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Friction or Fiction: Data-Driven Model for Lubricant Performance

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Abstract

One of the major tasks of the drill fluid is to lubricate the drill string and wellbore. This is important for high angle wells where friction limits depth because of buckling, high torque, severe stick/slip (SS), and low rate of penetration (ROP). While lubricity requirements are easily achieved in non-aqueous fluid (NAF), they remain a challenge for water-based mud (WBM). For this reason, lubricants are used to improve WBM lubricity to meet performance requirements of these wells without the cost and environmental concerns of NAF.

The literature on lubricity performance is limited to individual case studies and laboratory assessments which may not reflect performance in field conditions. To address this gap, a model was developed and applied to quantify performance benefits of a WBM lubricant in high-deviated and horizontal wells in a basin.

The workflow coupled field data with software, custom and proprietary, across domains, to quantify and visualise benefits on ROP, torque, and SS.

Introduction

Price shocks, climate change, and advances in digital information have driven recent transformation in the Oil and Gas industry (Volkenborn, Lea-Cox and Yi Tan 2017). One area of transformation in drilling is high-deviation and horizontal wells. This technology is cost-effective in several scenarios: i) offshore drilling from land; ii) drilling several wells from a single location; iii) developing mature fields; and iv) maximising benefits of a complex reservoir (Elgaddaf, et al. 2021). For these wells, friction is a critical issue that limits depth because of buckling, high torque, severe SS, and low ROP. To predict and detect this, torque and drag (T&D) models are used in both design and execution of these wells (Alsharif, Al Khudir and Khan 2017).

One of the major tasks of the drill fluid is to lubricate the drill string and wellbore. The lubrication is one of the most important factors to control friction. A measure of this lubrication is the fluid's coefficient of friction (COF). While low COF is easily achievable in NAF it remains a challenge for WBM (Mohammadi and Nowtarki 2015) (Chen, et al. 2018). For this reason, solid, liquid and nano-based lubricants are frequently used to reduce the inherent COF in WBM (Amanullah, Al-Arfraj and Al-Abdullatif 2011) (Growcock, et al. 1999) (Mondshine 1970). This enables lubricant enhanced WBM to meet performance requirements of high deviated and horizontal wells without the cost and environmental concerns of NAF (Heir and Lambert 2005).

The COF is determined in small batch assessments in a laboratory with calibrated equipment such as OFITE EP/Lubricity Tester and LEM II. This extensive process is reserved for high-profile campaigns because of cost. These assessments are performed under controlled environments which may not reflect performance in field conditions.

Despite the importance of COF, no systematic approach to field measurement or impact on field performance exists. To address this, a model was developed and applied in a single basin that used the same lubricant. The model connects lubricant concentration to T&D models, bottomhole assembly (BHA) and electronic drilling recorder (EDR) data to quantify impact on ROP, SS and torque.

The key feature of the model is lubricant concentration. This is measured at the wellsite by the mud engineer using a retort. The retort distills and condenses a 50ml sample of mud into oil, water and solid components. The oil component is the lubricant and measured at +/- 0.5% in a 1-2% range. The accuracy is reduced further when other additives contribute to the oil component, the interface is unclear, and the test is run once a tour. To provide the quality and volume of data to correlate with performance, measured concentration was substituted with modelled concentration.

Method

The developed model uses several algorithms: (1) determination of volume change points; (2) estimation of lubricant concentration; and (3) correlation to performance. These algorithms will be discussed in further detail.

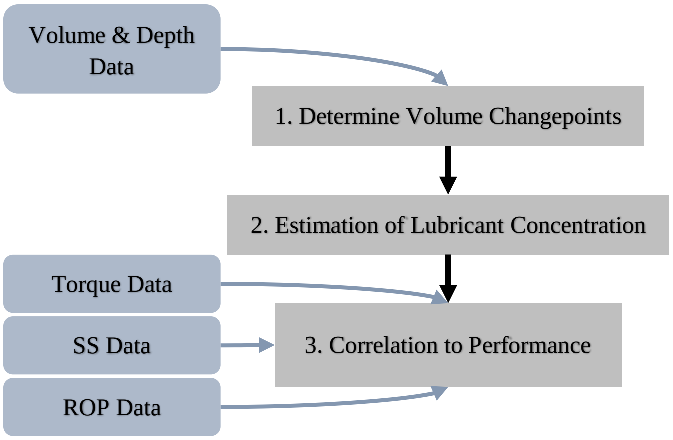

Figure 1: Model Inputs & Algorithms

Algorithms were performed in baseR at 1 second resolution sampled every 60 seconds, calculated on a standard laptop. Computation was batched into high-deviated 'S-shape' and horizontal wells to manage RAM limits. The horizontal batch was a 125,647 x 25 array which covered ~87 days of drilling. Computation was complete in ~27 seconds.

Key strategies for speed were pre-allocation of memory, functional programming, and vectorisation. The Apache Spark environment was used to bucketise and binarise visual output.

Algorithm – Determine Volume Change Point

Drilling requires additions of fluid to maintain surface volume. Each addition to total circulation volume dilutes the lubricant. To automate detection of each addition, a change point algorithm was developed to address the complexity of drilling data.

