Drilling Challenges in the North Atlantic Margin
S. Bagala, SPE, J. Getliff, SPE, J. Zaske, Chevron, I. Watt, SPE, Chevron.

Abstract

Chevron and its Partners are facing several challenges in the North Atlantic Margin exploration and development. These challenges affect drilling design and operations, which should take into account several important factors occurring concurrently in this area:

- deepwater conditions;
- complex lithological sequence and target imaging uncertainty;
- geomechanical conditions.

Hole section design is strongly affected by the uncertainty of the subsurface data, in particular the seismic data, where the presence of thick basalt flows, as strong reflectors, induce relatively poor seismic imaging of intra-basalt or sub-basalt drilling targets. This issue is mitigated with contingency plans for final hole section size and casing string setting depths. The complex lithological sequence, geomechanical conditions and lithological uncertainty also affect drilling fluid design and bit/bottom hole assembly (BHA) selection. The consideration of some of these factors had the outcome of using thixotropic muds to counter serious lost circulation events. A further successful outcome was the design and implementation of riserless drilling techniques, a first for Chevron Upstream Europe and Halliburton Baroid UK, to counter the threat of shallow water flows in the top hole sections. The paper demonstrates how a multi-disciplinary approach in both drilling design and operations is beneficial to successful drilling optimization in the North Atlantic Margin, a geographically and geologically challenging area.

Introduction

The North Atlantic Margin is a hydrocarbon province developed west of the Shetland Islands. It is characterized by a series of structures aligned in a NE – SW direction, each about 100 Km long, extending across the British and Faroe Islands boundary, see Figure 1. This area is characterized by the following geographical and geological features:

- occurrence of deepwater conditions up to 3,000 - 5,000 ft;
- complex lithological sequences constituting thick Tertiary shales, volcanioclastic sediments and basalt flow sequences. Multiple drilling targets are present comprising several layers of Paleocene sandstone interbedded with all above lithologies. Figure 2 shows an example of a lithological column in the North Atlantic Margin.
Figure 1. North Atlantic Margin. Blocks and Prospects.
Drilling design and operations must take into account these two important conditions, as they can have an important influence on the drilling hazards that can be encountered. Especially away from known well control these uncertainties should be anticipated and contingencies incorporated in the design and operational sequence.

Two very important consequences of deepwater conditions and the reduced thickness of the lithostatic column at each drilling depth are:

- the relatively low in situ state of stress at any given true vertical depth sub sea (TVDSS) with respect to other areas, such as the Central North Sea. Figure 3 compares Leak-Off Test values vs TVDSS from a West of Shetland location and a Central North Sea location, together with an interpretation of the vertical stress at each location (Leak-Off Tests are considered representative of horizontal stress).

- the unconsolidated nature of the rock. This has been determined by performing compression tests on core plugs. Unconfined Compressive Strength values for reservoir rocks in some typical locations in the North Atlantic Margin are relatively lower than North Sea locations at equivalent TVDSS.

The two geomechanical conditions as above translate in two main drilling hazards:

Figure 2. Typical lithological column in the North Atlantic Margin. Black circle: thick shale sequence. Green circle: basalt and volcaniclastic rocks. After Elllis et al. (2009).
- drilling mud losses, due to the relatively low minimum horizontal stress gradient, especially if the formation is fractured. Mud weights in excess of the minimum stress will re-open the pre-existing natural fracture systems resulting in drilling mud being lost to the formation.
- Wellbore collapse, due to relatively high shear failure gradient.

**Figure 3.** Comparison between state of stress in Central North Sea (blue) and West of Shetland (red) locations. Leak-Off Tests are here considered representative of horizontal stress. Vertical stress in West of Shetland is lower than horizontal stress in Central North Sea. From SPE 137071, modified.

In addition to this, some North Atlantic Margin prospects are known to have overpressured conditions. **Figure 4** shows an example of overpressure, with maximum values around 10 lbm/gal. Where overpressure occurs, the mud weight must be selected accordingly to prevent a potential drilling kick.

