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An Integrated Workflow for Improved Lateral Placement in Underbalanced Coiled Tubing Drilling Operations

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Abstract

This paper describes an integrated workflow that was developed to identify sweet spot and maximize lateral placement in underbalanced coiled tubing drilling (UBCTD). As fields mature and become more challenging, UBCTD becomes an effective solution to extract hydrocarbon. In some implementations, UBCTD encounters drilling challenges that result in shorter laterals or lower net-to-gross ratio than planned. Effective lateral placement precision in sweet spot is one of the main requirements to optimize productivity of oil and gas reservoirs. The constructed workflow maps key operational indicators extracted from offset wells to drive optimized well placement and maximized gas output.

The workflow involves selecting key indicators from multiple offset wells to identify vertical and spatial variations. These variation profiles are generated based on a pattern and trends with highest success rates across available data. Based on the ideal productivity profile identified and the matched target well placement, the operational plan is then integrated with seismic data to boost lateral placement accuracy across the target. Developed data maps and actual gas rate are assessed to verify placement accuracy, and call for decisions to adjust well trajectory plans in real time.

The introduced solution has demonstrated improvements in lateral placement by utilizing key operational indicators from offset wells data. The workflow was conducted on a synthetic thin carbonate reservoir box, where the generated stratigraphic window was adjusted based on an optimal performance data. The data collected during UBCTD operations was further inverted to enhance and improve operations. The developed workflow pinpoints operations variation and allows steering corrections to place the lateral within the expected target, where gas flow readings will confirm reliability of the operation parameters and thus model robustness and validity.

The process implemented focuses on integrating real-time data to optimize predictive models and avoids drilling non-reservoir footage. In addition, the workflow accounts for time delay challenge between bit position and logging tools in the bottom hole assembly during data acquisition.

Introduction

Underbalanced drilling (UBD) has been widely used in the oil and gas industry. Unlike conventional drilling (CD), where the formation is masked due to a heavy mud weight, UBD uses a light weighted fluid to allow the formation fluids to flow into the wellbore. By doing so, UBD completely eliminates the filter cake, hence, formation damage will be almost negligible. The main application of using UBD is to enhance well productivity and hydrocarbon recovery. UBD has also made its mark in carbon storage and injection wells. Delivering undamaged injection wells preserve the injectivity of the formation by protecting the near wellbore permeability ensuring maximum storage capacity. On the contrary, mud filtrate invasion is a common phenomenon in CD, alongside phase trapping and emulsifications (Bennion et al, 1996).

UBD is a technique where the density of the drilling fluid is artificially lowered to allow the reservoir fluids to enter into the wellbore. In its simplest form, UBD allows drilling and production at the same time. Typically, nitrogen gas is used to lower the density of the mixture. Due to the inert behavior of nitrogen, it can be injected into any single-phase fluid (water, oil, diesel or any polymer-based mud) without risking the overall operation (Mehta et al, 1998; Bennion et al, 1996). UBD also allows real time formation evaluation. More importantly, the production while drilling becomes an instant revenue stream by taking out any extended production or well tests. Rate of penetration (ROP) on the other hand, is another key factor that is enhanced in UBD. Due to a low stress on the formation, ROP tends to increase drastically in UBD, in some cases has gone up to 10 times the ROP on CD wells (Malik et al, 2010).

UBD approach can be implemented using both coiled tubing or conventional drill pipe. Both UBD techniques have demonstrated successes in different fields worldwide. In some fields, the UBCTD is implemented to re-enter an existing well in order to restore well productivity. For example, Sajaa field, onshore gas field in UAE, has hydrocarbon-bearing Thamama limestone with a reservoir pressure 1,100 to 1,900 psi. The implementation of UBCTD in seven wells improved the gas rate by two to four folds (Pruitt et al, 2004).

The robustness of the UBCTD technology lies in its ability to maintain the underbalanced conditions un-interrupted. However, the use of the technology presents its own challenges in optimizing the lateral placement well inside the sweet spot for the entire length of the lateral. This is due to the limited available numbers of Logging While Drilling (LWD) technologies that are compatible with the slim sized coiled tubing. The data transmission in UBCTD is conveyed through the e-line (more expensive option) compared to mud-pulse telemetry (less expensive option) in CD. The mud pulse telemetry is well suited for single-phase conditions where the pressure pulse variations are controlled to modulate and transmit data (Mwachaka et al, 2018). In UBCTD, the mud exhibits complex and multi-phased flow regime that jeopardizes the mud pulse telemetry reliability in data transmission (Li et al, 2022; Krueger & Pridat, 2016; Krueger et al, 2013).

In drilling, the term steering is commonly used to describe the activity of navigating, placing, and maintaining the lateral well inside the target hydrocarbon zone in order to maximize the net-to-gross ratio. In some implementations, the steering involves using measurement while drilling (MWD) technologies/sensors, particularly gamma ray. This type of steering is called geosteering and is used to make correlation-based decisions relying on gamma ray contact between layers to identify how far the bit position is from the target zone. In other implementations, the steering relies on capturing cuttings samples on surface and comparing them with previous cored sections of the same target. This type of steering is called biosteering and is used to make biofossil-based decisions by comparing the pattern of the drilling cuttings captured to that of the cored sections. Advancements in steering exceeds the comparative analysis of biofossil into a more detailed elemental and mineral composition quantification known by X-ray diffraction (XRD) and X-ray fluorescence (XRF) (Alsaud et al, 2024). Both geosteering and biosteering come with limitation in UBCTD due to the absence of gamma ray contrast in heterogenous complex reservoirs and the latency of cuttings arrival time, respectively.

