Rio Oil & Gas Expo and Conference 2020

ISSN 2525-7579

Conference Proceedings homepage: https://biblioteca.ibp.org.br/riooilegas/en/

Technical Paper

Drilling developments in Pre-Salt of Brazil: background and new horizons

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Abstract

Several challenges related to petroleum exploration and production have been encountered since the discovery of the pre-salt Santos Basin in 2006. The main challenges and technological demands have been in terms of special drilling equipment required to drill through the thick salt layers, dynamic positioning (DP) drilling rigs for Ultra-Deepwater (UDW) environments, complex logistics systems for drilling operations on fields far from the coast, wellheads manufactured to resist the high pressure conditions, and mooring systems to make the exploratory and production development designs viable. This paper aims to address these pre-salt drilling-related challenges based on literature review, and discuss some key improvement opportunities, such as the use of nano-fluids and artificial intelligence (AI) to provide reliability of drilling fluids selection aiming make the whole drilling operation safer and minimize non-productive time.

Keywords: Drilling. Artificial Intelligence. Nano-Fluids. Pre-salt. Petroleum Engineering

Received: March 15, 2020 | **Accepted:** Jun 06, 2020 | **Available online:** Dec 01, 2020
Article Code: 151
Cite as: Rio Oil & Gas Expo and Conference, Rio de Janeiro, RJ, Brazil, 2020 (20)
DOI: https://doi.org/10.48072/2525-7579.rog.2020.151

1. Introduction

In 2006, the oil and gas industry went through a major transformation with the discovery of the Brazilian pre-salt fields. Given the ultra-deepwater environment located far off the coast and with extremelychallenging geological conditions, the industry realized the need for the development of new technologies that allowed safe, reliable and profitable drilling operations through the challenging salt layers and high-pressure environments. The exploration of the Brazilian deepwater pre-salt carbonates faces great challenges, such as the complex geometry and mechanical behavior of the salt domes, high thickness of drilled formations, compartmentalization and rubble zones generating high pore pressure, formations with high abrasiveness and strength, heterogeneity and anisotropy, and complex permeability due to secondary porosity (vugs and caverns) (Silva et al., 2017). Salt diapirism is an active force in Brazil's sea basins. This plastic behavior of the salt formations further complicates the drilling operation, generating problems such as weakening of the wellbore wall, poor casing cementing, casing deformation, wellbore collapse and stuck pipe.

This paper was built through journals that are state of the art in the petroleum industry, as well as books and technical reports that address the main challenges faced in the exploration and production of hydrocarbons, and the way ahead for new projects for the pre-salt exploration and development since its discovery in 2006 to the present date.

2. Background

2.1. Pre-salt geology

The pre-salt play is located in the Campos and Santos basins in southeastern Brazil, mostly offshore of the states of Rio de Janeiro, São Paulo, Santa Catarina, and Espírito Santo. The play occupies an area of almost 500,000 km^2 with water depths that can pass 2,000m, and so the reservoir can be located over 7,000m deep (Carminati et al., 2008, 2009). Although Brazil’s pre-salt exploration efforts focus heavily on the Santos, Campos and Espírito Santo basins, layers of salt have also been found elsewhere along Brazil’s coast, such as in the Cumuruxatiba, Jequitinhonha, Camamu-Almada and Sergipe-Alagoas basins (Karner and Gambôa et al., 2007).

The pre-salt targets comprises a thick carbonate section in depths ranging from 5,000m to 6,500m,and the most commonly prospected reservoir formations include the coquina succession (Thompson et al., 2015), microbialites, spherulites, calcitic shrubs, and possible hydrothermal carbonates (Terra et al., 2010; Saller et al., 2016; Szatmari and Milani, 2016). Coquina reservoirs produce 1,000 to 3,000 barrels of oil per day (bopd) and can have initial flow rates of N10,000 bopd. It exhibits profound lateral and vertical changes in reservoir thickness and quality over short distances in response to diagenetic alteration, and biologic, topographic and climatic controls (Abrahão and Warme et al., 1990; Bruhn et al., 2003; Bruhn et al., 2017).Pre-Salt carbonate reservoirs have undergone a complex and heterogeneous diagenetic evolution, resulting in large vertical and lateral variations in the quality (permeability and porosity) of the reservoirs (Carminatti et al., 2009). Although depositional features exerted significant control over the diagenetic processes, most of the porosity that is currently present in the Pre-Salt reservoirs is of secondary origin (Tosca and Wright et al., 2015).

