatively unknown, there are several sedimentary basins that share similar tectonic and structural evolution of this, such as the Equatorial Margin of Ghana, the Ivory Coast, Liberia, Sierra Leone and French Guyana, where large exploration discoveries have been made in Upper Cretaceous petroleum system with thick high quality upper Cretaceous turbidite reservoirs (FAVERA et al., 2013).

However, as indicated previously, the oil industry is moving on to further test of deeper water lower (early) Cretaceous turbidite play. Consequently, Mundaú and Paracurú formations of the Ceará basin become on important well targets.

3.2 OPERATING ENVELOPE

Afterward of the geological interpretations, the next step to construct a well architectural basis according to API RP 96 (2013), is the determination of the acting subsurface pressures in order to compose the mud weight operating envelope.

Table 3.1 displays the four vertical wells in the Ceará basin selected for this work segment (well group within the red circle in figure 3.1). These wells, located specifically in the sub-basin Mundaú, are principally chosen because they were drilled in deeper water areas and their importance in the DW drilling history of Ceará basin. Particularly, 1-CES-112 being the first well in deep water and 1-CES-158 that was the first oil discover in ultra-deep water. Moreover, the stratigraphic columns shown in figure 2.2 is clearly identified in the four wells, which implies a great relationship with the geological features of the Mundaú sub-basin zone found in the literature.

Table 3.1 – Selected vertical well names and features

Well name	Water Depth (m)	Commentaries
1-CES-111B	1772	No signs of hydrocarbons
1-CES-112	1290	First well in deep water of Ceará basin Dry with signs of hydrocarbons.
1-CES-158	2130	First oil discovery in ultra-deep water
1-CES-159	1314	Dry with signs of gas

3.2.1 Geo-pressures estimation

Only well logging data of **1-CES-158** and **1-CES-159** (underlined in table 3.1) are employed to estimate and plot the geo-pressures curves along of their whole depth (BDEP - ANP/STD, 2016,2016b,2016c). Hence, these two actual pioneer wells are used as example to assess the DW and ultra-deep water operating envelopes in this section, and in the next segment to define the casing shoe depths and well barriers envelope.

The other two wells, **1-CES-111B** and **1-CES-112**, are not used for this purpose because of limited available information of well logging obtained from the BDEP.

Nevertheless, some data of the drilling reports of these wells are contemplated for determining expressions of the fracture gradient equation.

For this step is necessary to use the software Interactive Petrophysics[8] to read and extract the well logging data. Then, it is calculated and plotted the different geopressures curves by utilizing spreadsheet capability.

3.2.1.1 Overburden Gradient

The tables 3.2 and 3.3 shows the general sequences with which were developed the overburden gradient estimation by employing density profile data and sonic profile data:

[8] Interactive Petrophysics (IP) v4.2, is a Senergy software, which is used to interpret Petrophysical, geophysical and reservoir data.

Table 3.2 – Overburden gradient estimation sequence by using density log data.

Section	Depth range (m) 1-CES-158	Depth range (m) 1-CES-159	Phases
Water Column	2130	1314	a) It is assumed a common value of 1.03 g/cm^3 as the water density and it is calculated the water column pressure.
Superficial zone	836	667	b) As the surface segment does not have any density logging data, it is assumed an average value of density of 2 g/cm^3 for the entire zone to calculate the overburden pressure.
Deep zone	2954	2063	c) With **the density profile data** obtained in this section and using **eq. (2.1)**, the pressure increments are determined for each depth and they are summed to the items a) and b).
Total Depth	5948	4072	d) The overburden gradients for each depth is calculated by dividing of the item c) by the respective depth.

Table 3.3 – Overburden gradient estimation sequence by using sonic log data.

Section	Depth range (m) 1-CES-158	Depth range (m) 1-CES-159	Phases
Water Column	2130	1314	a) It is assumed a common value of 1.03 g/cm^3 as the water density and it is calculated the water column pressure.
Superficial zone	836	667	b) As the surface segment does not have any density logging data, it is assumed an average value of density of 2 g/cm^3 for the entire zone to calculate the overburden pressure.
Deep zone	2954	2063	c) Using the **correlation equation (2.3),** assuming the parameters A = 0.23 and B = 0.25, and **the sonic log data,** it is determined the density values for each depth of this section. After, the pressure increments are calculated by applying the hydrostatic pressure equation and they are summed to the items a) and b) as is shown in **eq. (2.1).**
Total Depth	5948	4072	d) The overburden gradients for each depth were calculated by dividing of the item c) by the related depth.

3.2.1.2 Pore Pressure Gradient

The phases to estimate the pore pressure gradient are detailed in the following:

Table 3.4 – Pore pressure gradient estimation by sonic log data.

Section	Depth range (m) 1-CES-158	Depth range (m) 1-CES-159	Phases
Superficial zone	836	667	a) As the surface zone does not have any sonic logging data, this section is not considered in the study, but according to literature review, this zone should have a behavior close to the normal pore pressure Gradient (≈8,66 ppg)
Deep zone	2954	2063	b) As most of correlations work with the theory of compaction of shales, sonic log data employed in this phase is only reduced to shale response points. Thus, the sonic log data is plotted versus the respective depth in a semi logarithmic graphic in order to identify the trend line of normal compaction of shales. c) With the equation of straight line determined in the previous step is estimated normalized travel times for the whole depth of this segment.
Deep zone (Total Depth)	2954	2063	d) The **Gardner equation (2.4)** is applied with an exponent value equal to 2.0, to estimate pore pressure gradient for each depth considered in b). The values of the overburden gradient utilized in this equation are those obtained using sonic log data.

3.2.1.3 Fracture Gradient

Similar to the previous overburden gradient and pore pressure gradient estimation procedures, the determination of the fracture gradient is developed in phases, as is displayed in table 3.5.

Table 3.5 – Fracture Gradient estimation sequence by using sonic log data.

(To be continued)

Section	**Depth range (m)**		**Phases**
	1-CES-158	**1-CES-159**	
Superficial zone	836	667	a) As the surface zone does not have any sonic logging data, this section is not considered.
Deep zone	2954	2063	b) LOTs values taken from the drilling reports of 1-CES-111B and 1-CES-112 are analyzed with the purpose of estimate a K correlation that can be applied in **eq. (2.6).** As these wells do not have the same water column than the study wells, LOTs values are standardized by employing the sediments depths. c) **Eq. (2.7)** is utilized with the normalizing LOTs gradients, estimated (sonic log data) pore pressure and overburden pressure gradients in the respective depth. The values obtained from the previous equation are plotted and it is determined a trend line with its related graphic equation.

Table 3.6 – Fracture Gradient estimation sequence by using sonic log data. (Conclusion)

Section	Depth range (m) 1-CES-158	Depth range (m) 1-CES-159	Phases
Deep zone	2954	2063	d) With the equation found in c) is calculated the K for the total depth range of each well.
Deep zone (Total Depth)	2954	2063	e) The fracture gradient for each depth considered in b) is estimated by applying the **eq. (2.6).** The values of the overburden gradient used in this equation are those obtained using sonic log data for each depth of the shale points.

3.2.2 Operating envelope building

To construct the mud weight operating envelope for each study well is plotted, in a Gradient vs Depth graphic, the overburden, pore pressure and fracture gradient curves obtained from the above sections. A schematic process of this development is described in Table 3.6.

Additionally, with the aim to observe the effect of water column in the overburden and fracture gradient, it is used for only this section the well 1-CES-56 (BDEP - ANP/STD, 2016d). Thus, for this well, drilled in shallow water of Ceará basin, it is estimated the operating envelope similar to other sample wells.

Table 3.7 – Schematic process of the determination of drilling operation windows.

Section	Depth range (m) 1-CES-158	Depth range (m) 1-CES-159	Phases
Superficial zone	836	667	a) This zone does not show pore pressure and fracture gradient curves because of lacking well logging information. However, overburden curves regarding to sonic log and density log data are plotted in a graphic of gradient (ppg) versus depth (meters), the depth column is formatted to values with inverse order.
Deep zone	2954	2063	b) In the same graph utilized in a) is plotted the overburden, pore pressure and fracture gradient curves calculated in the previous **section 3.2.1.** c) With the purpose of improving the understanding of the operation windows, the data from pore pressure and fracture gradient is reduced in depth step of 50-100 meters.
Total Depth	5948	4072	d) In a single chart is put on the items a), b) and c).

3.3 DEEPWATER WELL ARCHITECTURE

The next phase of this research project mainly consists in the developing and integration of casing design and well integrity. That is, in the following steps is estimated the casing shoe points of two studied wells by using two settlement criteria. Then, the casing depths are assessed considering associated drilling risks, DW complexities and typical well architectures, and finally it is introduced the BIS application to these casing setting depths and DW well architectural designs.

Note that in this work is not addressed a complete casing design that stablish casing sizes, hole sizes and phases by predicting the behavior of casing string mechanical properties and safety factors. However, typical DW and ultra-deepwater well configurations are explored to cover this gap.

3.3.1 Casing depth determination

The central objective of this stage is to stablish the casing depths by using the operating windows defined in the previous steps of this work. This determination is performed by applying two settlement criteria found in the literature. In addition, it is considered security margins, DW complexities and drilling risks that could affect the casing shoe setting.

The first casing setting depth methodology adopted in this thesis is the criterion based on operating envelope (bottom to top). This criterion is executed as shown in figure 2.10. Two safety factors of 0.5 ppg are included for both pore pressure and fracture gradient.

The second setting criterion based on kick tolerance is applied from top to bottom. Top to bottom approach is often applied to exploratory wells, then it can increase the accuracy of the results in the criterion application for the example pioneer wells. The following steps summarizes it:

1. the conductor and surface casing depths are assumed as 58 m and 500 m respectively;

2. It is added safety factors of 0,5 ppg to both pore pressure and fracture gradient;
3. the fracture gradient (minus safety factor) is fixed as the lowest, which is at the depth of the surface casing shoe;
4. starting from this depth, differential kick tolerance is calculated for each depth interval by applying **eq. (2.9)**;
5. a casing shoe is set, when the differential kick tolerance reaches a value equal to or less than the assumed safety margin of minimum allowable differential kick tolerance;
6. it is repeated the previous steps until finding the subsequent shoes, starting from the depth of the last shoe.

This procedure is developing by using spreadsheet iterations capability. Moreover, the below assumptions are done to obtain a representative result of the previous equation according to the literature. Although, the minimum differential kick tolerance (safety margin) is determined according to the desired level of safety, some oil companies typically establish it as 0,5 ppg.

This thesis adopts the volume and density of the occurred kick as 50 bbl and 2 ppg respectively in order to determine the kick length. Similarly, it assumes a bottomhole assembly (BHA) diameter of 5” for the whole depth.

After that, the presence of DW complexities (e.g. narrow operating envelope, shallow gas or water and salt zones) is reviewed to assess the casing shoe depths previously determined.

3.3.2 BOP working pressure

As the selection of BOP is an important phase in the developing of a well architectural design because it is a limitation factor regarding to kick occurrences, well integrity and well control procedures, BOP working pressure must calculate to select the suitable BOP. Three different ways are employed in this section to estimate the maximum allowable pressure into BOP: based on maximum pore pressure, based on water effects and pore pressure, and based on fracture gradient.

It is assumed that the maximum pore pressure expected is related to well final depth and a gas density of 2 ppg, then the BOP working pressure considering pore pressure gradient and water effects is stablished by **equations (2.11)** and **(2.12)** respectively. For the last estimation methods is considered the fracture gradient in the last casing shoe depth set previously determined for each studied well, and it is applied **eq. (2.13)**. The maximum BOP working pressure between the three pressures calculated above is the limiting pressure, and it must be compared with the standards BOP's ratings pressures to select the appropriate BOP.

