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Geomechanical Aspects of Cementing Casings in Exploration Wells: Significance of Fracture Gradient in Assuring Well Integrity

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Abstract: ***Borehole cementation is essential for achieving well objectives and ensuring the safe drilling of oil and gas wells, particularly during exploration. The primary aim of cementing operations is to uphold well integrity and ensure zonal isolation. A critical component of cement design involves accurately determining the cementing window, which is constrained by the lower limit of pore pressure and the upper limit of fracture pressure in an open hole. It is crucial to adhere to design standards that address subsurface hazards to prevent incidents similar to the Macondo well disaster in the Gulf of Mexico in 2010. A well-executed cement design can significantly mitigate the risk of losing well control and the potential release of hydrocarbons, events that can adversely affect both the environment and the bottom line of the business. Formation fracture pressure may be exceeded during cementing operations as a result of either static or dynamic cementing heads. Such formation failures typically occur when the equivalent circulating density of the cement fluid breaches the cementing window. Recent analyses of several exploration wells worldwide reveal that inadequate cementation at intermediate casings was often due to the cement slurry's density exceeding the formation's breakdown strength during the cementing process. In certain instances, the growth of fractures and the migration of subsurface fluids to the surface or seabed resulted in the early abandonment of these wells. Developing a cementing program for a well solely based on fracture gradient predictions derived from leak-off tests and formation integrity tests is insufficient. The implementation of real-time fracture gradient modeling is crucial as it offers a comprehensive range of fracture pressures that can be applied to enhance the cementing design, thereby reducing the risk of expensive cementing failures during operations. This paper highlights the importance of real-time fracture pressure modeling, supported by case studies from various locations worldwide.***

Keywords: Leak Paths, Fracture Gradient, Cementation Design, Well Security, Bad Cementation, Real Time Fracture Prediction, Root Cause

1. Introduction

Cementing is one of the most crucial issues in oil fields, especially for high-pressure and gas-bearing formations[1]. The fundamental purpose of cementing operations is to maintain well integrity and zonal isolation. Well integrity pertains to the application of technical, operational, and organizational strategies designed to reduce the likelihood of uncontrolled release of formation fluids throughout the entire duration of a well's life[2]. The cement forms an extremely strong, impermeable seal from an initially thin slurry. This seal is to assure that the chance of the following hazards occurring is as low as reasonably practicable (ALARP): (a) leakage of well fluids to the environment; and (b) unintended flow of fluids underground through holes, annuli, or fractures created during the drilling and production phases of the well. The placement of cement in the annulus between the casing and the wellbore facilitates the drilling of the deeper section. It acts as the primary barrier to prevent crossflow from deeper to shallower formations[3]. The casing-shoe track includes cement, which, in conjunction with the cement in the casing annulus, acts as a permanent barrier that prevents crossflow from deeper formations to shallower layers.

Achieving effective zonal isolation in high-pressure, high-temperature (HPHT) environments and deeper exploration formations is challenging due to the presence of abnormal pressure and the corrosive nature of the formation fluids and gases. A common problem associated with highly over-pressurized zones is crossflow after cementing[1]. The movement of fluid from a high-pressure area to a low-pressure, highly permeable zone can compromise the integrity of the current production hardware. Work-over operations that attempt to repair cement voids can sometimes provide temporary relief but may not provide long-lasting results[4].

2. Potential Leak Paths

A cased well features cement filling the annular space between the geological formation and the steel casing, protecting the casing's exterior. Upon the abandonment of cased wells, a cement plug is placed over the production zone, or a bridge plug may be employed, either with or without an additional cement plug on top[5]. The cement layer in cased wells is relatively thin compared to abandonment plugs, as its thickness is restricted to the annular area between the casing and the surrounding rock formation.