The reservoir poses numerous drilling challenges, including hard silicate nodules and low-porosity layers, which make the formation strength extremely high.The heterogeneity level of such carbonates imposes extra challenges, especially on drilling shock and vibration, with low rates-of-penetration (ROP), raising pre-salt well construction costs(Alves et al., 2009 and Ali et al., 2010).The evaporites composed primarily of halite and anhydrite also contains layers of carnallite and tachyhydrite, a varying composition of the evaporite interval that can be especially difficult to drill, since creep can lead to wellbore restrictions, stuck pipe and casing failure. Drilling through salt requires special attention to drilling fluids, and potential problems include sections of borehole enlargement and weakened borehole walls due to salt leaching. Low mud weight may allow creep to impinge on the drill string(Perez et al., 2008).

2.2.Well technology

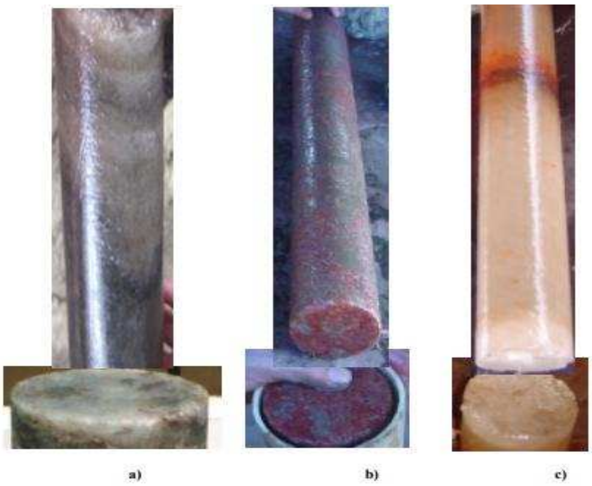
In 2006, the RJS-628A exploratory well was successfully drilled through a large salt layer in the Tupi area of the Santos Basin. This well was drilled in 2,126m water depth and had around 1,000m of post-salt section, followed by over 2,000m of salt. The target was reached just below the salt, a carbonate reservoir at about 5,200m deep. In addition to the successful drilling, the RJS-628A well revealed a huge potential for oil production and ushered in a new age of pre-salt exploration in the Santos Basin.

The subsurface rock is under a state of compressive stress formed by three main stresses, one vertical and two horizontal, known as in situ stresses. The vertical stress at a point in the rock – overburden – is due to the weight of the upper layers and can be calculated by summing the weight of the water depth and the upper formations. Due to overload loading, the rock tends to deform laterally, however, this displacement is restricted by the presence of neighboring formations, what generates horizontal in situ stresses, known as confinement state. Despite the extremely successful exploratory campaign in this particular area of Santos Basin, the development of Tupi and other fields already discovered in the same pre-salt area required overcoming many challenges associated with well construction. The presence of this salt section usually creates favorable conditions for hydrocarbon storage, which is a positive feature in terms of exploitation. On the other hand, the associated disadvantage is the many possible operational problems while drilling through the salt, as mentioned previously. Drilling through the evaporite layer is extremely difficult because the rock is composed of different types of salt with different creep rates. Halite is predominant and almost motionless, but there is also the presence of carnallite layers and taquihydryte, which have much higher creep rate.

The creep rate of salt rocks is responsible for the closure of the well as a function of time, creating significant difficulties for its construction (Poiate et al., 2006; Costa and Poiate Jr., 2008; Falcão, 2008). Figure 1-a, Figure 1-b and Figure 1-c show halite, carnallite and taquihydryte, respectively. Saline rocks have time-dependent strain when subjected to any level of shear stress due to their crystalline structure (Figure 2).

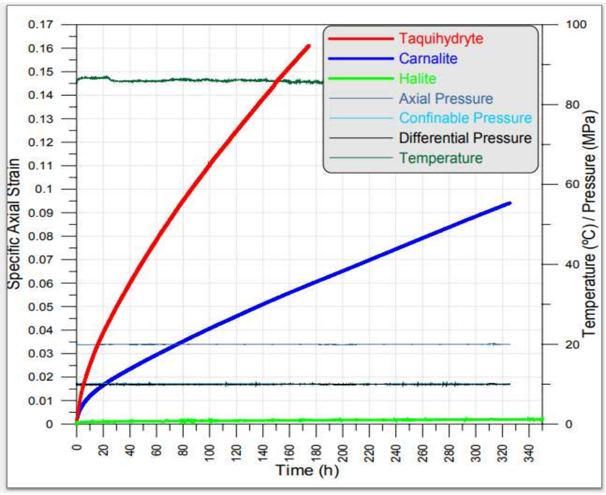
A positive fact is that the temperature of the salt layers, which is one of the most important parameters in terms of influencing creep behavior, is not too high in Tupi and surrounding regions, so creep rates are significantly lower than in other places that have higher temperatures. Besides being a function of the pressure and temperature of the overload, the salt creep rate is also influenced by the way it is housed with other formations and its composition, which generates great complexity in the operation, considering the different types of salts involved.