Another mean of assessment in UBCTD operation is well testing while drilling (Kardolus et al, 1997). Instantaneous productivity index (PI) can be used to identify potential productive zones while drilling (Suryanarayana et al, 2007). However, shortcomings of this method were observed. The results of pressure transient analysis (PTA) revealed that the effective footage (net-to-gross ratio) post UBCTD is significantly less than the effective footage anticipated while drilling using PI. In some cases, the PTA showed an effective footage of less than 10% (Abdul Aziz et al, 2021). Apart from the direct petrophysical, geophysical, and production data that are commonly used during the planning phase, inclusion of other techniques can assist in proper well placement. Modeled porosity, water saturation, and permeability can be estimated by correlating offset well logs with the XRF and XRD that are measured during the operation to create a multi mineral petrophysical model (Ibrahim et al, 2024). In addition, at bit syntactic porosity and bed boundary identifications based on the drill-ability of the formation from the motor power input in terms of differential pressure and flow rate can be used in geosteering (AnTech, 2018).

With the limitations of the current steering technologies in UBCTD operations, achieving effective lateral placement becomes challenging in reservoir that exhibit complex geology. The lateral placement effectiveness is heavily dependent on quality and accuracy of the well planning models and the reservoir characterization while drilling. During the well planning phase, mono frequency spectral decomposition ratio map is used to determine hydrocarbon bearing zones vertically and spatially. Also, porosity from the offset open hole logs is correlated to porosity data from minimum acoustic impedance attributes map to determine the target formation (Guizada et al, 2018). In some instance, the target formation is multi-layered and lateral placement is drilled across all layers before choosing one target layer.

Given the available steering technologies, getting an effective lateral placement becomes exceedingly challenging, especially in complex structural formations. Therefore, it is crucial to have an engineered fit for purpose workflow that considers operational risks that may occur during drilling. This paper provides detailed steps needed to achieve a successful lateral placement from planning phase until target depth.

Methodology

There is a demand for improved techniques in placing laterals more efficiently in UBCTD operation. This work presents an improved workflow that optimizes lateral placement. The goal of this work is to maximize the effective lateral length inside one target layer and subsequently enhances well productivity. The methodology developed in this workflow focuses on a multidiscipline approach between reservoir, geology, geophysics, and drilling. It also provides an additional contingency workflow to address operational surprises. Fig.1 shows the steps and decisions in the well planning phase (before drilling).

Currently, the UBCTD operation depends heavily on two variables: (1) MWD/ Gamma ray, and (2) mud cuttings on surface to characterize/navigate reservoir layer and make steering decisions. Unlike jointed pipe, UBCTD has not been very lucky with commercialized slim sized LWD tools at the time of writing this paper. This workflow focuses on providing measures to overcome lateral placement challenges raised in the absence of LWD steering capabilities.

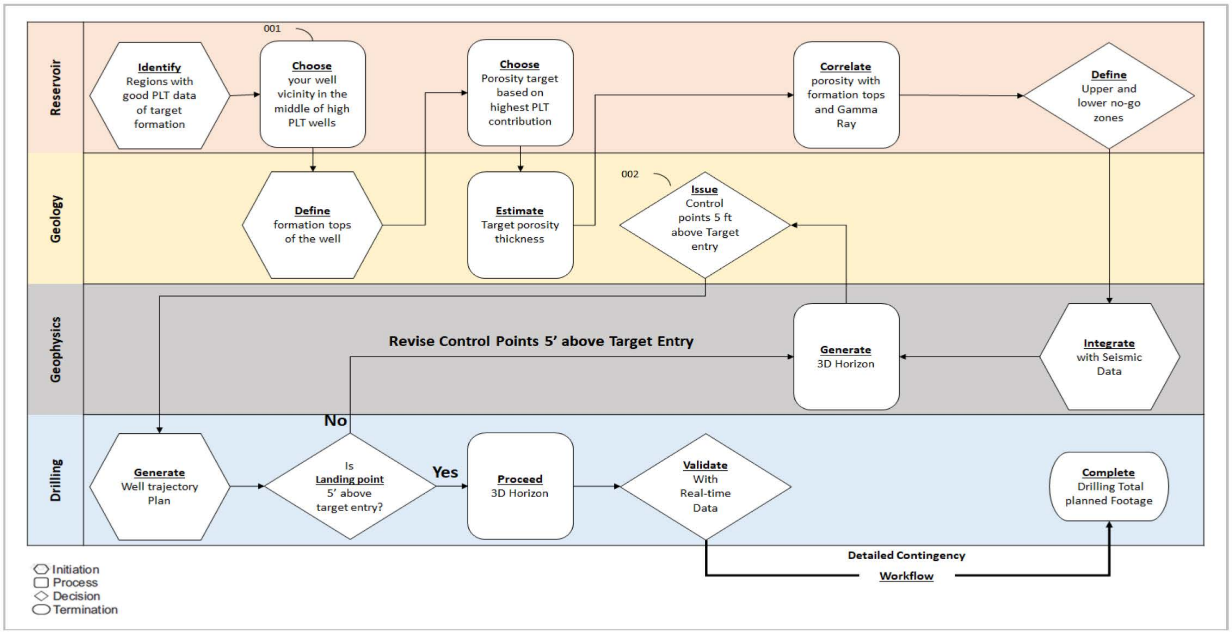


Figure 1—This integrated workflow brings together the expertise of reservoir, geology, geophysics to optimize lateral placement of wells from planning phase until target depth.