There are several possible leakage pathways along or through the cement (Figure 1). Leakage may occur at the interfaces between various materials, including the interface of the steel casing and cement, the connection between the cement plug and steel casing, or the boundary between rock and cement[6]. Additionally, leakage can happen through the cement itself, or any fractures present within the cement[7]. Leakage may also happen when wells are cemented over a limited section, or when the cement sheath does not consistently cover the entire circumference of the well, in addition to these smaller scale features[8]. Cased wells can sometimes have their casing directly exposed to the formation, as the casing is not always sealed with cement up to the surface. Additionally, a cased well that features a short cement interval within the casing presents another potential route for leakage.

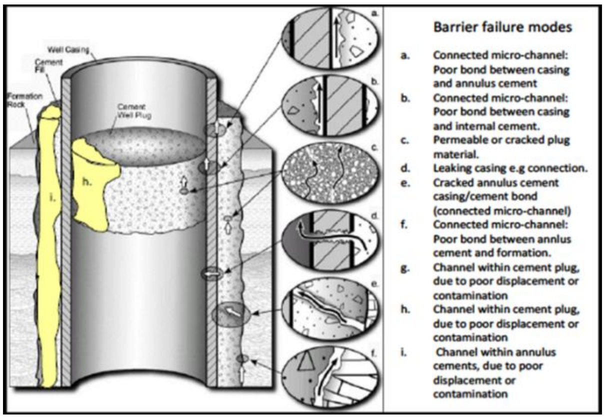

Figure 1: Possible leak paths through a cement barrier[7]

3. Formation Fracture Gradient

The pressure at which formation breakdown or fracture reopening occurs in an open hole is referred to as the "fracture pressure." The fracture pressure gradient, commonly known as the "fracture gradient," is defined as the pressure gradient (pressure per unit depth) that leads to the fracturing of the formation[9]. The orientation of induced fractures will be orthogonal to the minimum compressive principal earth stress, and the magnitude of the minimum stress provides a lower bound on the fracture pressure. At considerable depths, typically exceeding 1000 meters (or 3000 feet), the minimum principal stress is oriented horizontally, resulting in vertical fracture faces. Conversely, in shallow formations where the minimum principal stress is vertical, horizontal fractures, often referred to as pancake fractures, will form[10] (Figure 2A and 2B).

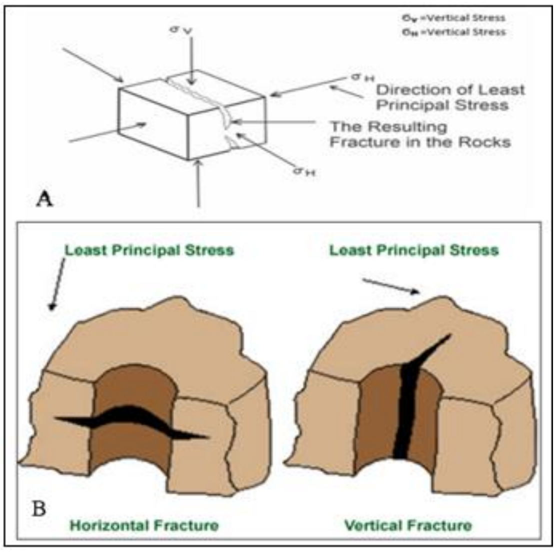

Figure 2A and 2B: Fracture gradient concept under different stress regimes[11]

4. Cementation Design: Typical Example

An important aspect of cement design is the proper estimation of the cementing window, which is a function of pore pressure (lower limit) and fracture pressure (upper limit) in an open hole[12] (Figure 3). The static and dynamic well security should be within the cementing window[13]. This implies that the cementing window must lie between the pore pressure gradient of the formation fracture gradient. Cement slurry design, operational practices, and proper consideration of in-situ rock properties are critical elements that define a successful job. The essential aspect of cement blending involves creating a consistent slurry that incorporates the correct amount of additives and mixing water, while maintaining the density within the specified cementing range. The weight of the slurry corresponds to the weight of the hardened cement, minus any weight of free water that is lost during the setting process. The properties of the cement slurry and its behavior are influenced by the various components and additives present in the mixture. Regulating the density is essential for maintaining reservoir pressure and avoiding the fracturing of geological formations. Controlling the density of the cement slurry is essential for successfully positioning a cement column, particularly in formations that could be compromised by a dense slurry or in wells that may experience flow if the cement slurry is less dense than the pore pressure[14]. When displacing cement, it is common to determine an optimum pump rate to attain a maximum flow rate. This ensures effective cleaning of the hole and removal of mud from the annular space designated for cement placement, while also preventing excessive dynamic pressure on the surrounding formations[15]. In case of fracture, there will be circulation losses (and hence cement losses) during cementation.

