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Coping with Shallow Hazards in Deep Water Drilling: Consequences and Mitigation

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Abstract: ***Exploration drilling in the deep-water environment is fraught with challenges. The difficulty in deep water drilling lies in the progressively narrower operational window, which results from the diminishing gap between the formation pore pressure and the fracture pressure needed as water depth increases. Just beneath the seafloor, the main hazard is the existence of shallow water or gas pockets, which can lead to blowouts or destabilization of the seafloor during and after drilling. If these geohazards are not identified pre-drill, they may pose considerable risks to drilling operations, and the worst-case scenario is of losing the well along with serious containment issues. As a measure of caution when there is uncertainty on the formation just below the seabed, the top-hole drilling of a pilot hole riserless, along with the acquisition of real-time high-resolution seismic data, mitigates the risk to a considerable extent. The lessons learned are applied to the mainhole drilling. This paper explains riserless drilling and how a pilot hole drilled enabled drilling the main hole successfully in a deep-water challenging situation in South East Asia off the Borneo coast.***

Keywords: Deep water, Shallow hazards, Shallow water flow, Remotely operated vehicle, Riserless drilling, Pilot hole drilling, Equivalent circulating density, Dynamic kill mud, Seafloor Crack

1. Introduction

Deep water[1] refers to the extensive areas of water that lie beyond the continental shelves, encompassing 63% of the Earth's surface(Figure 1). In these regions, sediment deposits are shaped by the ocean floor features and tectonic processes[2]. In deepwater drilling, several challenges arise due to the proximity of formation pore pressures and fracture pressures at shallow depths. As water depth increases in deepwater scenarios, both the fracture gradient and equivalent pore pressure tend to decrease[3]. At extreme depths, around 10,000 feet, the combination of a low fracture gradient, attributable to insufficient overburden, and a reduced equivalent pore pressure renders drilling impractical, even when using unweighted mud, as annular pressure losses lead to an increase in Equivalent Circulating Density (ECD). Typically, deepwater wells incorporate frequent shallow casing strings to isolate low fracture-gradient formations. These low fracture gradients can cause lost circulation issues due to surge and swab pressures. This is particularly problematic with synthetic, mineral oil, and diesel-based systems, which are compressible and can diminish the allowable fracture gradients. Surge, swab, and ECD pressures present considerable difficulties for deepwater drilling operations, particularly during running and cementing casing[4]. It is crucial to comprehend how temperature and pressure influence hydraulics and the rheology of drilling fluids in deepwater environments. The low temperatures of the water and the resulting low temperatures in the riser can lead to increased fluid rheology, resulting in heightened surge and swab pressures.

Deep water drilling is challenging given the narrow drilling window, which is a function of the diminishing difference between the formation fracture initiation pressure and formation pore pressure[5]. For all practical purposes, fracture pressure is the fluid pressure at which losses from the borehole will be observed, whereas the pore pressure is the pressure of the fluids in the rock. Naturally, open fractures tend to be pushed open, while in intact formations, new fractures will be created when the fracture initiation pressure is exceeded.

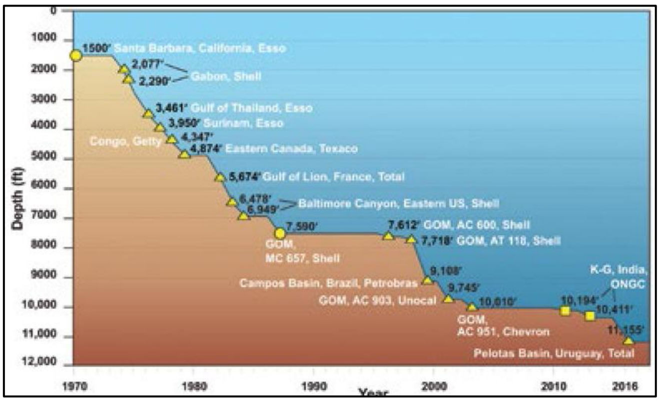

Figure 1: Deep water, water depths by the year[1]