Reservoir Phase

The hydrocarbon flow rate is the most reliable key operational indicator in the underbalanced operation to validate lateral placement within target. Therefore, assessing production logs is a critical step for layer selection in UBCTD. Given that some reservoirs are multi-layered with no vertical communication, the well plan must select the layer that is hydrocarbon contributing. In some cases, complex geology shows horizontal variation of formation. This heterogeneity could misinform decision to go deeper instead of landing the lateral and drilling few feet ahead to find the target. Therefore, well azimuth should be planned between two offset wells that have production log contribution from the target layers to minimize the risk of encountering horizontal formation heterogeneity, while considering a safe geomechanical window as shown in Fig.2

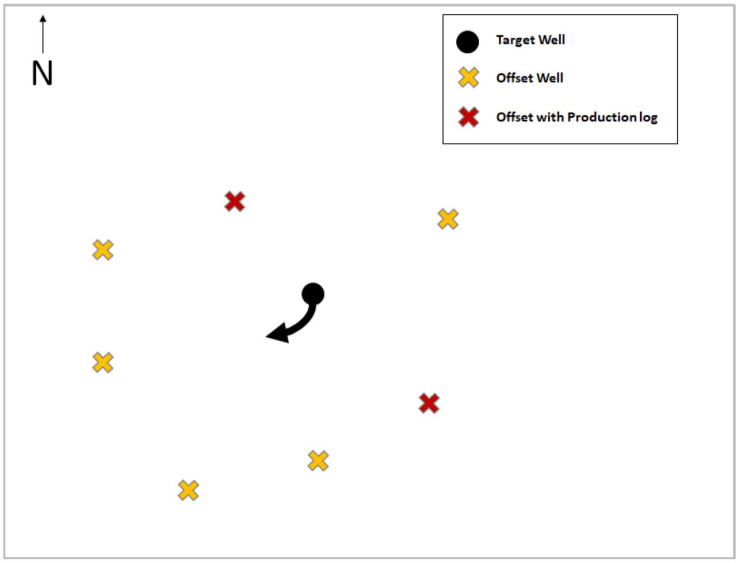


Figure 2—Insights from the production log should be incorporated to determine the optimal azimuth aligned with productive zones.

Geology Phase

Drilling Operational Window. Our approach to estimate the thickness is conservative when it comes to predicting the rim thickness of the reservoir. By leveraging thickness information of offset wells, we identified the most conservative thickness expected. Any thickness that falls outside the boundaries of the conservative thickness will be designated as no-go limits. These limits serve as a clear indicator of the range within which we can confidently navigate across target formation. For example, Fig.3 shows thickness frequency of dummy sample wells in a vicinity of a planned well X. A correlation model was constructed that suggests the average thickness @ 95% confidence interval is 12 ±2 with R2=0.77. That means 77% of the variation can be explained by the correlation model and 95% of the data falls between 10-14 ft within the vicinity of the well. Although the dataset is skewed to the right showing higher likelihood to encounter thicker reservoir, but looking at the map and given the unpredictability and heterogeneity nature of some reservoirs, a conservative approach is chosen. The most conservative thickness (9ft in the dummy sample) is chosen to plan the trajectory.

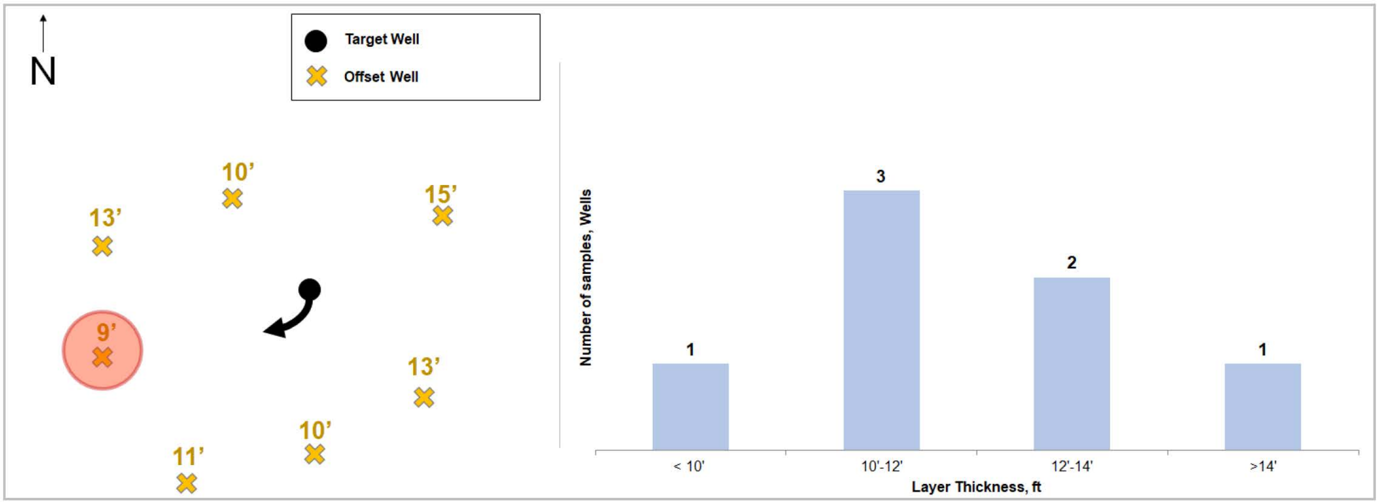


Figure 3—The data presented in this figure is artificially generated to illustrate the estimation of a conservative target thickness.