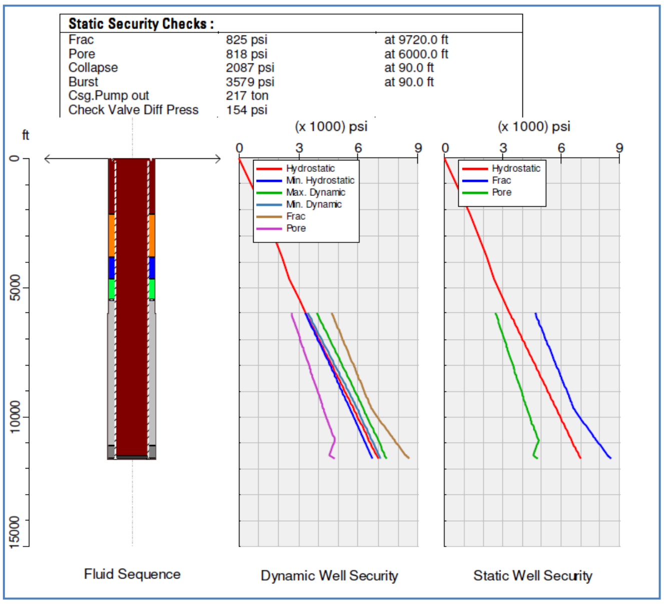

Figure 3: A typical casing cementation design.

Typically, the pump rate is lowered near the end of displacement to reduce the friction pressures exerted on the formation by the dense, viscous cement in the annulus. The rate is also lowered to minimize sharp increases in pressure when the top wiper plugs land on the float collar, which is known as “bumping the plug.” For an effective cementing operation, it is essential to know both the bottom hole temperature of the formation and an estimate of the circulating temperature[16]. While pressure can speed up the thickening and setting times of the cement, its impact is significantly less than that of temperature, which reduces the thickening time. Using an incorrect cement density can lead to various issues, including weak cement strength, insufficient cement bonding, gas migration, inadequate mud displacement, formation fracturing, and in severe cases, blowouts[16]. Cement slurry density must be rigorously controlled to enable the subsequent well completion steps to be carried out successfully. Design standards related to subsurface hazards need to be fulfilled to avoid situations like that in the Gulf of Mexico's Macondo well in 2010.

5. Consequences of Bad Cementation

The failure to maintain well control, resulting in the release of hydrocarbons to the surface, can cause explosions, loss of life, significant environmental harm, damage to equipment, and harm to reputation[17]. Formation fracture pressure could be exceeded in the cementing operations due to the static cementing head and/or the dynamic cementing head. Formation failure of this nature typically occurs when the cementing window is compromised by the equivalent circulating density of the cement fluid[18]. The recent experience in the Gulf of Mexico (GOM) is one such event where the annulus cement and shoe track barriers did not isolate hydrocarbons. The well construction and the sequence of events that led to the disaster is illustrated in the pore pressure plot (Figure 4). The design of the long-string casing utilized in the GOM well established strict restrictions on the permissible equivalent circulating density (ECD). The limited timeframe resulted in the creation of a cementing program that was excessively complicated and ultimately unsuccessful. While displacing the cement, the circulating pressure surpassed the fracture pressure, causing insufficient cement to rise within the annular space (Figure 5). The program specified a minimal cement volume, which did not accommodate a standard margin of error; it necessitated precise calculations of the annular volume and meticulous execution to establish an effective barrier to the reservoir[19]. The well's integrity was either not established or was compromised, as the barriers formed by the annulus cement and shoe track failed to adequately isolate hydrocarbons[20]. An efficient cement design can minimize the risk of losing well control and the subsequent discharge of hydrocarbons to the surface, occurrences that adversely affect both the environment and the financial performance of the business.