2. Shallow Hazards

While drilling deepwater wells, the concern is to avoid shallow gas hazards, as they potentially could cause a blowout. Shallow hazards, as defined **by IADC**, “are adverse drilling subsurface conditions that may be encountered before the setting of the first pressure containment string and the emplacement of the BOP upon the well.”[6]. Shallow hazards pose risks to drilling operations. In deep-water environments, the ocean floor may also exhibit unstable slopes, slumping, sliding, and sinkholes (Figure 2). Beneath the seafloor, various hazards to drilling operations arise from shallow water and gas flows, as well as from concealed channels and splays that contain water and gas. Additionally, active faults, gas clouds, chimneys, and plumes pose risks, along with disassociating gas hydrates and lateral pressure transfer effects that can elevate pressures into shallower regions. These risks are diverse and can encompass shallow gas, shallow water flows, disassociating gas hydrates, mud volcanoes, faulting, boulders, and instability within the wellbore. Shallow hazards are detected through exploration seismic surveys, pilot hole drilling, stratigraphic modeling,

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and analysis of offset data. A common practice for physically identifying shallow hazards and avoiding the potential dangers of shallow hazards beneath the sea floor is to drill a pilot hole through the shallow gas and water zone, with the hope that the smaller diameter hole will prevent such a large influx. Shallow hazards have the potential to inflict significant damage to the boreholes and present considerable risks to the drilling process. Consequently, identifying and delineating these hazards before commencing drilling is crucial for minimizing risk.

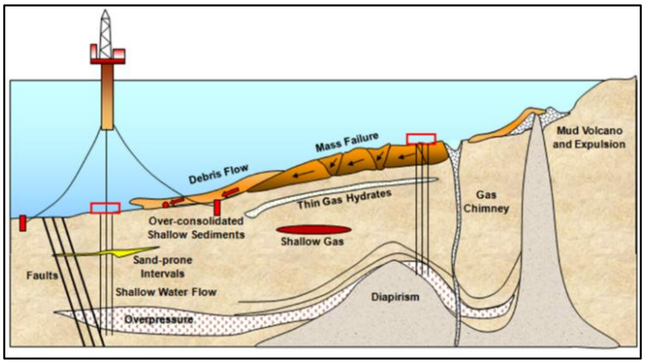

Figure 2: Modified from International Centre for Geohazards, Norwegian Geotechnical Institute (NGI)[7]

Shallow flow hazards are generally encountered prior to the installation of the marine riser. Consequently, if the formation begins to flow uncontrollably, it poses a safety threat to the rig and risks damaging the well structure, as well as affecting the adjacent seafloor[8]. Shallow water flow is particularly concerning, as it can result in the buckling of casing strings and significant sand accumulation on the seafloor. Additionally, an uncontrolled discharge of water or gas into the sea can have detrimental environmental consequences. Shallow flow can arise at any stage during drilling and cementing operations. If flow occurs during the cementing phase, it may create channels within the cement column, hindering proper isolation. This situation allows shallow formations to continue flowing post-cementing, making remediation efforts to achieve isolation exceedingly challenging and could spark containment issues. Preventing channel formation during the cement setting process introduces further complexities to the cement design. The major shallow hazard risks in deep water settings are shown in figure 3 with pictures from the remote operating vehicle (ROV) used to monitor while drilling.

The assessment of geohazards demands a collaborative effort from a multidisciplinary team. It involves the combination of several techniques, including deep tow surveys, high-resolution 3D seismic imaging, geohazard investigation, well logging, and geotechnical approaches. Additionally, numerical modeling for hydrate dissociation and slope instability serves as an essential predictive tool that can enhance the risk evaluation of these hazards concerning wellbores, rig foundations, and the seafloor[9].In deepwater regions, the sediments found on the seabed and just beneath it is predominantly soft, interspersed with occasional sandy layers. These sections frequently exhibit channelization and include sandy intervals characterized by increased porosity. Such layers may display a chaotic amplitude pattern, where bright amplitudes are linked to the presence of fluid or variations in lithology.

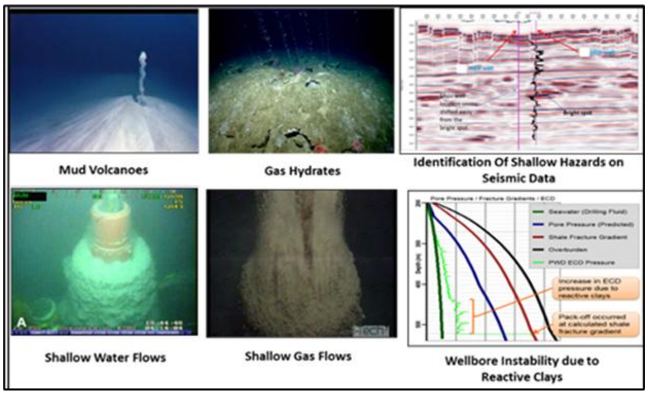

Figure 3: Major shallow hazard risks in deep water settings[10],[11,12]

Geohazards at drilling sites cannot be entirely eliminated; however, many can be circumvented by thoroughly analyzing sub-surface data and accurately interpreting and quantifying the related risks. In instances where a geohazard is unavoidable, it is essential to implement mitigation strategies to minimize the risk to levels that are as low as reasonably practicable (ALARP).