3.3.3 Well barrier envelope

This last step, with the purpose of assuring the well integrity for eventual exploratory drilling in Ceará basin, it is introduced the well barrier envelope application to the two sample wells. Despite, NORSOK Standard D-010 (2013) has been largely explored in the oil industry and conventional drilling operations, in this work is applied the BIS concept because it has been recently required in the offshore operation in Brazil by ANP regulation.

The application of BIS concept is introduced for only one drilling phase, but including the operations related to this phase, for example the cementing and the running of the casing. As the well construction next to reach the reservoir depth has higher operation risks and complexities, a related drilling phase is assessed in this work.

The 4^{th} drilling phase of the two sample wells starts immediately after the intermediate casing or liner is set and cemented. Thus, for each step of the 4^{th} drilling phase is detailed the primary and secondary BISs. The concern of independent BIS is also assessed. Additionally, the casing shoe points stablished in previous sections are checked regarding to BIS application requirements.

4 RESULTS AND DISCUSSIONS

4.1 RISKS ASSOCIATED TO DRILLING OPERATIONS IN BEM

The principal occurrences observed in the review of the drilling reports and their related offshore drilling hazards compared with the geological hazard conditions of the Ceará and Potiguar basins are described in the following table:

Table 4.1. Offshore drilling hazards/risks in Ceará and Potiguar basins.

Well	Drilling Hazard/Risk	Occurrence
1-CES-112	High sea currents/ riser disconnects and vortex shedding.	Due to a high current of 2-knot during the running of the 20 in casing, the drillship Discover Seven Seas was move off from the drilling site (Reduction of drilling site accuracy)
1-CES-121	Wellbore instabilities	The well 1-CES-121 showed many wellbore elongations in the drilling phase of 8 ½” borehole because of poorly-consolidated sandstones.
1-CES-111B	Loss of circulation (Narrow operating envelope)	It was presented a total loss of circulation at depth of 2175 m (Ubarana formation). LOTs values of this zone were considered very low to continue this drilling phase; hence a casing string was set sooner than planned.
1-CES-121	Loss of circulation	It was detected a partial loss of circulation at depth 1890 m (Ubarana formation). This lost-circulation incident was solved with a moderate rate of penetration (ROP).

The data obtained from the studied wells demonstrates that, in fact, in BEM can be found high currents, implying several inherent risks in the related drilling operations. The principal problems in high current areas are the slingshot effects during a riser/BOP disconnect, vortex shedding and deflected riser. The slingshot effect occurs by the riser recoil or motion of the suspended marine riser when it is tensioned, and it is disconnected of the lower BOP stack sitting on the ocean floor in emergency. However, these risks could be rapidly controlled or prevented with appropriate operational measures or equipment.

For this work purpose, it is crucial to identify the loss circulation zones where the mud hydrostatic pressure could fall below pore pressure and allow a kick occurrence that will affect the well integrity.

According to the findings shown in Table 4.1, the Ubarana formation must be considered as a possible zone of lost circulation for eventual drilling operations. That is, some of the studied wells present lost-circulations event at depths in the Ubarana formation, and even though it is a common occurrence that can be remediate with different effective methods (e.g. using fluid-loss control materials or moderate ROP), it can be principally prevented with a suitable mud weight determined by using the operating envelope.

Furthermore, conducting an accurate Leak-off test (LOT) is essential to preventing lost circulation after a casing string is set. For example, in the well 1-CES-111B is evidenced with very low LOTs values the need to set a casing to protect the formation of fractures and subsequently lost-circulation problems. This operation procedure is normally performed in areas with narrow operating envelopes.

Despite, shallow gas/water problems were not reported in the drilling operations of the studied wells, according to the literature, a deeper study about these geohazard should be performed due to the high risks that represent in operations relating the offshore drilling. One possible reason for does not have any finding of shallow gas/water formations is that the analyzed region is only two basins of five that compose the BEM.

An additional concern is whether there is presence of salt and subsalt zones in BEM that could be taken as drilling complexities, nevertheless the data acquired in this work does not show evidence of presence of salt zones neither rubble zones at least in DW studied areas of Ceará and Potiguar basins.

4.2 WELL ARCHITECTURAL DESIGN

The next findings are main based on the analysis of well-logging data and drilling configuration of the DW exploratory wells 1-CES-159 and 1-CES-158. Thus, it is displayed the development of the major well project considerations that compose the DW well architecture propose that will allow a safety drilling of eventual deep and ultra-deepwater wells in the Ceará basin, specifically in the Mundaú sub-basin.

4.2.1 Operating Envelopes

Figure 4.1 and 4.2 displays the charts with the overburden, pore pressure and fracture gradient curves for each of two sample wells. In addition, with the purpose of representing the rock layers intervals and formations crossed by the wells, a stratigraphic column is added to the above charts, nevertheless some depth intervals with interbedded sandstones and shales layers are hardly represented accuracy and visible.

The previous charts present two curves of overburden gradient, because two different methods of calculation are applied, with density log and sonic log data. The curve that represents the pore pressures gradient only shows estimated pore gradients of the shale points with depth step of 50-100 meters. Similarly, the fracture gradient curve is plotted at the same depth step of 50-100 meters.

In the determination of the fracture gradient is employed real LOTs values of the wells 1-CES-112 and 1-CES-111B, these values are extrapolated to the water column of the two sample wells as is detailed in appendix C. Appendix D shows the pore pressure and fracture gradient data with the respective depths used to plot the operating envelopes displays below.

Some behaviors of the pore pressure curves in the two operating envelopes are similar; this may be due to the fact that are in the range depth of the same formation, for example in the segment of the Ubarana formation (≈1300-3900m). In addition, the findings can highly indicate the possibility that the operating window obtained from 1-CES-159 does not be sufficiently representative of the pressures limits. One probably reason for this insufficiency is due to the total well depth only cover the Ubarana formation and a very short segment of Paracuru formation, and not the other target formation as Mundaú.

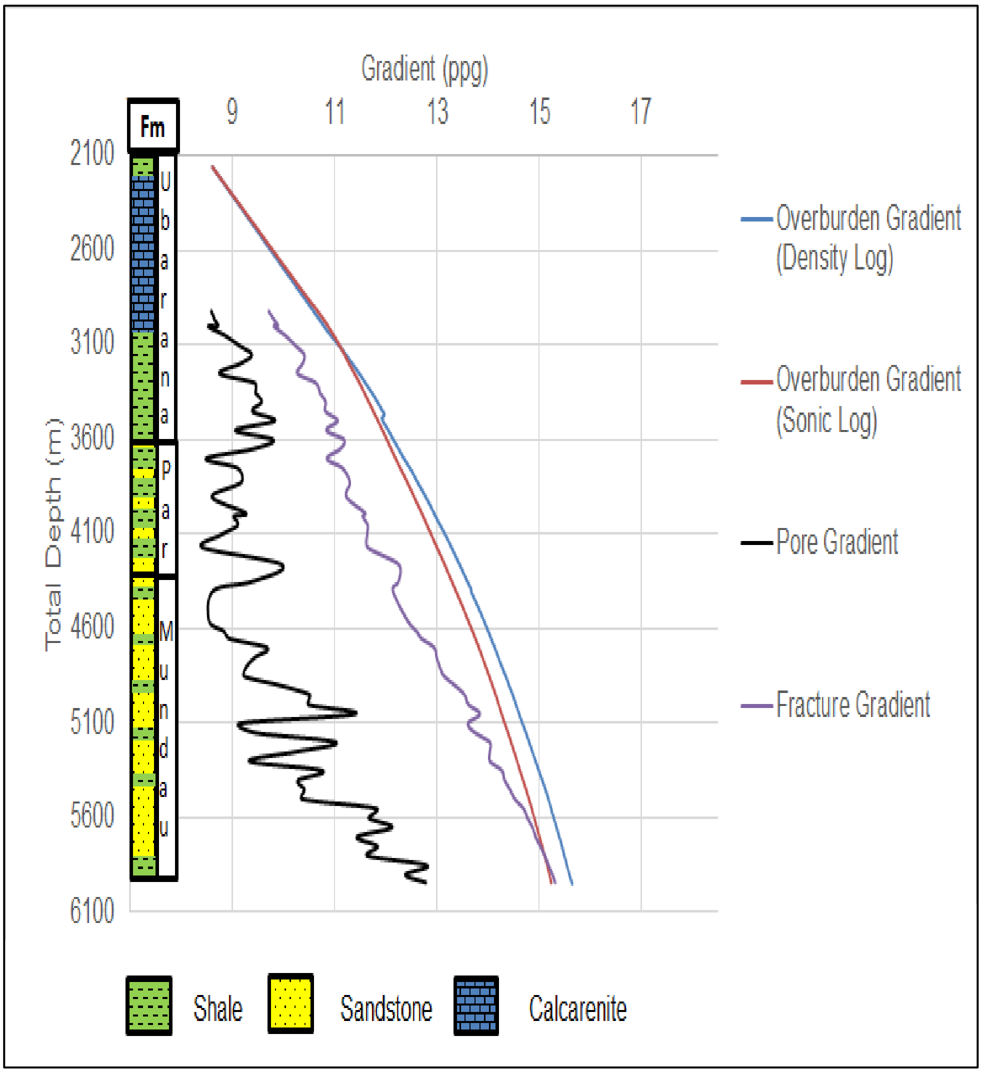


Figure 4-1 – Estimated operating envelope for the Ultra-deepwater well 1-CES-158.

In line with the existing literature, it is observed that the water column has a great influence in the overburden gradient curves and subsequently in the fracture gradient curves. Figure 4.3 shows an additional operating envelope of a shallow water well 1-CES-56 used with the aim to analyze the water column effect.

Table 4.2 presents a practical comparison of the water column and overburden gradient, where the depth of 3100 m is fixed for each operating window present in figure 4.1,4.2 and 4.3. It can be noted that as the water depth increases the overburden gradient decreases at the same depth point. Hence, the results from this study provide evidence consistent with the literature regarding to common presence of narrow operating window in deeper water environments as can be perceived in the depth range of 3000-3600 m (Ubarana formation) of operating envelope of 1-CES-158 and in the last section of Ubarana formation (≈3600-3900m) of 1-CES-159.

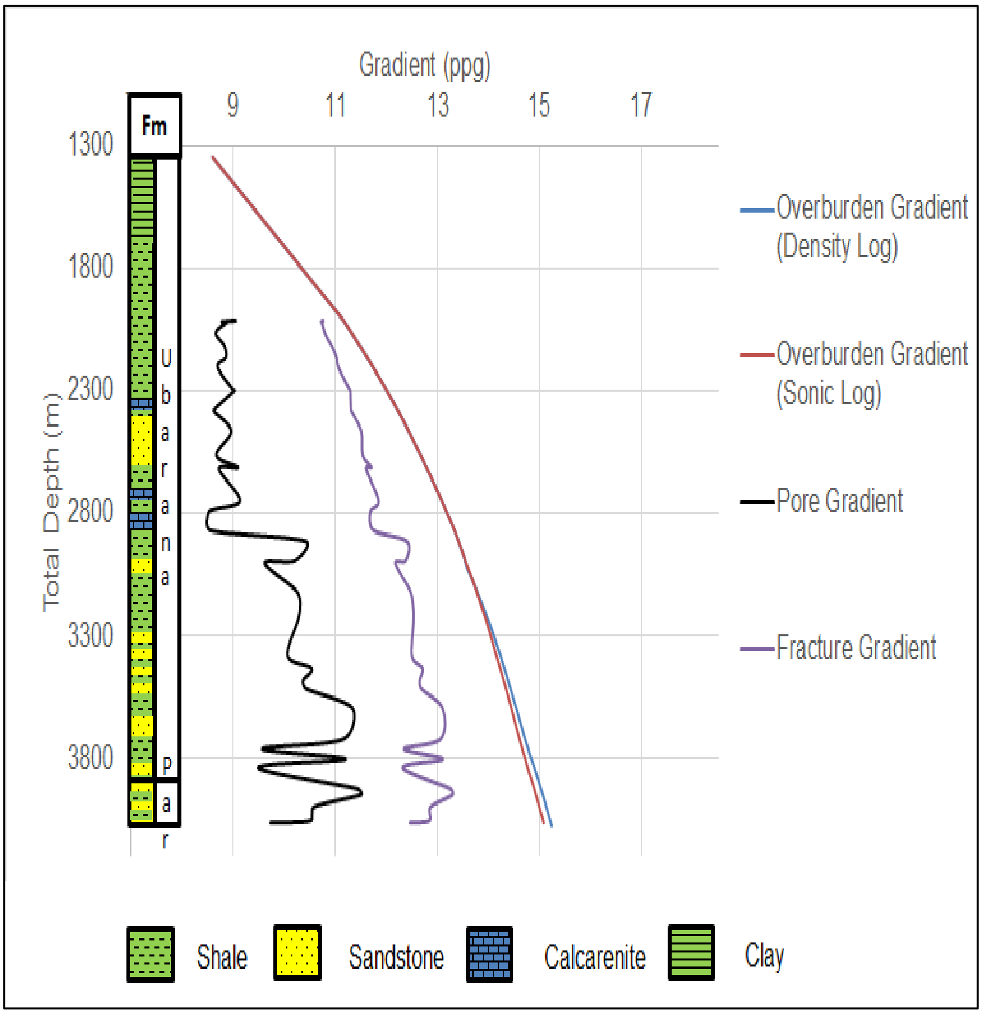


Figure 4-2 – Estimated operating envelope for the DW well 1-CES-159.