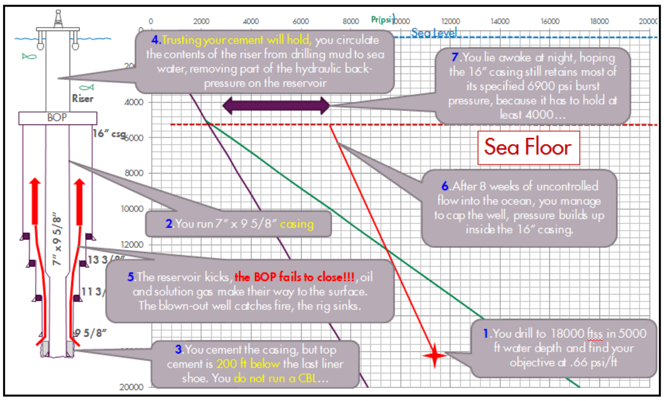

Figure 4: Well construction and pore pressure plot of the Macondo GOM well

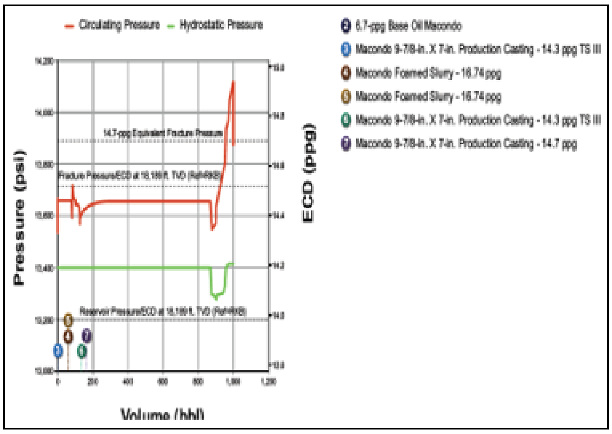

Figure 5: Circulating pressure and density plot showing that fracture pressure exceeds during displacement[19].

6. Recent Field Experiences

Analyses of a few recent exploration wells around the globe, where the cementation jobs of intermediate casings indicated that cement slurry gravity exceeded formation breakdown strength during cementation. In some cases, the fracture growth and movement of subsurface fluid to the surface led to the premature abandonment of the wells.

6.1 North Sea

A deepwater well recently drilled in the North Sea while cementing the intermediate 16" casing experienced a complete loss of returns (Figure 6). The cement bond log revealed the absence of cement behind the casing, and the hole was sidetracked. The cementation of the sidetracked hole was no better than in the main hole, with just a few metres of soft cement at the casing shoe, which, however, was enough to go ahead with drilling deeper. Analyses revealed that the formation fracture gradient was exceeded by the cement slurry density in both cases.

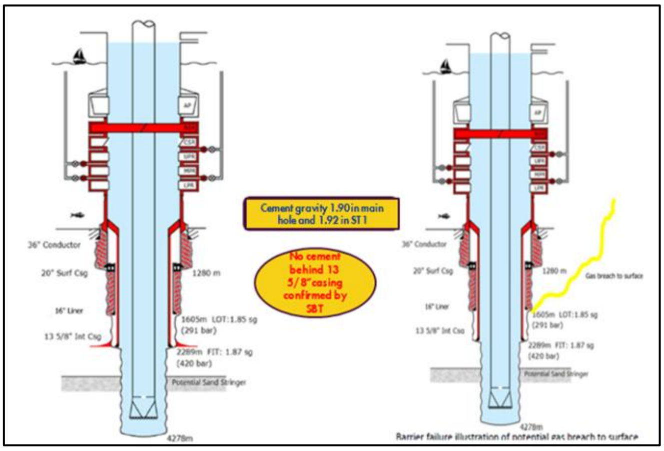

Figure 6: North Sea well construction.