The algorithm determines a pair of events: when a tank is offline, as dead volume is reached; and when a tank is taken online, to maintain surface volume. The steps are as follows:

1. Apply simple moving average (SMA) on total volume
2. Apply first order difference to SMA
3. Filter on first order difference between bounds
4. Determine local minima and maxima on SMA
5. Match event pairs and calculate dilution ratio
6. Remove duplicates
7. Export visualisation for quality control (QC)

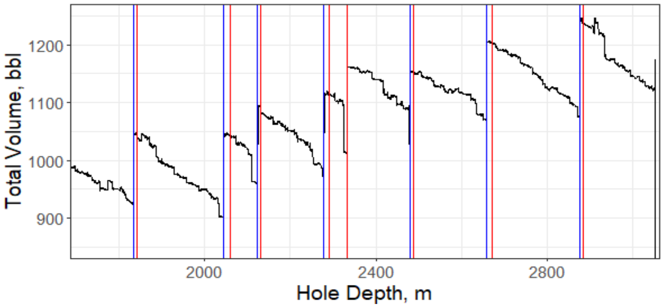

Figure 2: Visualisation of Change Point Algorithm

The algorithm reduced noise and errors in EDR data, ready for external QC. This ensures the analysis remains grounded by domain knowledge. To develop further, a user interface (UI) with a wizard would guide and push edge cases to the user to consider before further computation.

Algorithm – Estimation of Lubricant Concentration

Output of the previous algorithm was ingested, along with data on total volume and lubricant addition, to determine a high-resolution model of lubricant concentration by depth and time. This is a radical new way to visualise, discuss, and investigate lubricant additions. The estimate accounts for pump lag and assumes complete mixing.

Lubricant addition details were manually sourced through data mining tour sheets, daily mud reports (DMR), daily drilling reports (DDR) and EDR comments. The process as follows:

1. Supply event data
2. Determine lag and adjust timeframe
3. Allocate lubricant over duration
4. Calculate concentration based on following pseudocode:

```
FOR each t
        IF (The initial condition – no lubricant prior)
        $QS_t = QA_t$
        $C_t = QS_t / V_t$
        END IF
$C_t = C_{t-1}$
        IF (Changepoint occurs)
        $C_t = C_{t-1} / DF$
        END IF

        IF (Addition to active)
        $QS_t = (C_t * V_t) + QA_t$
        $C_t = QS_t / V_t$
        END IF
END FOR
```

Where,	QS	is lubricant quantity in system
	QA	is lubricant quantity added
	C	is concentration
	V	is total system volume
	DF	is dilution factor at change point
	t	is time

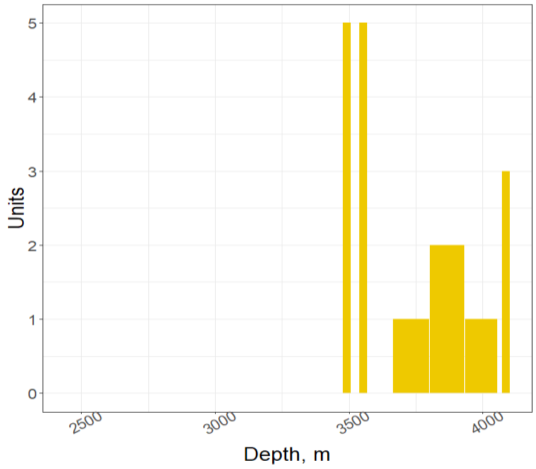

Figure 3: Lubricant Quantity Added

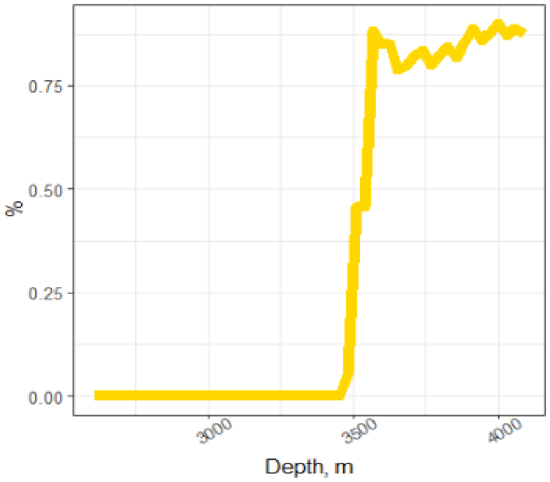

Figure 4: Modelled Lubricant Concentration

A core assumption was that concentration is conserved from one time period to another unless addition or dilution occurs. Therefore, depletion was assumed negligible despite known mechanisms such as evaporation, adsorption, biodegradation, and irreversible chemical reactions. Because direct or proxy measurement of these mechanisms were not available, these mechanisms were omitted from the modelled concentration but accounted for in interpretation of results.

Algorithm - Correlation to Performance

The estimated lubricant concentration was then coupled with pre-processed data on ROP, SS and torque for analysis.

Torque

To assess torque, a T&D model was constructed in a proprietary geophysics software. Each interval was assessed to benchmark torque with respect to well design, BHA, drill fluid properties, and trajectory.