In the following sections the Authors highlight how a multi-disciplinary approach in the design and operational phases permitted overcoming the various drilling challenges presented in drilling wells on several North Atlantic Margin prospects.
Hole Section Design

In the North Atlantic Margin, the design of hole sections has to consider the different features described above. In particular:

- weak soils at seabed and potential hole wash-out require careful selection of cement slurry to provide conductor support back to seabed;
- potential over-pressure and the threat of saltwater flows de-stabilising the open hole drilling operations;
- drilling in the Tertiary shale should take into account the drilling risk constituted by the wellbore collapse due to the relatively weak rock. Wellbore collapse may occur for relatively high well deviations, i.e. higher than 45 -50 degrees;
- the basalt flows, characterized by relatively low minimum horizontal stress gradient, often contain numerous natural fractures. High mud weights, especially mud weights that exceed the minimum stress, are likely to induce significant mud losses.

In the early stages of exploration, some areas were affected by a high degree of uncertainty in the characterization and imaging of the reservoir sand from seismic data, due to the presence of a thick overlying basalt cover that acts as a strong
reflector and limits the amount of seismic energy travelling deeper and masks deeper reflectors. An example of this is shown in Figure 5. Uncertainty in the seismic imaging of the reservoir required contingency plans for final hole section size and final casing string setting depths.

Figure 5. North Atlantic Margin. Uncertainty in reservoir imaging. Target sands encased in basalt sequence.

Figure 6 shows a typical example of hole section and casing design for an appraisal well in the North Atlantic Margin area.
Figure 6. Hole sections design.

**Table 1 to Table 3** give drilling objectives, from 16 in. to 8 ½ in. hole section.

**Table 1. North Atlantic Margin. 16” hole section objectives.**

<table>
<thead>
<tr>
<th>Hole Section</th>
<th>Objectives</th>
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| 16”          | Drill hole section in one run and meet directional objectives.  
               Obtain good quality logging while drilling (LWD) data throughout hole section.  
               Maintain good control of mud weight / equivalent circulating density (ECD) to prevent hole collapse at high angle.  
               Ensure section TD is at +/- 100 ft into the Volcaniclastic formation.  
               Build angle to land out at 55 deg inclination in the Volcaniclastic sediments.  
               Install 13.3/8” casing to provide zonal isolation of Hildasay sandstone, and to isolate Breydon and Balder shale prior to entering reservoir section. |
Table 2. North Atlantic Margin. 12.1/4” hole section objectives.

<table>
<thead>
<tr>
<th>Hole Section</th>
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<tbody>
<tr>
<td>12.1/4”</td>
<td><strong>Appraisal Well.</strong> Build angle to + / - 83 deg inclination. Obtain good quality LWD data throughout hole section. Maintain good control of mud weight / equivalent circulating density (ECD) to prevent losses. Land section in reservoir. Run 9.5/8” liner to case off build section. Achieve quality cement job on 9.5/8” liner to provide zonal isolation in a multi-layer reservoir. Protect against the formation of gas hydrates. Maintain highest possible salinity to counteract gas hydrates forming at the blowout preventer (BOP) from the penetration of gas bearing formations. Spot a separate highly saline suppression fluid across the BOP for any potential prolonged periods out of hole.</td>
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Table 3. North Atlantic Margin. 8.1/2” hole section objectives.

<table>
<thead>
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<th>Hole Section</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1/2”</td>
<td><strong>Exploration Well.</strong> Uncertainty in the seismic imaging of the reservoir requires contingency plans for final hole section and final casing string setting. <strong>Appraisal Well.</strong> Demonstrate technical feasibility of high angle drilling without experiencing wellbore instability, as per geomechanical model. <strong>Appraisal Well.</strong> Prove ability to geosteer in the reservoir and optimize reservoir section with high angle / horizontal drilling. <strong>Overpressured Prospects.</strong> Design section recognizing a potentially reduced kick tolerance. Obtain good quality LWD data throughout hole section. Drill hole section in one run. Protect against the formation of gas hydrates. Maintain highest possible salinity to counteract gas hydrates forming at the BOP from the penetration of gas bearing formations. Spot a separate highly saline suppression fluid across the BOP for any potential prolonged periods out of hole.</td>
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Drilling Fluids Design

Drilling fluids design is strongly influenced by deepwater conditions and complex lithological conditions. It is driven by the following factors:

- environmental impact;
- suppression of gas hydrates;
- shale stability;
- losses mitigation;
- well control.