3. Shallow Hazards Monitoring

Detecting shallow flow can be challenging, as monitoring changes in the return rate at the seafloor with a remotely operated vehicle(ROV) is difficult[13]. ROVs, or remotely operated vehicles, are unmanned submarines fitted with cameras and various sensors. This technology enables operators to control them from a distance, facilitating activities such as equipment inspection, underwater structure repairs, and sample collection. This removes the necessity for divers and significantly lowers the danger to human life[14]. The return of drilling fluid and cuttings often obscures the well location, complicating the observation of returns or any variations from the wellbore. To identify shallow flow hazards, seismic data and structural mapping are utilized, along with information from offset wells. However, it is daunting to completely avoid shallow flow hazards; while the risk can be mitigated, it is seldom entirely eliminated. This complicates efforts to navigate the challenges posed by shallow flow hazards. When drilling through formations known to contain shallow flow hazards, operators must be adequately prepared to manage these risks and implement appropriate safety measures.

Most conventional operations data are not available during riserless drilling as the mud returns are always to the seafloor[15]. However, during riserless section, we do have a ROV continuously monitoring the wellhead during drilling and connection to pick up any indication of shallow water flow (SWF) or gas flow. Typically, the gas flows are easier to pick due to associated gas bubbles and density contrast on the ROV's looking sonar. Interpreting SWF from ROV videos is tricky and should be done in consultation with relevant experts. Additionally, integrating annual pressures while drilling (APWD) data, subsurface geology (i.e., presence or absence of any permeable lithology), and real-time pore pressure trends are strongly recommended before interpreting any shallow water flow event[16].

Pore pressure and fracture pressure serve as essential parameters in the design of wells and the decision-making processes related to operations. Miscalculating these factors can result in severe adverse events that could jeopardize both human safety and environmental integrity. Process Safety focuses on ensuring that our physical assets, such as wells, drilling rigs, and offshore platforms, are designed effectively, operated safely, and maintained properly. It is a collaborative endeavor that necessitates both skilled technical contributions (including modules on Concepts, Data, Models, etc.) and proactive communication and leadership (such as modules on Plots, Assurance, Preparations, Monitoring While Drilling). A crucial aspect of Process Safety management involves continuously questioning what could potentially go wrong, what measures are in place to prevent such occurrences, and whether these controls are functioning as intended or require enhancement.

4. Riserless and Risered Drilling

In deep-water offshore drilling, the marine riser serves to move fluids from the mudline (seafloor) to the drill floor on board a mobile offshore drilling unit (MODU)[17]**.** For the initial segment of the well (first few thousand feet), it is common to drill without having a marine riser in place. This phase of the drilling is called riserless drilling (Figure 5). Riserless drilling primarily utilizes seawater instead of drilling mud for borehole management, as drilling mud cannot be recirculated. The density of seawater is considerably lower than that of drilling mud, which increases the likelihood of borehole collapse with increasing depths, particularly when the pore pressure surpasses the hydrostatic pressure provided by the seawater[18].

In risered drilling, the drill cuttings and mud returns are always to the drill floor, whereas in riserless drilling, the returns are to the seabed (Figures 4 and 5). Also, in risered drilling, the annulus (space between drill pipe and surrounding open hole/casing/riser) is always isolated from the seawater, leading to circulation of a relatively uniform density fluid and hence a single annular pressure gradient profile (Figure 4). In riserless drilling, the system remains exposed to seawater above the mudline and discharges back to the seafloor[19]. This leads to a natural dual gradient system where we generally have a heavier fluid (drilling mud/ seawater plus cuttings) in the annulus from mudline to bottom of hole and seawater from mudline above. This, in turn, leads to a dual pressure gradient profile where pressure increases along a hydrostatic gradient up to the mudline, and below the mudline, it increases along a higher gradient dependent on ambient mud-weight (inset Figures 4 and 5).