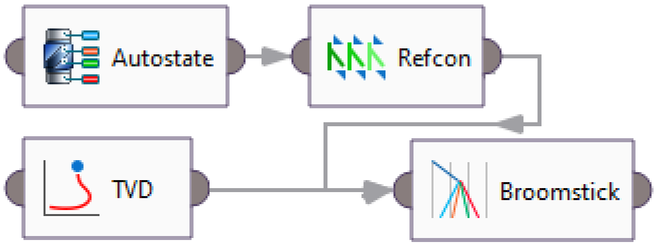

Figure 5: T&D Model Workflow

The *Autostate* is a rigstate and drillstate engine that identifies an activity. The connection activity was passed onto *Refcon* to detect off-bottom torque (OBT). The OBT was passed on to *Broomstick*, a calibrated T&D model which friction factor (FF) is extracted from. The entire process is automated except for a block weight input. This enables friction and torque to be interchanged and evaluated at different depths, and across different wells and rigs, as seen in *Figure 6*.

To ensure accuracy on the OBT value, 1 second resolution was used. This required 40-400MB for each interval and is often a task analysed by a dedicated drilling engineer.

The boxplot in *Figure 8* used a modified bin for concentration. The bin was restricted to 0.5% increments and required >20% of the non-zero data to be valid. This reflected measurement error of the retort and removed minor or transitory bins.

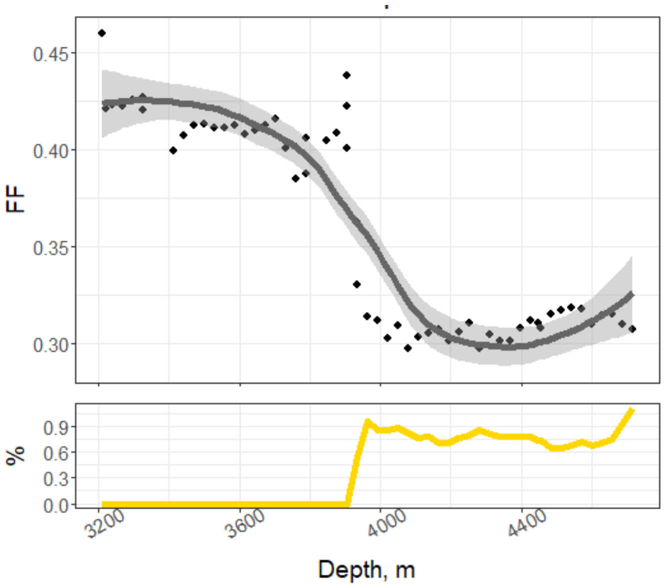

Figure 6: Friction Factor and Lubricant Concentration

Stick/Slip

Stick/Slip is a drilling dysfunction characterised by oscillations of bit speed which lead to fatigue and failure (Ramirez & Pritchard, 2020). SS lowers ROP and damages the BHA.

SS is measured by SS ratio as shown below. Recorded BHA is accessed and SS ratio is then computed from the SS indicator and MWD collar RPM channels. The SS indicator measurement interval was 126-129 seconds, which was lower than the MWD collar RPM at 18-21 seconds. To calculate SS ratio, SS indicator was matched to the nearest MWD collar RPM.

$$SS_{Ratio} = \frac{SS_{Indicator}}{2\overline{RPM}}$$

The SS ratio was combined with modelled lubricant concentration based on a fuzzy join with date and well as key. There were two types of horizontal wells examined: sandstone and shale wells.

ROP

ROP was assessed with a SMA on instantaneous ROP (iROP) and an on:off-bottom ratio. Data was sourced from EDR at 1 second resolution, filtered on the following conditions, then sampled every 60 seconds. While many methods to assess ROP exist, this method was chosen for its simplicity.

$$\text{Depth}_{\text{Hole}} - \text{Depth}_{\text{Bit}} \leq 40\text{m}$$
$$\text{GPM} \neq 0$$
$$\text{iROP} \geq 1\text{m/hr}$$

The off-bottom condition was defined as:

$$\text{Depth}_{\text{Hole}} \neq \text{Depth}_{\text{Bit}}$$

Results & Discussion

Torque

Torque assessed on horizontal wells covered 13 wells and 15 intervals. Only the lateral section of the interval was evaluated.

Figure 7 shows wide distribution in FF with clusters at 0.475 and 0.35FF, at 0 and 0.75-1.25%. This indicates that the lower FF ranges are unlikely to be achieved without lubricant. Noise is attributed to performance delay in the model and transition to steady state. Transition impacts the extremes, 0-0.5% and 1.5-2%. On the other hand, model assumptions of i) evenly allocated additions across the duration and ii) complete mixing after one circulation may in fact result in faster or slower mixing of lubricant. Furthermore, the step-change in concentration caused by changes in volume is in fact more gradual than the model predicts.

