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MPD AS A HOLISTIC SOLUTION FOR VACA MUERTA CHALLENGES: MINIMIZING WELL CONSTRUCTION TIME IN HIGH-PRESSURE ENVIRONMENTS

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Synopsis

This paper investigates the expanded role of Managed Pressure Drilling (MPD) in optimizing high-pressure, extended-reach drilling (ERD) operations. Building on MPD's success in *Vaca Muerta* (VM), this study focuses on advancements beyond drilling ahead. Key optimizations include enhanced ECD management for longer laterals, improved well control during tripping with reduced mud needs, and streamlined cementing operations. The study aims to demonstrate how MPD can significantly improve the economics and safety of ERD projects.

This study employs a comparative analysis of conventional and MPD drilling methods for ERD. Limitations of conventional methods (e.g., ECD-induced losses, restricted lateral length, narrow tripping margins) are contrasted with MPD's use of lighter fluids for lower ECDs, extended reach, and improved footage per day. This also includes the impact of MPD-optimized fluid composition on downhole tool longevity. The analysis extends to MPD-enabled stripping for BHA tripping and underbalanced well completion, for reduced flat time and improved mud volume efficiency. Furthermore, it explores managed pressure cementing (MPC), benefiting from underbalanced slurries and offline cementing, to minimize flat time and enhance cement placement.

The MPD application in ERD wells results in lower ECD and BHP compared to conventional drilling and constant bottom hole pressure-MPD, increasing both surface equipment and downhole tool pressure margins. This facilitates longer drain sections while mitigating losses and wellbore breathing.

MPD also compensates for swab pressures while tripping, significantly reducing tripping downtime linked to influx management. Moreover, it removes the need of full well displacement to kill mud enabling optimized mud rollover designs, minimizing ECD peaks, losses, and required mud volume. In turn, this leads to stripping operations for casing deployment with statically underbalanced mud weight, reducing surge-induced losses and enhancing gas management, thereby eliminating secondary well control requirements and associated NPT. Hence, there's a significant impact on operational efficiency and flat time.

Finally, MPC demonstrated improved cement placement and reduced lost circulation, coupled with effective gas management during the operation. Furthermore, the MPD equipment-setup facilitated offline cementing for the production section, removing the waiting on cement (WOC) time from the rig's critical path, significantly increasing the rig's operational efficiency.

This paper presents MPD as a holistic optimization tool for ERD, beyond influx management. MPD enhances lateral length, tool longevity, tripping speed, and well control, improving ERD safety, efficiency, and economics. It introduces novel MPC applications, enabling offline cementing and lighter slurries for enhanced cement placement. The paper evaluates MPD's transformative impact on ERD by addressing ECD challenges and streamlining well construction.

Introduction

As shown in **Fig. 1**, horizontal laterals in Argentina have steadily increased in length to maximize reservoir contact from a single vertical section—typically drilled deeper than 2,500 m. Since 2015, standard lateral lengths have grown from around 1,500 m to over 2,000 m, with YPF drilling a 3,200-m lateral by late 2017 (Ardito & El Idd, 2022; Carpenter, 2024).

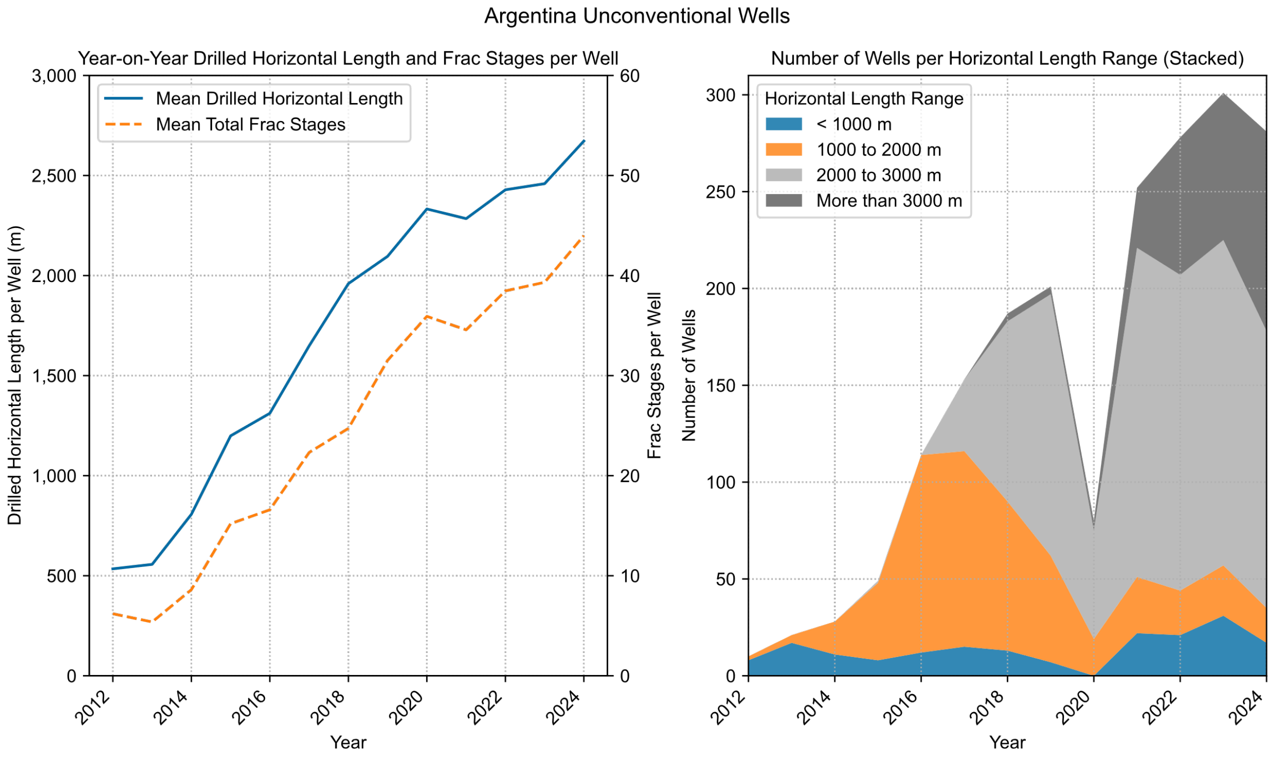


Fig. 1 Year-on-Year mean reported drilled horizontal length and total frac stages per well, for Argentina unconventional Wells (Secretaría de Energía, 2025)

Drilling longer horizontal sections introduces several pressure management challenges. As lateral length increases, equivalent circulating density (ECD), surge, and swab pressures also rise, narrowing the horizontal drilling window (Palacio et al., 2023). These effects drive higher pump pressure requirements, pushing surface equipment closer to operational limits. In addition, these pressure-related factors reduce hole cleaning efficiency–a critical aspect for successful delivery of extended-reach wells to ensure casing runnability.

The *VM/Quintuco* system presents unique geomechanical challenges due to its depth, pore pressure variability within the *Quintuco* formation, and fracture connectivity leading to pressure uncertainties (Carpenter, 2024). In this context, most operators drill both pay zones in a single production section to eliminate a full casing string. While this approach reduces completion complexity, it also constrains the maximum lateral length due to the unpredictable pressure regime in the *Quintuco* (Palacio et al., 2023).

As noted by Badessich & Krasuk (2014), "*drilling through highly over pressured naturally fractured shale can bring a myriad of challenges to the drilling engineers*". This combination of pressure variability, fracture complexity, and extended lateral demands creates a high-risk environment for extended-reach production sections. The primary non-productive time (NPT) drivers are identified as (**Fig. 2**):

- Unplanned trips due to jammed bottom-hole assemblies (BHA), and low rate-of-penetration (ROP) (Bulant et al., 2019; Medina & Romero Mc Intosh, 2017)
- Well control operations (Badessich & Krasuk, 2014; Bulant et al., 2019; Lage et al., 2019), resulting in losses over 2.4 MMUSD for a single well, requiring additional 25 days to drill a re-entry well
- Reaming and backreaming (Telles et al., 2020)
- Loss of circulation, severe wellbore breathing and cross-flow, due to high BHP and mud weight requirements (Badessich & Krasuk, 2014; Gildardo Osorio Gallego, 2017), resulting in:
    - Feedback loop of increasing mud weight and narrowing operational window
    - Inability to reach target depth, shortening the well's total depth (TD), with poor production performance

- Gas cut mud, requiring extended circulation to condition mud (Lage et al., 2019)
- Induced wellbore instability (Calegari et al., 2023; Frydman et al., 2018; Palacio et al., 2023)
- Severe losses during cementing operations due to very narrow operating windows, with poor cementing results and the need of remedial cementing operations (Braghieri et al., 2017; Romero Mc Intosh et al., 2015)
- Extremely high fluid densities required to drill conventionally overbalanced (i.e. without MPD), resulting in high rheologic parameters, and elevated stand-pipe pressures close to the rig's operational limit (Bustos et al., 2017; Lage et al., 2019; Salcedo et al., 2017), therefore causing:
    - Limited flowrate output to drill lateral drain
    - Insufficient hole cleaning, due to lower than required flowrates
    - High torque and reduced ROP, due to insufficient hole cleaning
    - Additional drag while tripping, due to insufficient hole cleaning

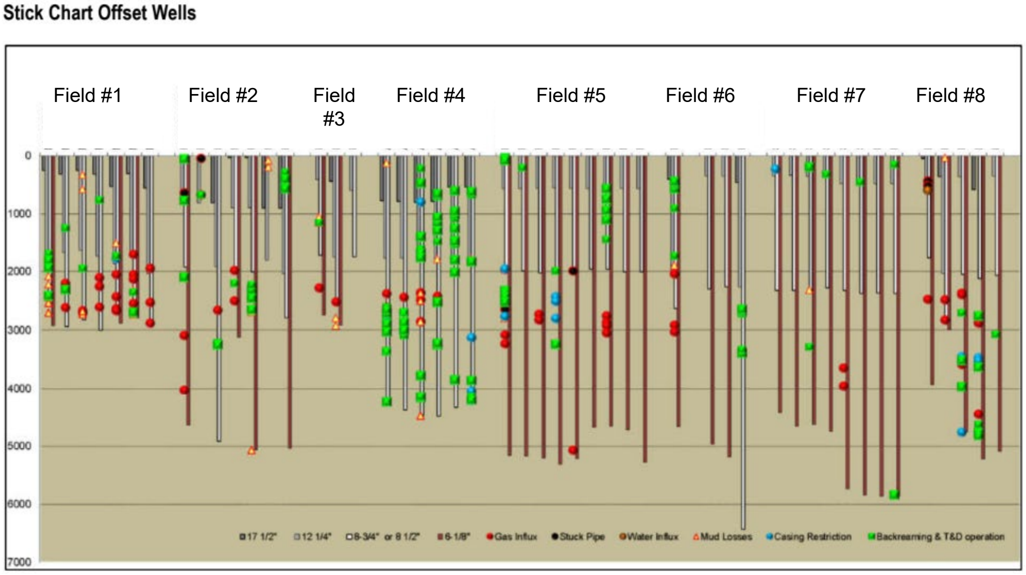


Fig. 2 Stick chart reflecting the common NPT drivers for several *Vaca Muerta* fields (Telles et al., 2020)

MPD has emerged as a practical solution to maintain flexibility and control across pressure and loss zones (Lage et al., 2019; Rassenfoss, 2018). It enables drilling through both pay zones in a single section while proactively addressing key non-productive time (NPT) drivers that commonly affect performance. However, much of the literature focuses primarily on MPD's role in reducing well control time through Dynamic Influx Management, with limited discussion on its broader optimization potential in ERD environments. The following section provides a detailed assessment of these challenges and outlines how, based on field-proven practices, MPD can be leveraged not only for pressure control but also to enhance overall efficiency in drilling longer horizontals within shorter timeframes.