Figure 1 - Types of salt formations: a) Halite; b) Carnalite; c) Taquihydryte



Source: Costa and Poiate Jr, 2008; Falcão, 2008.

Figure 2 - Specific strain, temperature and pressure as function of time for different salt types layers



Source: Costa and Poiate Jr, 2008; Falcão, 2008.

The background developed so far due to the vertical drilling operations of these thick salt layers in and around Tupi shows that the well closure process occurs at small rates, (Pattillo and Rankin 1981; Goodwin 1984; Rike et al., 1986).

2.2.1. Well trajectory control

Another challenge related to the development of pre-salt areas is the construction of directional wells in thick salt layers (Pattillo and Rankin, 1981). Although rotary steerable technology provides accurate control of the well path and precise adjustments, if it deviates from its design path, the creep rate of salt makes this control very difficult. Under these conditions, it is possible to relieve and evenly distribute the load due to salt movement, avoiding the casing collapse with the consequent closure and possible loss of the well.

In addition to the problems associated with casing collapse, as salt is generally more difficult to drill than other sediments at the same depth, salt hardness not only affects the penetration rate (ROP), but also makes directional control more difficult.

2.2.2. Loss of circulation and managed pressure drilling (MPD)

Due to high permeability and porosity properties of the pre-salt carbonates, cave sections were found that generated a large loss of drilling fluid to the formation. This loss of circulation incurs in a loss of hydrostatic pressure in the well and thereby reduces reliability in the primary safety barrier, i.e. the drilling fluid. Another issue caused by the loss of drilling fluids is the damage to the formation, locally reducing the permeability and impairing the productivity of the reservoir. An alternative used was the pressurized mud cap drilling (PMCD) technique, which consists of injecting solids into the formation to buffer the regions where there are caves and thus reduce severe losses.

In 2013, an offshore rig used the managed pressure drilling (MPD) technique for the first time for drilling in formations that presented this problem. In this technique, the pressure in the well is controlled by means of an automatic choke, which adjusts the opening area whenever needed. Drilling fluid from the well passes a gas-mud separator (MGS) and can then be reinjected into the well.

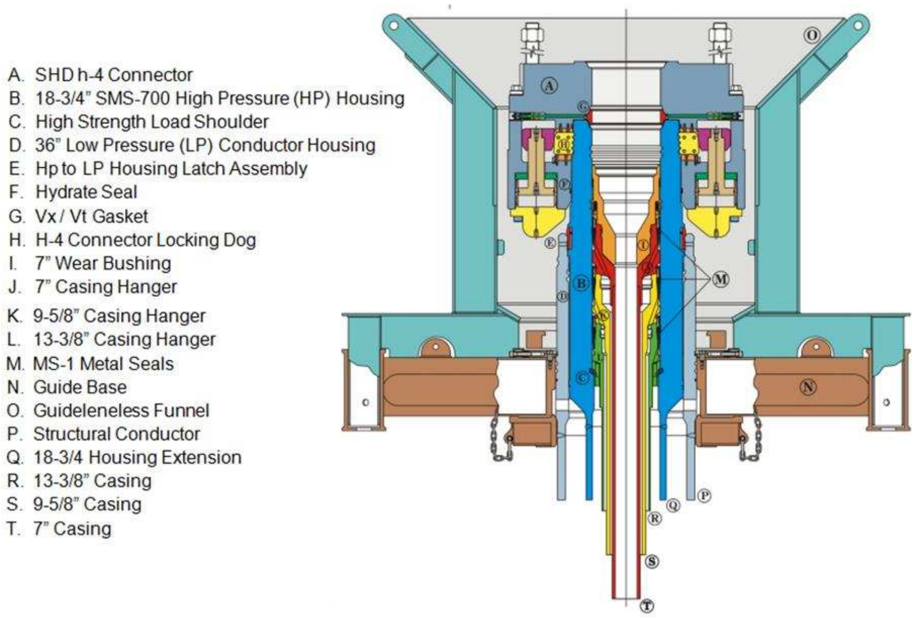
Pressurized mud cap drilling (PMCD) is a variation of managed pressure drilling (MPD). This technology was introduced at Petrobras in 2006 to solve ballooning and kick detection of HPHT wells offshore Northeast of Brazil drilled with synthetic mud. It proved to be a successful technology on the 4th well of the Technological Agreement where it gave Petrobras the possibility to drill more 500m in a secure manner on an exploratory well offshore Espirito Santo. After that the technology was pushed to solve problems in Santos basin (BM-S-12) in a HPHT well that had losses and kicks. It was the first Brazilian offshore operation with MPD in 490m water depth, in a moored rig.