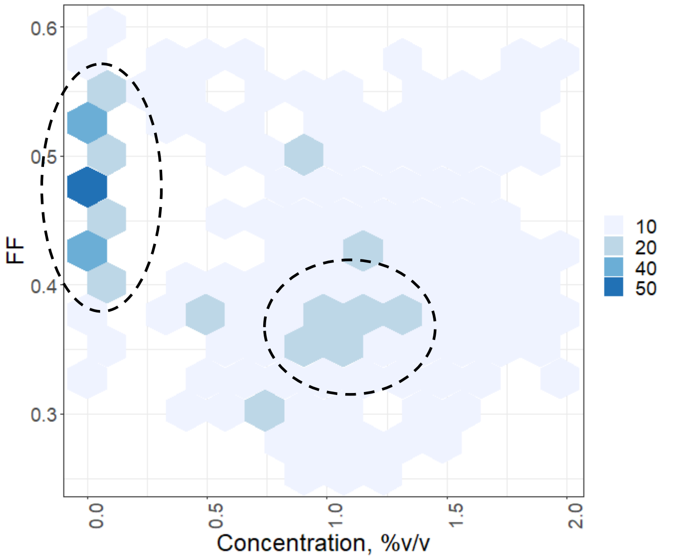

Figure 7: Friction Factor Analysis

To reduce error in performance delay, FF results were visualised in *Figure 8* with modified bins to reflect retort measurement at ±0.5%. This reduced the distribution to ±0.1FF on all bins. A clear distinction in median with and without lubricant is seen at ~0.375FF, which corroborates the central cluster in *Figure 7*.

Figure 7 and *Figure 8* suggest that >1% of this lubricant did not yield additional benefit.

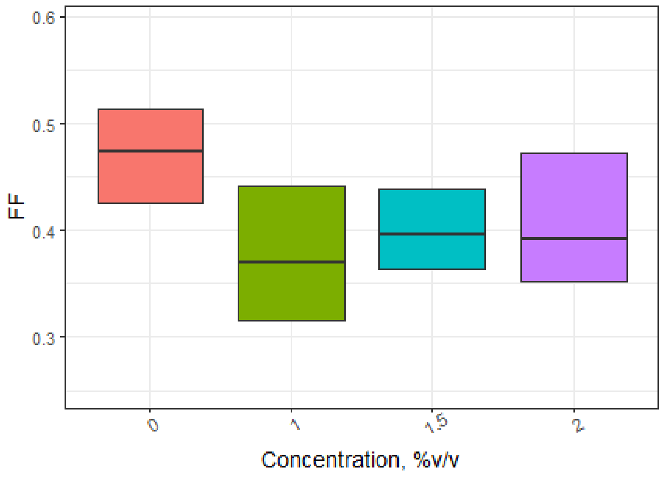

Figure 8: Major Lubricant Concentration Analysis

Well-specific performance (displayed in *Figure 9*) was operationalised as the torque difference from a 0% baseline at the bin depth range and concentration. As in *Figure 8***,** no additional benefit was seen at higher concentrations on any case. For these wells, a reduction on OBT of 1-5 kft-lbs was achieved.

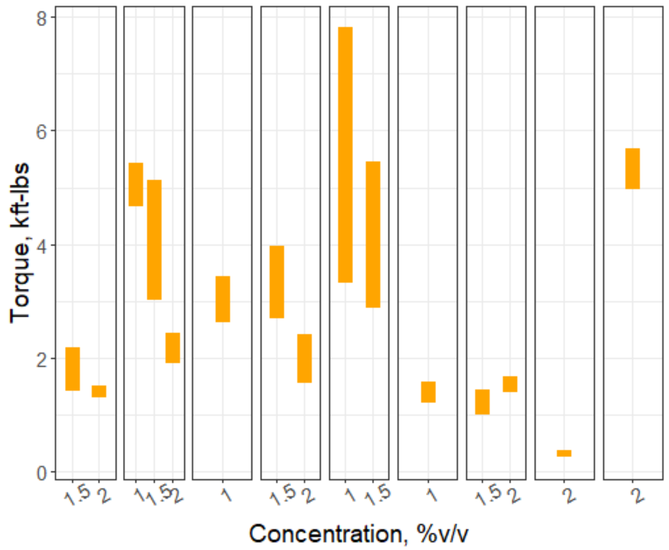

Figure 9: Torque Reduction on Horizontal Wells

Lower values for torque reduction were observed on wells with abnormal torque and inconsistent FF that remained after lubricant addition. This led to a poor baseline for the projection, and may be the cause of low projected reduction in torque.

Similar trajectory and parameters were present in two well pairs, where, in each pair, one well was drilled with lubricant and one without. This is shown in *Figures 10-12*. In both pairs, 20-25% less OBT is sustained on the well with lubricant compared to the well without.