Development

Mud Weight Window & Wellbore Schematic

This study focuses on the horizontal production sections typically drilled in the VM play, primarily targeting the *Quintuco* and *Vaca Muerta* formations, as previously noted. As shown in the geomechanical mud weight window (**Fig. 3**), a steep pressure ramp begins at the top of the *Quintuco* formation around 2,250 m true vertical depth (TVD), leading to a significantly narrowed drilling window within the VM formation around 2,800 m TVD. The average mud weight margin is approximately 152 g/L (~610 psi/4206 kPa), with a maximum pore pressure (PP) of 2,071.34 g/L @ 2820 m TVD and a minimum horizontal stress of 2,223 g/L @ 2810 m TVD. However, even more restrictive conditions have been reported in the field, with mud weight windows ranging from 60 g/L to as low as 30 g/L (Bulant et al., 2019). Under these conditions, a Mud Weight Window Index (MWWI) of 2—indicating a high-risk, narrow margin—was calculated at total depth using Equation (1) by Dow et al. (2025) signaling the need for proactive pressure management strategies to safely drill within such constrained operational windows.

$$MWWI = \frac{Annular\ Friction\ Losses}{Mud\ Weight\ Window} = \frac{ECD_{TD} - ESD_{TD}}{SH_{min} - PP} = \frac{2383\frac{g}{L} - 2080\frac{g}{L}}{2223\frac{g}{L} - 2071\frac{g}{L}} = \frac{303\ g/l}{152\ g/l} = 2 \qquad (1)$$

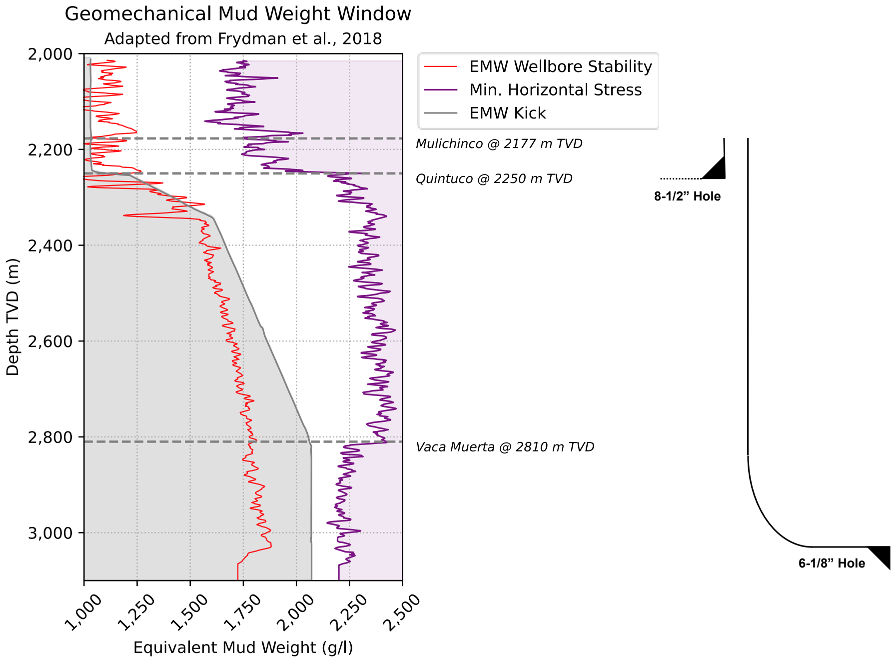


Fig. 3 – Production section mud weight window (left) and simplified wellbore schematic (right), after (Frydman et al., 2018)

Although several authors advocate for a robust four-casing design — including a contingency section that splits the production interval into two parts (Bulant et al., 2019; Frydman et al., 2018; Palacio et al., 2023) — the standard field practice remains a slim three-casing design, as shown in **Fig. 3** (Braghieri et al., 2017; Filipich et al., 2024; Medina & Romero Mc Intosh, 2017). Typical open hole diameters for the production section range from 6-1/8 inches to 8-3/4 inches (155.57 to 222.25 mm), with 6-1/8 inches being the most common configuration. Landing targets for the horizontal section regularly include “la cocina” and “organico” levels, which are the richest in organic content (Filipich et al., 2024).

The reference case study well in this paper (**Fig. 4**) uses a 3 string design, with a 6-1/8 inches (155.57 mm) open hole section starting at 2260 m measured depth (MD) / 2250 m TVD, right below the Upper *Quintuco* top. The curve kick-off point is at 2540 m MD / 2533 m TVD, entering *Vaca Muerta* at 2840 m MD / 2810 m TVD, and a landing point (LP) at 3245 m MD / 2982 m TVD. The well’s total depth (TD) is set at 6842 m MD / 2982 m TVD, with a total drain length of 3600 m.

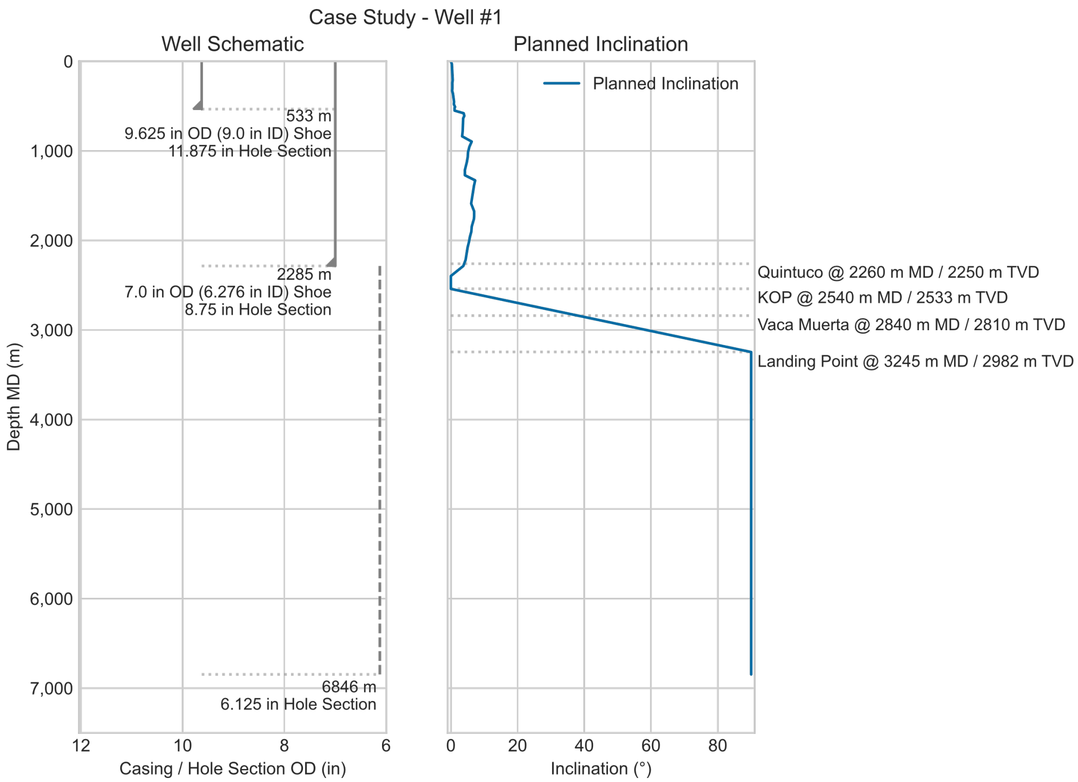


Fig. 4 Case Study - Well #1 - Wellbore Schematic, Planned Inclination and Key Depths for Production Section

Mud Weight Selection

Conventional Drilling

Based on the conditions defined in **Table 1** and **Fig. 5**, the minimum SMW required to drill conventionally $\left(\rho_{SMW_{conv}}\right)$ is defined as 2,100 g/L, after equations (2), (3) and (4). Conventional drilling results in drilling muds with higher rheology and solids content, due to the higher SMW requirement to keep drilling conditions overbalance both dynamically and statically. As discussed by Bustos et al. (2017) and Salcedo et al. (2017), drilling with high rheology can be troublesome, as described during the **Introduction** section. Furthermore, high solids content muds limit downhole tool durability, requiring additional unplanned trips which have a severe impact on efficiency and NPT (Parayno et al., 2019).

$$Downhole\ Pressure\ Safety\ Factor = P_{SF} = 150\ psi \qquad (2)$$

$$SMW\ Safety\ Factor = \rho_{SF} = \frac{P_{SF}}{g\ Z_{PP_{max}}} = \frac{150\ psi}{0.001422 \times 2820\ m\ TVD} = 11\ \frac{g}{L} \qquad (3)$$

$$\rho_{SMW_{conv}} = \rho_{SP} - \rho_{PT} + \rho_{SF} = 2071.3\frac{g}{L} + 23.5\frac{g}{L} + 11\frac{g}{L} = 2{,}106\frac{g}{L} \qquad (4)$$

Table 1 6-1/8 inches Production Section MWW and MPD Parameters

Reference	**Value & Unit**
Shoe Depth (Z_{Shoe})	2285 m MD / 2274 m TVD
Minimum Horizontal Stress @ Shoe	2,250 g/L
Depth of Maximum Pore Pressure $\left(Z_{PP_{max}}\right)$	2850 m MD / 2820 m TVD
Maximum Pore Pressure $\left(\rho_{PP_{max}}\right)$	2071.3 g/L (8306 psi)
Equivalent Mud Weight Set-Point at Max. PP Depth (ρ_{SP})	2071.3 g/L (8306 psi)
Downhole Pressure and Temperature Effects Equivalent Mud Weight (ρ_{PT})	-23.5 g/L
Annular Friction Losses @ Max. PP Depth $\left(P_{AFL}^{kick}\right)$	421 psi

Annular Friction Losses @ Shoe Depth (P_{AFL}^{shoe})	313 psi
Minimum Static Surface Back Pressure at MPD Manifold ($P_{choke_{min}}^{static}$)	23 psi
Minimum Dynamic Surface Back Pressure at MPD Manifold ($P_{choke_{min}}^{dynamic}$)	48 psi
Maximum Static Working Pressure @ 0 RPM (P_{MSWP})	1,800 psi
Maximum Dynamic Working Pressure @ 180 RPM (P_{MDWP})	800 psi
Minimum Flowrate for Effective Hole Cleaning at Drain (fluid vel. = 200 ft/min)	185 gpm

Fig. 5 shows the resulting MWW for the 6-1/8 inches production section for conventional drilling, using a statically overbalanced SMW of 2,100 g/L. As observed, the selected SMW provides enough margin with respect to the PP, but at the selected drilling parameters it runs too close to the minimum horizontal stress $\left(\rho_{SH_{min}}\right)$, intersecting and exceeding the $\rho_{SH_{min}}$ limit from 3540 m MD onwards. This issue arises from the fact that the ECD at the landing point is 2194 g/L (~15 psi / 3 g/L away from the $\rho_{SH_{min}}$), increasing 73 psi (17 g/L) every 500 m on a 150 g/L MWW. This will eventually generate severe losses, leading to wellbore breathing and further wellbore integrity issues.

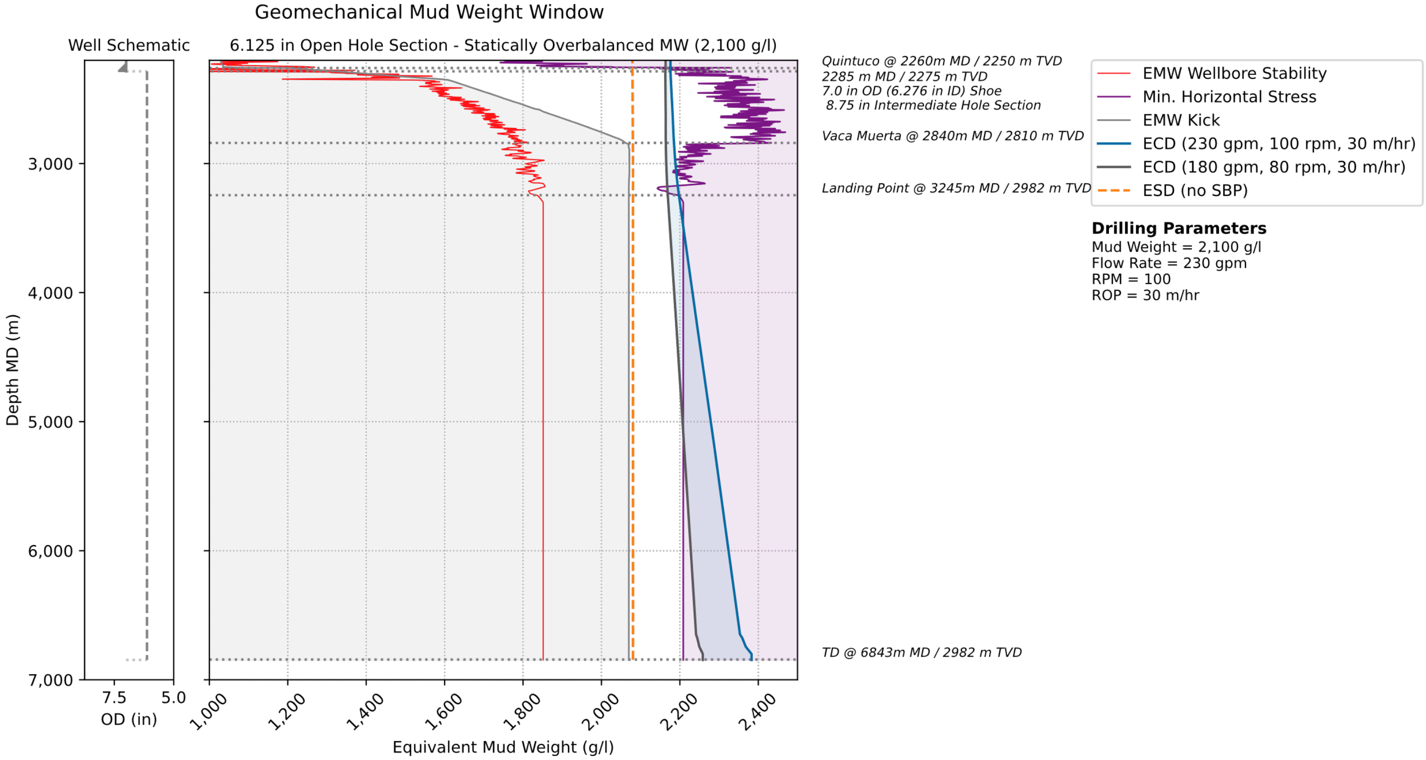


Fig. 5 6-1/8 inches production section MWW for conventional drilling, using a statically overbalanced SMW of 2,100 g/L, with 230 gpm flowrate, 100 RPMs, and 30 m/h ROP (blue curve). Additionally, the minimum to drill the drain section ECD is included, for 180 gpm (min. flowrate for effective drain cleaning), 80 rpm and 30 m/hr. The blue shaded area represents the ECD range with the bit at TD.

Additionally, Stand-Pipe Pressures (P_{SPP}) range close to the rig's pumping limit, limiting the available pressure range for downhole tools. This requires controlling the parameters while drilling the horizontal section, which as documented by Bustos et al. (2017) and Salcedo et al. (2017), can eventually lead to hole cleaning issues, and consequently severely impact the ability to reach the target depth. This might also affect the required clean-out circulation at TD, with limited margin for the required flowrate and RPMs, which will also limit the tripping capability with additional drag. As detailed by **Fig. 6**, reducing flowrate and RPM can aid on the ECD control while drilling the drain section.