Furthermore, having confidence on the technology, Petrobras management decided to use the technology on deepwater rigs for the pre-salt area to solve issues related to losses and narrow mud window on the reservoir section. One important application was in the Lula field where conventional drilling was not applicable and PMCD technique allowed drilling to total depth (TD). Note that this doesn't mean that every pre-salt well need MPD, every case needs to be analyzed by the technical team involved to determine if the MPD technique for safe drilling operations is a requirement. Since the first MPD application, the technology has evolved with the lessons learned from many wells and operators.

2.2.3. Wellhead background

A wellhead (Figure 3) is a group of equipments connected to the upper part of the well, being the structural anchoring, sealing and pressure restraining point. The orientation of the well is defined, and operations of safety, maintenance, monitoring, and flow assurance are performed from the wellhead. The main wellhead components are the Production Adapter Base (PAB), the Christmas Tree (WCT), the Tree Cap, and vertical connection module with this equipment performing functions for drilling and completion operations.

Figure 3 - Wellhead Equipments



Source: Vetcogray™, 2020.

Another equipment connected to the wellhead that communicates with the drilling rig is the drilling riser, which has the function of protecting and guiding the drill string, as well as allowing the drilling fluid to return from the well to the platform in a closed system. The drilling riser has to endure the effect of complex loads, wave movement, platform movement, vortex-induced vibration, cycle torsion, rotating bending and so on. Hence, the wellhead needs to ensure a good performance with the riser. (Wang et al., 2010).

The selection of each type of equipment takes place according to the operating pressure of each well, being a challenge for pre-salt field development. Considering the high pressure and high temperature (HPHT) conditions found in the Brazilian offshore fields, new technologies needed to be developed with equipment that would allow production under these critical conditions. The equipment frequently adopted are for operating pressures ranging from 5,000 psi to 10,000 psi and in specific cases even of 15,000 psi. Today, wellheads with an operating pressure capacity of 20,000 psi and weighing up to 50 tons are found in operation. With the news technologies developed, the environmental conditions increase the fatigue stress found in this equipment, and that is one of the recent problems approached by the industry. Among the factors for this problem are the water depth, wave actions, and hence, the higher number of riser joints and the robustness of the equipment.

Howells (2015) presents a study on this effect and how the use of larger equipment, longer-lasting drilling, and wells have an increased life span, act on the fatigated loading on wellheads. Thus, the monitoring of fatigue help ensure that well operations are performed safely together with integration with the BOP. The studies by McNeil et al. (2015) show how real-time wellhead fatigue monitoring can make a difference in drilling operations. This application results in a rapid return, allowing information to be used for decision-making when the drilling environment demands a high degree of uncertainty about the strength of the components. In addition to measuring wellhead fatigue, monitoring is also used in assessing riser fatigue, and used to increase analytical predictions in the next applications. An important safety concern is the sealing condition provided by the wellhead, since the equipment is not replaced and must withstand the entire life of the well, which exceeds 25 years of operation. In the pre-salt there are situations in which the flowing wellhead temperature reaches 205ºC and Hendrie (2006) concludes in his study, that under these conditions of HPHT, the only efficient way of sealing is the use of metal to metal seals as a primary seal in the wellhead. For this approach to work, statically underbalanced fluid and backpressure control are required. Thus, this operation, which proved to be extremely necessary to overcome the production challenges in this environment, is described by Aranha (2019) as only possible with accurate monitoring of the wellhead pressure conditions. Along with this, Fu (2019) presents a research background of offshore pre-salt hydrocarbon development in Brazil, and that among the challenges were the well control measurements and that for this reason the Santos Basin's deepwater target is considered one of the most challenging blocks the world.

Naveiro and Haimson (2015) developed a study applying a conceptual design on Sapinhoá Field, located in the Santos basin of the Brazil pre-salt. In this study, one of the ways to mitigate the geological uncertainties was the use of a large-bore wellhead. Since most of the wells were vertical, there was space for an increase of the conventional subsea wellhead system, to be applied as a design with a big bore wellhead with five phases, presenting an alternative to achieve the thickness of the post-salt formations. Despite the challenges, the Sapinhoá field application was considered useful and served as a pilot plan for other operations to be carried out in other prospects offshore Brazil.

2.3. Demands for new technologies in drilling rigs

As a result of the deepwater depths and severe weather conditions encountered in the Brazil pre-salt, mooring rigs were not appropriate for the accuracy and safety requirements for the drilling operations. There was a need to contract dynamic positioning (DP) drilling rigs with high level of redundancy in their systems to keep their positions during the whole operation, since large movements and/or loss of position could result in losses of well integrity, risks to the rig crew and environmental accidents.