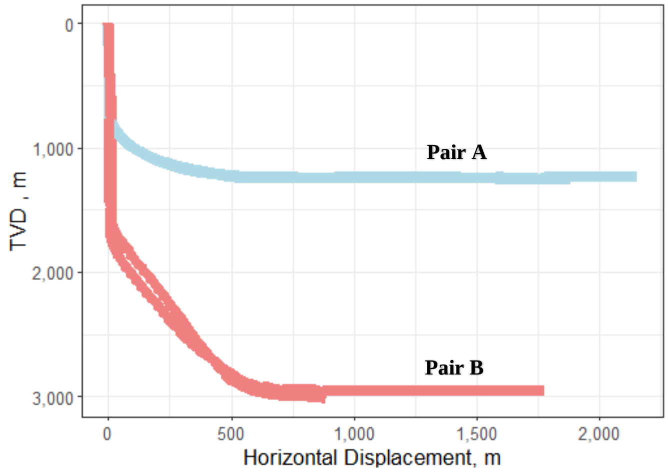

Figure 10: Trajectory of Pair A and B

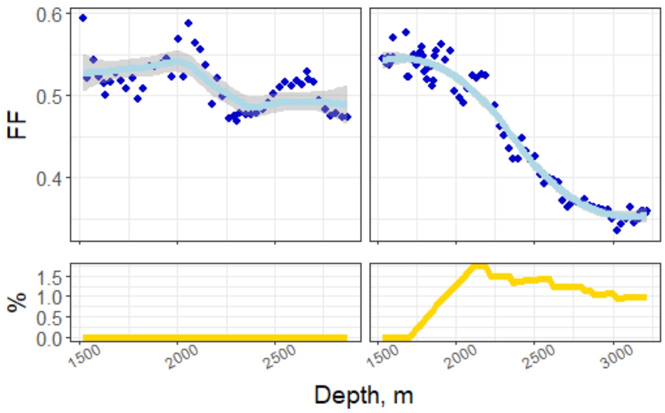

Figure 11: Friction Factor & Lubricant - Pair A

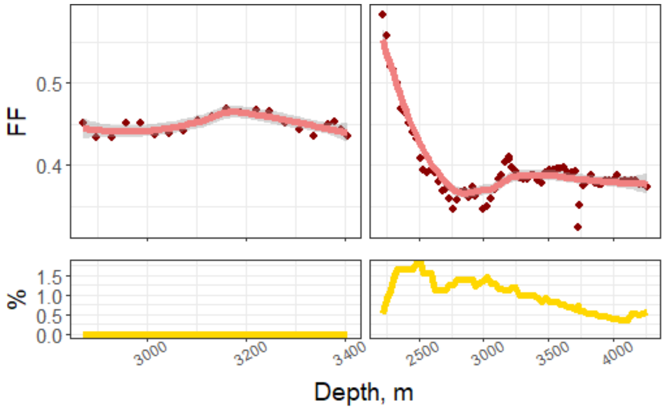

Figure 12: Friction Factor & Lubricant - Pair B

In Pair A, a reduction in FF is observed on the well with lubricant. The reduction took 33 hours from modelled concentration peak at 2,110m to reach equilibrium at 0.45FF. From this point, FF was sustained for 22 hours until total depth (TD) at 0.97-1.24%.

In Pair B, the well without lubricant was consistent at 0.45FF while the well with lubricant reached equilibrium at 0.375FF from 2,750m for 9¼ days at 1.25 – 0.5%. Despite low modelled lubricant concentration on approach to TD, change was not observed in FF. This may suggest that the reduction in FF becomes permanent once equilibrium is reached.

In wells that achieve FF equilibrium with a lubricant FF remains stable across different BHA at high bottom hole static temperatures (BHST) at length, as shown in *Figure 13*. This supports the argument that depletion mechanisms are minor for this lubricant.

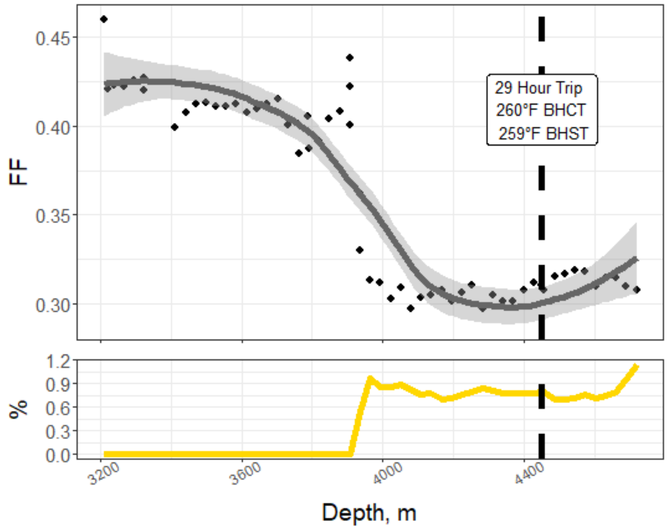

Figure 13: Lubricant Thermal Stability

To corroborate findings on horizontal wells, S-shape wells from 2018-2020 with lubricant >0.5% were reviewed, as shown in *Figure 14*. Result were similar to horizontal. FF without lubricant measured 0.3±0.05FF and reduced with the addition of lubricant to 0.2±0.025FF from 1.5%v/v. The largest torque reduction occurred in wells with the largest horizontal displacement (high torque wells). A step change occurred on all wells when lubricant was added. This suggests the transition to FF equilibrium is unique to horizontal wells.