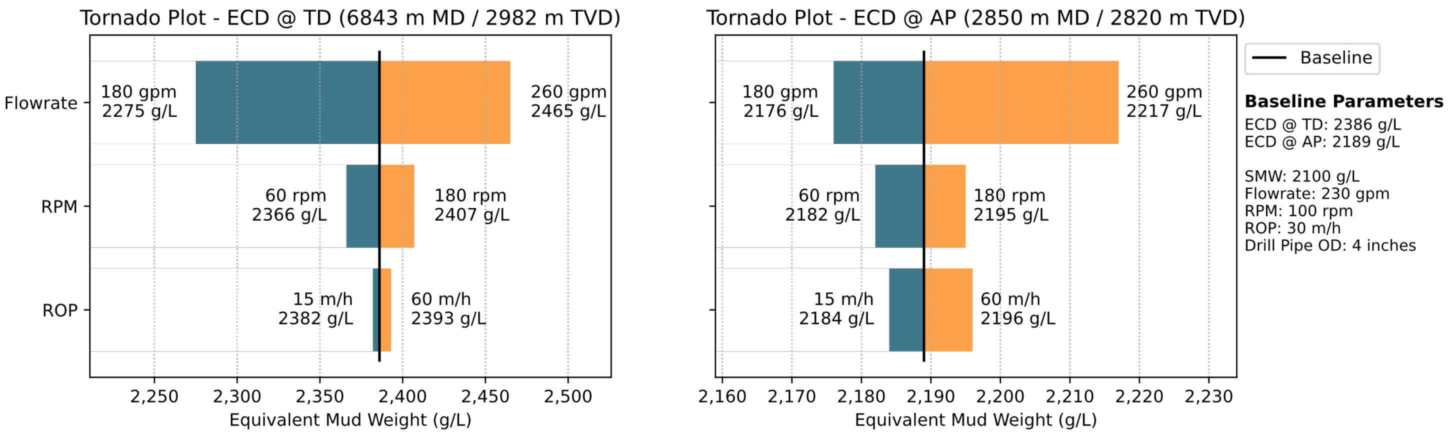


Fig. 6 Tornado Plot of 6-1/8-inch production section, showing the sensitivity analysis for ECD at TD and Anchor Point (AP) for Flow Rate, Density, ROP and surface RPM. As observed, dropping the Flow Rate to 180 gpm (minimum for effective hole cleaning, min. fluid velocity ~ 200 ft/min) provides an ECD drop of 111 g/L, and only 13 g/L at the AP.

Constant Bottom-Hole Pressure MPD (CBHP)

Based on the MWW and MPD parameters defined on **Table 1**, the static and dynamic SBP ranges versus surface mud weight (SMW) are defined, as shown in **Fig. 7** (Abuelaish, 2021). The equivalent mud weight set-point (ρ_{SP}) is set as the maximum PP @ 2850 m MD. **Fig. 8** then shows the resulting available SBP Range, between drilling/connections SBP and Maximum Allowable Annular Surface Pressure (MAASP). From these its observed that the ideal MW to drill with MPD is 1,978 g/L, which is the lowest MW to drill dynamically overbalanced to the reference PP. This brings the following benefits:

- This MW ensures the maximum SBP range in dynamic conditions (594 psi, after **Fig. 8**), which enables more capability for MPD Dynamic Influx Management (MPD DIM) using the MPD equipment.
- Drilling with the lowest possible SBP, which ensures longer bearing and sealing element durability under maximum RPMs.

The available capability for MPD DIM is verified building the Influx Management Envelope (IME). The maximum downhole influx volume to avoid exceeding surface equipment limits during MPD DIM (Culen et al., 2016) is determined for a selected SMW range (**Fig. 9**). This shows again that drilling dynamically overbalanced ensures the maximum MPD DIM capability, since there is a downward trend on the max. downhole influx volume as the SMW is reduced.

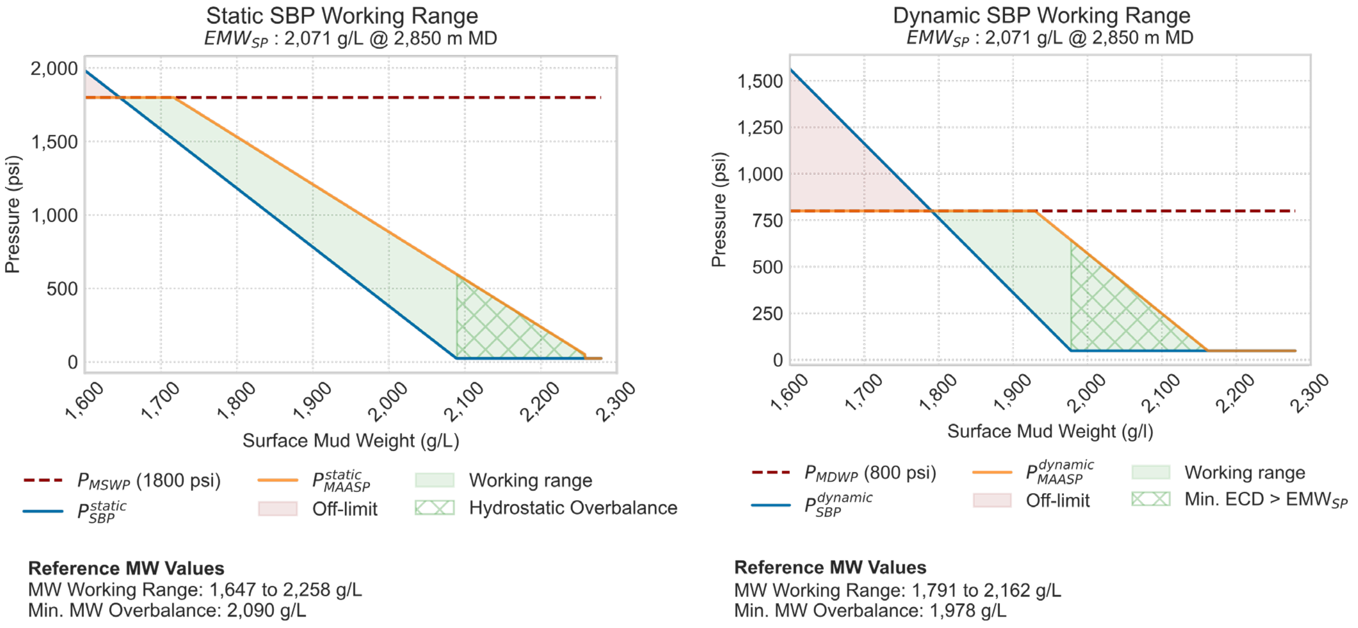


Fig. 7 Static and Dynamic SBP Working Ranges, for 6-1/8 inches production section, after Abuelaish (2021). P_{MAASP} is defined with respect to fracture gradient at the shoe and maximum surface equipment working pressure (P_{MSWP} and P_{MDWP}). P_{SBP} represents the SBP required to achieve the ρ_{SP}. SMW Working

Range under static conditions goes from 1,650 g/L to 2,260 g/L, where 2,090 g/L is already statically overbalanced with respect to the ρ_{SP}. On the dynamic case, the SMW Working Range goes from 1,790 g/L to 2,160 g/L, where dynamic overbalance is achieved with 1,980 g/L SMW.

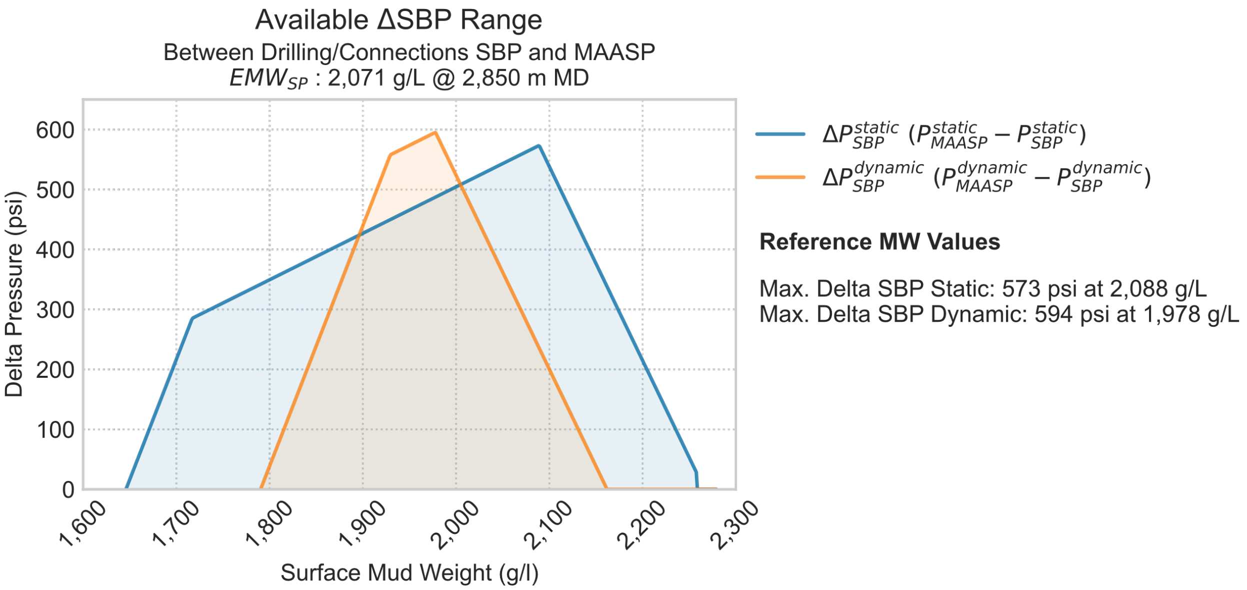


Fig. 8 Available Delta SBP Range, between drilling/connections SBP and MAASP, for 6-1/8 inches production section.

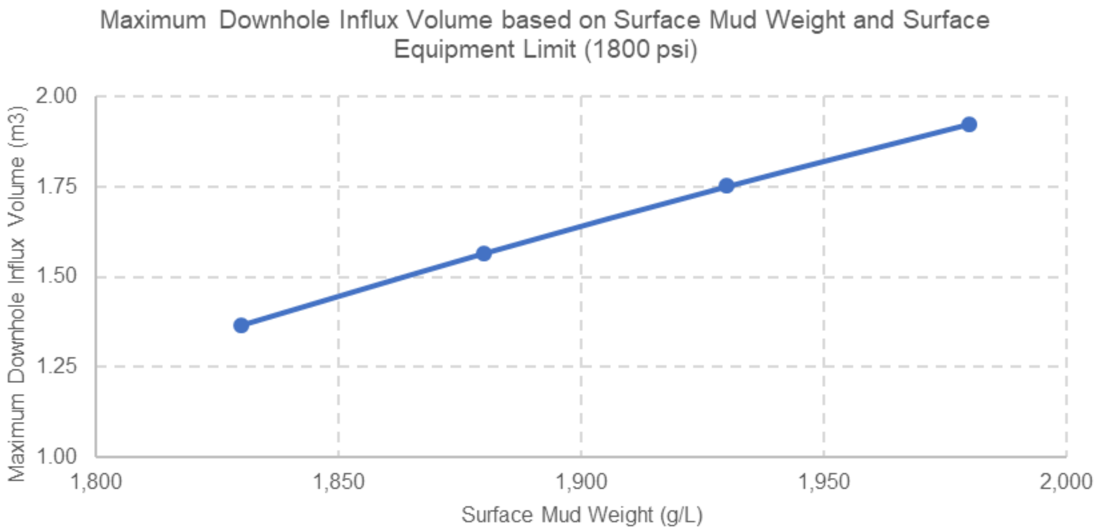


Fig. 9 Maximum Downhole Influx Volume to reach Surface Equipment Pressure Limit (1800 psi) during MPD DIM, after Culen et al. (2016)**. Initial SBP is set to Dynamic MAASP $\left(P_{MAASP}^{dynamic}\right)$ determined on Fig. 7. It is worth mentioning this method considers single-bubble kick, which is conservative, therefore, volumes verified with advanced simulations are higher and closer to the real case.**

Fig. 10 and **Fig. 11** present the resulting mud weight window (MWW) for the 6-1/8" production section using Constant Bottomhole Pressure (CBHP) MPD. A single pressure set-point is maintained at the anchor point (~2,081 g/L) through to total depth (TD), using a statically underbalanced system mud weight (SMW) of 1,980 g/L. This combination of SMW and surface backpressure (SBP) provides adequate equivalent static density (ESD) and equivalent circulating density (ECD) to manage wellbore pressure at the *Vaca Muerta* Top, while allowing sufficient margin for dynamic influx management (DIM)—equivalent to 594 psi or a kick intensity of approximately 140 g/L.

However, the projected ECD in the lateral (drain) section still exceeds the minimum horizontal stress$\left(\rho_{SH_{min}}\right)$, although the pressure management strategy extends the viable drain length by an additional 2,500 m compared to the conventional approach—**an increase of approximately 70% in total lateral reach**. To remain within the narrow margin and reach TD without inducing losses, flow rate and rotary speed (RPM) are gradually reduced in the final section.