3. The challenges for the new horizons

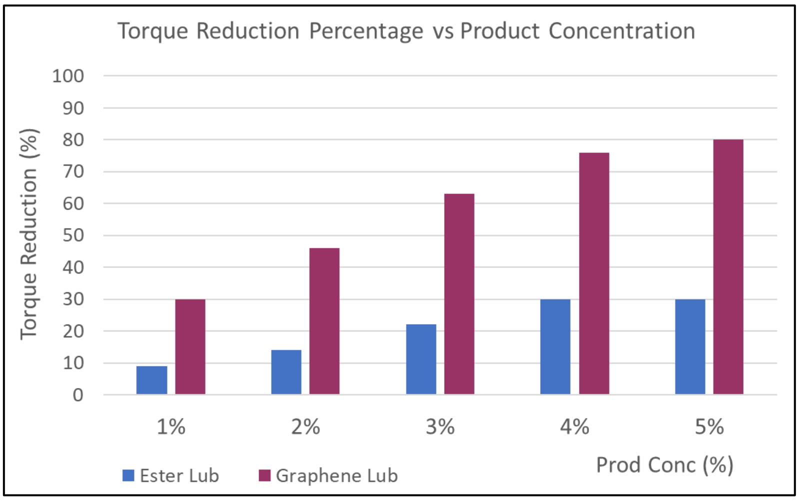
Nowadays, many researchers, petroleum and chemical engineers are motivated to investigate the influence of nano-fluids on improvement of drilling fluids properties e.g. increase the heat flow rate between formation and drill bit, a Newtonian behavior that makes modeling simpler for rock-fluid interactions, fluid loss control and drill bit lubricity. Artificial intelligence (AI) such as machine learning and neural networks have been widely applied to solve well construction problems and issues with dynamic position (DP) rigs motion due to strong environmental conditions that are undesirable for drilling operations. Finally, logistic issues have been improved by implementation of remote-control rooms, optimizing onboard vacancies availability and speeding up timely decisions.

3.1.Drilling fluids technology

Nanofluids technology has been applied in the industry due to their thermal, mechanical and chemical stability. The state of the art about nanoparticles is nanographene, that has an individual layer of crystalline carbon with a thickness of an atom. There is a mix of modified surfactants with nanographene in order to provide a penetration in microscopic tubulars pores of the drill string and create a coating film to protect tubular walls and improve lubricity, minimize bit wear, reduce fluid loss, improve BHA life and ROP. The application of nanographene for drilling fluids program occurs due its high capability of conduction and heat transfer convection, that is a key issue for maintaining drill bit integrity and lubricating properties. Besides, nanographene has Newtonian behavior and sealing propriety that can be applied for zones with poor cement bond and minimizes circulation losses in high porosity and permeability rocks, e.g. carbonates reservoirs located in pre-salt environments. Addition of nanographene to drilling fluid has shown significant increase in ROP, reduction in torque and increase in life span of drilling bit without negatively impacting the rheological properties of the drilling mud. Graphene has great mechanical strength (around 100 times steel strength), Young’s modulus around 0.5TPa and tensile strength of 130GPa and, therefore, can be used in drill bits for increase ROP in drilling operations, potentially saving rig time. The thermal resistance of graphene is in the order of 4,500K of temperature and therefore it is appropriate for HPHT wells.

Due to the challenges encountered in the pre-salt environment, several companies have researched nanographene application in drilling fluids aiming to improve fluids loss control instead of using pressurized mud cap drilling (PMCD). Considering costs, HSE issues and properties mentioned above, graphene can be used in several scenarios. The graphene-enhanced drilling fluid is biodegradable and thermally stable for high temperatures. Its lubricating property is activated due to mechanical frictional contact between drilling fluid and drill string (physical reaction) and thermal conditions (chemical reaction). The graphene-enhanced mud is designed to reach high mechanical contact areas of metal surface through an appropriate carrier fluid mixture and its success is due to its chemical structure and property of forming a strong cohesive film on rough metal surfaces. Laboratory tests indicated 70% to 80% of torque and drag reduction on a water-based drilling fluid combined to nanographene against only 30% to 40% of reduction, when compared to conventional lubricants. Figure 3 illustrates torque reduction between ester-based drilling fluid and graphene-enhanced mud, and it is possible to realize that in all concentrations, graphene provides torque reduction.

Figure 3 - Comparison of torque reduction with nanographene in drilling fluid and ester-based drilling fluid



Source: International Petroleum Technology Conference, 2015.