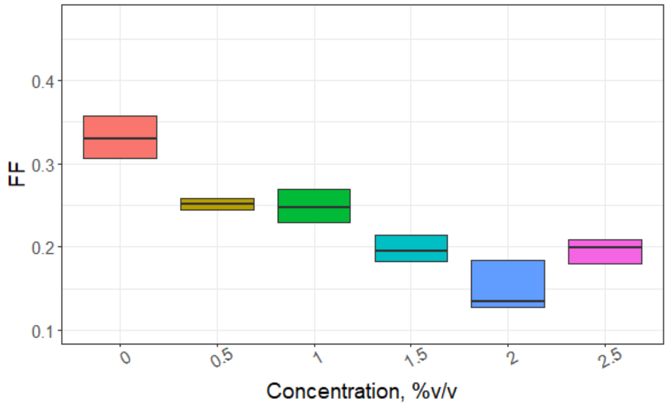

Figure 14: Lubricant and Friction Factor on S-Shape Wells

Stick/Slip

Figure 17 depicts SS ratio in sandstone wells. When lubricant was added to begin the interval, SS ratio remained low with isolated peaks. When lubricant was added after severe SS, the reduction in SS ratio was gradual. In all cases, reduction in SS ratio was sustained at 1-1.5%.

On the single well without lubricant, SS ratio developed to 1 and was sustained for 48 hours before TD. This result was higher than wells with lubricant.

Figure 15 depicts SS ratio in shale wells, which all displayed low SS ratio. This indicates lubricant is independent of SS ratio in the shale formations for this basin. However, it should be noted that the dataset for shale wells is smaller than for sandstone wells.

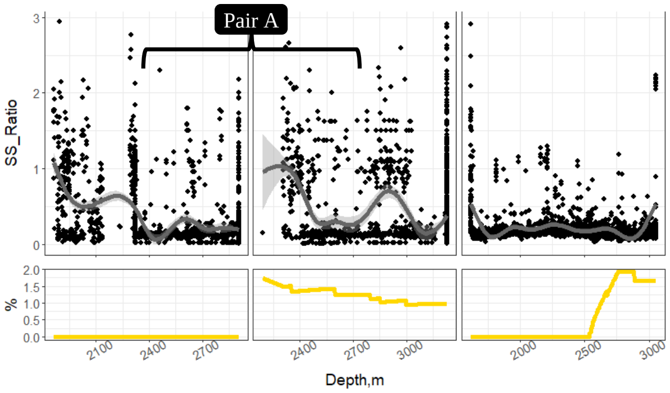

Figure 15: Shale Stick/slip Ratio and Lubricant

ROP

For iROP, no general trends or step changes were observed. This is particularly evident when observing wells initially drilled without a lubricant (*Figure 16*).