Cuttings Handling and Logistics

Environmental issues are one of the key drivers for the selection of the drilling fluids and cuttings handling and logistics are also serious considerations. The North Atlantic Margin is a remote region with challenging logistics for both fluids supply and more importantly for cuttings disposal. Skip and ship operations are very challenging in the harsh weather commonly encountered in the area even in summer and the long distances involved also complicate logistics.
Because of the low environmental impact, all Chevron’s North Atlantic Margin drilling to date adopted water-based drilling fluids. Cuttings re-injection is not feasible for mobile drilling operations in deepwater.

Cuttings cleaning technology that can reduce the oil on cuttings to less than 1% content does exist, but Chevron and Partners use water based drilling fluids (WBM) wherever possible as both they and the cuttings can be discharged into the marine environment and do not have to be returned to the shore for disposal unless contaminated with more than 1% reservoir hydrocarbons.

Riserless Drilling Fluids

In some circumstances parts of the top hole section need to be drilled using a weighted mud system even though the section will be drilled riserless with returns to the seabed. This would be required in those North Atlantic Margin prospects with shallow water flow risk. Hole sections that present this risk would require drilling fluids heavier than seawater, but the hydrostatic head associated with the riser may exceed the leak – off pressure in the section. As the fluid and cuttings are discharged to the marine environment at the sea bed and are not returned to the rig for fluid recovery, this technique requires large volumes of fluid to be pumped, which in turn requires a large volume of weighted (16 lbm / gal) water based mud to be blended with seawater to give the correct density drilling fluid. This required installation of a high shear, high rate mixer offshore to mix the fluid on the fly and, due to the long distances and large volumes of mud involved, it required the simultaneous use of three UK mud plants and one in Norway so that the majority of the 16 lbm / gal mud could be pre-loaded onto the drill ship before it sailed to location. As it was planned to use a flow rate of 1200 gpm to ensure good hole cleaning and as the desired mud weight is 11.5 lbm /gal, it was anticipated that the total volumes of fluid required to drill the 24” section riserless would be 48,000 Bbl, of which 18,900 Bbl was the 16 lbm / gal mud and the remaining 29,100 Bbl seawater. Due to operational concerns, close to 30,000 bbl of 16 lbm / gal fluid was actually shipped to the rig.

Weather plays a distinct role in the success of this operation due to the sheer volume of fluid required, despite the vast storage capacity of the latest generation of drill ships several thousand barrels of fluid were still required to be stored on the supply boats. This highlights operational sensitivity to adverse weather and successful operations require good weather forecasting and adequate weather windows to allow boat-to-boat transfers during the operation in order to deliver the necessary mud volumes required to keep the hole full of the correct weight fluid.

Due to the larger volumes of fluid (and fluid storage) required, this technique had not been considered practicable until the arrival of 6th Generation Drillships, like the Stena Carron, and has not been used in the UK and was new to Chevron Upstream Europe operations.

Suppression of Gas Hydrates

The combination of cold sea floor temperatures and the high hydrostatic head that results from the use of long risers in deep water operations allow the formation of gas hydrates, particularly when formation gas is encountered and water-based drilling fluids or completion brines are used. Invert emulsion drilling fluids are less susceptible to hydrates provided that the brine phase has a high enough salinity, but these muds are not being used in Chevron currently drilled wells, which utilise water based drilling fluids, to be designed in a way to minimize the risk of hydrate formation whilst also maintaining good shale inhibition.

Thermodynamic inhibition is one way to reduce the potential for hydrate formation. This involves lowering the water activity of the fluid, which in turn raises the pressure or reduces the temperature at which hydrates will form. Inorganic salts are the primary choice for use as thermodynamic hydrate inhibitors and selection involves a number of factors such as density (of the fluid required), shale inhibition and, in the case of completion brines, crystallisation point. For example, in one deepwater operation West of Shetland, the single-salt KCl/Polymer system used for the 16” and 12.24” sections will only provide basic hydrate suppression. The triple NaBr/NaCl/KCl salt blend used in the 8½” section will provide a greater degree of inhibition, but is still not capable of providing full hydrate suppression.