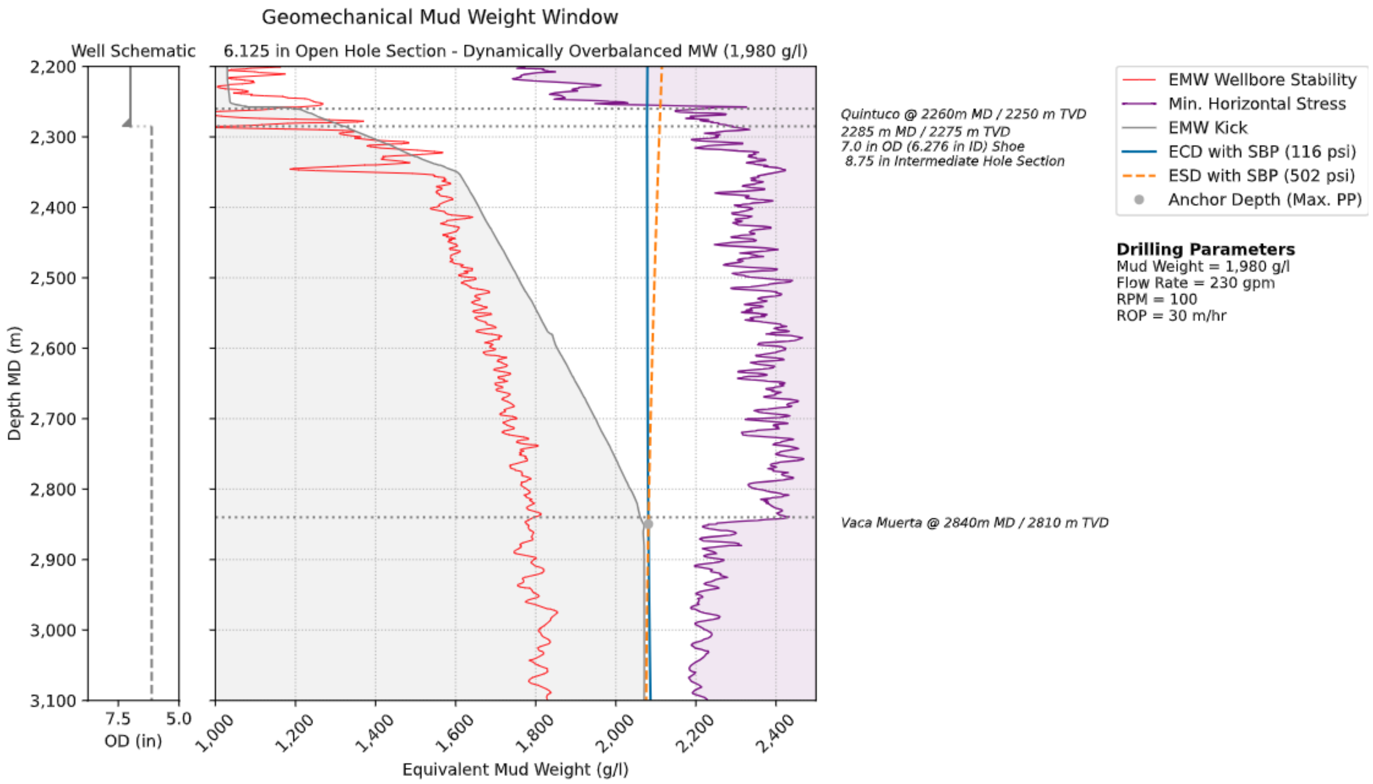


Fig. 10 CBHP MPD Mud Weight Window for 6.125 inch Open Hole Production Section, for a dynamically overbalanced condition at VM with a 1,980 g/L SMW. Anchor depth is set at VM Top @ 2850 m MD / 2820 m TVD, with a 2081 g/L ESD / ECD, where the maximum EMW Kick or estimated pore pressure (PP) is present with PP ~ 2071 g/L

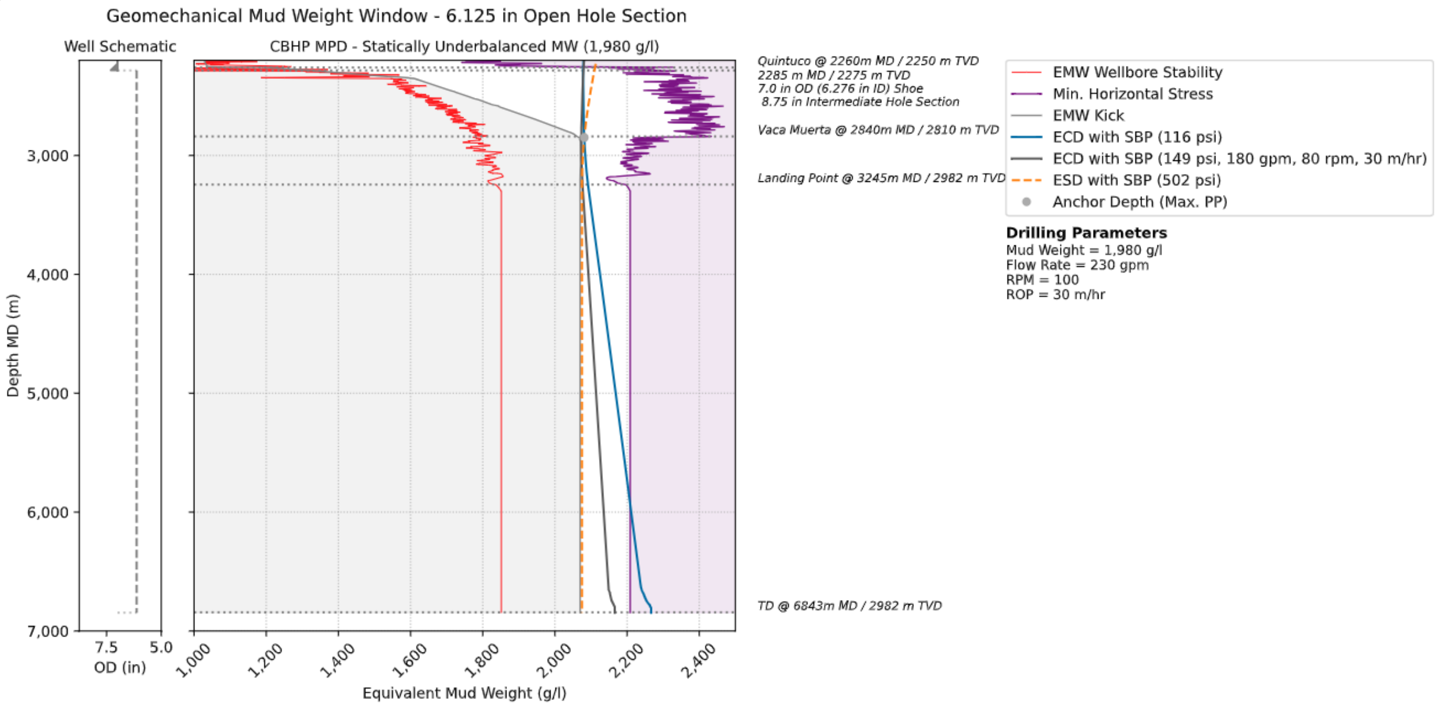


Fig. 11 CBHP MPD Mud Weight Window for 6.125 inch Open Hole Production Section, for a dynamically overbalanced condition at VM with a 1,980 g/L SMW. Anchor depth is set at VM Top @ 2850 m MD / 2820 m TVD. As observed, the drilling ECD exceeds the Min. Horizontal Stress close to 5,800 m, requiring to reduce the drilling parameters to reach TD.

Pressure Trapping MPD

Drilling with a statically underbalanced mud weight (MW)–where the equivalent static density (ESD) without surface backpressure (SBP) is below the formation pore pressure (PP)–enables the use of pressure trapping during connections. This approach involves allowing the well to build pressure against the MPD choke once fluid movement ceases, delaying choke closure until after fluid inertia dissipates (**Fig. 13**). As a result, a small, controlled gas influx is allowed into the well during the static period. This technique offers two key benefits:

1. **Real-time pore pressure mapping:** Each connection provides an opportunity to assess the pore pressure at the bit depth, effectively defining the lower limit of the mud weight window as drilling advances. This enables a "feel-the-way-down" approach (Callerio et al., 2024).
2. **Efficient depletion of gas pockets**: The gas influx is quickly vented through the MPD system—using the MPD mud gas separator (MGS) and flare—returning connections ESD and drilling ECD values to pre-influx levels, as illustrated by **Fig. 12** and also in Fig. 5 by Badessich & Krasuk (2014). Given the low permeability and limited connectivity of the reservoir, these gas pockets are easily depleted. Over successive connections, this results in a measurable downward trend in SBP, ESD, and vented gas volumes, as shown in **Fig. 12**. **An average reduction of ~75 g/L (300 psi)** of the measured influx pressure can be achieved, as shown by the mean connection pressure and ESD values (**Fig. 12**).

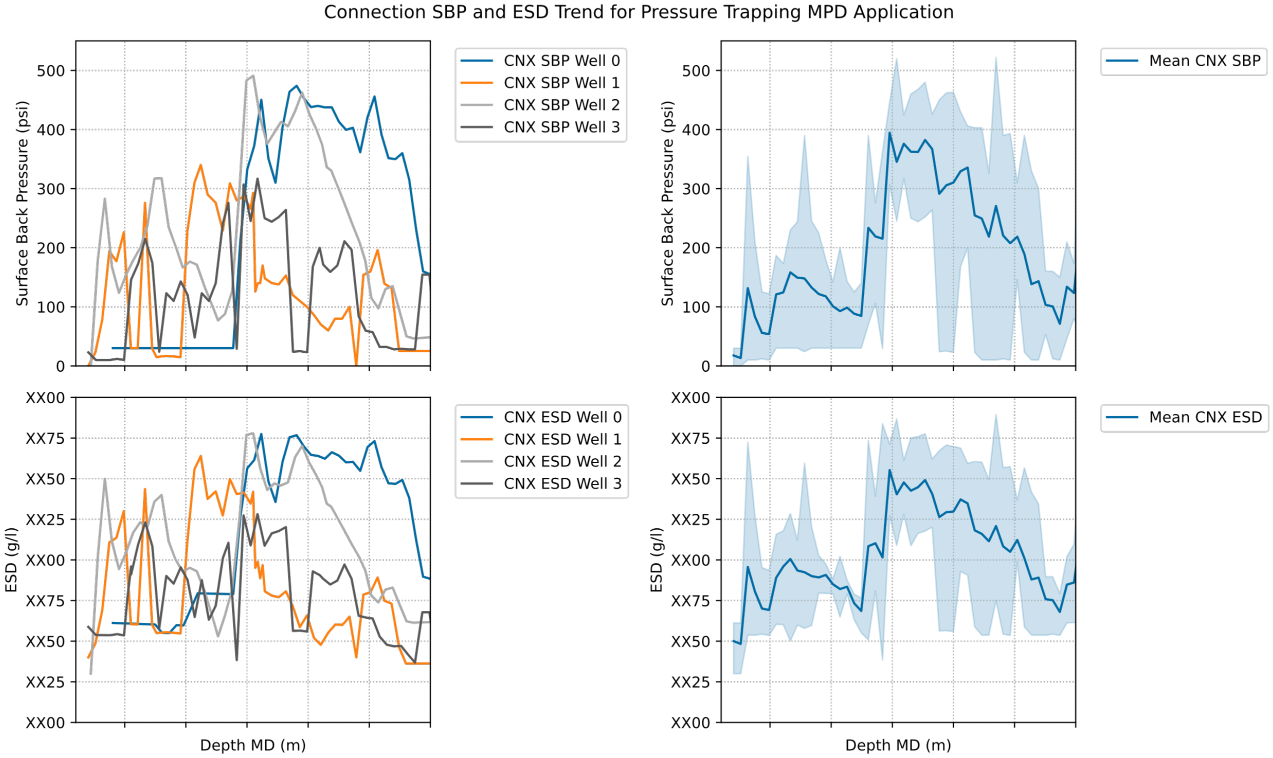


Fig. 12 Connections (CNX) SBP and ESD for Pressure Trapping MPD Application. The left plot is showing the SBP and ESD values for 4 similar wells, where each line represents one well, whereas the right plot is showing the mean values plus the 95% confidence interval for these. Two distinctive peaks can be observed in both values, which correspond to the transition between *Quintuco* and *VM* (*Pre-Q*), and further down the transition into *VM.* The mean values show an average reduction of ~75 g/L (300 psi) of the measured influx pressure.

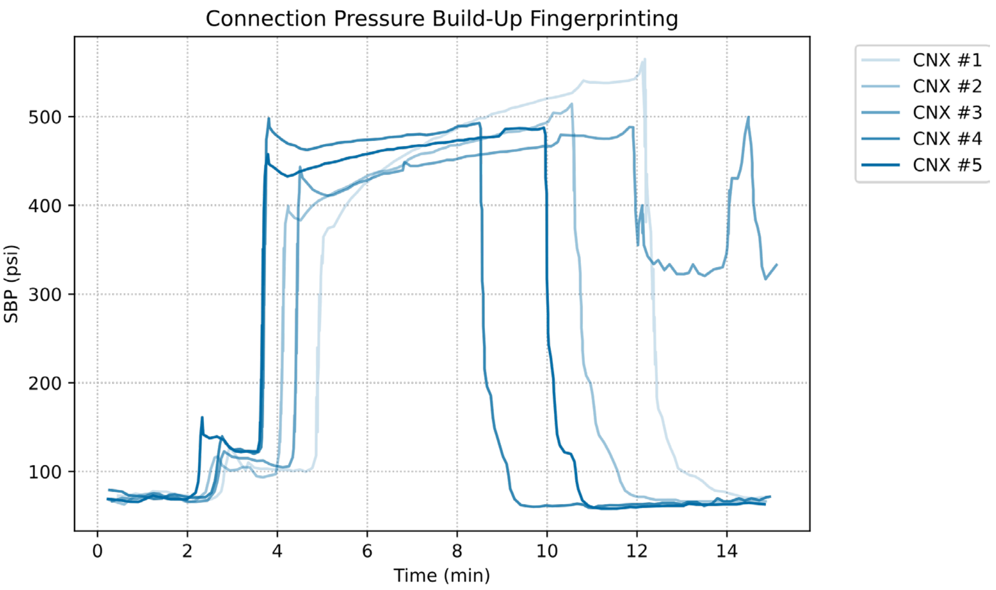


Fig. 13 Connections Pressure Build-Up Fingerprinting, for five sequential connections after an influx, with an initial max. SBP of 565 psi (3895 kPa), lowering to a max. SBP of 487 psi (3358 kPa) by the fifth connection.