Table 4.2 – Water column and Overburden gradient relationship.

Well	Water column (m)	Overburden gradient @ 3100m (ppg)
1-CES-56	47	18.23
1-CES-159	1314	13.74
1-CES-158	2130	11.08

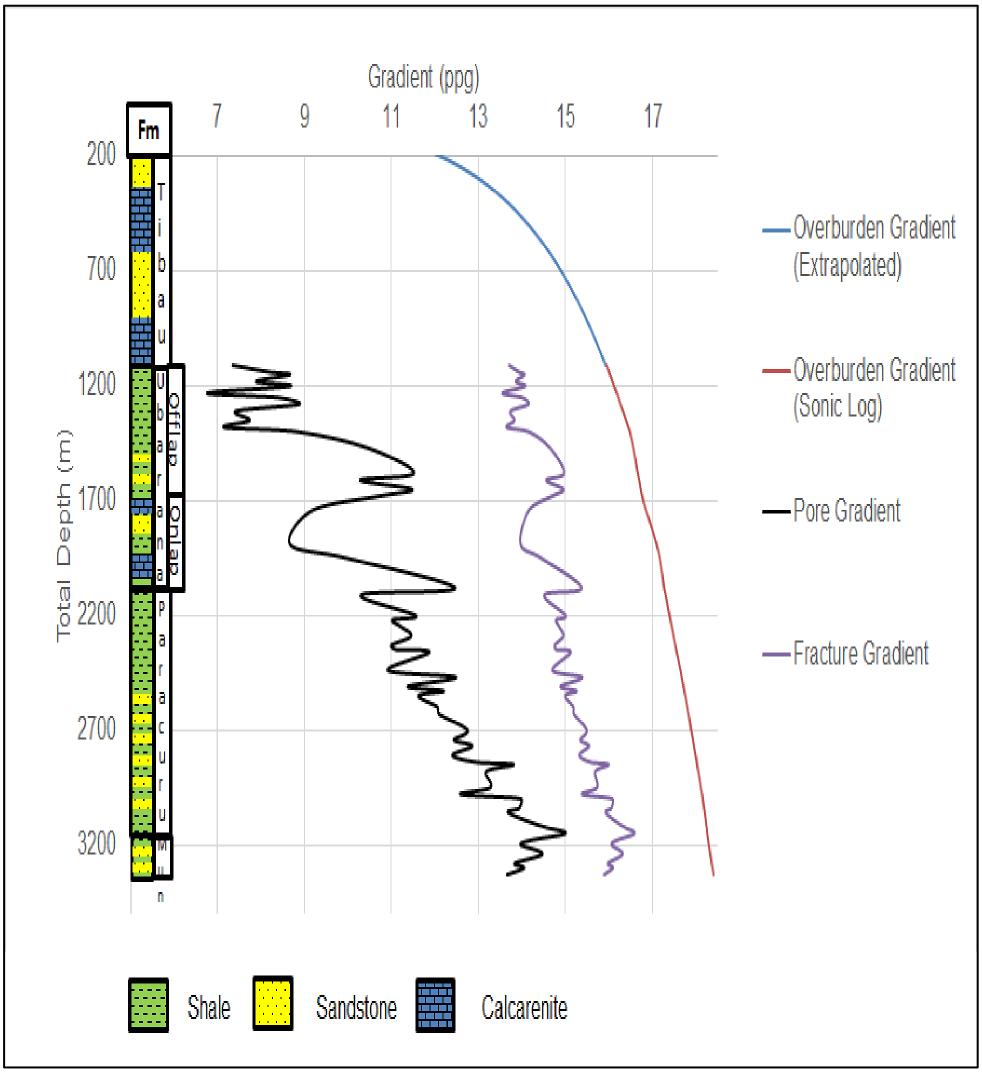


Figure 4-3 – Estimated operating envelope for the shallow water well 1-CES-56

4.2.2 Casing shoe depths, DW complexities and BOP working pressure

The determined casing depths based on operating envelope and kick tolerance criterion of the DW well 1-CES-159 are displayed in figures 4.4 and 4.5, respectively. The running of the casing string into the well 1-CES-59 in hole section of 12 ¼" was not performed in the actual well because it was found a dry reservoir during this drilling phase, consequently the well was abandoned. However, for the purpose of this paper, it is estimated the settlement of 9 5/8" casing string for this hole section.

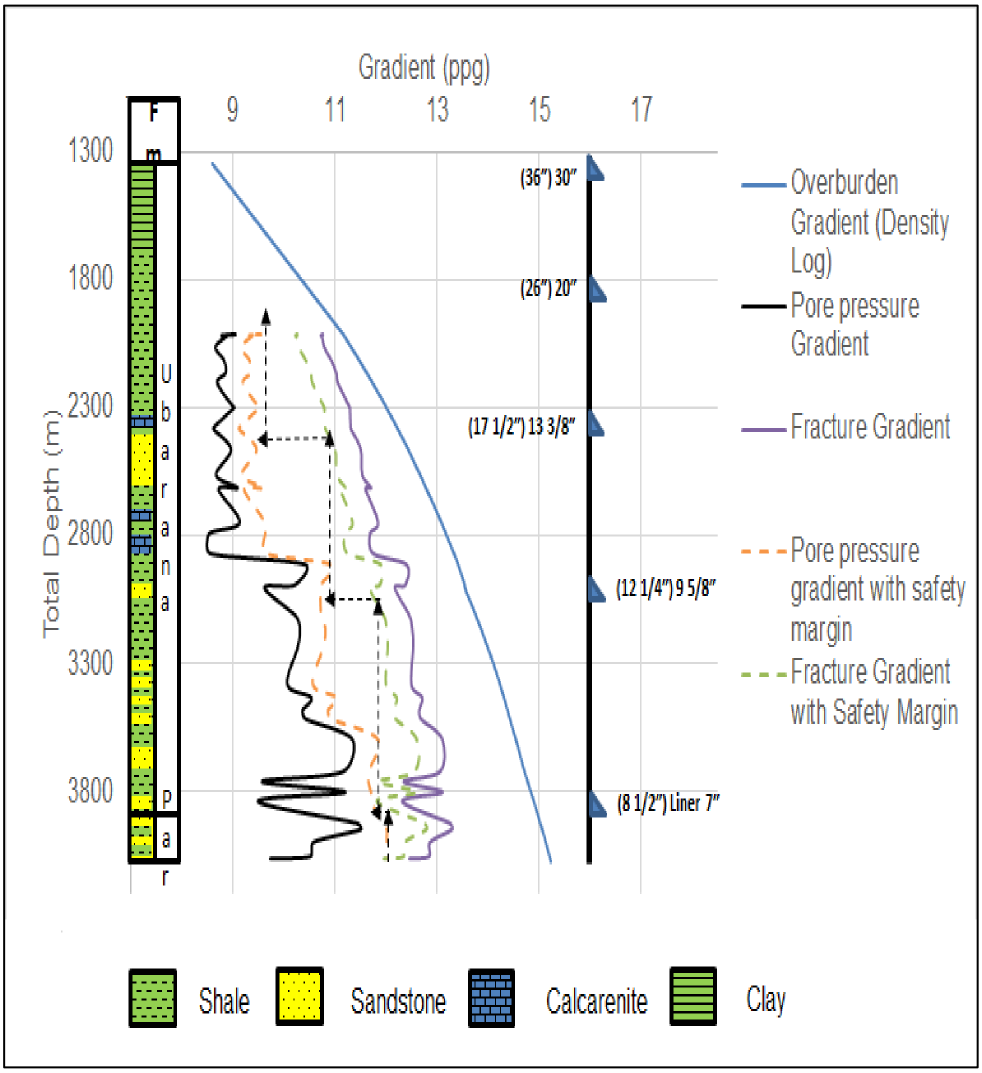


Figure 4-4 – Casing shoe depths based only on operating envelope (bottom to top) in the DW well 1-CES-159.

The casing string sizes and hole sizes in figure 4.4 and figure 4.5 are selected according to a normal-clearance design used in zones with low pore pressure gradients relative to fracture gradients. This area feature can be observed in almost the whole depth of the well 1-CES-59, nevertheless in the last segment (≈3600-3900m) of the hole is noted a narrowing of the operating envelope. One possible reason for this DW complexity, additional to water column effect previously discussed, is the existence of abnormal pore pressures, specifically an overpressure zone that could cause the need during drilling operation to increase the mud weight to avoid kick.

However, higher mud weights could overpass the fracture gradient and fracture the formation, thus implying to set more casing strings (before or after to 9 5/8" casing) than planned to protect the formation and preventing drilling risks associated to loss of circulation.