Where full hydrate suppression cannot be achieved using salt alone, then glycols are commonly added to the fluid formulation to improve the degree of inhibition. Low molecular weight glycols, e.g. mono-ethylene glycol (MEG), are the most effective in inhibiting gas hydrate formation and may be used along with salt in completion brines. The poly-alkylene glycols used for shale inhibition in water-based drilling fluids also have useful hydrate inhibiting abilities but are less effective than MEG and unfortunately, the 3% MEG SP concentration to be used in the fluids from the base of the 16” section onwards is designed primarily for shale inhibition and is not intended to provide full hydrate suppression. The high
concentration of salt and poly-glycols that would be required to give sufficient hydrate suppression for a well in 5,000 ft of water, and the consequent water-demand would also make rheology difficult to control and markedly increasing plastic viscosity at lower temperatures.

Hydrates are also more likely to form when the drilling fluid is static and its temperature is close to that of the seabed so additional procedures and fluids need to be developed to displace the choke and kill lines to fluids that are more resistant to hydrate formation. One way forward is to model and formulate the drilling fluid for suppression of natural gas hydrates under dynamic, circulating conditions and have a second fluid available for localized static conditions. The choke and kill lines are then kept full of a blend of mono-ethylene glycol (MEG) and brine which provides full suppression at mudline temperatures and maximum allowable BOP pressure. When the well is to be left static for any period of time and gas migration is a risk, the glycol/brine blend can be circulated through the BOP stack and into the lower section of the riser.

Shale Stability

Formations drilled in the North Atlantic Margin do not feature highly reactive or swelling shales and can usually be drilled using standard KCl glycol drilling fluids (subject to hydrate suppression as discussed above).

Losses Mitigation

The volcanic formations encountered can provide significant challenges with moderate losses to extreme lost circulation events being observed in some wells. Figure 7 shows an example of losses in a fractured basalt flow. The Formation MicroImager (FMI) image logs show evidence of natural fractures in a well section where the equivalent circulating density (ECD) was higher than the minimum horizontal stress gradient. This induced re-opening of natural fractures with resulting losses.

A variety of lost circulation strategies have been tried during several operations, with the aim of eliminating loss events, or mitigating losses to an acceptable level to allow the drilling of the hole section to be completed. In one extreme case, after a variety of lost circulations strategies were tried, it was only when the KCl polymer/glycol fluid was swapped with a highly thixotropic mixed metal oxide drilling fluid developed for drilling highly fractured formations that progress was made and the losses reduced to an acceptable level. However, as the mixed metal oxides are very sensitive to anionic materials and brines, they cannot be designed for either shale or hydrate inhibition which unfortunately limits their use to a very narrow range of circumstances.
Figure 7. North Atlantic Margin. Example of dynamic losses. The mud weight window in 3\textsuperscript{rd} track from left shows that equivalent circulating density (ECD) is higher than minimum horizontal stress gradient. The image logs in 4\textsuperscript{th} and 5\textsuperscript{th} track from left show a level of fractured basalt flow. Legend. BREAKDOWN: fracture gradient. COLLAPSE: wellbore collapse gradient. SHMIN_GRAD_CAL: minimum horizontal stress gradient or losses gradient. ECD: equivalent circulating density. PPRS: pore pressure gradient. MW: static mud weight. FMI: Formation MicroImager. GR: wireline Gamma Ray log.

Drilling Bit Design and Optimization

The design of the drilling bit and BHAs in the North Atlantic Margin prospect should take in account the great variability of lithologies, as highlighted in the Introduction. Lithology changes correspond to changes in the strength properties of the rock, and these influence the selection of the appropriate drilling tools. Unconfined Compressive Strength (UCS) is a parameter from rock mechanics tests and a useful consideration for drilling bit selection. UCS shows great variation for different lithologies, as some average values show in Table 4.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Unconfined Compressive Strength Average (Psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basalt Flow</td>
<td>17440</td>
</tr>
<tr>
<td>Reservoir X (sandstone)</td>
<td>3020</td>
</tr>
<tr>
<td>Reservoir Y (sandstone)</td>
<td>2127</td>
</tr>
</tbody>
</table>

In the early stages of North Atlantic Margin exploration, a rock mechanics study was performed in order to review drilling
efficiency on the first wells and to provide bit recommendations and optimum drilling parameters for further drilling programs. The scope of work was to:

- perform rate of penetration (ROP) prediction using a Chevron proprietary algorithm. This considers as input:
  - rock properties and state of stress, such as unconfined compressive strength, friction angle, vertical pressure, pore pressure;
  - real-time data: measured equivalent circulating density (ECD), weight on bit (WOB), rotational speed (RPM);
  - bit properties: bit size, bit-specific coefficient of sliding friction, and bit efficiency;

- review bit vendor proposals according to prediction results.