Building on the average depletion trend observed in Fig. 12, Fig. 14 and Fig. 15 illustrate the resulting mud weight window (MWW) for Pressure Trapping MPD applied to the 6.125 inches open hole production section. Initially, the equivalent circulating density (ECD) and equivalent static density (ESD) at the anchor point are approximately 2,081 g/L (represented by the light blue solid line and light orange dashed line, respectively). As drilling progresses, both values decrease to ~2,014 g/L (dark blue solid line and dark orange dashed line), effectively broadening the drain section's MWW from 150 g/L to 210 g/L.

This reduction in BHP helps lower the EMW in the lateral section, enabling the well to reach total depth (TD) at full flow rate and RPM without exceeding the minimum horizontal stress. At the same time, the EMW remains above the wellbore stability threshold, maintaining wellbore integrity throughout the operation.

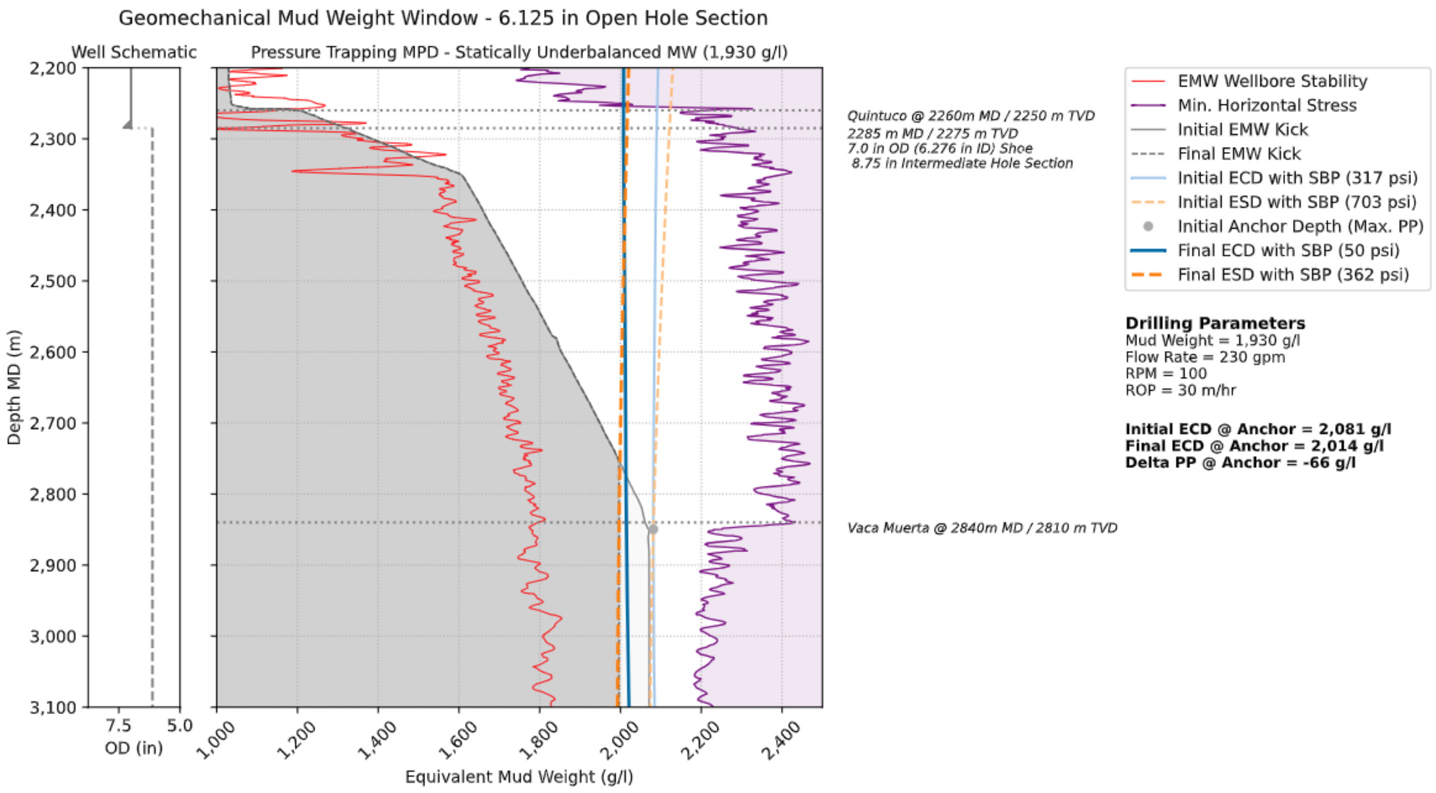


Fig. 14 **Pressure Trapping MPD Mud Weight Window for 6.125 inch Open Hole Production Section, for a dynamically overbalanced condition at VM with a 1,980 g/L SMW. Anchor depth is set at VM Top @ 2850 m MD / 2820 m TVD, with a 2081 g/L ESD / ECD, where the maximum EMW Kick or estimated pore pressure (PP) is present with PP ~ 2071 g/L. A reduction of 66 g/L is observed between initial and final values at the anchor point.**

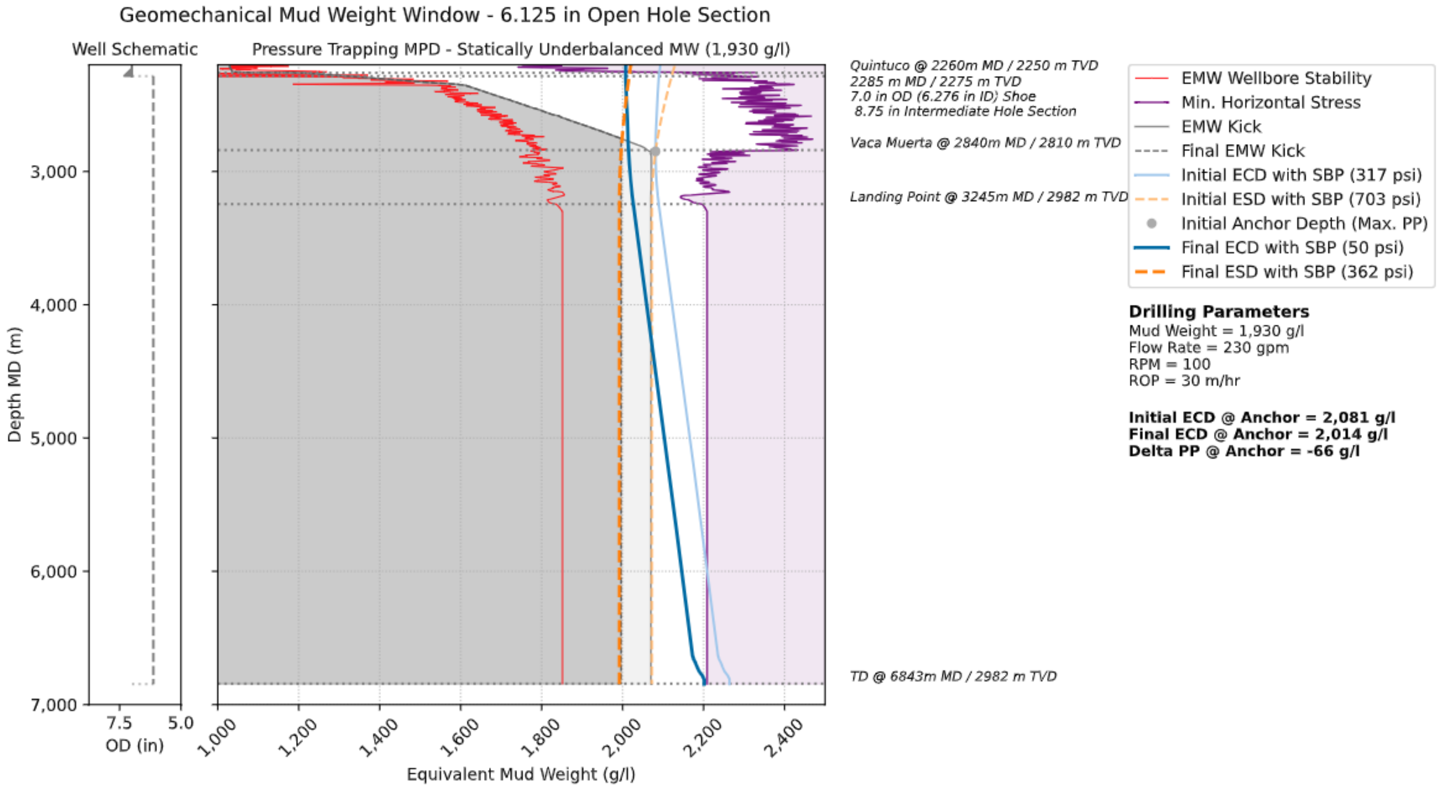


Fig. 15 **Pressure Trapping MPD Mud Weight Window for 6.125 inch Open Hole Production Section, for a dynamically overbalanced condition at VM with a 1,980 g/L SMW. Anchor depth is set at VM Top @ 2850 m MD / 2820 m TVD, with a 2081 g/L ESD / ECD, where the maximum EMW Kick or estimated pore pressure (PP) is present with PP ~ 2071 g/L. A reduction of 66 g/L is observed between initial and final values at the anchor point.**

As a result, the broader mud weight window achieved through Pressure Trapping MPD in the 6.125 inches open hole production section provides several operational benefits, as detailed in the next section:

- Reduced kill mud weight requirements for tripping, due to a wider swab margin
- Faster casing running, enabled by lower surge pressures and reduced drag
- More efficient and safer cementing, with an expanded pressure window improving displacement and zonal isolation

Table 2 presents a summary of the main parameters and downhole pressure reference for the different proposed drilling methods.

Table 2 Drilling downhole pressures and parameters summary table, for every drilling method

Drilling Method	Conventional	CBHP MPD	Pressure Trapping MPD
Drilling Limits			
Max. Pore Pressure (g/L)	2,070	2,070	2,070 / 1,996
Min. Horiz. Stress (g/L)	2,200	2,200	2,200
Drilling Mud (g/L)	2,100	1,980	1,930
ECD @ Anchor Point	2,080	2,081	1,996
ESD @ Anchor Point	2,185	2,081	2,015
ECD @ TD	2,081	2,075	1,992
ESD @ TD	2,383	2,267	2,201

Drilling SBP	0	116	50
Connections SBP	0	502	362

Tripping back to surface

Once total depth (TD) is reached and the well is cleaned out, tripping out to run the casing string requires a mud rollover to a kill mud (KM). The KM must provide sufficient overbalance to offset swab pressures generated during tripping, ensuring safety margins with respect to both pore pressure and the wellbore instability limit. As shown in **Fig. 16**, swab pressures during the BHA pull out of hole (POOH) operation can reach approximately 230 psi at the maximum pore pressure depth and 400 psi along the lateral section. **Table 3** details the downhole parameters for each drilling case, with the determined KM weight (after Eq. (5)) and rollover depth.

$$Kill\ Mud\ Density = \rho_{KM} = \rho_{ESD_{AP}} - \rho_{PT} + \rho_{swab_{AP}} \tag{5}$$

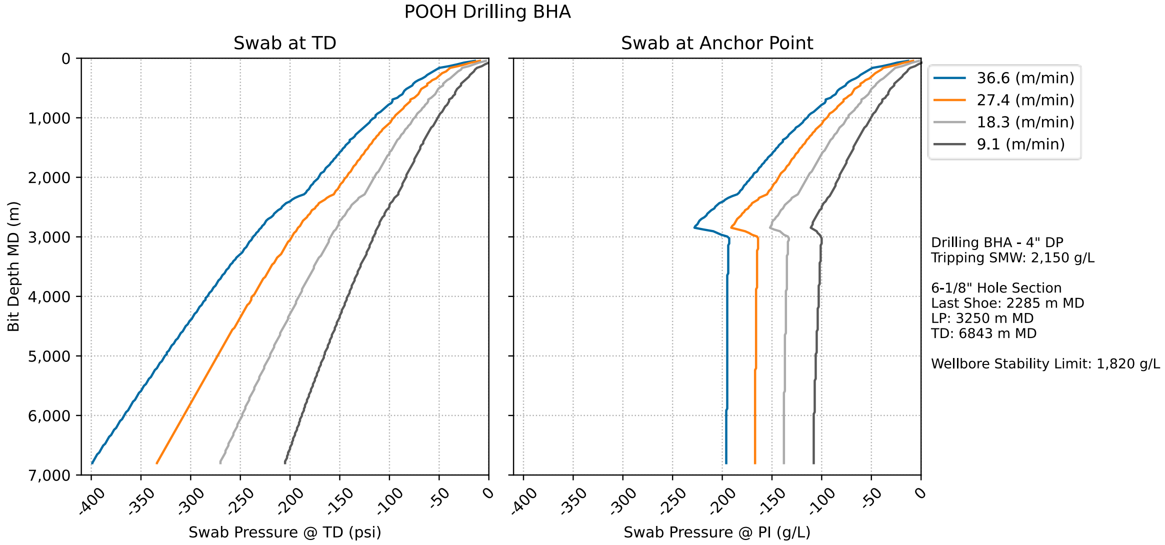


Fig. 16 – Swab Pressures at TD (left) and LP (right) during POOH of the drilling BHA

Table 3 Tripping and Rollover downhole pressures and parameters summary table, for every drilling method

Drilling Method	**Conventional**	**CBHP MPD**	**Pressure Trapping MPD**
Drilling Mud (g/L)	2,100	1,980	1,930
Max. Pore Pressure (g/L)	2,070	2,070	1,996
ESD @ Anchor Point (g/L) ($\rho_{ESD_{AP}}$)	2,080	2,081	1,996
Pressure & Temp. Effects at AP (g/L) (ρ_{PT})	-24	-24	-24
Max. Swab at Anchor Point (g/L) ($\rho_{swab_{AP}}$)	70	70	70
Kill Mud (g/L) (ρ_{KM})	2,150	2,150	2,050
Rollover Depth (m)	6,843	3,250	3,250

Conventional Tripping

Without MPD, this operation requires circulating the entire well volume at TD with a KM that is at least 200 psi heavier than the drilling mud—equivalent to approximately 50 g/L at TD TVD. This assumes a maximum tripping speed of 27.5 m/min. However, swab pressures at the start of the trip-out may exceed 200 psi, requiring further reductions in tripping speed or an increase in KM density to avoid influx risk.