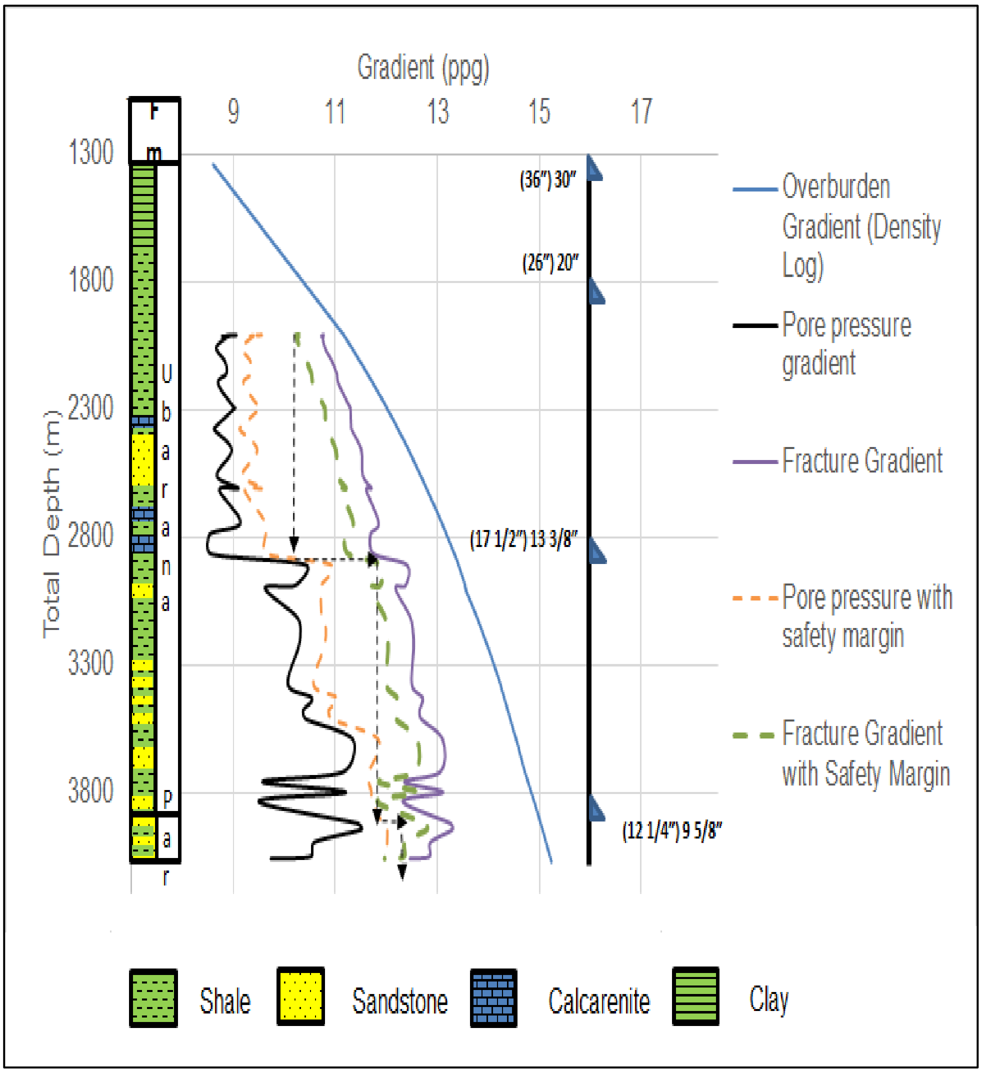


Figure 4-5 – Casing shoe depths based on kick tolerance criterion (top to bottom) in the DW well 1-CES-159.

Similarly, figures 4.6 and 4.7 show the calculated casing points of the ultra-deepwater well 1-CES-158 calculated by employing operating envelope and kick tolerance criteria respectively.

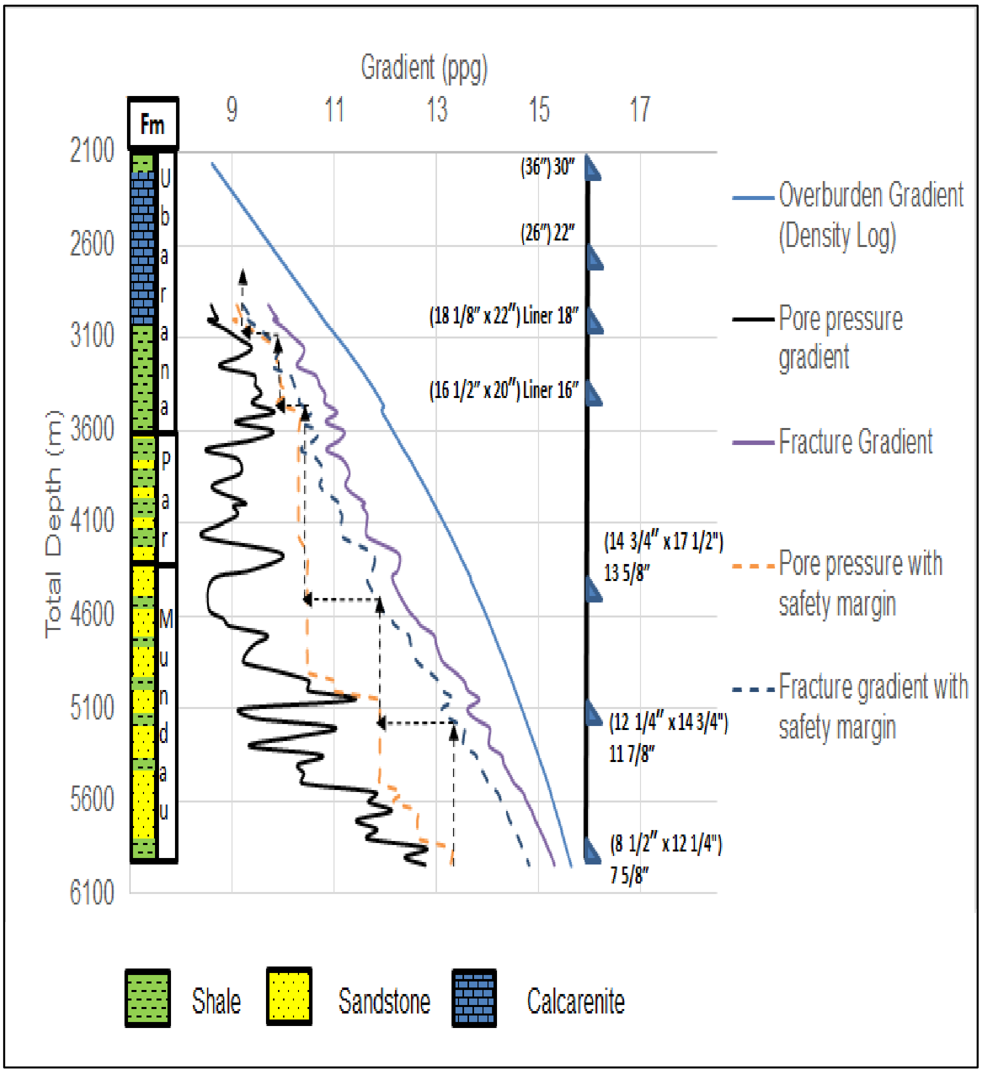


Figure 4-6 – Casing shoe depths based only on operating envelope (bottom to top) for 1-CES-158.

The obtained data indicate that this well presents a shallow area (≈3000-3600m) with narrow operating envelope very similar to early mentioned in the final segment of well 1-CES-159. Therefore, a tight-clearance architectural design could be appropriate to construct this ultra-deepwater well where the water column effect is more evident. Clearly, shallow intermediate liners (i.e. 18" and 16" liners) are hung in the surface casing to allow drill with appropriate mud weight in the next hole section protecting of fracturing the formation, and a larger and stronger intermediate casing (13 5/8" casing) is set to provide additional casing shoe integrity. In contrast of the actual well architectural design that uses a unique short intermediate casing string (13 3/8” casing) to cover the interval depth related to narrow margin zone.

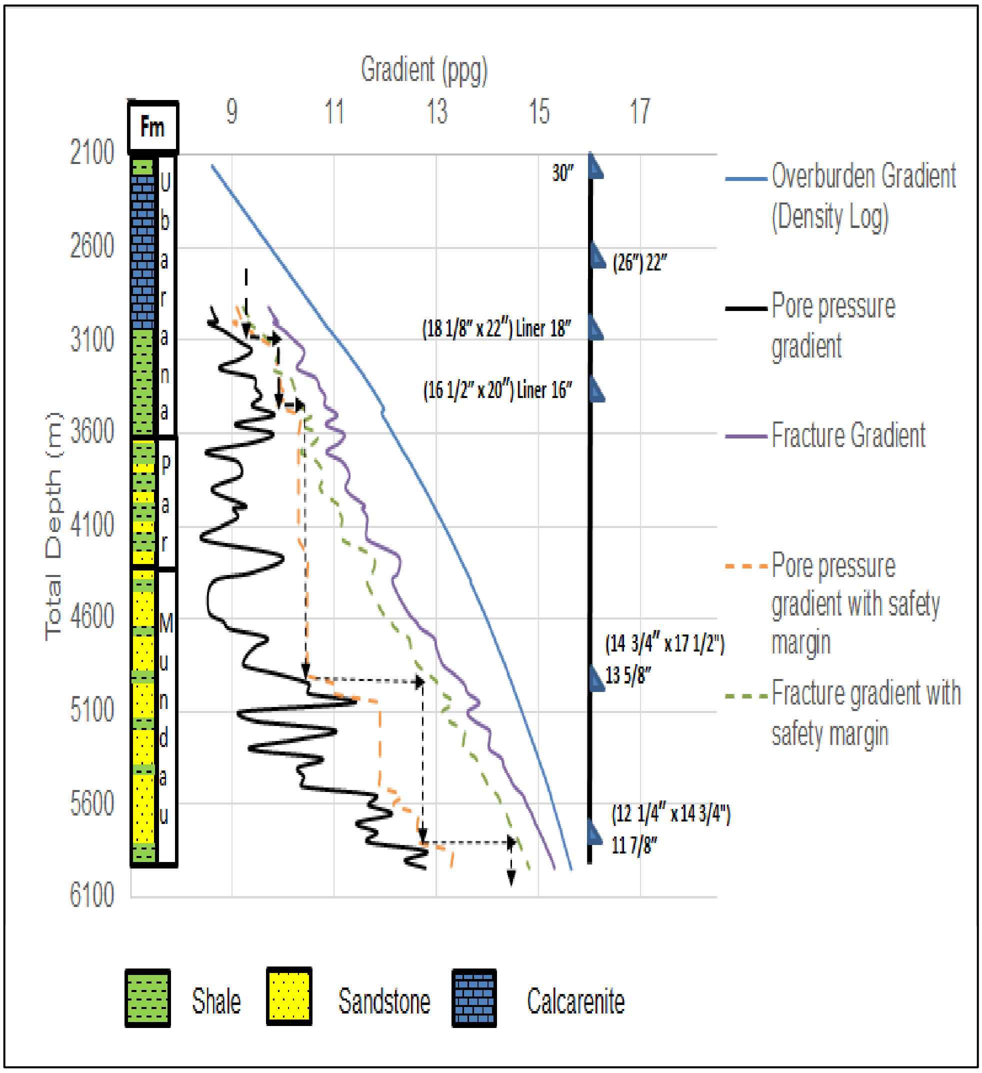


Figure 4-7 – Casing shoe depths based on kick tolerance criterion (top to bottom) for 1-CES-158.

In practical comparison, Tables 4.3 and 4.4 show the casing depths for the three cases for each studied well, i.e. actual drilling and the casing depths determined by for each of the two setting criteria. The first point to note is the casing shoe setting from top to bottom increases the length of the shallow well zones and reduce the amount of casing needed in the well. Hence, in line with the literature, the casing depths given by kick tolerance criterion, from top to bottom, are more representative for this work than those obtained by using only operating envelope, in a specific case where the main objective is to construct exploratory wells.

Secondly, as is shown in table 4.3, the results from this analysis provide consistent evidence with the architecture design of the actual exploratory well 1-CES-159, in the sense that setting depth of 13 3/8” casing calculated by employing the kick tolerance criteria is quite similar to the depth of actual well. One possible reason for the depth is not exactly equal is due to difference in the conductor and surface casing setting depth assumption between the actual well and this study.

Table 4.3 – Casing setting depths of the actual well 1-CES-159 and those determined by casing shoe setting criteria.

Casing (in)	Actual Well 1-CES-159		Operating Envelope approach (bottom to top)		Kick Tolerance approach (top to bottom)	
	Shoe depth (m)	Casing string length (m)	Shoe depth (m)	Casing string length (m)	Shoe depth (m)	Casing string length (m)
36-30	1413	71	1400	58	1400	58
20	1999	657	1900	500	1900	500
13 3/8	2997	1655	2400	1058	2910	1568
9 5/8	-	-	3040	1698	3945	2603
7 (Liner)	-	-	3890	850	-	-

Table 4.4 – Casing setting depths of the actual well 1-CES-158 and those determined by casing shoe setting criteria.