Upon HPHT conditions, graphene-enhanced drilling fluid gets crystallized in layers, forming a coating to prevent oxidation and direct contact between drill string surfaces, therefore provides reduction in friction coefficient and consequently, increased bit life. Nano graphene coating also concentrates the fines generated by the drilling process onto drill string surface and thus minimizes the risk of these particles accumulating in the drill bit, reducing its life span and forcing early bit replacement. About fluids loss control, for a formation damage evaluation of permeability return after the mud cake is formed, ester drilling fluid and graphene-enhanced mud were also investigated, and it was observed that returned permeability of ester drilling fluid was 5% against 36% of graphene-enhanced drilling fluid. Another application of graphene is to avoid shale swelling when drilling fluid is in contact to formation.

3.2.Geomechanical model for Brazilian pre-salt

The development of a geomechanical model for the behavior of pre-salt carbonates consists on the estimation of different parameters that characterize the rock material, such as mechanical and elastic properties, in situ stresses and pore pressure. Once these parameters are defined, it is possible to estimate fracture and collapse gradients, and lastly, define the optimum mud weight window for wellbore drilling.Each parameter mentioned is estimated differently. In the topics below, it is presented ways to estimate the main parameters for a geomechanical model.

3.2.1. Vertical stress (overburden stress)

The magnitude of vertical stress (σ_v), in an interest depth, is estimated from the integration of all rock layers density above this depth. However, since Brazilian's pre-salt wellbores are offshore wellbores, it is necessary to set the influence of the water in this parameter, as shown in Equation 1.

$$\sigma_v = \rho_w * g * d_w + \int_{d_w}^{z} \rho_i * g * dz_i \approx \rho_w * g * d_w + \sum \rho_i * g * z_i \qquad (1)$$

Where ρ_w is the water density (g/cm3), g is the gravity acceleration (m/s²), d_w is the water depth (m), ρ_i is the density of the rock layer (g/cm3), z_i is the thickness of the rock layer (m), z is the interest depth and i is the index of the rock layer. It can be seen from Equation 1 that vertical stress is a function of the rock density. For a project wellbore, it is necessary to use available data from offset wells. Gardner (1974) and Bellotti & Giacca (1978) presented equations to estimate the rock density using compressional transit time of the formation and matrix compressional transit time.

3.2.2. Pore pressure

Pore pressure is a very important information when considering wellbore stability. However, it is not a simple parameter to estimate for carbonates due to its diagenetic formation procedure and its complex internal structure. Therefore, the best way to set the pore pressure profile is by using pressure measurements in the well.

3.2.3. Minimum horizontal stress

The minimum horizontal stress (σ_h) can be estimated from leak-off tests (LOT) and mini-fracs. Considering null horizontal deformations and linear poroelastic behavior of the rock, σ_h can be estimated as shown in Equation 2. For a wellbore project, LOT data from offset wells can be used, however, the differences in water influence must be considered. If LOT data are not available, it is possible to estimate minimum horizontal stress if considering elastic model scenario, null horizontal deformations and σ_h aligned with north direction, as shown in Equation 3.

$$\sigma_h = LOT \qquad (2)$$

$$\sigma'_h = \left(\frac{\nu}{1-\nu}\right).\sigma'_v \qquad (3)$$

Where σ'_h is the effective minimum stress (psi), ν is Poisson's ratio and σ'_v is the effective vertical stress (psi).

3.2.4. Unconfined compressive strength (UCS)

Militzer & Stoll (1973) developed a correlation to obtain the magnitude of unconfined compressive strength (UCS) of carbonates in general, as a function of the transit time of the formation. This equation is shown in Equation 4. CPM (Santos e Ferreira, 2010) also presented a correlation (Equation 5) to estimate UCS of carbonates, but specifically for pre-salt Brazilian carbonates.

$$UCS = \left(\frac{7682.0}{\Delta t}\right)^{1.82} \qquad (4)$$

$$UCS = 1{,}214.10^{-18}.\rho_b{}^2.\frac{1}{\Delta t^4}.\left(\frac{1+\upsilon}{1-\upsilon}\right)^2.(1-2\upsilon) \qquad (5)$$

Where UCS's unit is psi, Δt is the transit time of the formation (µs/ft), ρ_b is the formation density (Kg/m^3), $\upsilon$is Poisson's ratio.