As discussed in the **Conventional Drilling** subsection, the ECD margin to minimum horizontal stress $(\rho_{SH_{min}})$ is extremely limited. Circulating a heavier fluid through the entire lateral back to surface must be done at controlled flow rates to avoid formation losses, as illustrated in the rollover plot (**Fig. 17**). Total displacement with the bit at TD requires approximately 4.5 hours of circulation time—not including the flowcheckwith a minimum required KM volume of 120 m^3 (optimal with safety factor ~180 m^3, in case a contingency presents, as per Eq. (6) and (7)). The flowcheck procedure itself may be prolonged due to wellbore breathing, consequence of elevated ECD values exceeding $\rho_{SH_{min}}$, therefore, increasing the risk of fluid losses. Ensuring the well is static before continuing adds to invisible lost time (ILT). Severe wellbore breathing during such operations is well documented in the literature (Badessich & Krasuk, 2014; Gildardo Osorio Gallego, 2017), with cases where securing the well for tripping has taken several days (e.g. up to 5.1 days and 461 kUSD over planned budget), due to the presence of open natural micro-fractures which might open further when exposed to high BHP.

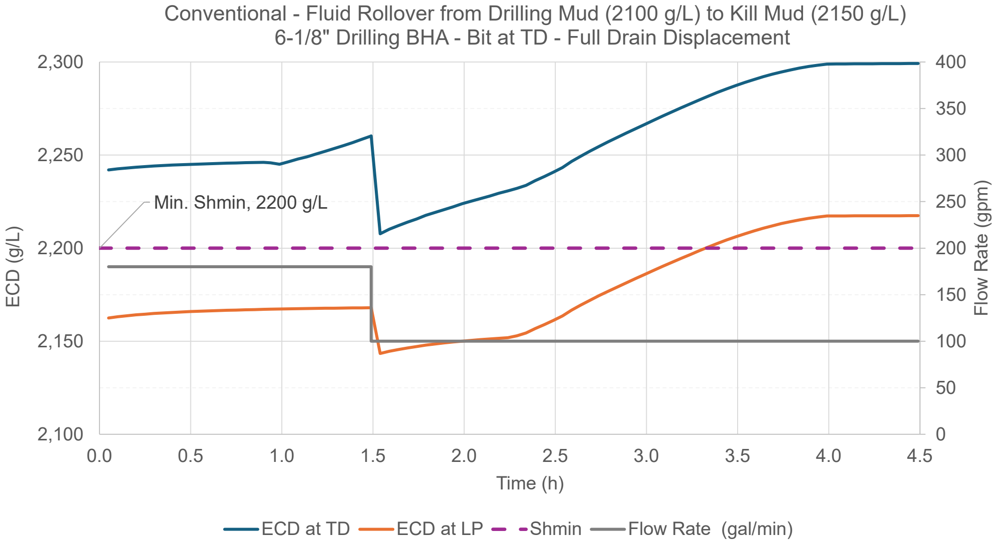


Fig. 17 – Drilling mud to Kill mud rollover at TD, for conventional tripping operations. Due to the tight margins, flowrate needs to be limited to the minimum at the 1.5 hours mark (as KM starts to build up the curve), and circulate at minimum flowrate up to surface, for the subsequent 3 hours. The total elapsed time is of 4.5 hours, without considering the flowcheck and prior wellbore clean-out circulation.

Table 4 Rollover data reference

Parameter	**Value**
Annular Volume @ TD	80.18 m^3
Drillstring Volume @ TD	38.57 m^3
Capacity Annulus to Drillpipe (DP)	0.0114 m^3/m
Capacity Annulus to BHA	0.00857 m^3/m

$$Minimum\ Kill\ Mud\ Volume\ Required = V_{KM_{min}} = V_{DS} + V_{An} = 38.57\ m^3 + 80.18\ m^3 = \ 119\ m^3 \qquad (6)$$

$$Optimal\ Kill\ Mud\ Volume\ Required = V_{KM_{opt}} = V_{KM_{min}}\, F_S = 1.5 \times 119\ m^3 = \ 178\ m^3 \qquad (7)$$

As detailed in **Fig. 18**, the displaced KM provides sufficient overbalance to offset swab pressures at the landing point (LP). However, the drain section from LP to TD exhibits a limited margin for safe tripping, requiring a staged increase in trip-out speed (**Table 5**). Furthermore, in the conventional case, the influx depth is not precisely identified, and a uniform pore pressure is assumed across the entire lateral section. Under these constraints, the total estimated trip-out time is 19.7 hours, assuming three-minute connections (**Table 5**).

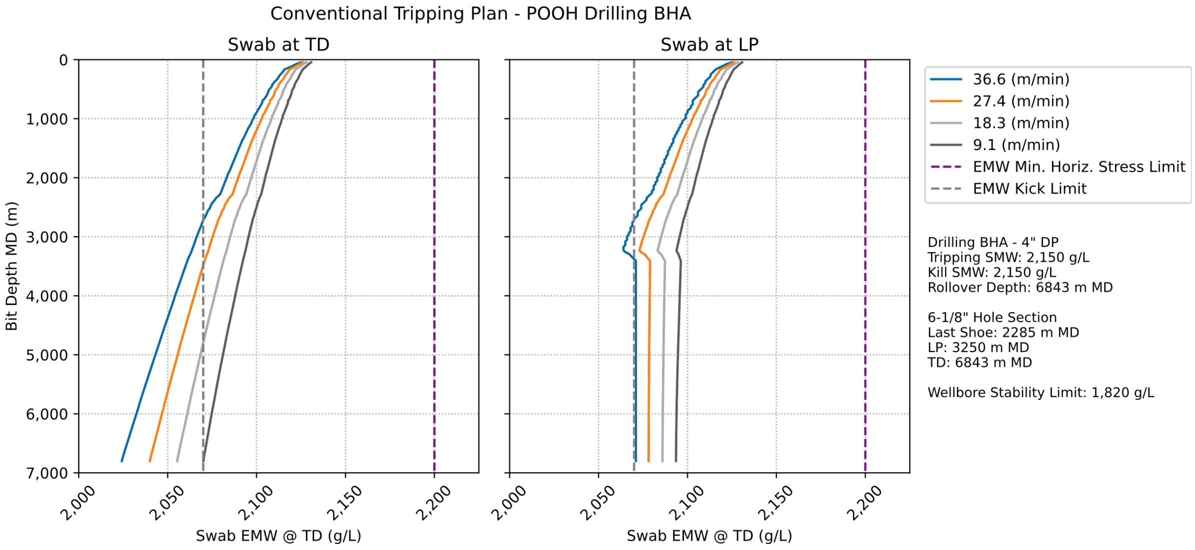


Fig. 18 Conventional tripping plan, showing the sensitivity for swab downhole pressures at TD and the LP (reference for the anchor point), for 4 different tripping speeds.

Table 5 Trip plan to POOH Drilling BHA during conventional operations, with a 2,150 g/l KM over the full drain section. Connection time is assumed as 3 minutes for all connections.

from MD (m)	to MD (m)	Distance (m)	Running Speed (m/min)	Net Tripping Time (h)	Gross Tripping Time (h)
6843	4,500	2,343	9.1	4.3	8.6
4,500	3,250	1,250	18.3	1.1	3.5
3,250	2,700	550	27.4	0.3	1.4
2,700	0	2,700	36.6	1.2	6.2
		Total Time		**7.0**	**19.7**

These limitations also affect casing running operations. With the heavy kill mud (KM) occupying the entire lateral section, surge pressure margins are significantly reduced (**Fig. 19**). As a result, casing must be run at controlled, reduced speeds to avoid exceeding the minimum horizontal stress $\left(\rho_{SH_{min}}\right)$, while wellbore breathing and increased drag due to the higher mud weight further complicate the process. Under these conditions, running 5" casing to total depth (TD) is estimated to require a minimum of 42.3 hours (gross tripping time), assuming three-minute connections, to remain within safe surge limits (**Table 6**).

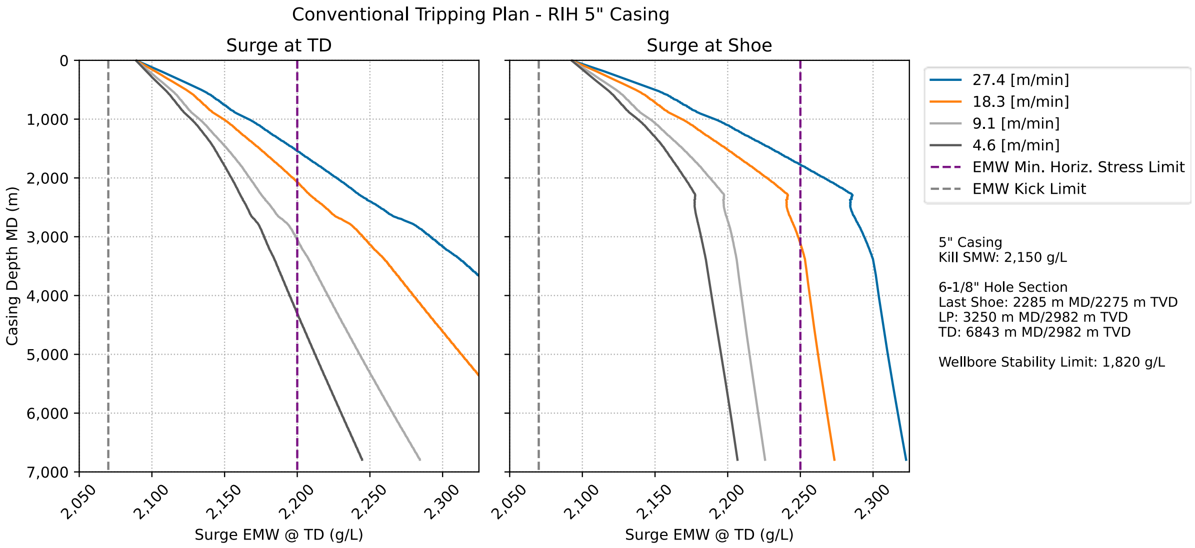


Fig. 19 – ECD at TD as a product of surge pressures while RIH the 5" Casing string. The four solid curves represent running velocities from 4.6 to 27.5 m/min (1 casing pipe every 3 minutes, to under 30 seconds).

Table 6 Trip plan to RIH 5" casing during conventional operations, with a 2,150 g/l KM over the full drain section. Connection time is assumed as 3 minutes for all connections.

from MD (m)	to MD (m)	Distance (m)	Running Speed (m/min)	Net Tripping Time (h)	Gross Tripping Time (h)
0	1,800	1,800	27.4	1.1	7.5
1,800	2,200	400	18.3	0.4	1.8
2,200	3,000	800	9.1	1.5	4.3
3,000	6,843	3,843	4.3	14.9	28.6
		Total Time		**17.8**	**42.3**

Managed Pressure Tripping

Managed Pressure Tripping (MPT) offers a more efficient solution to manage well integrity during tripping and mud rollover operations, ultimately reducing formation losses and minimizing the volume of kill mud (KM) required to secure the well. In horizontal sections where there is no significant true vertical depth (TVD) difference, the hydrostatic effect of the KM only begins to impact the drain section once the fluid reaches the landing point (LP at 3,250 m MD). In this context, the anchor point for MPD operations is established at the maximum pore pressure depth ($Z_{PP_{max}}$ at 2,850 m MD), located higher in the well profile. Focusing pressure control at this anchor point allows the operation to proceed safely, as long as the equivalent static density (ESD) at $Z_{PP_{max}}$ remains above the local pore pressure. As a result, MPD eliminates the need to displace KM through the entire lateral and lower curve sections below $Z_{PP_{max}}$—removing approximately 3,922 m of wellbore, or 45.46 m³ of KM. This represents a **53–67% reduction in total kill mud volume**. Additionally, it improves conditions for running casing, reducing surge pressures along the drain section and enabling a faster, safer operation.

Because the MPD drilling fluid is statically underbalanced, the trip-out operation is performed using a stripping technique—applying surface backpressure (SBP) through the rotating control device (RCD) to maintain wellbore overbalance during tripping. SBP is set to offset swab pressures and the static underbalance margin at $Z_{PP_{max}}$, ensuring safe conditions throughout the operation. Depending on the drill pipe size, condition (e.g., presence of tong marks or hard-banding), and required SBP, stripping speeds can range from 9 m/min to 27 m/min (approximately 3 to 1 minutes per stand), as shown in **Fig. 20**. Bulant et al. (2019)also reported a 54% reduction in tripping time from TD to surface, after RCD field trials to double the stripping speed to 27 m/min.

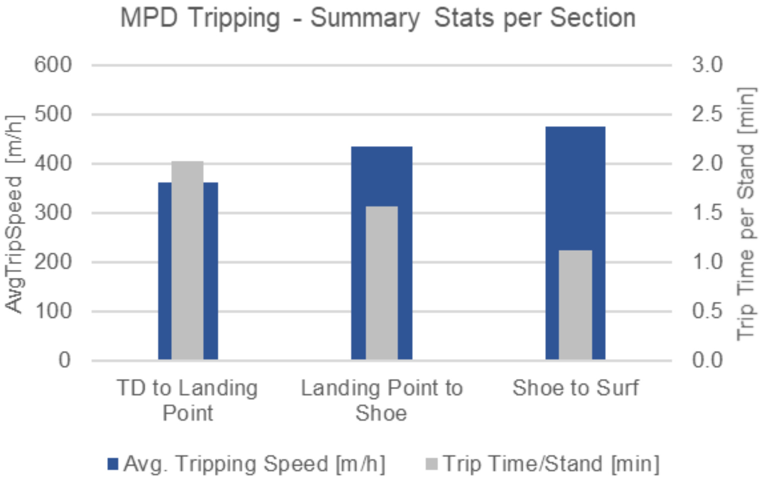


Fig. 20 Single-well MPD Tripping summary statistics

During stripping, surface circulation is maintained through the MPD choke manifold to keep BHP stable. The integration of a Coriolis flowmeter into the MPD system allows for accurate, real-time measurement of displaced volume, providing continuous monitoring of wellbore conditions throughout the operation.