Casing (in)	Actual Well 1-CES-158		Operating Envelope approach (bottom to top)		Kick Tolerance approach (top to bottom)	
	Shoe depth (m)	Casing string length (m)	Shoe depth (m)	Casing string length (m)	Shoe depth (m)	Casing string length (m)
36-30	2245	87	2216	58	2216	58
20-22	2898	740	2716	500	2716	500
18 (Liner)	-	-	3080	364	3101	385
16 (Liner)	-	-	3480	764	3400	684
13 3/8 - 13 5/8	3488	1330	4510	2352	4950	2792
11 7/8	-	-	5200	3042	5850	3692
9 5/8	4400	2242	5900	700	-	-

The next point to note is the quite differences between the intermediate and production casing depths of the actual well and the casing points calculated by the casing setting criteria for the well 1-CES-158 as is presented in table 4.4. It could be argued that these differences are due to the existence of narrow operating envelope in the shallow segment of the well, requiring additional casing strings aim to maintain the well integrity.

Beside to set the casing shoes depth following the kick tolerance, it is also crucial to check that these estimated casing shoe depths are at the impermeable formation zone or low permeability layers, e.g. shale and Marlstone. For example, Figures 4.8 and 4.9 displays composite well logs between 1845-2060m and 2690-2905m depth intervals respectively, which check the setting depths of 20" casing and estimated by kick tolerance criteria of the two actual wells are in an impermeable or low permeability layer, in this case a shale layer (green interval) and marlstone layer (purple zone).

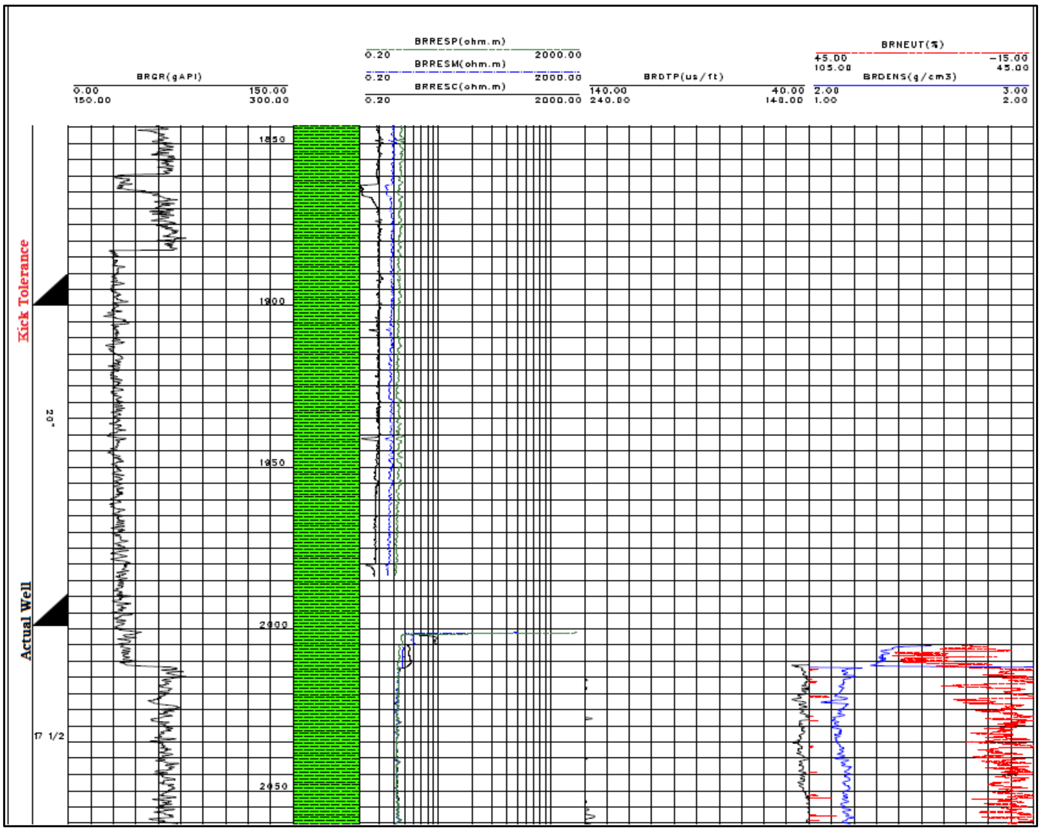


Figure 4-8 – Composite well logs (Gamma ray, resistivity, sonic, density and neutron logs) of well 1-CES-159 between depth interval of 1845-2060m.

Other complexities associated to DW drilling activities such as the presence of shallow gas/water and salt zones are not considered in this well architectures because they are no evidenced in the early study of the risk associated to drilling operations in BEM. However, with the intends to face the complexity associated to BOP limits, Table 4.5 shows the BOP working pressures considering pore pressures with and without water effects, and fracture pressure respectively. In addition, it is suggested standard BOP pressure for each well architectural according to calculated BOP working pressures.

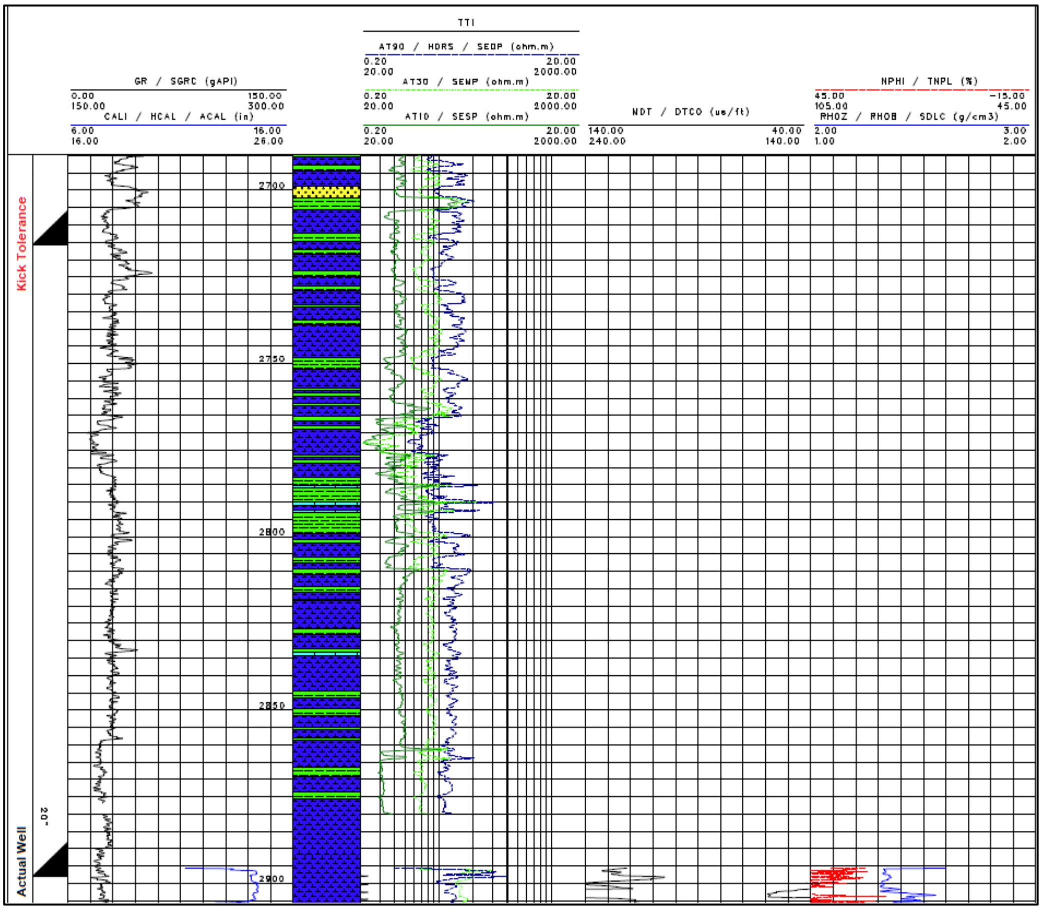


Figure 4-9 – Composite well logs (Gamma ray, resistivity, sonic, density and neutron logs) of well 1-CES-158 between depth interval of 2690-2905m.

Table 4.5 – BOP working pressures and suitable standard BOP pressure for each studied well.

Well	BOP Depth (m)	BOP working pressure			Selected standard BOP pressure (psi)
		Pore pressure (psi)	With Water effect (psi)	Fracture Pressure (psi)	
1-CES-158	2158	11650	8550	13879	15000
1-CES-159	1342	6852	4939	8055	10000

4.2.3 BIS application in the 4th drilling phase

Figures 4.10 and 4.11 displays the final well architecture proposed in this thesis for both 1-CES-159 and 1-CES-158. Then, in this last section is introduced the application of BIS approach in the fourth drilling phase related to below well architectural designs.

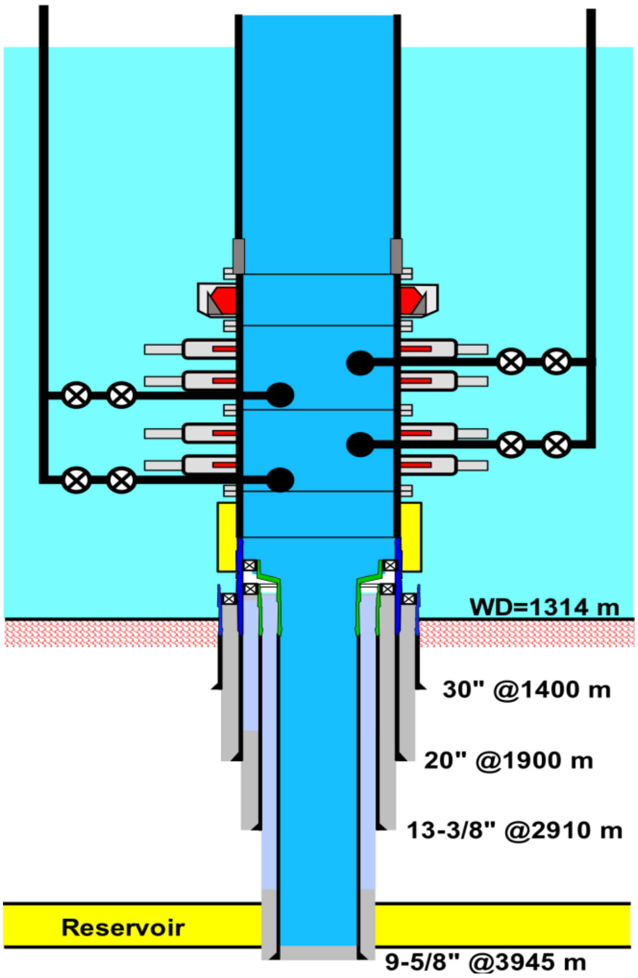


Figure 4-10 – Well architecture proposal of deep water well 1-CES-159.

The application of the BIS approach in the 4th drilling phase of the two well under analysis is quite similar, the essential difference lies in the intermediate liner that is set in the well 1-CES-158 instead to an intermediate casing that is run into the well 1-CES-159.

Then, the fourth drilling phase starts just after the 13 3/8” intermediate casing and 18” intermediate liner are set and cemented in the wells 1-CES-159 and 1-CES-158, respectively. Figure 4.12 and 4.13 describe these initial wellbore conditions. The Primary BIS and Secondary BIS are highlighted by a blue line and red line, respectively. The barriers of each BIS are also detailed in the right side of the figures.