3.2.5. Maximum horizontal stress

Silva et al. (2017) suggests the use of the stress polygon diagram to constrain the magnitude of maximum horizontal stress (σ_H). This tool shows the state of stress on Earth's crust as a result of the strength of the faults. The authors state that by using the friction equation, it is possible to define a range of possible values of σ_H as a function of σ_h according to each failure regime: reverse, strike-slip and normal. If breakout data is available, it is possible to estimate σ_H through Equation 6.

$$\sigma_H = \frac{UCS+(P_f-P_p)\frac{1+sen\emptyset}{1-sen\emptyset}\sigma_h(1+2\cos 2\theta)+(P_w+P_p)}{1-2cos2\theta} \qquad (6)$$

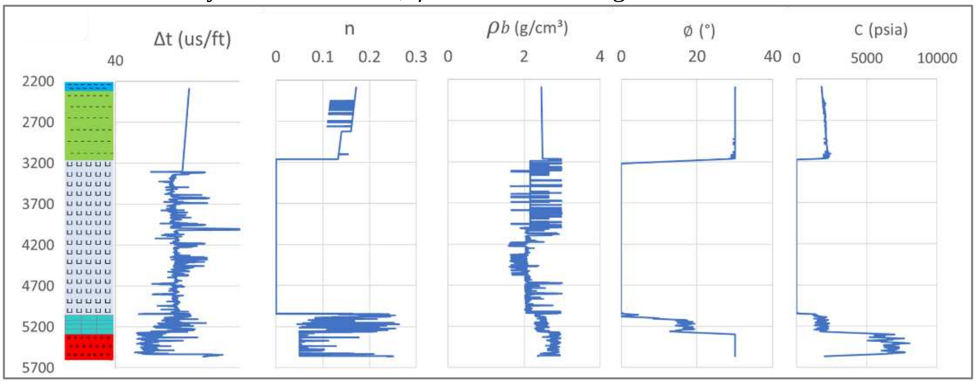
Where UCS is the unconfined compression strength (lb./gal), P_f is the mud weight (lb./gal), P_p is pore pressure (lb./gal), $\emptyset$ is the internal friction angle (°), θ is the breakout angle, witch can be calculated as:

$$\theta = \frac{\pi}{180}\left(90 - \frac{w}{2}\right) \qquad (7)$$

Where w is the width of the breakout.

In Figure 4-Figure 6, it can be seen an application of the geomechanical model. It will not be approached a geomechanical model for salt or igneous formations, hence, the reliable results are shown for carbonates and clay layers. Figure 4 shows the initial data needed to apply the model, therefore, it is assumed to have these data available to follow the methodology. Figure 5 presents the results after the application of the geomechanical model, and with these parameters it was possible to calculate the fracture, upper collapse and lower collapse gradients, which are shown in Figure 6, on the mud weight window. Note that there are two results for UCS, CPM and Militzer & Stoll method, however, for further calculations , CPM equations were considered.

Figure 4 - Initial data available to apply the gomechanical model: Δt is the transit time, n is the porosity, ρ_b is the density of the formation, ϕ is the friction angle and C is coesion.



Where:

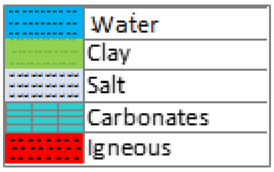


Figure 5 - Parameters calculated using the geomechanical model presented.

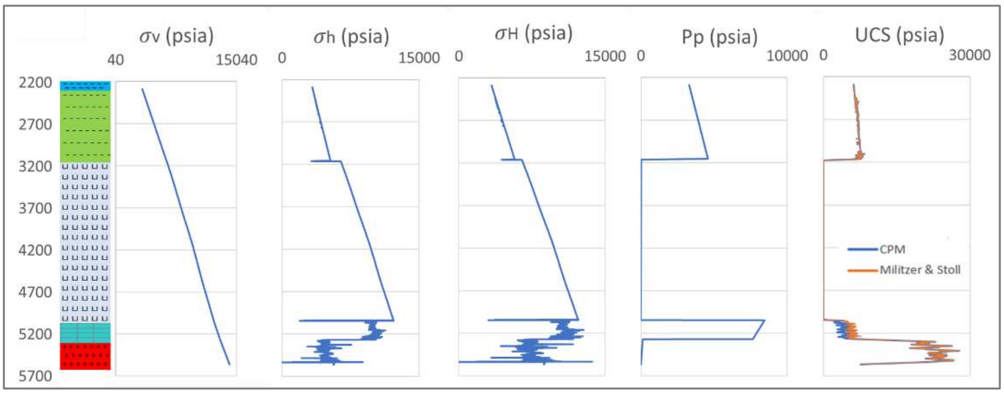
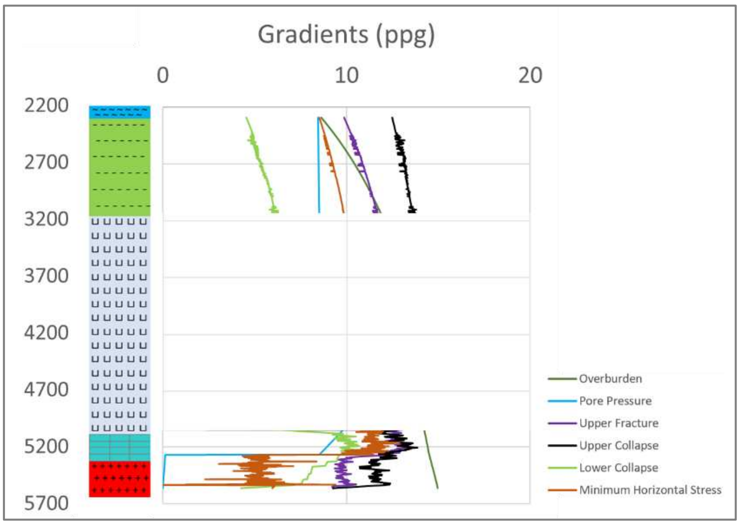