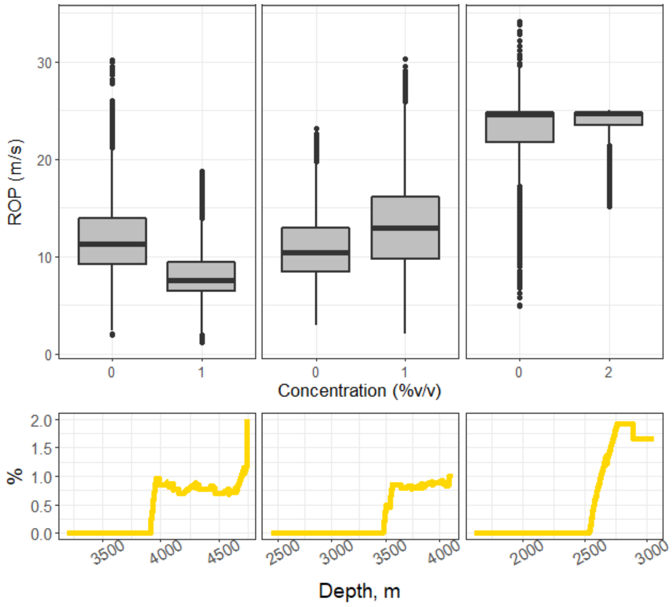

Figure 16: iROP subset and Lubricant

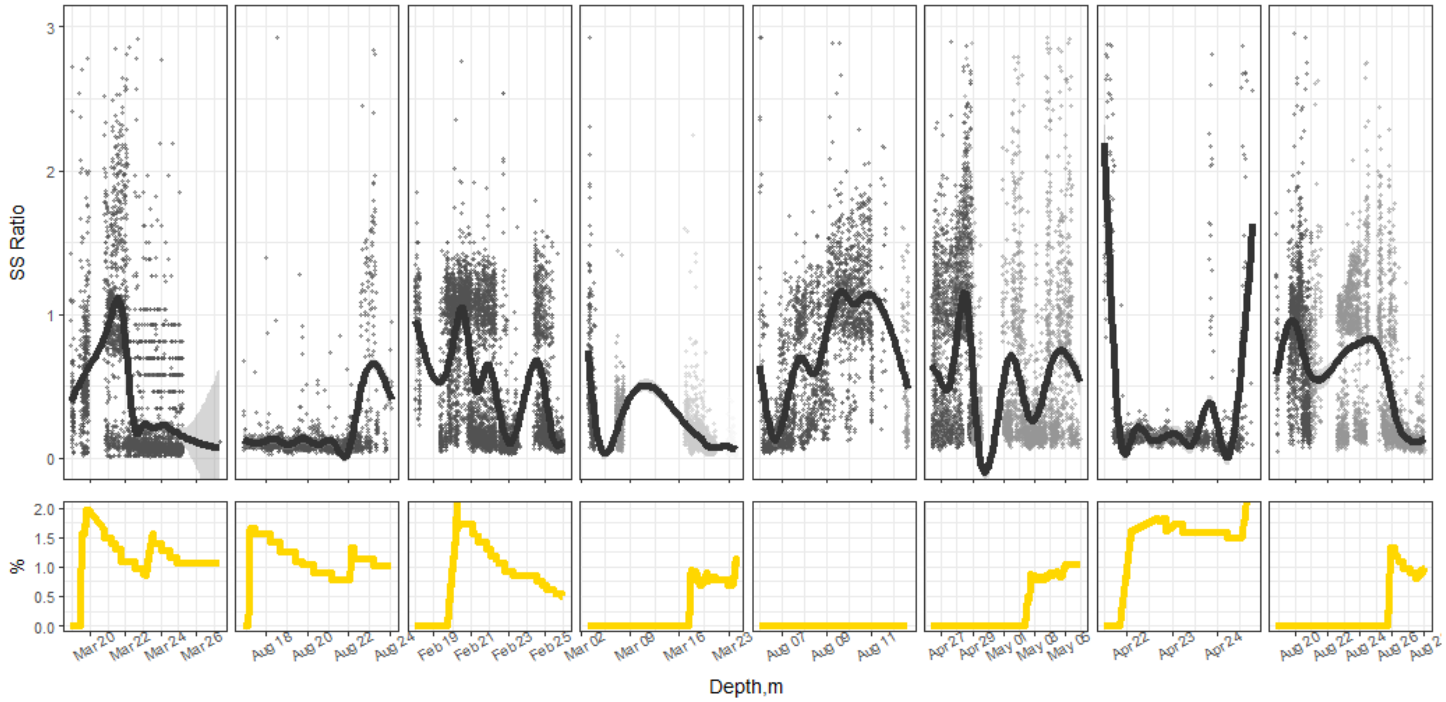

Figure 17: Sandstone Stick/slip Ratio and Lubricant

No general trends were observed in on:off bottom ratios. In *Figure 18*, which depicts the same subset as *Figure 16*, the sandstone wells presented higher on:off bottom ratios when lubricant was present than without lubricant. This may be caused by reduced SS however did not lead to increased iROP. The shale well in *Figure 18* had a decrease in both on:off bottom ratio and iROP range with the presence of lubricant.

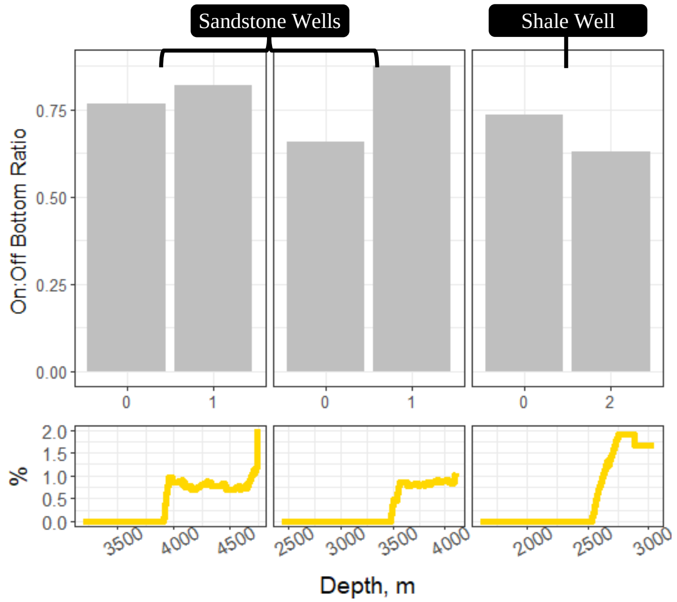

Figure 18: Stick Slip Ratio Subset and Lubricant

Pair A (*Figure 19*) experienced a 78% increase in iROP. This increase was attributed to lower FF caused by the addition of lubricant which enabled more on-bottom torque. In turn, increased iROP resulted in more frequent drilling connections and decreased the on:off bottom ratio. As SS was not problematic in shale wells no improvement to on:off bottom ratio was expected from the addition of lubricant. This pattern matches that of the shale well in *Figure 18.*