It is important to observe that the returns are directed towards the seabed. This establishes a natural dual gradient system, wherein weighted mud (if utilized) is present from the bottom of the hole to the mudline, while seawater extends from the mudline to the mean sea level.

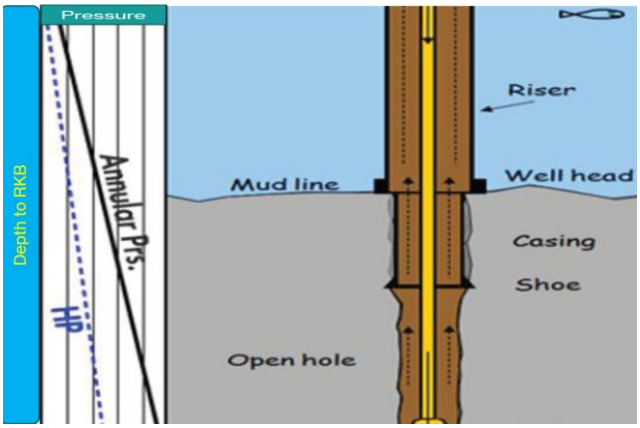

Figure 4: Schematic illustration of a risered drilling setup.

It is significant to recognize that the drilling riser serves to separate the circulating mud and drill cuttings from the surrounding seawater. This results in a circulating fluid that maintains a relatively consistent density, thereby creating a uniform gradient in the annular pressure profile.

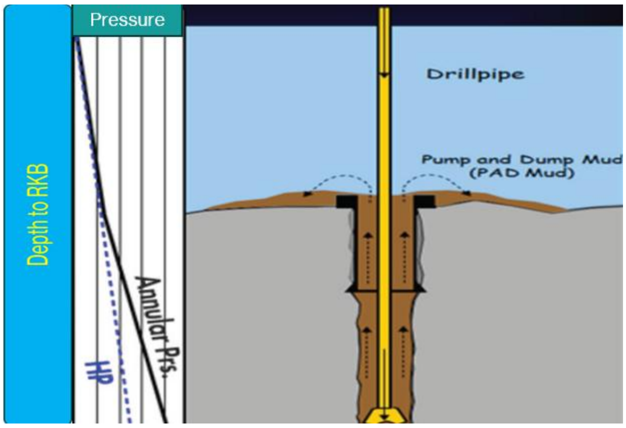

Figure 5: Schematic illustration of riserless drilling setup.

5. Why riserless drilling?

Since in a risered drilling setup, the gradient in the wellbore is relative to the drill floor, this leads to additional pressure being applied at the mudline(mud density-seawater density times water depth times a constant unit). The increased backpressure at the mudline results in a reduction of the drilling distance between casing points. Riserless drilling enables drilling through the shallower section of a well without the need for an additional casing string[20]. Figures 6 and 7 show a hypothetical deep-water well pore and fracture pressure profile along with the mud weights needed to drill through a shallow interval. Riserless drilling of the upper sections of subsea wells has become a common method in the construction of deepwater wells, with mud returns being directed to the seabed[21].

Note that in the case of risered mode (Figure 6), an additional casing string is needed to successfully negotiate the shallow pore pressure ramp (red star in Figure 6). However, the same interval can be drilled in riserless mode without the need for any additional casing (Figure 7). Riserless drilling (with weighted mud or DKD mud) is key to safe and cost-effective execution of deep-water wells in shallow water flow (SWF) prone areas, i.e., Mississippi Canyon in the Gulf of Mexico.

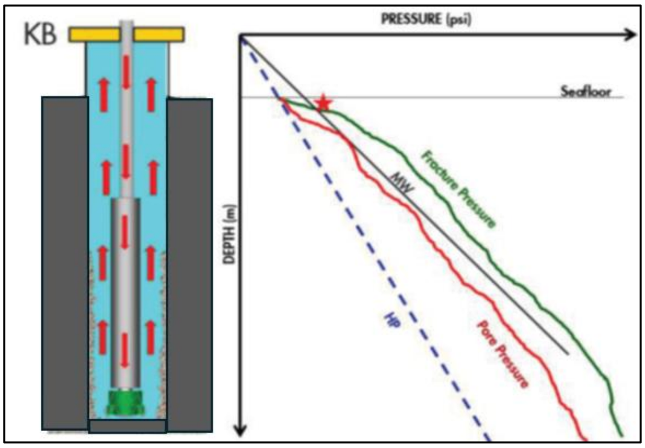

Figure 6: Schematic illustration of risered drilling setup. Single gradient in the annular pressure profile due to the riser