6.2 South China Sea

A recent deepwater well in the South China Sea experienced a kick whilst drilling, and during well control operations, extensive mud losses were observed. Isolation plugs were set with variations from the initial plan. Lost circulation analysis indicated that the shoe strength had weakened in comparison to leak-off test values, which was later confirmed by the leak-off test while sidetracking. While drilling at deeper depths, it was observed by the remotely operated vehicle (ROV) that gas bubbling and sediment clouding were taking place in the annular space between the casings. This observation prompted the premature abandonment of the well. Analysis revealed that the vertical fracture induced during well control operations transmitted pressure from the overpressured deep depths to the shallower hydropressured zones, causing crossflow (Figure 7).

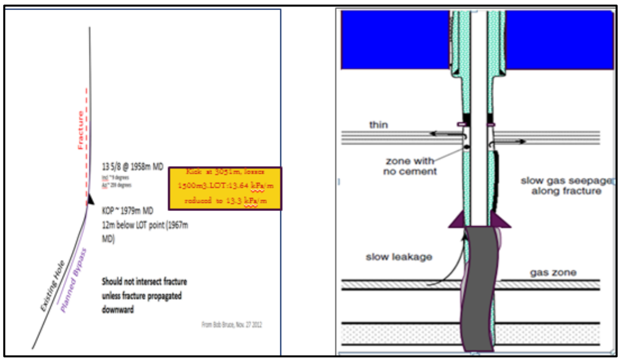

Figure 7: South China well fracture growth model. Notations are the σ_r mud pressure, P_o for pore pressure, σ_h for fracture stress and σ_v for overburden stress

6.3 Offshore Gabon

A shallow water drilled offshore Gabon indicated cement losses during the job, and a low leak-off test at the casing shoe was suggestive of bad cementation. Drilling deeper into a gas-bearing formation led to activity in the casing outer annulus, and the flow of saline water was observed. After dumping different grain-sized sands into the annulus, the flow was reduced to minor seeping. However, at about the same time, the nearest lagoon became connected with the sea, causing a water-level reduction of about 2 metres in the lagoon. Subsequently, the cementation of the production casing was also poor, and pressure buildup was noticed again in the outer annulus. The cratering effect was later confirmed by detailed analysis of cementing volumes, losses, leak-off test plots, and well activity. The vertical fracturing by the cement slurry density exceeding the formation fracture pressure, and the resulting fracture propagation at shallower depths into the lagoon caused the reduced water level in the lagoon (Figure 8).

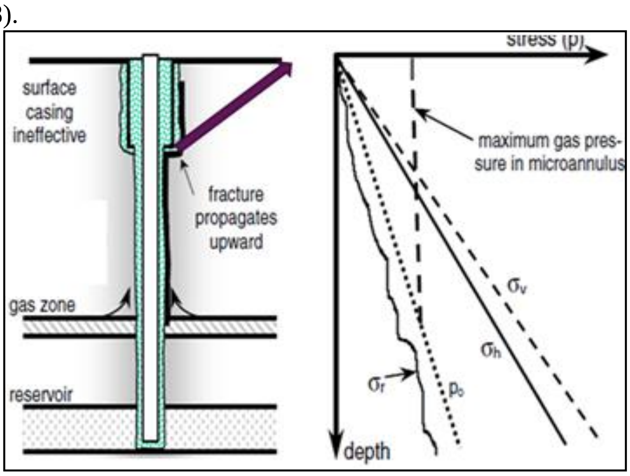

Figure 8: Failure model of the offshore Gabon well. Notations are the σ_r mud pressure, P_o for pore pressure, σ_h for fracture stress and σ_v for overburden stress

6.4 West Africa

A recent well in West Africa experienced hydropressured reservoir sands getting charged at the time of completion, either through the cement behind the casing or leakage through the cement plugs and bridge plugs set to isolate the overpressured gas zones from the hydrostatic reservoirs. Although it was not possible to pinpoint the exact cause of the increased pressures, the onus falls on the cementation. The kick was controlled, and the well was killed. The geomechanical model illustrating the kick is presented in Figure 9.