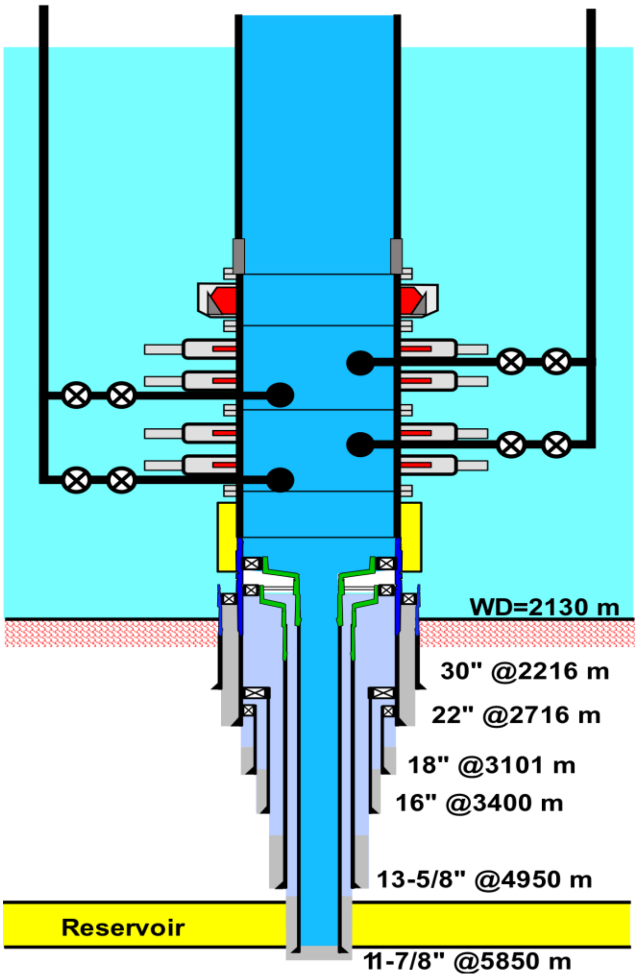
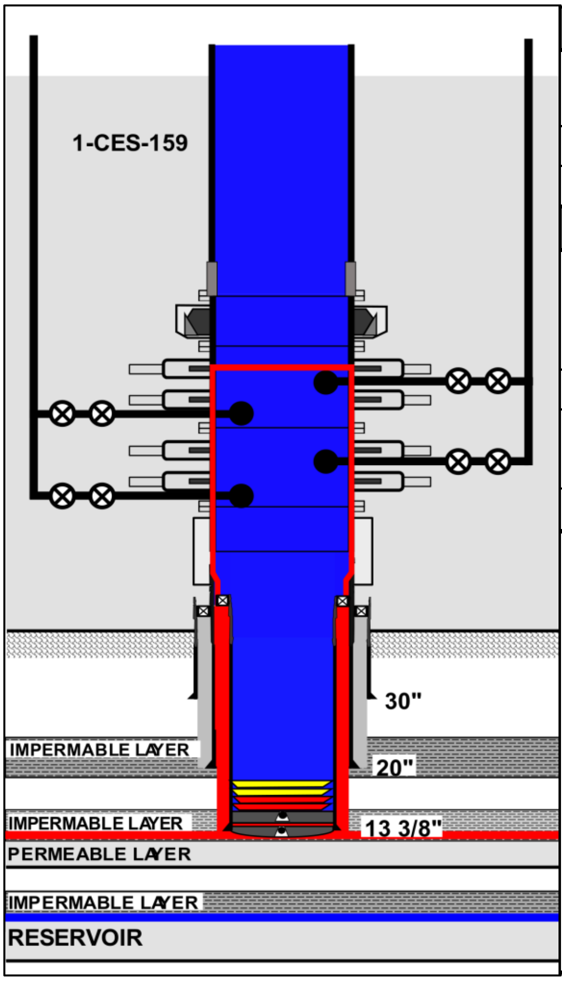


Figure 4-11 – Well architecture proposal of deep water well 1-CES-158.

The Primary BIS is composed of the undrilled impermeable layer and the drilling fluid. The impermeable layer is considered an active well barrier because it is holding fluids in place of a permeable and porous formation along several geological eras and it has not allowed the leakage of any formation fluid so far. The drilling fluid (mud) as a well barrier has the function to block at the same time three of the main leakage pathways: the well annulus, the drilling string and the well itself. This special characteristic is not shown in other well barriers; therefore, it is mandatory that the operator to constantly test the drilling fluid because it may be degraded as a barrier during the drilling (e.g. gas-cut mud).

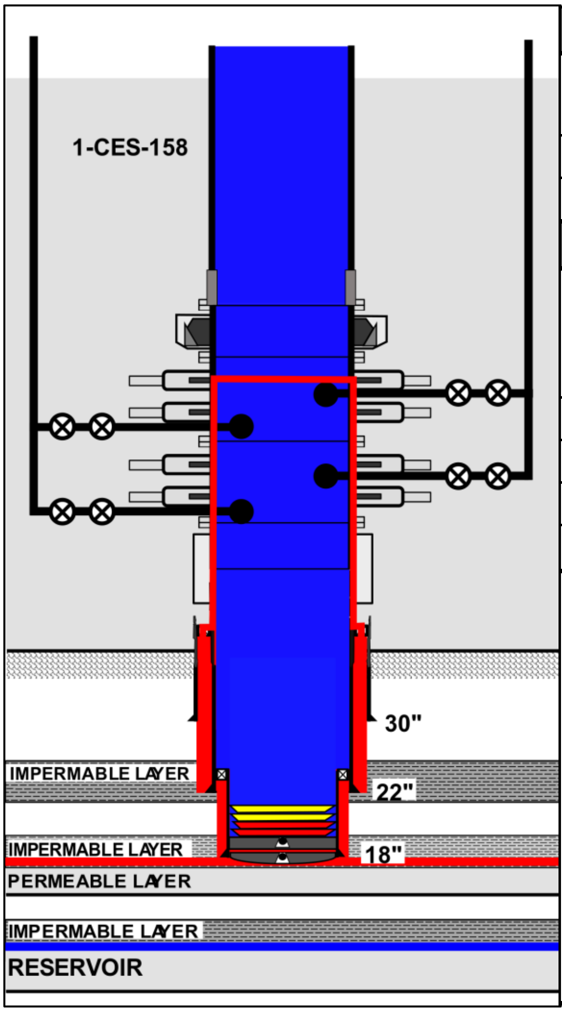


Primary BIS
Undrilled Impermeable Formation
Drilling Fluid
Secondary BIS
Drilled Impermeable Formation (tested by LOT)
Cement
13 3/8" Intermediate Casing
BOP (shear ram)

Figure 4-12 – Initial condition Well 1-CES-159: Intermediate casing is set and cemented. The Primary BIS (blue) and Secondary BIS (red) are highlighted.

The Secondary set of barriers is composed of the impermeable rock layer where the intermediate casing or liner is set and the BOP, more precisely the shear blind ram. As the impermeable layer is drilled, it is crucial to cement around to the intermediate casing or liner to hold it in place and to prevent fluid migration between subsurface formations, assuring well integrity. Thus, the cement and intermediate casing or liner are also components of the Secondary BIS.

In the special case of the well 1-CES-158, both surface casing and intermediate liner are well barriers of the Secondary BIS at the same time because of the intermediate liner is hung just above of the superficial casing shoe, therefore the both works in two of the main potential leakage pathways: well annulus and well paths.



Primary BIS
Undrilled Impermeable Formation
Drilling Fluid
Secondary BIS
Drilled Impermeable Formation (tested by LOT)
Cement
22” Surface Casing
18” Intermediate Liner
BOP (shear ram)

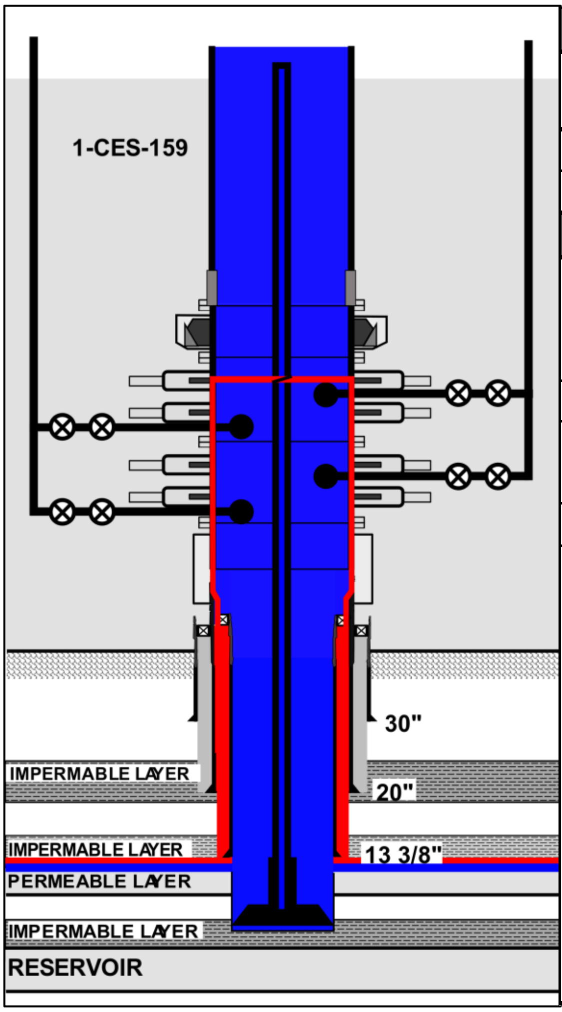
Figure 4-13 – Initial condition Well 1-CES-158: liner is set and cemented. The Primary BIS (blue) and Secondary BIS (red) are highlighted.

Moreover, it is necessary to verify the cement job quality using a sonic log to continue to next stage. After that, it is drilled the float collar, casing shoe and cement in preparation to the *Leak-Off Test* (LOT) at the surface casing shoe.

As is previously discussed in the drilling risks section, conducting the (LOT) is essential to estimate the breakdown point of the formation and specially under SGIP, the LOT is mandatory because it tests two barriers, namely, the cement and the formation. That is, if the surrounding area at the casing shoe depth faces a pressure above the LOT result (e.g. kick circulation), it can be assumed that this formation become in a nonoperational well barrier.

Other component of the secondary BIS is the BOP and it is active only when it is closed, therefore in this case it is necessary operational barriers such as the detection of an influx and the process to close BOP activating the shear ram. Thus, the operator must test the ram functionalities and BOP leakage. The leakage is tested pressurizing BOP and the functionalities closing the rams. The other components are already tested during the LOT.

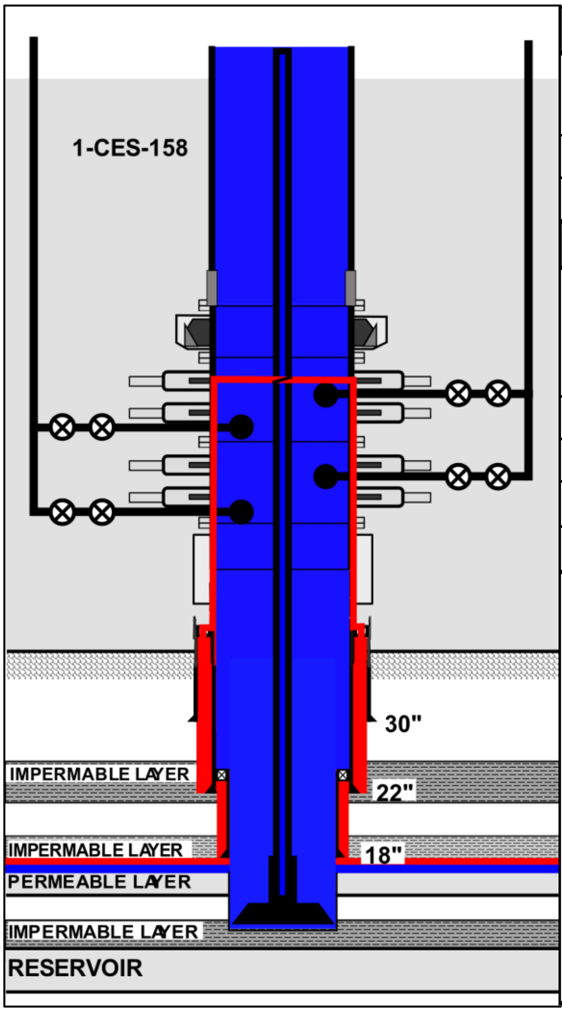
The fourth drilling phase continues as is showed in Figures 4.14 and 4.15. Here, it is fundamental to note that the impermeable formation that was assumed as unique component of the primary BIS above, is drilled along this operation, altering its original features. Hence, this impermeable layer is degraded as barrier until be tested by LOT.