Landing Above Target. Before mobilizing the CT rig, the wells are drilled and cased with a liner until a preset depth as shown in Fig.4 The CT rig drills the buildup section in an overbalanced condition to ensure this section is stable for a sidetrack option. The normal practice is to drill few feet (Up to 5’) into the hydrocarbon bearing target and land the well without pumping nitrogen. In our approach, as a risk mitigation step, the End of Build point (EOB) is planned at least 5 ft above target to avoid any potential hole stability issues, then nitrogen is pumped to establish underbalanced condition.

Pumping nitrogen to establish underbalanced condition is a very critical step to assess where to place the lateral, as the flow rate is the most reliable indicator of spotting the sweet spot. However, nitrogen injection is commenced after reaching the EOB. Therefore, the workflow emphasizes the buildup section to be drilled in an overbalanced condition but chooses to end the buildup section slightly above target. This ensures that underbalanced condition is established before entering the reservoir sweet spot. As a result, underbalanced condition mode will confirm the reservoir layer as soon as it is penetrated.

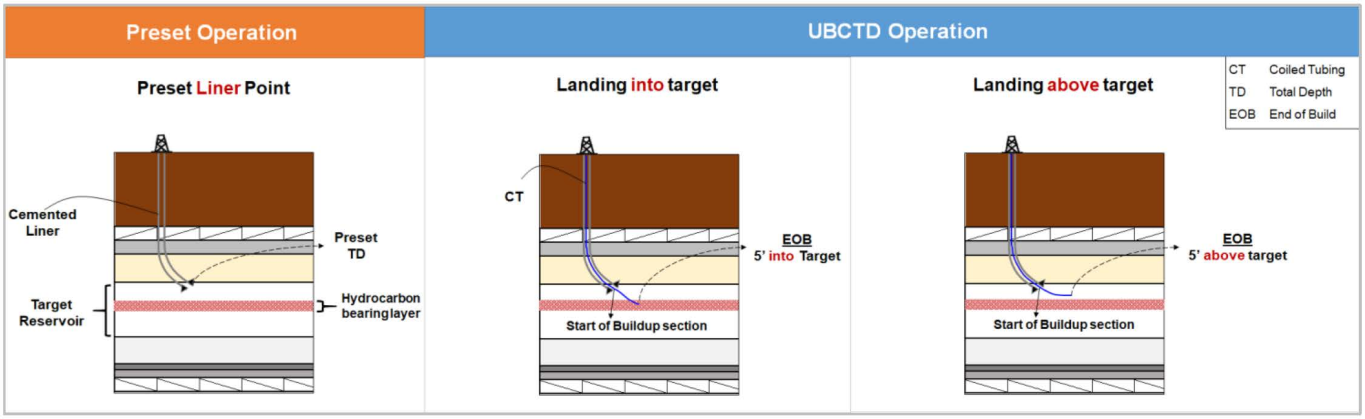


Figure 4—A schematic to show different types of landing modes in preset drilling and UBCTD operations.

Geophysics Phase

Upper and Lower no-go Limits. After identifying the upper and lower no-go boundaries, the workflow uses the available seismic data to account for dip inclination and spatial variations – generating 3D drilling window. Fig.5 shows the process from identifying conservative thickness in 2D to generating a 3D drilling window.

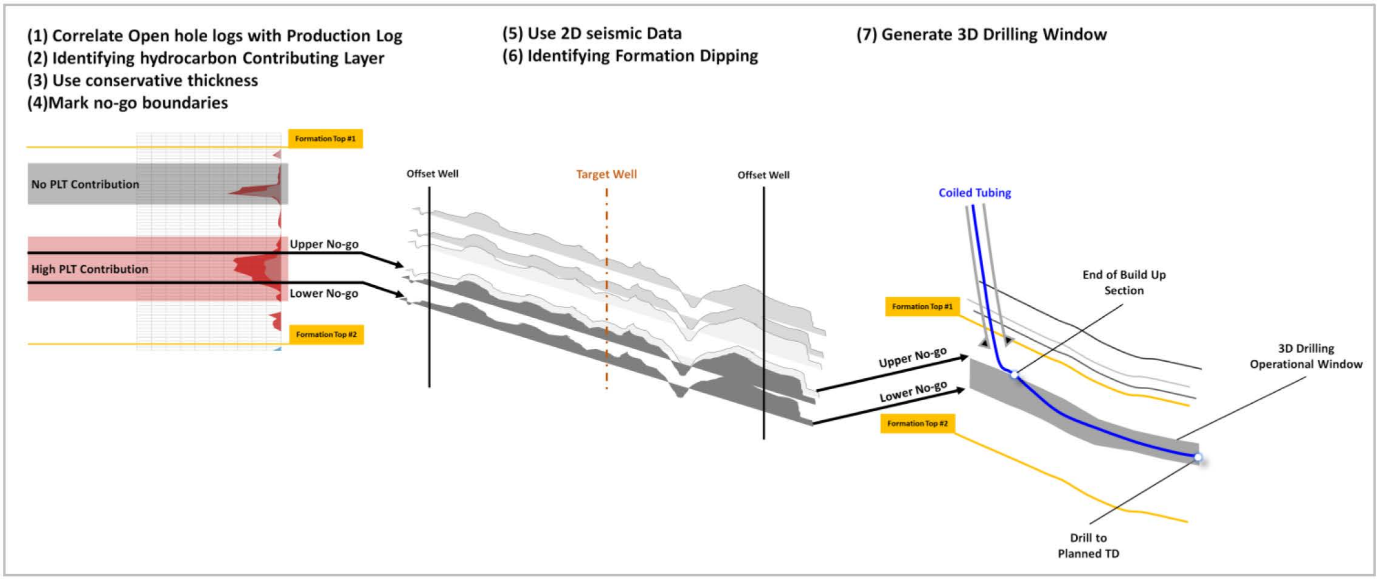


Figure 5—Integrating the conservative thickness estimation with seismic to generate a 3D drilling window.