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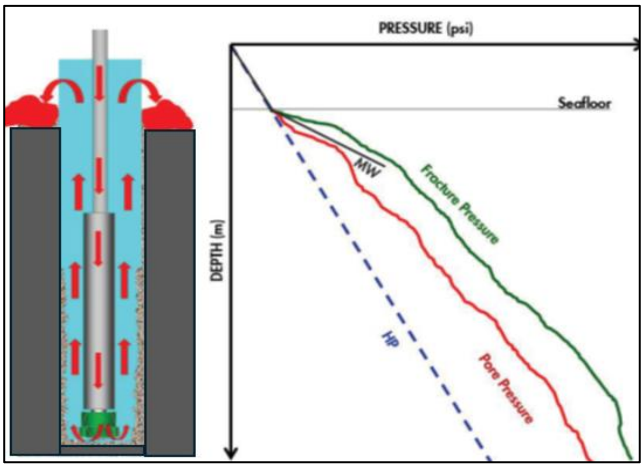


Figure 7: Schematic illustration of riserless drilling setup. Natural dual gradient created by the returns to the seabed

A schematic representation of a riserless drilling configuration is provided. It is important to observe that the returns flow back to the seabed. This results in a natural dual gradient system, where weighted mud (if utilized) extends from the bottom of the borehole to the mudline, while seawater is present from the mudline up to the mean sea level.

When the level of uncertainty is high while mapping uncharted deep water territory, it is always advisable to drill a pilot hole and carry out the learning to successfully drill the main hole.

6. Pilot Hole Drilling in South East Asia off Borneo

The geological environment of the deep waters in the South China Sea is complex. The SWF hazard has emerged as a significant geological risk in contemporary deep-water drilling operations in the Borneo Sea. Consequently, it is essential to precisely identify the SWF hazard, assess the associated risks, and implement suitable strategies to mitigate both engineering and financial losses. During deep-water drilling, the presence of shallow gas is frequently observed, posing significant risks of severe incidents, including blowouts and fires. The fluid used to drill this interval to total depth (TD) is seawater, supplemented with 100-150 bbl of viscous bentonite sweeps at each drill pipe connection[22]. This assists in proper hole cleaning. To address the potential risks associated with uncertainty in the geological formation beneath the seabed, the implementation of riserless top-hole drilling for a pilot hole, combined with the acquisition of real-time high-resolution seismic data, significantly reduces the associated risks[23] (Figure 8).

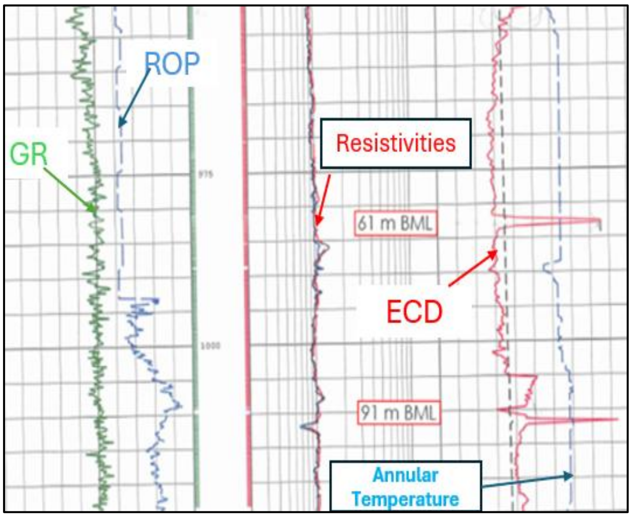


Figure 8: Spiking of ECD whilst drilling just beneath the seabed in a Borneo deep water well

An incident occurred while drilling a 9 7/8” pilot hole in the South China Sea at 920 metres water depth. It began with a rise in equivalent circulating density during gel sweeps in a gas sand layer (Figure 8). At a depth of 1009 m referenced to rotary Kelly bush (RKB), the sand encountered did not flow, indicating hydrostatic pressure (Figure 9). Gas was observed while drilling through the sand at 1265m RKB (Figure 10). During a pipe connection at 1298 m RKB, gas was released and the well started flowing, causing a fracture on the seafloor, and a sheen on the water surface was observed (Figure 11). Dynamic kill mud was then pumped to stop the gas flow and resume drilling. After using kill mud, ROVs confirmed no further hydrocarbon flow from the crack or wellbore.