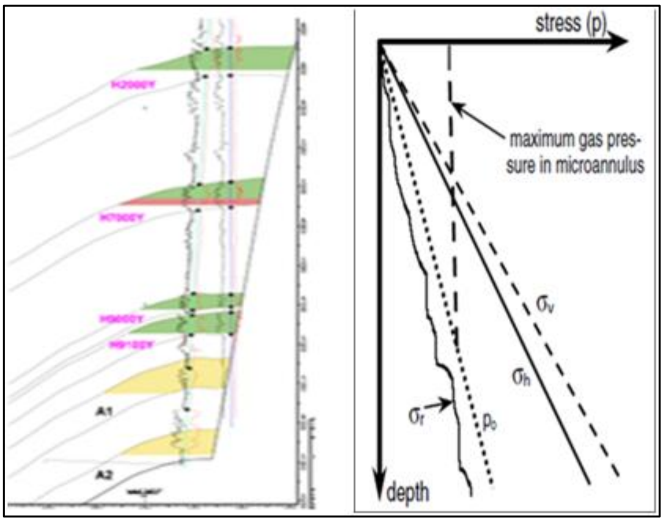

Figure 9: Failure model of the West Africa well. Notations are the σ_r mud pressure, P_o for pore pressure, σ_h for fracture stress, and σ_v for overburden stress

7. Real-Time Fracture Prediction

Planning a well's cementing program based on fracture gradient predictions from leak-off tests and formation integrity tests is inadequate. The fracture gradient is dependent on various factors, such as the magnitude of overburden stress, the formation stress in the area, and the pore pressure of the formation. To achieve an accurate and realistic prediction of the fracture gradient, any forecasting method must consider most of these factors[21].

Real-time fracture gradient modeling is essential for determining the range of fracture pressures that can be applied in optimal cementing design, thereby reducing the risk of expensive cementing failures during operations. To attain the necessary accuracy for effective well construction, it is crucial to update the pre-drill model in real-time as drilling progresses. These updates primarily depend on measurements taken during drilling (MWD) and logging while drilling (LWD), while also considering mud logging data and drilling reports. When implemented correctly, this approach provides highly effective recommendations for mud weights that ensure the well remains within safe operating limits and establishes a suitable cementing window. Until recently, obtaining real-time pressure updates was often impractical due to the significant computational demands and specialized knowledge required[22]. Typically, such analyses were costly, highly technical, and limited to high-profile, high-risk wells, particularly in deep-water environments.

The integrated pre-drill pore pressure prediction utilized for the entire well profile in the recent North Sea well, which was adjusted during drilling, is illustrated in Figure 10. Failure to adhere to the real-time cementing window led to a total loss of returns during the cementation of the intermediate casing. Conversely, following the real-time fracture gradient limits resulted in a successful cementation for the deeper casing. This scenario demonstrates that relying solely on pre-drill modeling does not eliminate the risks associated with pore pressure management. It may be necessary to adjust the cement design if real-time predictions differ from the pre-drill parameters related to well control and formation fracture[22]. In this instance, the cement design for the deeper casing was modified in real time by maintaining the cement density below the real-time fracture gradient prediction, which resulted in effective cement placement behind the casing. In contrast, the cement slurry density for the intermediate casing exceeded the fracture gradient, leading to poor cementation, as shown in Figure 10.