Figure 6 - Mud weight window obtained from the data calculated.



3.3.Applied artificial intelligence (AI)

Most AI techniques applied to drilling fluids involve all the background acquired in well designs already applied in the pre-salt environment. In this way, the entire history of successes and failures is analyzed and the probability of certain problems occurring is estimated through numerical simulations (Ablat and Qattawi, 2017). The main artificial intelligence techniques involved in drilling fluid problem solving are artificial neural networks, genetic algorithms, and applied machine learning to drilling fluids schedule.

3.3.1. Artificial neural networks

Artificial neural network is a type of artificial intelligence that has been proven to provide a high level of competence in solving many complex engineering problems that go beyond the computational capacity of classical mathematics and traditional procedures (Agwu, et al., 2014).

In drilling fluid engineering, artificial neural networks are applied to the prediction of the rheological properties of the fluid; fluid filtrate loss control; prediction of permeability in the plaster region (mud cake); flow pattern estimation in fluid invasion in the formation; debris and sediment decanting speed; frictional pressure drop prediction and efficiency in the transportation of debris and sediment generated by the drilling process.

3.3.2. Genetic algorithms

A genetic algorithm is a tool that has been widely used to find resolutions among a very large range of parameters, through the simultaneous evaluation and refinement of sets of solutions to find the most ideal ones, instead of looking for just one. Its use is suitable for complicated multidimensional problems for which the objective function is not linear and can provide fast and efficient solutions to large metadata problems (Noshi, 2018).

Barati, et al., (2014) used this technique to estimate the drag coefficient in the flow around a sphere and noticed results of 16% to 69% improvement when compared to the techniques previously mentioned. A summary of research articles on the application of this technique in drilling fluid engineering indicates that its use is increasing and is under the spotlight (Agwu, et al., 2014).

3.3.3. Applied machine learning to drilling fluids schedule

The drilling fluids parameters need be determined with good precision, and a challenge to the engineers is that there is not a tool that predicts the mud weight with the wellbore and lithology information, and very often the simulators are not the better option to provide realistic results. In pre-salt cases, this choice is made during the drilling job with offset wells inputs and employees experience, but the imprecision on estimating the correct mud weight has caused several operational problems to date. Teixeira et al. (2013) presented research that a Petrobras team developed a computational tool to predict an appropriate mud weight for salt zones based on multivariable analysis, and not on a physical model, of the whole historic of all pre-salt wells drilled by the company. This tool uses machine learning to analyze the effects of situations in a well following the lithology and geothermal gradients and other aspects that would be difficult to be considered in a physical model, like the compressional environment, the presence of interlayers types and igneous rocks. Beyond the parameter already mentioned, the dataset contains 9445 records of drilling measurements and 216 incidents reports. With this, the obtained results demonstrate that this tool can be successfully applied to drilling fluid estimation for drilling in the pre-salt offshore Brazil.

Furthermore, another powerful tool that also deserves highlights and has been gaining more space in research is the use of digital twins. This technique simulates in real-time what occurs in the field on a model, integrating other techniques of machine learning to achieve results.

Samnejad et.al. (2020) discuss that some specific problems cannot be solved with algorithms that predict drilling fluids behavior due to restrained data access or neglect of the physics behavior. In this study, the rheology measurement needs to be analyzed in standard conditions (API), but on the wellbore there are HPHT conditions. Thus, accurate real-time estimation of rheological properties at the API standard and downhole HPHT conditions is essential for proper well control, wellbore stability, and hole cleaning. The use of this hybrid technique outperformed the other widely used technics of machine learning.

4. Closing Remarks

The discovery of pre-salt, the enhancement of existing technologies and the creation of new ones for exploration and production development represented one of the biggest technological challenges of the Brazilian oil industry in the last decade, so that optimization could be achieved in all cycles of operations. The background acquired in the drilling and completion phases was of utmost importance for more complex projects, as wells were built in a shorter time, reducing costs. The use of MPD and intelligent completion (IC) have made operations safer and reduced exploratory and exploitative risks, while also reducing cost, even though they are more expensive technologies.

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