Drilling Phase

Control point inside the 3D drilling window will be provided to generate an initial drilling trajectory plan. During drilling operation, the plan will be modified based on real time well test, geology, and drilling data. A contingency workflow was constructed to suggest the actions to be taken during the operation as shown in Fig.6.

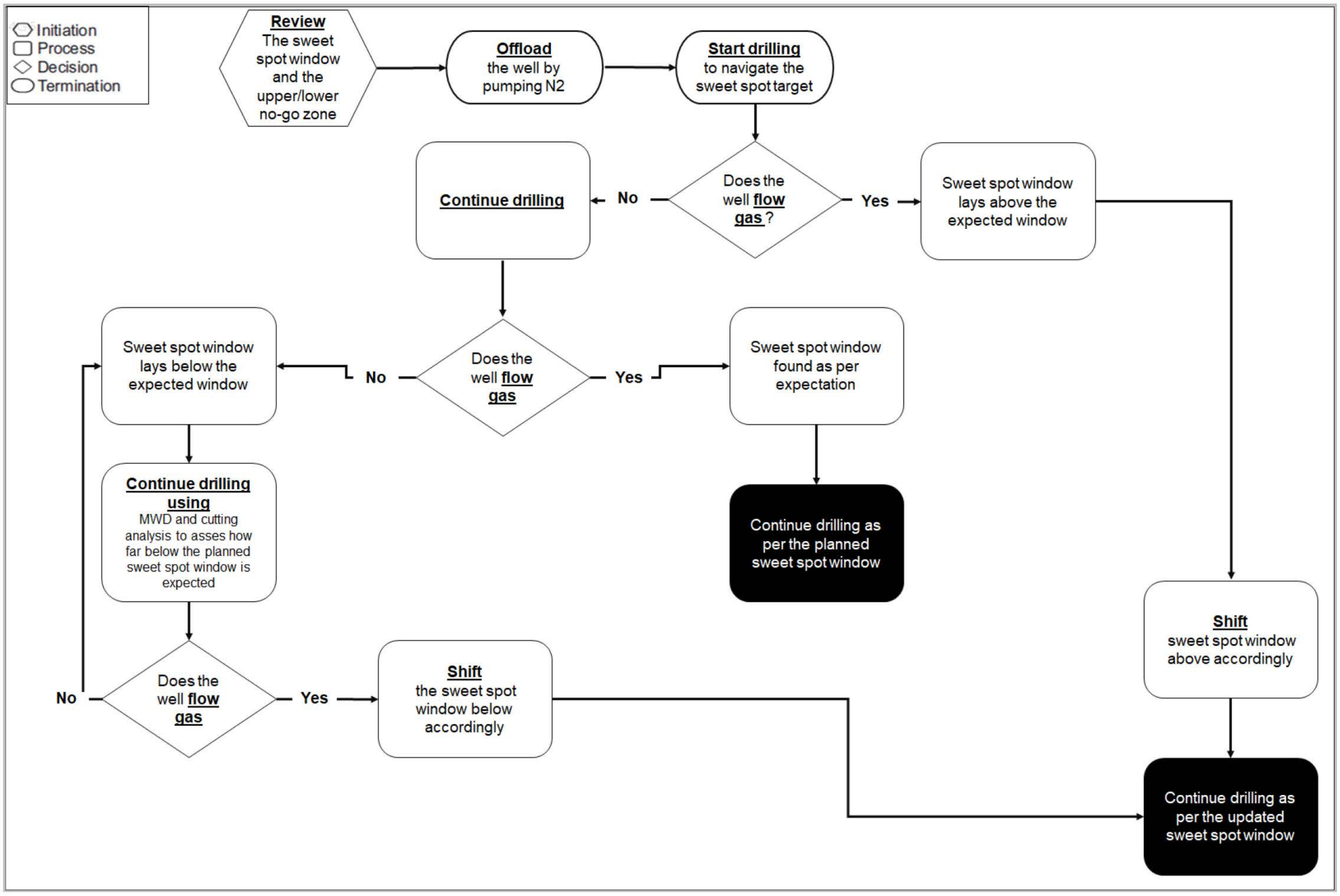


Figure 6—Contingency workflow to be used when the real time data differs from the anticipated 3D drilling window.