Primary BIS
Drilled Impermeable Formation (tested by LOT)
Drilling Fluid
Secondary BIS
Drilled Impermeable Formation (tested by LOT)
Cement
13 3/8” Intermediate Casing
BOP (shear ram)

Figure 4-14 – Well architecture of 1-CES-159 at drilling operation highlighting both Primary BIS (blue) and Secondary BIS (red).

Subsequently, the tested impermeable layer at the intermediate casing or liner depth turn into a component of the Primary BIS. It can observe in Figures 4.14 and 4.15 that the same impermeable layer is a common component for both BIS’s. This is an exception to the independent BIS approach. The reasons for this exception is that this barrier has been operational for several geological eras and the LOT verified its strength after cementing job. Then, if the fracture pressure is not overpassed during the drilling operation, there is no arguments for the impermeable formation to be degraded as a barrier.



Primary BIS
Drilled Impermeable Formation (tested by LOT)
Drilling Fluid
Secondary BIS
Drilled Impermeable Formation (tested by LOT)
Cement
22” Surface Casing
18” Intermediate Liner
BOP (shear ram)

Figure 4-15 – Well architecture of 1-CES-158 at drilling operation highlighting both Primary BIS (blue) and Secondary BIS (red).

Additionally, Figures 4.14 and 4.15 details the components of both BISs for each well architecture. One the one hand, the Primary BIS is composed by drilled impermeable formation and the drilling fluid or mud. On the other hand, the Secondary BIS components are the BOP, more precisely the shear blind ram, the same drilled impermeable formation, cement and the casings or liner.

Furthermore, the operator must make sure that the shear blind ram may close not only when the drillpipe is inside the BOP. For example, Figure 4.16 show the running of an intermediate casing of the well 1-CES-159 and an intermediate liner in the case of the well 1-CES-158. Primary and secondary BISs are the same featured in Figures 4.14 and 4.15 for the both well architectural designs. Nowadays, most of subsea BOP for ultra-deep water are equipped with casing shear ram. However, the operator should test the casing cutting with specimen/sample of each casing string that will be run into the well after the surface casing to validate this functionality.

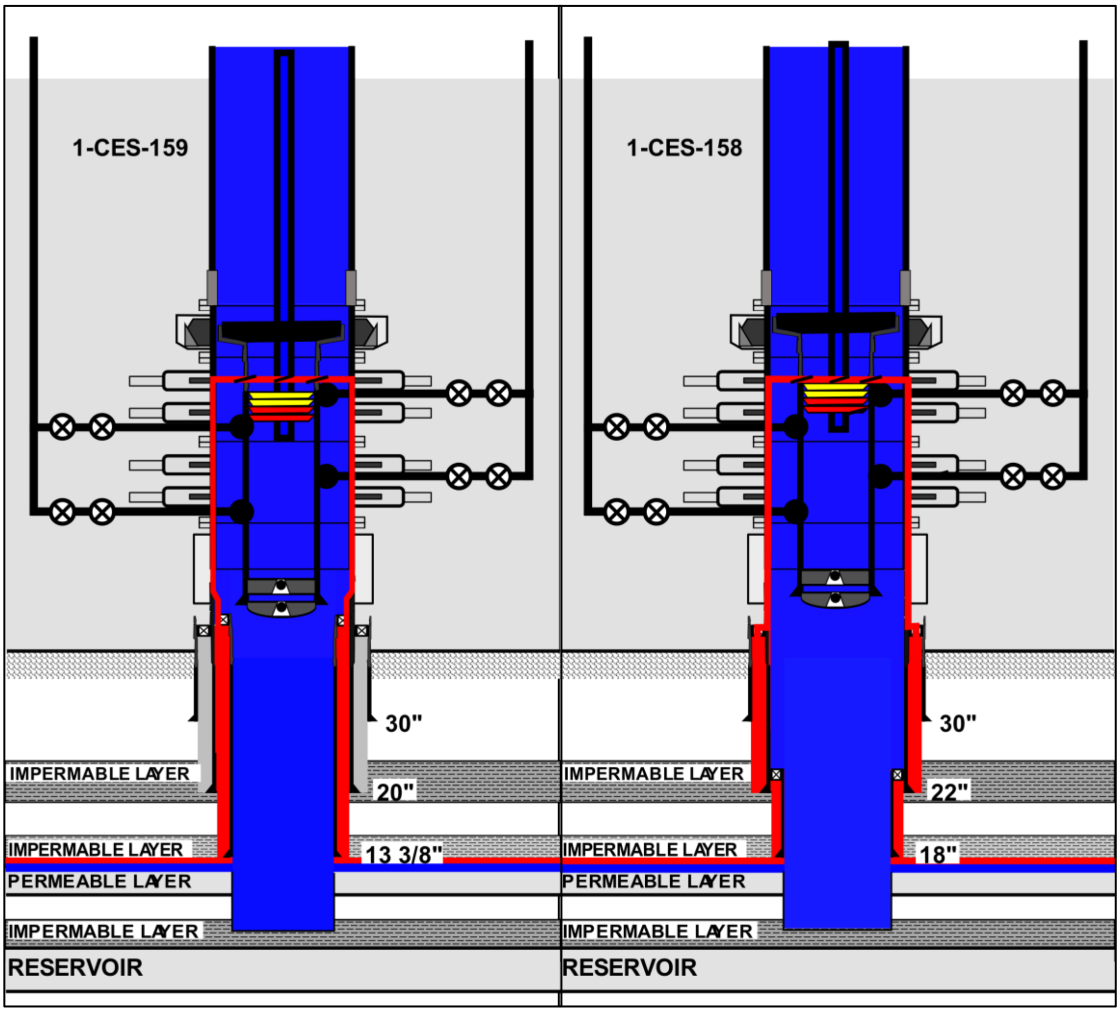


Figure 4-16 – BIS schematic during the running of a casing and a liner respectively, highlighting both Primary BIS (blue) and Secondary BIS (red).

5 CONCLUSIONS

Lost-circulation event was a common problem in the Ceará basin, specifically in the formation Ubarana. It can be avoided by performing a LOT at the formation immediately below the last casing shoe as well by predicting the narrow operating envelope areas.

The assessment of the operating envelopes in the three studied wells with different water depths at the same basin validated that in deepwater and ultra-deepwater zones, the operating envelopes become narrower.

Comparing two casing shoe setting methodologies, Kick tolerance presented, as expected, less necessary casing strings and larger intermediate casing than the conventional method, i.e. bottom to top. In addition, both methodologies exhibited the need to set more casing string, e.g. liners, in the intermediate wellbore phase to face with the DW well complexity related to narrowing of the operating envelope.

BIS implementation demonstrated that it requires a special care in choosing casing shoe depth, looking for a suitable impermeable rock layer because this formation will be an important BIS barrier, which will be used for both Primary and Secondary BIS during some operation. Moreover, as BOP is active only when it is closed, must be tested its ram shear functionalities and leakage as well must be selected its appropriate working pressure.

The dependence of both primary and secondary BIS on the same competent impermeable rock layer shows the importance of its selection and test (LOT or XLOT) before each drilling phase.

Despite some well design considerations are not addressed in this study such as borehole stability, casing structural features, drill string, bit, cementing and directional drilling, the suggested well architectures can be used as basis to develop a more extensive and interdisciplinary study about planning and constructing exploratory wells in BEM.

5.1 FUTURE WORKS

With the purpose of stablishing a more representative scheme of the geological identification of BEM, the study zone explored in this work, i.e. Ceará and Potiguar basins, should be extended to other basins that compose BEM, to find out significant geohazards.

Most of the methods used to estimate the geopressures are empirical, meaning a certain amount of errors due to the assumed data and parameters obtained from a different geological region. However, the findings in this work can be calibrate by applying these methods for a bigger sample of wells and, subsequently determining the best correlated parameters and exponents for the study region. In addition, other methods could be explored and compared with the methods applied in this project, to determine the most representative criterion for geopressures behavior.

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APPENDIX A – WELL NOMENCLATURES FOR EXPLORATORY WELLS IN BRAZIL

All wells are denominated in a mixture of letters and numbers, from different nomenclatures. The Petrobras nomenclature is given by the following sequence:

(A) – (B) – (C)

In addition to the Petrobras nomenclature, the exploratory wells are given the ANP nomenclature, which is established by ANP resolution No. 49 (09/20/2011) to identify, classify, order and to indicate the geographic location and the exploratory well environment. The guidelines for assigning this ANP nomenclature are the following:

(A) – (E) – (C) (D) – (B)

Where A, B, C, D, and E are:

A. **Key Number** representing the purpose of the well, from the table A.2.

B. **Geographical reference:** Acronym for the state where the well is located (*e.g. CE for Ceará state*), plus the letter "S" when referring to offshore environment.

C. **Specific numbering:** Chronological order of wells drilled by the operator for the case that is used the *ANP nomenclature* and Chronological order of wells drilled in the same field / area for the case of *the Petrobras nomenclature*.

D. **Letter** corresponding to the type of drilling, from the well geometry, as in the table.

Table A.1 – Exploratory well classification.

Type	Letter
Vertical Well	*No letter is added in this case*
Directional Well	*D*
Horizontal Well	*H*
Repeated Well	*Alphabet letters except for D, H and P. For instance, if a well was repeated for the first time, it includes the letter "A".*
Multilateral Well	*P*

E. Nominal reference (2 up to 4 uppercase letters): to represent the operating company. *For example, BRSA (Petrobras S.A.), STAT (Statoil), SHEL (Shell), etc.*

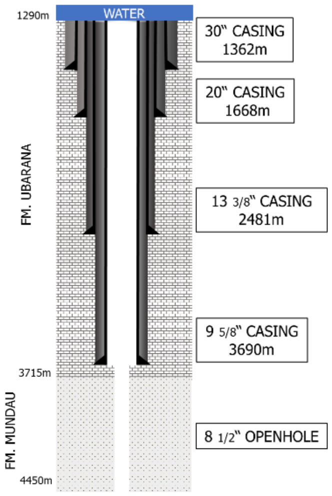
Table A.2 – Exploratory well classification.

Key Number	Category	Description
1	Pioneer Well (Wildcat)	A Well that aims to test the occurrence of oil or natural gas in one or more objectives of a geological prospect;
2	Stratigraphic Well	A drilled Well with the purpose of knowing the stratigraphic column of a basin and obtaining other geological information of subsurface;
3	Extension Well	A Well that intends to delimit the accumulation of oil or natural gas in a reservoir, and can be drilled in any Phase of the Concession Agreement;
4	Adjacent Pioneer Well	A Well that aims to test the occurrence of oil or natural gas in an area adjacent to a discovery;
5	Exploratory Well Shallower Reservoir	A Well with the objective of testing the occurrence of shallower deposits in a given area;
6	Exploratory Well for a Deeper Reservoir	A Well with the objective of testing the occurrence of deeper deposits in a given area;