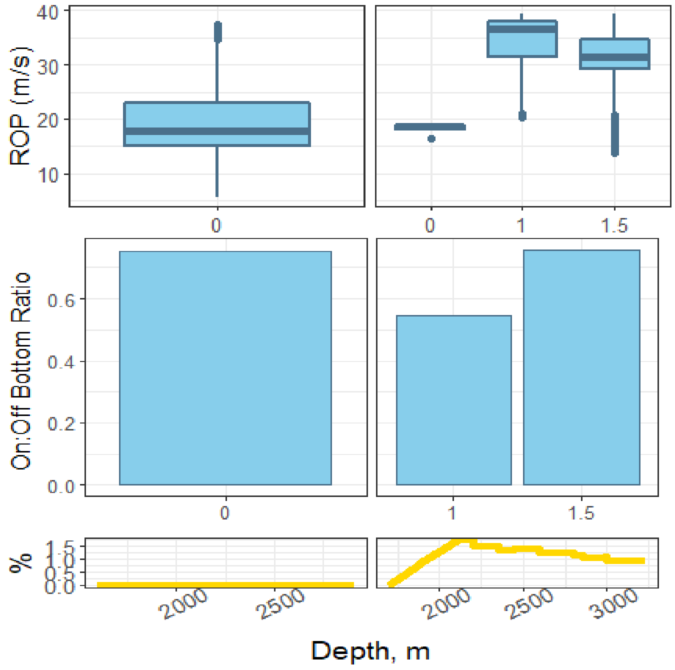

Figure 19: iROP & On-Bottom Ratio - Pair A

Pair B (*Figure 20*) displayed an increase in on:off bottom ratio, though no change was observed in median iROP. It is noted that distribution of iROP on the lubricant well was narrower at ±5m/hr for both pairs.

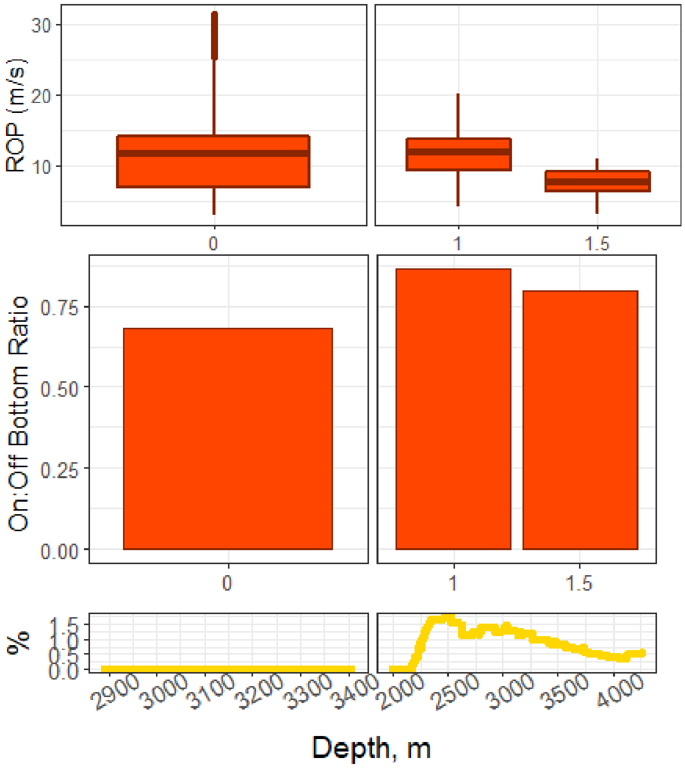

Figure 20: iROP & On-Bottom Ratio - Pair B

The data presented indicates that the presence of lubricant did not increase median iROP, though it did reduce iROP distribution. The addition of lubricant did not change on:off bottom ratios in shale wells. In contrast, the addition of lubricant increased on:off bottom ratios in sandstone wells.

Conclusions

This paper describes the development and application of a data-driven model in a basin to assess performance benefits of a WBM lubricant in high-deviated and horizontal wells.

Previously, determination of lubricant performance would require extensive laboratory testing under controlled conditions which may not reflect actual performance. The current model was developed to address this gap. The workflow coupled field data with custom and proprietary software across domains to quantify and visualise benefits on ROP, torque and SS.

While the study described in this paper warrants further research, the following conclusions can be made:

1. Lower torque, estimated at 20-25% less OBT, occurred on wells with lubricant. For horizontal wells, additional benefit was not seen >1%. On high-deviated wells, additional benefit was not seen at >1.5%.
2. The lubricant is stable in static and dynamic high temperature environments for >24 hours.
3. The lubricant had substantial performance lag of >24 hours until equilibrium was reached. Once established, equilibrium was resistant to change.
4. Reduction in SS was seen in sandstone wells with lubricant at 1-1.5%. When lubricant is added to begin the interval, SS ratio remained low with isolated peaks. When added after severe SS occurred, reduction was gradual.
5. The presence of lubricant did not directly improve iROP. In a shale well, lubricant will reduce FF which may lead to higher iROP. In sandstone wells, lubricant reduced SS, which led to less time off bottom. In both cases narrower iROP distribution occurred on with lubricant than without.

Acknowledgements

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Nomenclature

BHA	*Bottomhole assembly*
BR	*Build rate*
COF	*Coefficient of Friction*
DD	*Directional driller*
DDR	*Daily drilling report*
DMR	*Daily mud report*
DS	*Drill string*
EDR	*Electronic drilling recorder*
EOW	*End of Well*
FF	*Friction factor*
FP	*False positive*
MA	*Moving average*
MWD	*Measurement while drilling*
NAF	*Non aqueous fluid*
OBT	*Off-bottom torque*
OH	*Open hole*
QA	*Quality assurance*
ROP	*Rate of penetration*
RT	*Real time*
nROP	*Normalised ROP*
iROP	*Instantaneous ROP*
SMA	*Simple Moving Average*
SS	*Stick/slip*
T&D	*Torque and drag*
TD	*Total depth*
UI	*User interface*
WBM	*Water based mud*
WOB	*Weight on bit*

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