An important benefit of the pressure trapping MPD application is the identification of the influx depth, and mapping of the pore pressure on every subsequent connection. This allows to accurately map the conditions required for tripping and killing the well to remove the BHA, besides broadening the operational window, as described before. SBP is then computed to offset the swab pressures at the anchor point, and if possible over the drain section (since the influx depth is the anchor depth, there is no concern with the drain section besides the wellbore instability limit) (**Fig. 21**). However, it is important to verify the minimum swab EMW generated at TD when pulling out of hole, since that the swab effect can be significantly higher at TD due to the lateral extension.

As shown by **Fig. 21** and **Table 7**, SBP is sufficient to offset swab pressures both at the anchor and total depth for this case (benefit of broadening of the MWW), allowing to strip at maximum speed if the drill pipe and sealing element are in good state. This represents a reduction of at least 4 hours to POOH, when compared to the conventional case (still not considering the reduction in rollover time). The rollover is performed at the LP, swapping 1,930 g/L for 2,050 g/L, and stripping is continued until 1,000 m where the bearing assembly is removed. This ensures the correct well filling as well as continuous well monitoring using the benefit of the closed-loop system and Coriolis flow meter.

As **Fig. 22** displays, the MPD rollover can be done in just 1.1 hours at the LP, without exceeding the minimum horizontal stress $\rho_{SH_{min}}$. As observed, this represents a substantial saving in both required circulation time and mud volume, when compared to the conventional case. Moreover, this alternative prevents any potential fluid losses and wellbore breathing caused by the KM circulation, and provides improved conditions for RIH the 5” Casing.

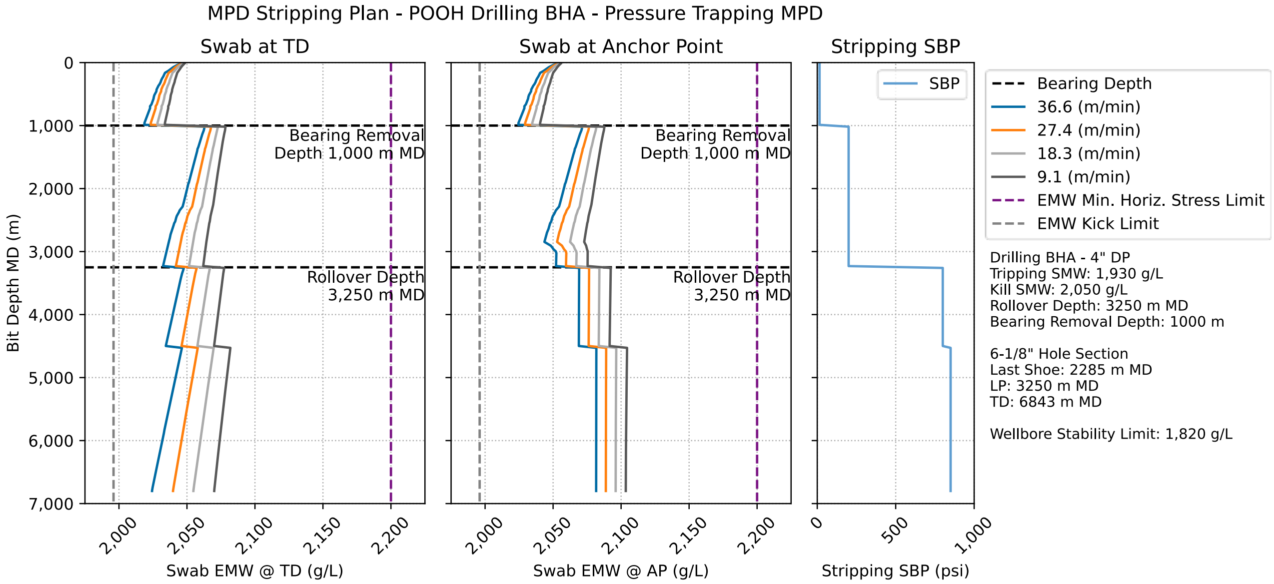


Fig. 21 MPD Stripping Plan from TD to Surface for the Drilling BHA POOH. Initially the well is full with 1,930 g/L drilling mud, stripping is done up to the LP where the mud rollover is done, swapping 1,930 for 2,050 g/L from the LP to surface. As observed the SBP offsets the swab pressures at the anchor point, for stripping speeds up to 36.6 m/min (less than a minute per drilling stand).

Table 7 MPD Stripping Plan to POOH Drilling BHA, with a 1,930 g/l SMW over the drain section, and a 2,050 g/l KM from LP up to Surface. Connection time is assumed as 3 minutes for all connections.

from MD (m)	**to MD (m)**	**Distance (m)**	**Running Speed (m/min)**	**Net Tripping Time (h)**	**Gross Tripping Time (h)**	**SBP (psi)**
6843	4,500	2,343	36.6	1.1	5.4	850
4,500	3,245	1,255	36.6	0.6	2.9	800
3,245	1,000	2,245	36.6	1.0	5.2	200
1,000	0	1,000	36.6	0.5	2.3	15
		Total Time		**3.1**	**15.8**	

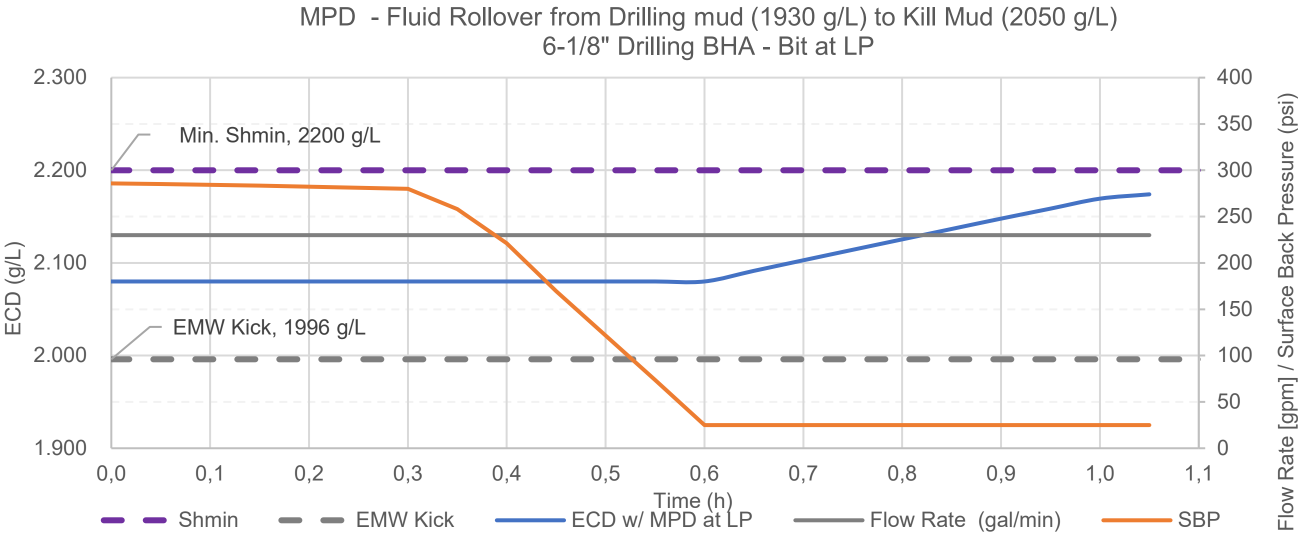


Fig. 22 MPD Mud Rollover Sequence at LP, swapping 1,930 g/L drilling mud for 2,050 g/L KM.

Lastly, the tripping plan to run the 5” casing with MPD (**Fig. 23, Table 8**) shows an appreciable improvement in average running speed and elapsed time **70% reduction in net tripping time and 30% reduction in gross tripping time**, when compared to the conventional case. This is mainly due to the improved pressure management conditions present after the rollover is performed at the LP, keeping drilling mud in the drain section of the well. Once the Kill Mud is displaced at the LP, SBP is applied during connections to maintain the overbalanced condition.

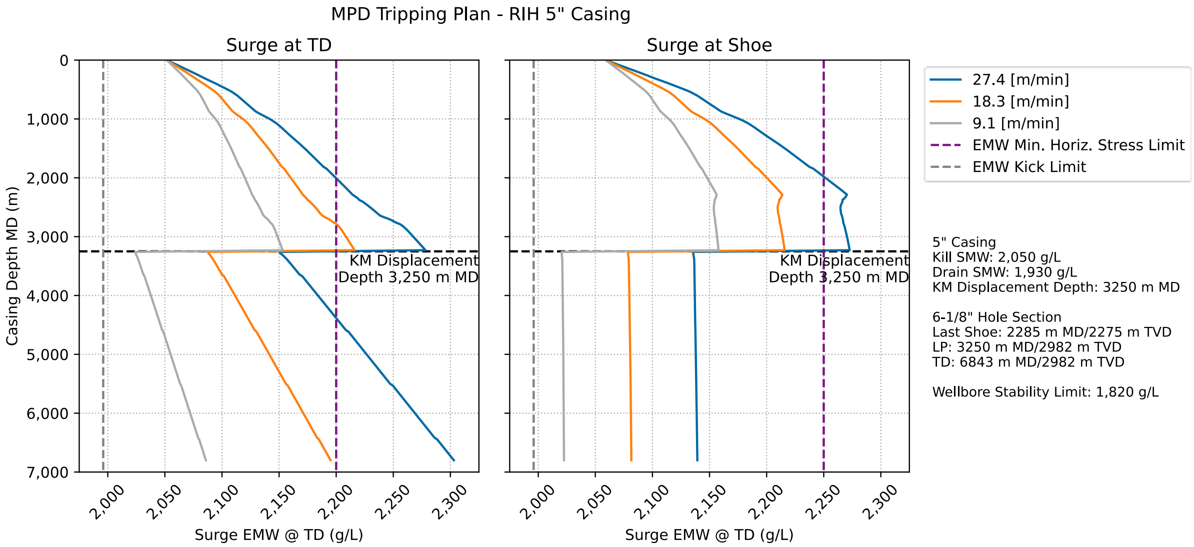


Fig. 23 MPD Tripping Plan from Surface to TD, to RIH 5” Casing.

Table 8 MPD Tripping Plan to RIH 5" Casing

from MD (m)	to MD (m)	Distance (m)	Running Speed (m/min)	Net Tripping Time (h)	Gross Tripping Time (h)	Connections SBP (psi)
0	2,100	2,100	27.4	1.3	8.8	0
2,100	3,250	1,150	18.3	1.0	5.2	0
3,250	4,500	1,250	27.4	0.8	5.2	362
4,500	6,843	2,343	18.3	2.1	10.5	362
		Total Time		**5.2**	**29.7**	

Additional Rollover Considerations

When planning the mud rollover depth, the priority is to circulate below the kick depth to remove any annular gas before initiating stripping operations. Additionally, as shown in **Fig. 24**, the closer the rollover depth is to the shoe (i.e., higher up in the well), the higher the required mud density to achieve the target equivalent static density (ESD) at the MPD anchor point. This increase in density results in elevated ECD and ESD values at the shoe, which can compromise well integrity and raise the risk of formation losses.

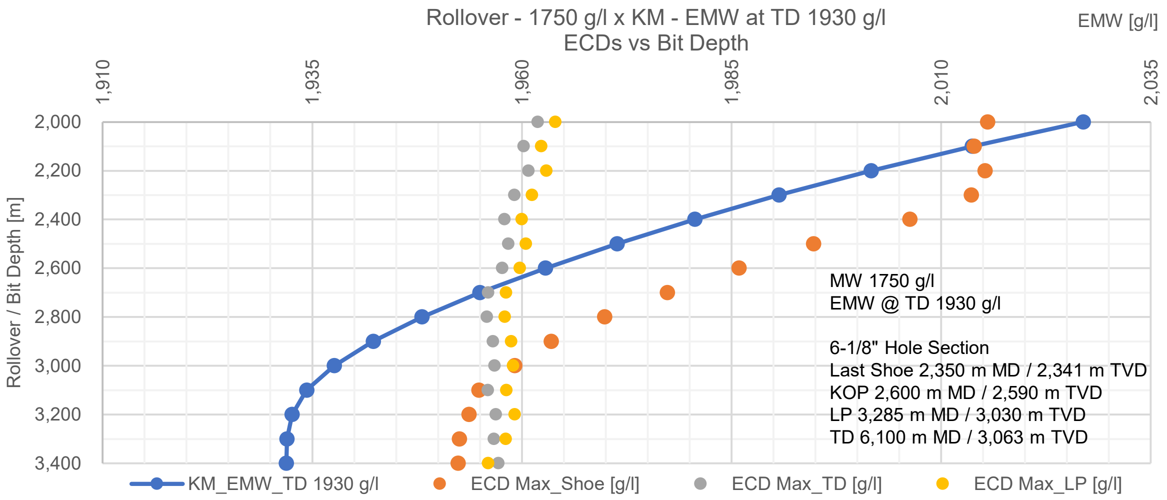
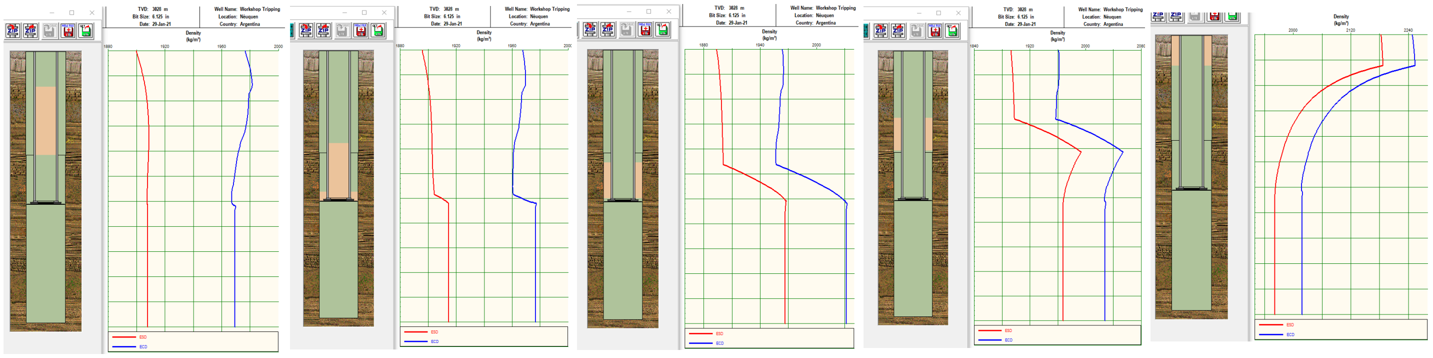


Fig. 24 Sensitivity Analysis of resulting ECDs for sequential rollover depths, starting from the LP to further up the last shoe. Each point is extracted from a rollover pumped at the reference rollover / bit depth (e.g. points at 3000 m were generated positioning the bit at 3000 m and pumping the rollover), all the rollovers keep the same target pressure and target depth (EMW @ TD 1930 g/l). The KM (blue curve) is designed to reach the target EMW of 1,930 g/L at TD in all cases.