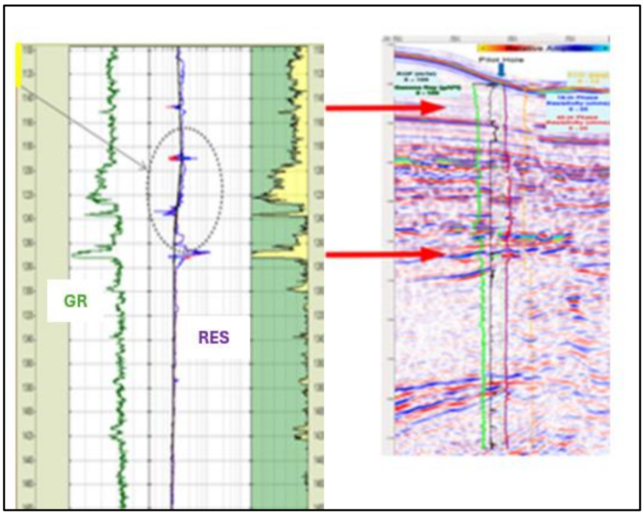


Figure 9: Real-time monitoring of riserless section whilst drilling just beneath the seabed in a Borneo deep water well

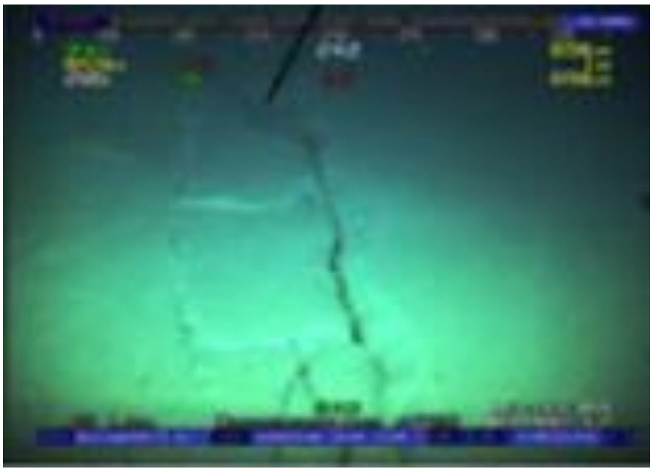


Figure 10: Seafloor Crack observed through ROV monitoring before kill mud usage in the vicinity of the pilot hole

Figure 11: ROV Close-up of Water and gas flow around the seafloor near the pilot hole

7. The cause of the seafloor fracture while drilling with seawater

The fracture was initiated due to ECD spiking during gel sweeps of the bentonite suspension to facilitate proper hole cleaning. The first sweep caused pressure changes. After the second sweep, the spikes reduced, likely due to the fracture's presence. A flow event continued the fracture's growth.

The sequence and cause of the seafloor fracture while drilling with seawater beneath the sea floor is interpreted as :

- Fracture initiation was due to ECD spiking during sweeps.
- Early gel sweeps exceeding the hole volume reached a fracture gradient, a viscous gel filled the borehole, and a fracture formed after the second gel sweep.
- ECD spikes were muted, suggesting prior fractures, and a flow event used this fracture to expand it.

The lessons from the pilot hole were used to mitigate shallow hazards and safely drill the main hole to the targeted depth to set the casing and riser before drilling ahead to deeper depths.