Results & Discussion

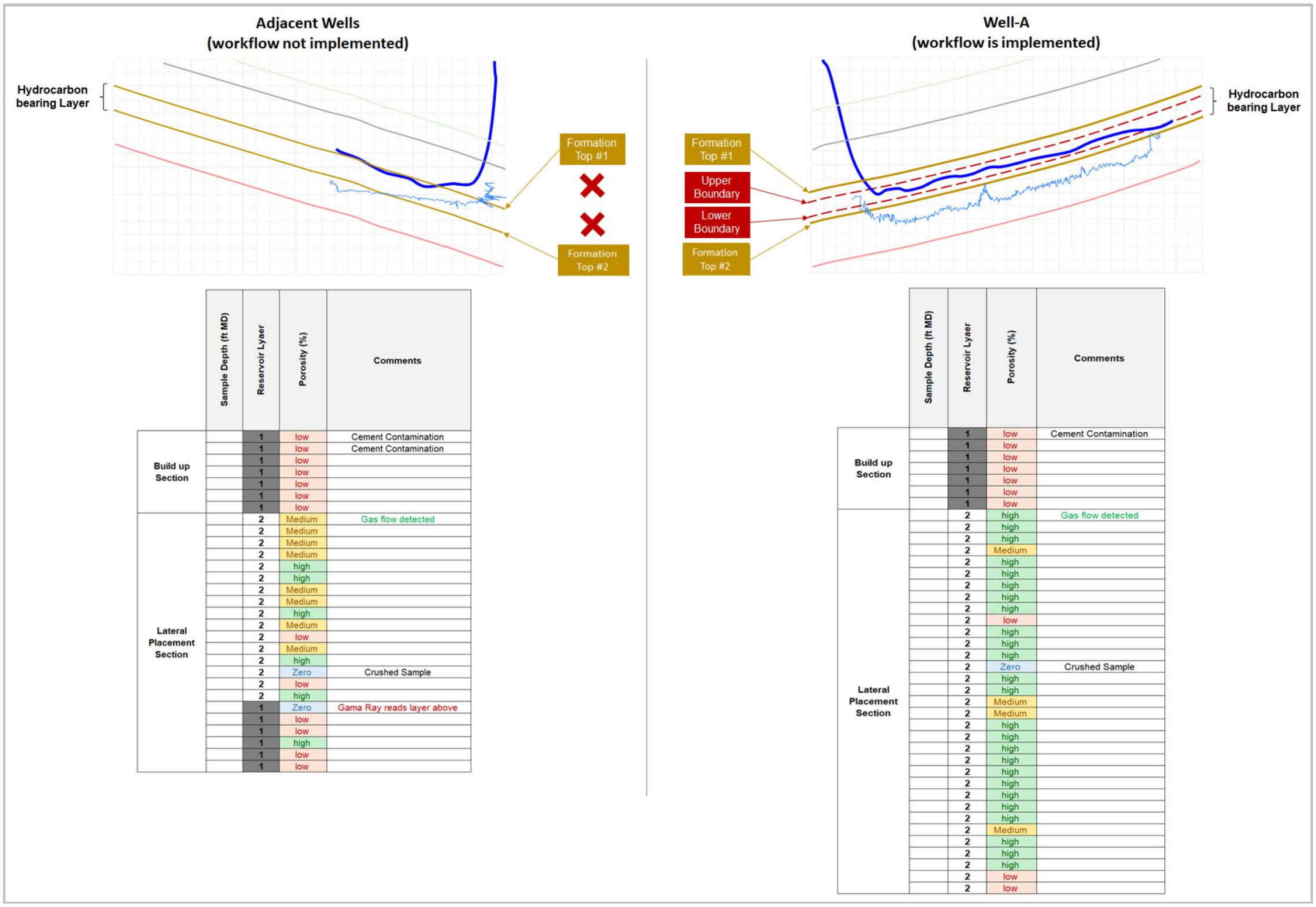
The improved workflow was implemented in three wells targeting a specific layer inside the multi-layered hydrocarbon-bearing carbonate reservoir. Each well was drilled in a different grid of the field, A, B, and C respectively. Each grid has its own geologic complexity and formation characteristics; hence has its own challenges when it comes to lateral placement. To illustrate the results of the implemented workflow, each grid will be discussed separately. The comparison of lateral placement will show the improved effective footage of the sample well compared to the average effective footage of offset wells located in the same grid.

Grid A:

This grid had several offset wells and the formation was relatively flat. In this grid, the sample Well-A was drilled using the improved workflow. The well landed as per expectations and flowed gas instantly indicating entry into the sweet spot. In this grid, the offset wells drilled with UBCTD fell short of meeting the required reservoir contact due to some wellbore instability caused by crossing dead rock above or below the target during the sweet spot navigation. On the contrary, implementing the workflow resulted in longer lateral and improved placement compared to the average of the offset wells in the same grid. The following results were observed:

Well-A lateral drilled 600ft more compared to the next highest lateral footage in the same grid and showed an overall improvement of 35% higher footage compared to the average footage in the grid.

Cuttings analysis showed improvement in the net-to-gross ratio at 0.91 compared to offset wells at 0.65. Fig.7 shows the cuttings analysis of well-A and an adjacent offset well.



	Sample Depth (ft MD)	Reservoir Lyaer	Porosity (%)	Comments
Build up Section		1	low	Cement Contamination
		1	low	Cement Contamination
		1	low	
		1	low	
		1	low	
		1	low	
		1	low	
Lateral Placement Section		2	Medium	Gas flow detected
		2	Medium	
		2	Medium	
		2	Medium	
		2	high	
		2	high	
		2	Medium	
		2	Medium	
		2	high	
		2	Medium	
		2	low	
		2	Medium	
		2	high	
		2	Zero	Crushed Sample
		2	low	
		2	high	
		1	Zero	Gama Ray reads layer above
		1	low	
		1	low	
		1	high	
		1	low	
		1	low	

	Sample Depth (ft MD)	Reservoir Lyaer	Porosity (%)	Comments
Build up Section		1	low	Cement Contamination
		1	low	
		1	low	
		1	low	
		1	low	
		1	low	
		1	low	
Lateral Placement Section		2	high	Gas flow detected
		2	high	
		2	high	
		2	Medium	
		2	high	
		2	high	
		2	high	
		2	high	
		2	high	
		2	low	
		2	high	
		2	high	
		2	high	
		2	Zero	Crushed Sample
		2	high	
		2	high	
		2	Medium	
		2	Medium	
		2	high	
		2	high	
		2	high	
		2	high	
		2	high	
		2	high	
		2	high	
		2	high	
		2	high	
		2	Medium	
		2	high	
		2	high	
		2	high	
		2	low	
		2	low	

Figure 7—Well-A drilled with UBCTD shows improvement in lateral placement, total footage drilled, and the net-to-gross ratio compared to an offset well.