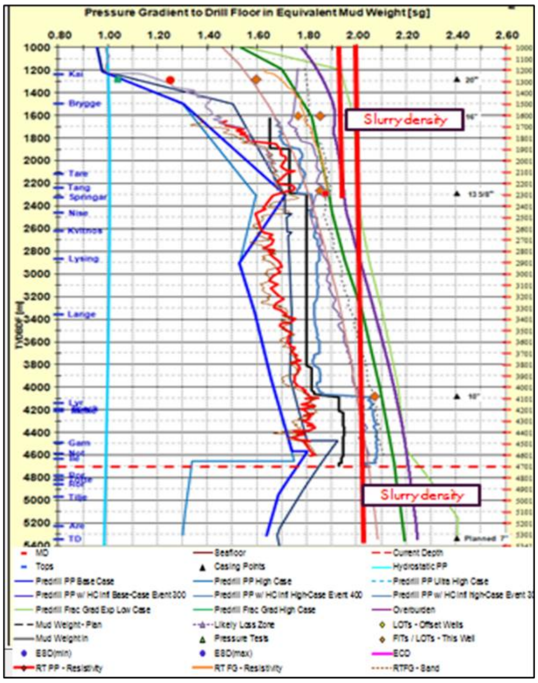

Figure 10: Real-time pore pressure and fracture gradient prediction in the North Sea well.

8. Root Causes of Cementing Issues

Well integrity and well construction are fundamentally interconnected. The deterioration of wellbore integrity primarily results from time-dependent formation leakage, which is influenced by factors such as fluid movement, solute migration, chemical interactions, mechanical pressures, the quality and integrity of the annulus, degradation of the casing, deterioration of seals, and improper abandonment procedures throughout the life cycle of a wellbore[23]. The primary cementing process is essential for preventing the vertical movement of fluids throughout the productive lifespan of the well and beyond[24]. Detailed evaluations of the cementing operations examined in this discussion indicate that, in several instances, the cement pressure surpassed the formation fracture pressure, leading to formation failure and allowing access to deeper formation fluids and pressures from shallower hydrostatic formations. A significant concern highlighted by the cases presented is the density of the cement slurry exceeding the formation breakdown strength during the casing string cementation, as depicted in Figure 11. Additionally, the excessive pressure needed to fracture shallower formations may also stem from prior well control operations that created fractures, which act as pathways for the transfer of fluids and pressures from deeper to shallower formations.

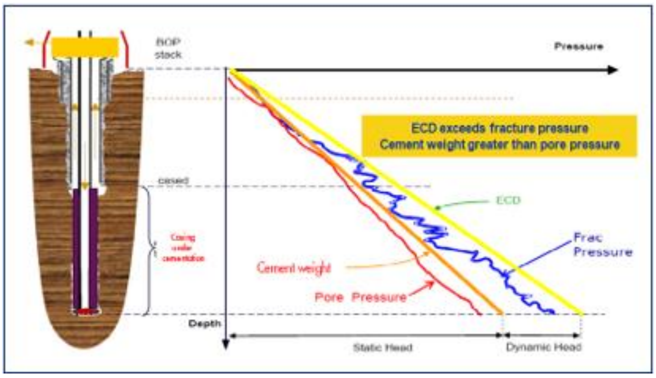

Figure 11: Root cause of cementing failures in recent wells.

9. Concluding Remarks

The design and construction of wells aimed at reducing the risk of failure criteria are essential for safe exploration drilling. In addition to employing fundamentally sound cementing techniques, several supplementary measures are recommended, including but not limited to: the application of back pressure; the incorporation of cement additives, viscosifiers, and foams; the utilization of external casing packers; the reduction of cement column height, potentially through multistage cementing; the implementation of reverse-circulation cementing technology to manage equivalent circulating densities (ECDs); the use of stress caging methods such as Frac-AttackTM treatment to reinforce weak casing shoes; and the acquisition of real-time data through closed-loop drilling systems. Furthermore, real-time modeling of fracture gradients is crucial in determining the range of fracture pressures that can be leveraged for optimal cementing design. Continuous monitoring of fracture pressures is vital for ensuring effective cementation, which is a cornerstone of well success and particularly critical for effective exploration drilling.

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Author Profile

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