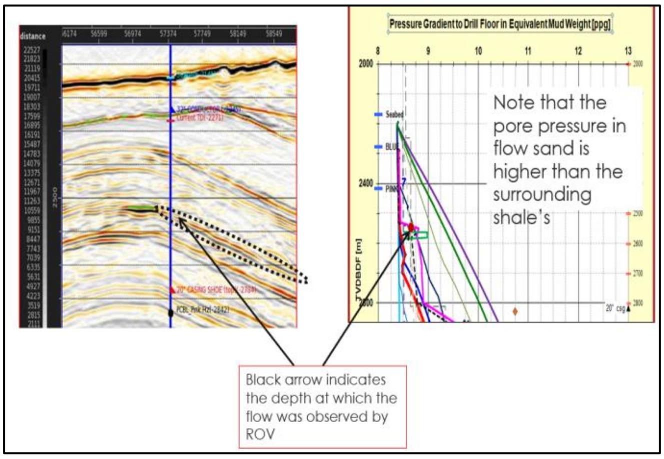
8. Main Hole Riserless Drilling

Real-time resistivity measurements of pore pressure showed similar trends to the pilot hole in the larger hole. The maximum value reached was about 11.65 kPa/m at 1148 m deep. At 734 m below the mud line, the value was 13.85 kPa/m. No flow was observed in sand at 1073 m, suggesting stable hydrostatic pressure. Additional sands between 1082 m and 1089 m were found, also showing hydrostatic pressures. Drilling in a preventive mode, anticipating the pore pressure transition based on the learnings from the pilot hole, dynamic kill mud (DKD) was used from 1165 m. The sand layer below 1158 m did not flow, and there were no signs of shallow gas or water. An overbalance of about 269 kPa was noted, but concerns mainly apply to riser drilling, which does not strictly affect riserless drilling.

9. Geological Explanation of the Pilot Hole Events

The common manifestation of pore pressure in the riserless section is the shallow water flow sands, and shallow pore pressures are more than the hydrostatic seawater gradient in such sands. In the shallow gas flow sands, the shallow pore pressures are more than the hydrostatic seawater gradient. Pore pressure in shallow sands exceeds the hydrostatic gradient of seawater due to the effect of hydrocarbon buoyancy. It depends on the type of hydrocarbon liquid, such as gas or oil, as well as the length of the column: the longer the column, the higher the hydrocarbon inflation pressure.

The seismic section at the pilot hole location and the pore and fracture gradient plot of the pilot hole indicates that the pore pressure in the sand that flowed is greater than that of the surrounding shales (Figure 12). The geological model explains the events in the pilot hole due to structural overpressuring and disequilibrium between the sands and shales has been conceived and is illustrated in Figure 13. The "geologic modeling" approach can be seen to sense-check any pore pressure interpretation from the shallow just beneath the sea bed events while drilling riserless. The permeable sand bodies provide pathways that focus flow and perturb the pore pressure distribution. This process has been termed "lateral transfer" and the "centroid effect." An alternative that could also explain the difference in pore pressure in the sands and shales in overpressure zones is the presence of structural inclination of the beds as seen in the seismic (Figure 12).



Note that the pore pressure in flow sand is higher than the surrounding shale's

Black arrow indicates the depth at which the flow was observed by ROV

Figure 12: Seismic, pore, and fracture pressure at the pilot hole, offshore Borneo

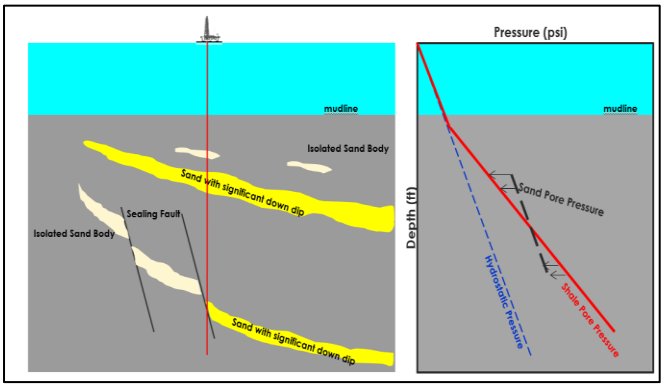


Figure 13: Geological model that explains the SWF in the Borneo Offshore

The riserless drilling of the pilot hole facilitated the management of shallow hazards in an area of significant uncertainty in shallow hazards occurrence. The insights gained from this pilot hole allowed the safe drilling of the main hole. Subsequently, the marine riser could be installed, enabling the continuation of drilling towards the deeper geological target. Addressing shallow hazards in deep water environments is crucial, as it represents a challenge that must be confronted in every deep-water operation.

10. Concluding Remarks

Shallow hazards constitute the challenge in deep water drilling just beneath the sea floor due to the narrow margin between the pore and fracture pressures. The typical shallow hazards include shallow gas, abnormal pressure zones, gas hydrates, slope instability, and complex seabed morphologies. Riserless drilling of the top hole before installation of the marine riser in deep water wells needs to be closely monitored. Where the pre-drill evaluation indicates significant uncertainty, it is advisable, though not mandatory, to drill a pilot hole. The South China Deepwater well is a typical example of how to deal with geohazards and mitigate shallow hazards to drill the main hole for drilling ahead to the geological objective.

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