APPENDIX B – CONFIGURATION OF THE STUDY WELLS

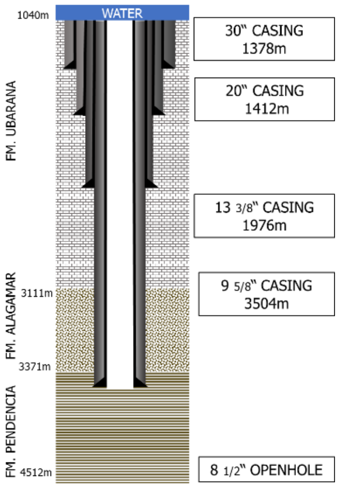
1-CES-112

Lat: 2° 54’ 21.64” S
Long: 38° 38’ 30.55” W
Seafloor depth: 1290 m



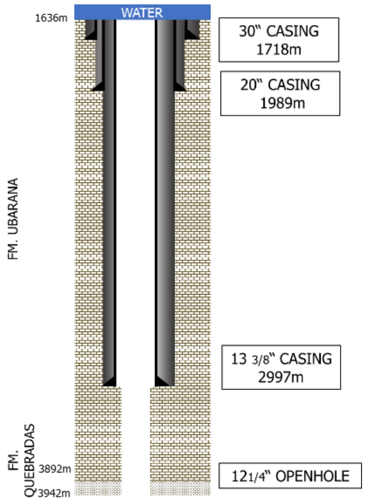
1-CES-121

Lat: 3° 50’ 53.27” S
Long: 37° 30’ 46.73” W
Seafloor depth: 1087 m



1-CES-154A

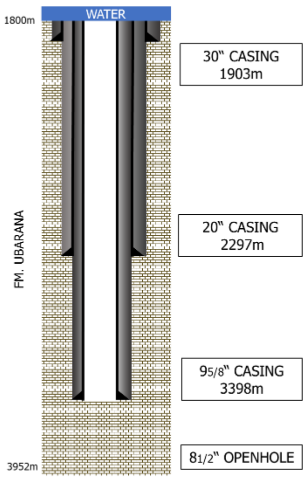
Lat: 3° 53’ 28.75” S
Long: 37° 20’ 40.97” W
Seafloor depth: 1615 m



1-CES-155

(1-BRSA-90-CES)

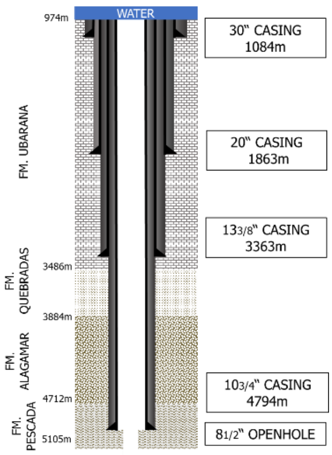
Lat: 3° 58’ 26.52” S
Long: 37° 8’ 28.62” W
Seafloor depth: 1800 m



1-CES-157

(1-BRSA-1158-CES)

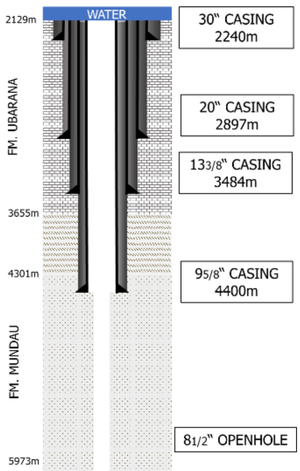
Lat: 4° 9’ 56.217” S
Long: 37° 9’ 35.547” W
Seafloor depth: 974 m



1-CES-158

(1-BRSA-1080-CES)

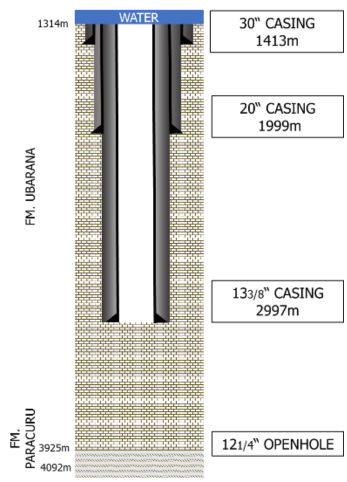
Lat: 2° 49’ 0.939” S
Long: 38° 36’ 55.596” W
Seafloor depth: 2130 m



1-CES-159

(1-BRSA-1150-CES)

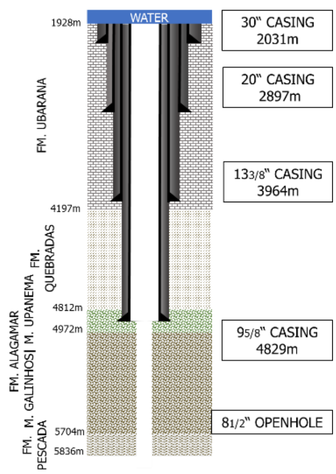
Lat: 2° 49’ 30.902” S
Long: 38° 49’ 7.179” W
Seafloor depth: 1314 m



1-CES-161

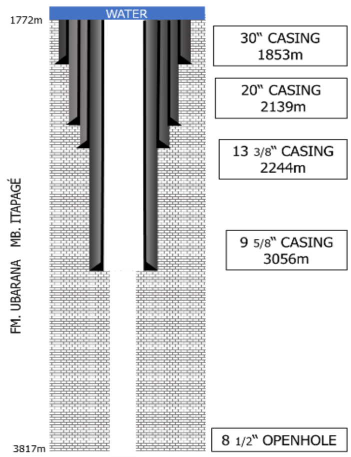
(1-BRSA-1175-CES)

Lat: 3° 53’ 18.81” S
Long: 37° 12’ 2.705” W
Seafloor depth: 1928 m



1-CES-111B

Lat: 2° 58’ 13.33” S
Long: 38° 29’ 27.74” W
Seafloor depth: 1772 m



APPENDIX C - EXTRAPOLATED LOTS

Table C.1 – LOT Data from correlated wells

Well Name	LOT (Ppg)	Total Depth (m)	Water Depth (m)	Sediment Depth (m)	Water column Pressure (psi)	Sediment Pressure (Psi)
1-CES-112	10.13	1707	1290	417	1868.436	1076.681
1-CES-112	11.30	2513	1290	1223	1868.436	2970.894
1-CES-112	12.54	3707	1290	2417	1868.436	6054.128
1-CES-111B	11.17	3056	1772	1284	2566.565	3248.414

Table C.2 – Extrapolated LOT Data for 1-CES-158

1-CES-158 data		**Extrapolated data for 1-CES-158**		
Water column Pressure (psi)	Water Depth (m)	Total Pressure (m)	Total Depth (m)	**Extrapolated LOT (Ppg)**
3085.092	2130	4161.773	2547	9.59
3085.092	2130	6055.986	3353	10.60
3085.092	2130	9139.220	4547	11.80
3085.092	2130	6333.506	3414	10.89

Table C.3 – Extrapolated LOT Data for 1-CES-159

1-CES-159 data		**Extrapolated data to 1-CES-159**		
Water column Pressure (psi)	Water Depth (m)	Total Pressure (m)	Total Depth (m)	**Extrapolated LOT (Ppg)**
1903.198	1314	2979.879	1731	10.10
1903.198	1314	4874.092	2537	11.27
1903.198	1314	7957.326	3731	12.52
1903.198	1314	5151.611	2598	11.64

APPENDIX D - PORE PRESSURE AND FRACTURE GRADIENT DATA

Table D.1 – Pore pressure gradient and fracture gradient for 1-CES-158.

Total Depth (m)	Pore Pressure Gradient (Ppg)	Fracture Gradient (Ppg)
2920.441	8.580919	9.703034
2975.305	8.66	9.829942
2975.458	8.672621	9.835914
2975.61	8.672852	9.83625
2999.232	8.703171	9.887445
3000.908	8.515712	9.805303
3050.896	8.858367	10.0358
3101.34	9.122724	10.22481
3151.023	9.37436	10.40263
3200.095	9.130084	10.36282
3250.082	8.738616	10.26894
3300.07	9.43248	10.6307
3352.648	9.439715	10.705
3352.8	9.440018	10.70533
3352.952	9.440322	10.70566
3353.105	9.440625	10.70599
3400.044	9.567656	10.82022
3450.031	9.381421	10.813
3500.089	9.821555	11.05523
3550.229	9.047813	10.82852
3600.064	9.79386	11.18227
3650.051	9.375473	11.09552
3700.038	8.46946	10.83925
3749.568	9.091535	11.14511
3825.311	9.164992	11.2946
3901.968	8.590592	11.22603
3987.922	9.258223	11.59299
4003.619	9.014598	11.53963
4051.168	9.096682	11.64309
4105.422	8.751384	11.63056
4170.344	8.412307	11.6466
4261.48	9.965871	12.25564
4350.024	9.37651	12.24676
4558.132	8.532921	12.42635
4613.301	8.823531	12.60151
4650.943	8.929929	12.69792
4700.016	9.67708	12.94981
4750.003	9.436382	12.99148
4800.143	9.269345	13.05252
4850.13	9.222209	13.13889
4900.117	9.937355	13.35875
4950.105	10.50814	13.5433
5000.092	10.47932	13.62157
5050.079	11.39063	13.84231
5100.066	9.142405	13.60691
5150.053	9.45491	13.75097
5200.041	11.02211	14.03839
5250.028	10.24491	14.03673
5300.015	9.324808	14.03769
5350.002	10.75092	14.27304
5400.142	10.27573	14.32627
5450.129	10.40764	14.43294
5500.116	10.3527	14.52517
5550.104	11.81705	14.6971
5600.09	11.66085	14.77188
5650.078	12.12504	14.87051
5700.065	11.42696	14.93483
5750.052	11.83892	15.02894
5800.04	11.63991	15.11125
5850.026	12.80272	15.1858
5900.014	12.37892	15.26573
5941.467	12.78102	15.31652

Table D.2 – Pore pressure gradient and fracture gradient for 1-CES-159.

Total Depth (m)	Pore Pressure Gradient (Ppg)	Fracture Gradient (Ppg)
2009.851	9.055463	10.68943
2010.004	8.958324	10.66784
2010.461	8.949973	10.66697
2010.613	8.916049	10.65965
2010.766	8.90369	10.6572
2010.918	8.910298	10.65903
2011.07	8.916881	10.66086
2011.223	8.917159	10.66126
2011.375	8.914286	10.66095
2011.528	8.901896	10.65849
2011.68	8.879743	10.65383
2011.832	8.86705	10.6513
2011.985	8.870576	10.65244
2012.137	8.890223	10.65722
2012.29	8.896902	10.65907
2012.442	8.897178	10.65947
2012.594	8.894255	10.65915
2012.747	8.894531	10.65955
2012.899	8.881941	10.65705
2013.052	8.859434	10.6523
2013.204	8.849838	10.65047
2013.356	8.866525	10.65459
2013.509	8.883042	10.65866
2013.661	8.883317	10.65906
2013.814	8.857516	10.65357
2013.966	8.854498	10.65323
2014.118	8.844855	10.65139
2014.271	8.804817	10.64268
2014.423	8.777626	10.63687
2014.576	8.788246	10.63962
2014.728	8.839296	10.65151
2014.88	8.869267	10.65863
2015.033	8.853111	10.65531
2015.185	8.876341	10.66091
2015.338	8.886352	10.66351
2015.49	8.880144	10.66245

Total Depth (m)	Pore Pressure Gradient (Ppg)	Fracture Gradient (Ppg)
2059.686	8.66	10.70699
2110.283	8.825074	10.85141
2160.118	8.859665	10.95954
2199.894	8.697119	10.99591
2295.144	9.016436	11.25009
2295.296	9.030487	11.2539
2366.01	8.660903	11.27645
2380.488	8.623612	11.28873
2460.041	8.964994	11.50183
2560.32	8.670806	11.55793
2610.002	9.097111	11.73991
2615.489	8.7194	11.63945
2745.791	9.135224	11.91791
2789.682	8.531877	11.78239
2866.034	8.554667	11.8669
2910.078	10.41968	12.48438
2990.241	10.21005	12.48545
3000.299	9.618812	12.30559
3065.069	8.849092	12.11252
3110.027	10.22972	12.59956
3160.014	10.31502	12.66472
3230.118	10.27621	12.70365
3380.079	10.06998	12.72214
3430.067	10.53723	12.91591
3480.054	10.36682	12.88285
3513.582	10.4241	12.9219
3593.135	11.34289	13.30244
3635.959	12.23318	13.65602
3720.084	11.15388	13.2983
3758.946	9.569623	12.71295
3800.094	11.2078	13.36588
3835.908	9.488848	12.71484
3922.166	11.43321	13.52589
3945.788	11.51697	13.57175
3995.928	10.58518	13.22559
4050.944	10.51955	13.22504
4059.783	9.733818	12.90862