Another important consideration is the use of drill string tripping pills, which are necessary to allow for dry pull-out—enabling faster tripping speeds and cleaner rig operations. This is particularly important in MPD operations, where non-return valves (NRVs) are required in the drill string, and stripping applies surface backpressure (SBP) against the NRVs. The tripping pill is circulated into the wellbore once the rollover depth is reached, which increases both ESD and ECD, as illustrated in **Fig. 25**.

To minimize the risk of losses during pill circulation and reduce overall rollover time, various pill configurations can be used. These include a single heavy pill, a kill mud (KM) pill, or a combined KM + heavy mud pill strategy.



Pill inside Drillstring

Pill @ Bit

Pill at bottom of Annular space

Pill at Shoe

Pill at Surface

Fig. 25 Tripping pill circulation to surface during a mud rollover, showing the resulting ESD (red curve) and ECD (blue curve) as the pill is circulated back to surface.

A practical and field-proven approach involves using the same KM as a tripping pill. The pill volume is calculated to counteract the expected SBP generated during stripping, with an added safety margin. Depending on the required SBP and the KM density, the volume may be large enough to extend into the curve section of the wellbore. Therefore, volume calculations must account for the TVD component. If the drill string volume from surface to the LP is insufficient, two alternatives may be considered: pumping an additional pill with a higher density than the KM, or—less ideally—reducing tripping speed to lower swab pressure and, consequently, the SBP requirement.

Once the bit reaches the designated kill depth, the remaining pill volume is circulated and left in the wellbore. This method minimizes rollover time, as it eliminates the need to circulate the pill out of the well. However, its effectiveness relies on not having to circulate the well while tripping out in the horizontal section; doing so would displace the pill in the wellbore and negate its intended effect.

Cementing the Production Section

As previously discussed, conventional drilling operations are constrained by a narrow MWW, which poses a continuous risk of formation losses. This limitation extends into the cementing phase, where the risk is often exacerbated. As shown in **Fig. 5**, circulating at TD generates ECDs that exceed the minimum horizontal stress—particularly in wells designed with 5" casing, due to narrower annuli and the need for high-density fluids.

Conventional cementing operations under these conditions frequently result in suboptimal cement quality, primarily due to:

- Severe fluid losses, which prevent the planned cement column height from being achieved. This often results in incomplete coverage of the open hole section or failure to isolate key zones (Medina et al., 2015).Braghieri et al. (2017) report cases where up to 67% of the theoretical cement volume was lost, with only 23% reaching the surface.
- Insufficient cement coverage and channeling, leading to poor zonal isolation and pressure communication between productive zones—such as hydrocarbon and water-bearing intervals—up to the wellhead (Romero Mc Intosh et al., 2015).

These outcomes often require remedial cementing jobs, increasing both operational time and cost (Braghieri et al., 2017; Medina et al., 2015).

Several factors contribute to these challenges. First, the narrow annular space in extended lateral sections significantly increases circulation pressure. Second, conventional cementing practices prioritize static well control by using fluid systems with hydrostatic pressures intentionally above the estimated formation pressure. This is further compounded by the typical fluid hierarchy—drilling mud, spacers, and cement slurries—designed with progressively higher densities. While this approach aims to prevent influxes, it also increases the dynamic pressure exerted on the formation during displacement. As a result, the total circulating pressure can easily exceed the fracture gradient, leading to severe fluid losses and excessive overbalance (Braghieri et al., 2017)

Moreover, in cases where conventional mud weights were insufficient to control high formation pressures, wells were sometimes intentionally flowed to decompress the formation before resuming drilling or running casing and cement. This practice added significant time and cost to the operation (Medina et al., 2015).

Managed Pressure Cementing (MPC) as a solution

Designing the drilling phase with a statically underbalanced mud weight, combined with the use of Pressure Trapping MPD to broaden and accurately map the MWW while drilling (i.e. identifying influx and loss depths and downhole pressures), establishes the necessary conditions for implementing MPC. To address the limitations of conventional cementing, MPC applies the same pressure control principles used in MPD to maintain well control and manage narrow operational windows. By operating in a static underbalance, dynamic overbalance regime—where hydrostatic pressure is below formation pressure, but total dynamic pressure (including friction losses and surface backpressure) remains above it—MPC prevents influx while avoiding losses (Braghieri et al., 2017; Medina et al., 2015). A key enabler of MPD is the accurate mapping of the MWW while drilling, which enables accurate management of pressures at key points of the well during MPC (Medina et al., 2015).

MPC significantly reduces fluid losses by keeping the equivalent circulating density (ECD) within formation limits during displacement (e.g. in the same way as MPD mud rollovers, with staged flow rates and SBP). This pressure control allows the cement to reach the planned column height, ensuring coverage of both the *Quintuco* and *Vaca Muerta* formations for effective zonal isolation (Braghieri et al., 2017). Post-placement, SBP is applied to maintain well control while the cement sets—especially critical when hydrostatic pressure alone is insufficient—ensuring proper compressive strength development and cement bonding (Medina et al., 2015; Romero Mc Intosh et al., 2015).

Field results confirm the effectiveness of MPC: improved cement quality and adherence were consistently observed, even in sections previously affected by severe losses, with Cement Bond Logs (CBLs) validating good zonal isolation. Consequently, MPC eliminated the need for remedial cementing in 83% of cases reported by Medina et al. (2015). Overall, MPC enables cementing success where conventional methods fail, by matching wellbore pressure conditions to the formation's narrow tolerances throughout the entire process.

Offline Cementing

One additional optimization made possible by Managed Pressure Cementing (MPC) is the execution of offline cementing for the production section. Once the casing string and wellhead are installed and the well is secured, the rig can be skidded to the next well on the pad. Cementing operations are then performed on the previous well while the rig is engaged in preparing the next one.

In this setup, the wellhead of the previous well is connected to the rig choke line, and fluids are circulated through the MPD system and returned to the rig pits. This enables parallel operations: while the rig assembles the BHA for the new well, cementing of the previous well proceeds under managed pressure conditions.

This approach results in significant time savings along the critical path by eliminating the rig time typically required for cementing and, more importantly, the wait-on-cement (WOC) period—which can range from 6 to 24 hours. Tecpetrol (2022) reported savings of up to 31 rig hours and USD 150,000 using this strategy.

Conclusions

As technically demonstrated throughout this work, MPD stands-out as a key enabler for high-pressure unconventional extended reach wells, such as the *Vaca Muerta* wells. MPD help navigating the deep pressure uncertainties presented in the *Quintuco-Vaca Muerta* complex, providing the required insurance to drill the production and drain sections in a single section. Furthermore, it broadens the limits for the required drilling parameters, ensuring longer and faster laterals.

Pressure Trapping MPD presents a great alternative for unconventional reservoirs, enabling benefits such as real-time mud weight window mapping

This study demonstrates that MPD is an enabler in the construction of high-pressure, extended-reach wells, particularly in complex environments such as *Vaca Muerta*. By addressing the full well construction cycle—from drilling and tripping to cementing—MPD significantly enhances both technical performance and operational efficiency. The following key conclusions have been drawn:

1. **Broader Mud Weight Window Enables Longer Laterals:** Pressure Trapping MPD allowed the mud weight window (MWW) to be expanded from 150 g/L to 210 g/L, allowing for full-length lateral drilling at target flow rates without exceeding the minimum horizontal stress. This was achieved through gradual ECD and ESD reduction while drilling, without compromising wellbore stability.

2. **Extended Lateral Reach**: Compared to conventional drilling, MPD-enabled wells demonstrated up to **70% longer drain sections** by safely maintaining dynamic overbalance with reduced ECD and improved margin to fracture gradient, even in narrow operational windows.

3. **Optimized Tripping and Rollover Operations**: MPD fundamentally changes the approach to tripping out of hole. Compared to conventional tripping—which requires full well displacement with high-density kill mud (KM), prolonged circulation, and increased risk of losses—MPD enables a focused pressure control strategy anchored at the maximum pore pressure depth. This **reduced kill mud volume requirements by up to 67% and cut net tripping time by 55% (Fig. 26)**, with real-time wellbore monitoring maintained via closed-loop flow measurement.

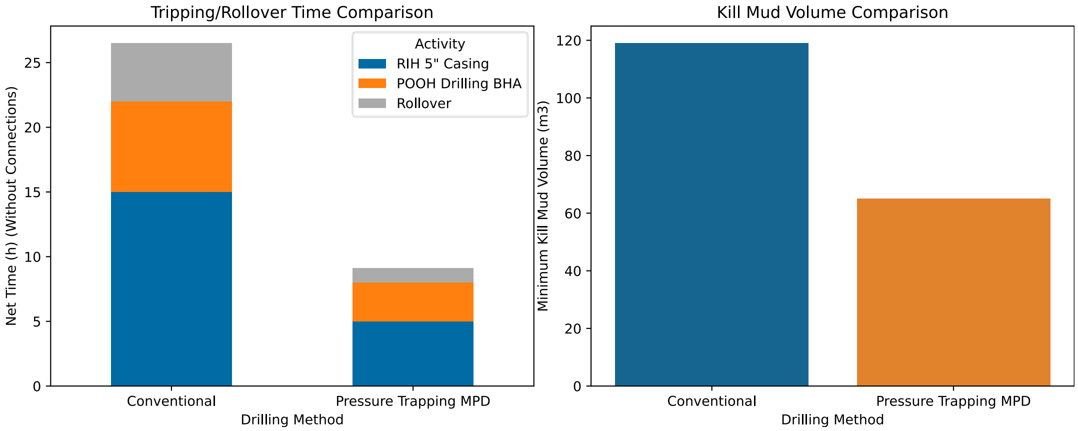


Fig. 26 Tripping and Rollover Time comparison for the different drilling methods (left), and Kill Mud Volume comparison (right). As observed, the MPD application provides an average 50% reduction on tripping and circulation time, the same for the required KM volume.

4. **Enhanced Casing Running Efficiency**: In conventional operations, casing running with heavy KM resulted in minimal surge margins, requiring low running speeds and extended rig time (up to 42 hours). With MPD, casing was run with the lateral section still filled with statically underbalanced mud, while SBP was applied during connections. This reduced net casing run time by over 12.6 hours—an **efficiency gain of approximately 71%**—while preventing surge-induced losses and minimizing drag.

5. **Improved Cementing Success with MPC**: MPC, enabled by prior MPD mapping of influx/loss depths, allowed dynamic pressure control during cement placement. Operating in a static underbalance and dynamic overbalance regime minimized ECD overbalance and prevented losses. This mitigated severe losses, enabled full cement coverage, and improved zonal isolation, with validated bond quality, even in zones historically prone to circulation loss. Field data showed an **83% success rate** in avoiding remedial cementing (Medina et al., 2015).

6. **Offline Cementing for Reduced Flat Time:** Leveraging the MPD setup, MPC enabled offline cementing of the production section. Once the casing was installed and the well secured, cementing proceeded while the rig advanced to the next well. This approach removed the wait-on-cement (WOC) time from the critical path, **saving up to 31 rig hours and approximately USD 150,000 per well**, according to field data (Tecpetrol, 2022).
7. **Integrated Operational Benefits**: Throughout the MPD-enabled well construction process, key advantages included:
    a. Accurate mapping of pore pressure and loss zones during drilling.
    b. Reduced mud volume, density and rheology, improving hydraulic performance and tool longevity.
    c. Better hole cleaning through optimal flowrate management.
    d. Improved tripping efficiency by real-time swab/surge control, and closed-loop monitoring.
    e. Minimized fluid losses.
    f. Safer gas handling and elimination of secondary well control needs.

Overall, MPDespecially when integrated with Pressure Trapping and MPChas evolved from a well control contingency into a proactive and field-proven optimization tool for extended-reach drilling. It significantly improves drilling efficiency, enhances safety margins, reduces NPT, and enables cost-effective construction of technically complex wells. These results reinforce MPD's role as a critical enabler for the safe and economical development of unconventional resources like those in *Vaca Muerta*.

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