Inevitably, experience gained after several drilling campaigns in the North Atlantic Margin prospects has permitted better optimization of drilling bits for any given lithology. However, in such a high cost environment as the North Atlantic Margin, bit costs represent a very minor factor on overall cost/drilled foot figures, where the emphasis is more on durable bits and reliable Bottom Hole Assemblies (BHA) to minimize trips per hole section rather than optimized Rate of Penetration (ROP). Once some familiarity with hole section variability has become established, the bit selection can get more aggressive. Some general guidelines applicable to some of North Atlantic Margin areas are given in Table 5.

<table>
<thead>
<tr>
<th>Hole Section</th>
<th>Lithologies</th>
<th>Bit type</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>16”</td>
<td>Shale sequence to top volcaniclastic</td>
<td>Rotary Steerable (RS)</td>
<td>Rock with low compressive strength and low abrasiveness. Aggressive bit with 5 to 6 blades may be suitable.</td>
</tr>
<tr>
<td>12 ¼”</td>
<td>Basalt flow and volcaniclastic sequence</td>
<td>PDC / TCI Bit Impreg Bit</td>
<td>Heterogeneous rock. Formation compressive strength varies with lithology. If thick basalt flows are present, drilling can be inefficient with PDC. Impreg Bit and turbine allows for greater durability in mixed lithologies, but still need to manage weight on bit (WOB) and rotational speed (RPM) to suit different rock compressive strength for optimum rate of penetration (ROP); drill basalt with high WOB and low RPM. Drill volcaniclastic with low WOB and high RPM.</td>
</tr>
<tr>
<td>8 ½”</td>
<td>Reservoir sandstone, interbedded shale</td>
<td>PDC bit</td>
<td>Decrease in the compressive strength of the formation and variable abrasiveness. PDC may be suitable for enhanced ROPs and adequate durability.</td>
</tr>
</tbody>
</table>
Drilling Performance

Both during operations and after drilling, it is important to monitor and review drilling performance. This will allow revision of the design and operational improvements, where necessary. Design validation or optimization is achieved through the acquisition of Real – Time data. Figure 8 shows an example of Real-Time data from a 16” hole section, with typical Logging While Drilling logs used to monitor drilling performance, displayed together with the pre – drill mud weight window.

![Figure 8. Example of 16” hole Real-Time data from North Atlantic Margin drilling. ROP: rate of penetration. GR: Gamma Ray. BHA: bottom hole assembly. HKLD: hookload. SWOB: surface weight on bit. STOR: surface torque. FLW: pump flow. RPM: rotational speed. ECD: equivalent circulating density. SHKPK: shocks. First track from right displays the pre – drill mud weight window.](image-url)
Real-Time data and drilling records permit sub-division of hole section drilling operations into activities, in order to better monitor any non-productive time and verify that drilling operations stay in budget. Figure 9 and Figure 10 show drilling performance of a successful well drilled in one North Atlantic Margin prospect. “Well 3” was drilled significantly below the budget and with 10% non-productive time (well below the 17% benchmark excluding Wait-on-Weather) and with a top quartile drilling performance against Atlantic Margin industry benchmark. The budget drilling days (“AFE Days” in Figure 9), by hole section, are a little conservative, while the “Technical Limit” parameter is essentially a best informed appraisal as this was only the second well drilled with the new-build drillship.

The true capabilities of the drillship and even the Drilling Contractor’s willingness and confidence to undertake simultaneous operations with the dual rig vessel was yet to be established at final planning / commencement of these well operations and contributed to some understandable conservatism in the estimated timings.

Figure 9. North Atlantic Margin, “Well 3” time breakdown chart.
Discussion and Conclusion

The North Atlantic Margin is a challenging hydrocarbon province, due to variable deepwater conditions and complex geological conditions. These affect several aspects of drilling design and operations, such as hole section design, drilling fluid design, bit/BHA design and performance optimization. Chevron and Partners have gained expertise in design and operations for Atlantic Margin conditions and, thanks to a multi-disciplinary approach where Geology, Petrophysics, Geomechanics, Drilling Engineering, Fluid Management combined with good drilling practices, have realised excellent drilling performance.

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