Grid B:

This grid has fewer offset wells; hence fewer control points. The formation dipping inclination is quite high at 94°. A sample Well-B was drilled to a specific layer inside the multi-layered hydrocarbon-bearing carbonate reservoir. The first attempted lateral (B-1) was drilled without implementing the workflow and encountered wellbore instability before flowing gas. Therefore, lateral B-1 was aborted. The second lateral (B-2) was drilled utilizing the improved workflow targeting the same layer with a slight shift in azimuth. Upper and lower no-go boundaries were identified. Implementation of the workflow resulted in sweet spot identification and longer lateral placement with higher net-to-gross. The following are the results of the improvement of Lateral B-2 over Lateral B-1:

- The gas flowed from the target as per the anticipated 3D drilling window. This confirmed the upper no-go boundary of the sweet spot. The lateral was maintained inside the 3D drilling window.
- The total drilled footage improved by 70% compared to B-1.
- The cuttings analysis confirmed 1.00 net-to-gross ratio.

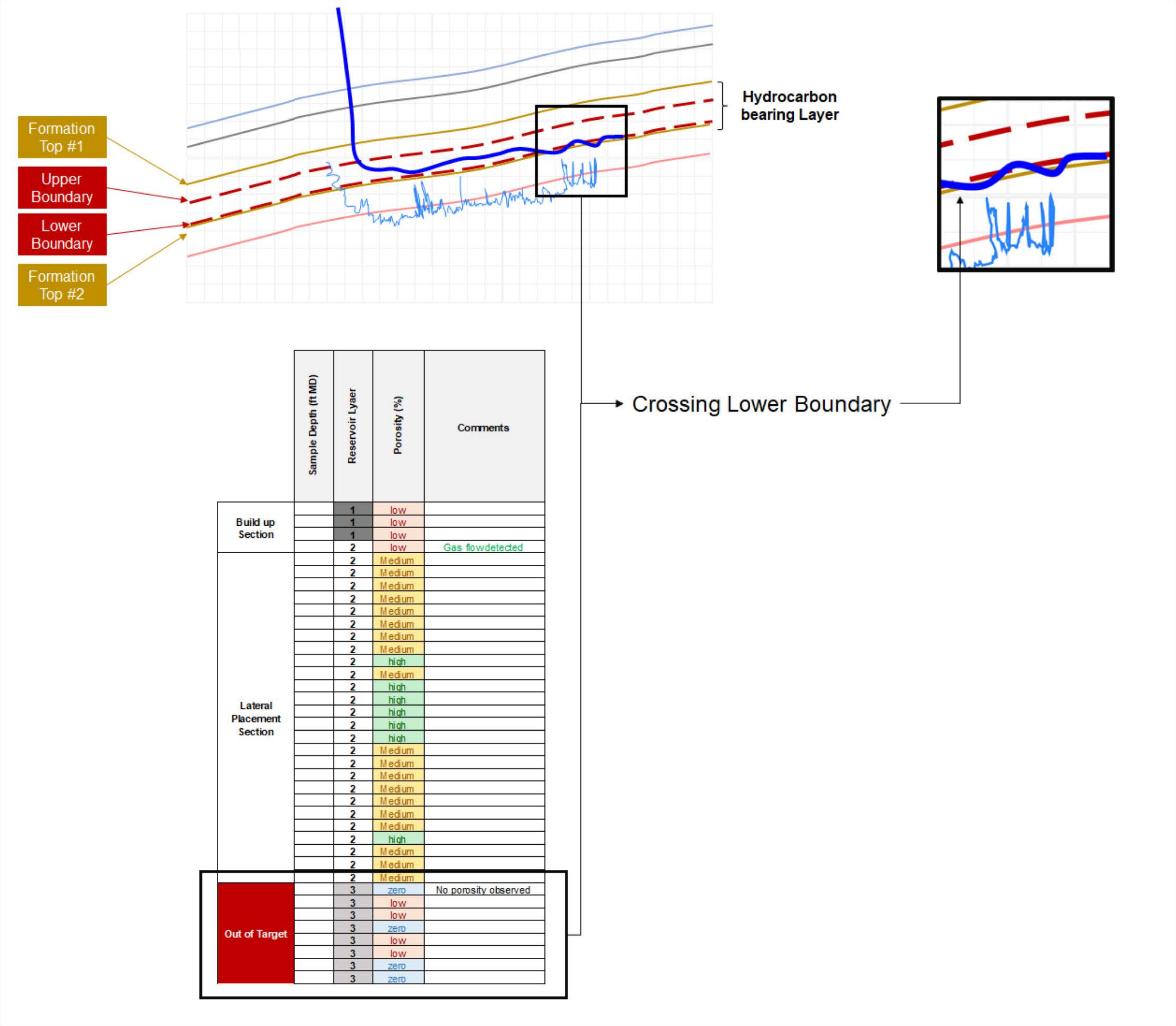
Grid C:

This grid exhibited the most complex geology caused by localized dipping variation. The grid exhibited heterogeneity and risk of wellbore instability when crossing non-reservoir rock while drilling prior offset wells with UBCTD.

A sample Well-C was drilled using the improved workflow. The target thickness to generate the 3D drilling window was estimated conservatively to minimize all risk of crossing non-reservoir rock from offset wells. However, after the no-go boundaries were identified, an additional safety buffer was accounted for and the lower no-go boundary 2 ft above the planned. The buffer was moved up to ensure the lateral does not cross non-pay footage during its placement. while navigating and placing the lateral. The following are the results of the improvement seen in sample Well-C compared to the offset wells drilled with UBCTD in the same grid:

- The gas was not detected as the lateral crossed the anticipated upper no-go. The lateral was shifted below until the sweet spot was identified using the contingency workflow in Fig.6.
- The gas flowed when the bit reached the modified 3D drilling window upper no-go boundary. This confirmed the lateral was placed inside the sweet spot. The lateral was maintained inside the modified 3D drilling window.
- The total drilled footage in Well-C exceeded all offsets by more than 50%.
- Cuttings analysis confirmed 0.75 net-to-gross ratio.

In this case, the net-to-gross ratio was not maximized due to encountering dead rock at the base of the 3D drilling window. Once the bit reached a dead rock zone, the drilling team onsite reported un-controllable drop due to an aggressive formation dip inclination. Fig.8 shows the lateral was placed at the bottom of 3D drilling window (around the lower no-go boundary), the cuttings analysis showed deteriorating porosity confirming bit departure from the lower reservoir boundary. This realization confirms the benefit of having conservative estimation of the target thickness in the planning phase before generating the 3D drilling window.



	Sample Depth (ft MD)	Reservoir Lyaer	Porosity (%)	Comments
Build up Section		1	low	
		1	low	
		1	low	
		2	low	Gas flowdetected
Lateral Placement Section		2	Medium	
		2	Medium	
		2	Medium	
		2	Medium	
		2	Medium	
		2	Medium	
		2	Medium	
		2	Medium	
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		2	Medium	
		2	Medium	
		2	Medium	
		2	high	
		2	Medium	
		2	Medium	
		2	Medium	
Out of Target		3	zero	No porosity observed
		3	low	
		3	low	
		3	zero	
		3	low	
		3	low	
		3	zero	
		3	zero	

Figure 8—A lateral drilled using the improved workflow. The lateral encountered dead rock and wellbore instability when the well trajectory exited the 3D drilling window from the base.

Observations and Lessons Learned

Inverted drilling (Drilling at high inclination angle) can be detrimental to lateral length. In this technique, the gravity and friction force will act against the CT which reduces the weight transfer applied at the bit. Consequently, the CT is more likely to get locked up before reaching the planed reservoir contact. It is recommended to plan the direction of the UBCTD lateral in a formation that is dipping downward. With steep upward target formation, drilling from the base of the formation presents challenges when using gamma ray. Typically, gamma ray tool is placed 15 ft behind the bit at best. In steep upward formation, there will be a significant delay in detecting the target boundary. Therefore, timely adjustments to the trajectory cannot be made by the time the gamma ray sensor reads the target boundary, let alone, the risk of drilling out of the target

Biosteering technique has limitations and inaccuracy in lateral placement because of the latency in cuttings arrival time or poor cuttings sample quality. It is recommended to use the bio-fossils to validate the

3D drilling window upper and lower no-go limits. When the upper and lower no-go limits are confirmed by gas flow, biosteering can be used to navigate for the best porosity within the no-go limits.

Identifying accurately the sweet spot upper boundary enables the operator to effectively place the lateral in the desired target. It is recommended to ensure underbalanced mode is established before crossing the anticipated upper no-go limit in the 3D drilling window. The gas influx, when detected, can help the operator to precisely identify the upper and lower no-go limits and reduce the chance of drilling out of target. Another recommendation is to intentionally ending the buildup section few feet above the target to provide a buffer zone before entering the critical zone. As the drilling commences in underbalanced condition, this will allow early detection of the gas bearing zone upper limit. The nitrogen injection can then be adjusted once the well starts flowing the reservoir gas, a common practice that is followed in many UBD operation.

Conclusions

- The position of gamma ray 15ft behind the bit introduces a lag between the bit position and the depth of the reading. The delayed detection will have a significant effect on making adjustment precisely and timely.
- Finishing the End of the Build-up (EOB) section a few feet above the target provides a buffer zone before entering a critical gas zone.
- Establishing Underbalanced condition in the buffer zone before entering the 3D drilling window (anticipated sweet spot) enhances the early detection of gas influx.
- Geosteering and biosteering technique can be used to validate the improved workflow input. If the anticipated 3D drilling window fails, the workflow uses biosteering and geosteering techniques in the contingency verification workflow.
- Biosteering data is important to evaluate the success of the placement through estimating the net-to-gross ratio of the cuttings on surface.
- Drilling in steep formation presents challenges both in drilling mechanics and reservoir characterization.
- After the entry in the sweet spot, continuous monitoring is important to maintain the lateral and avoid accidental target exit. The real time monitoring should always integrate data from well test, geology, and drilling to inform the decision of trajectory adjustments.

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