Using advanced bit sensor modules for measuring vibrations, torque, and weight on bit to optimize PDC bit drilling efficiency in geothermal applications

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ABSTRACT

Vibration is one of the major contributors that reduce bit performance in geothermal drilling, resulting in excessive wear, low rates of penetration (ROP) and pulling out of hole before reaching total depth (TD). Conventional surface and downhole tools fail to detect vibrations occurring directly at the bit, with sensors located above in the bottomhole assembly (BHA). An advanced in-bit sensor system was developed to record memory-based measurements of vibration types, downhole torque (DTQ), and downhole weight on bit (DWOB). This integration of the in-bit sensor system offers valuable insights into the subsurface conditions during PDC bit drilling in geothermal applications, thus enabling reduced bit wear and improved drilling performance in challenging environments.

Data collected from the in-bit memory module revealed that torsional vibrations were most prominent during hard rock drilling, while stick-slip vibrations frequently occurred in transition zones where the BHA unwinds due to reduced formation resistance. Analysis of in-bit measurements also indicated that bit damage on the shoulder and gauge areas was primarily caused by lateral impact while rotating off-bottom. The results also showed that managing bit aggressiveness within a controlled critical depth of cut (DOC) effectively reduced stick-slip amplitudes.

Insights gained from the data will impact subsequent drill bit design improvements and operational adjustments, enhancing both technical and economic performance in geothermal drilling operations. Accurate identification of vibration sources during drilling facilitated the creation of a targeted drilling parameters roadmap aimed at ensuring dynamic stability of the bit/BHA combination across varying lithologies, significantly reducing bit wear and optimising ROP.

1. BACKGROUND

1.1 Introduction

PDC bit performance in geothermal drilling is often constrained by extreme downhole conditions including high temperature, hard formations, and severe vibration profiles. Traditional surface and downhole measurements fail to capture the real-time dynamics occurring at the bit-rock interface. This study evaluates the application of an in-bit sensor module for capturing high-resolution vibration, DTQ, and DWOB data during the drilling of the 12-1/4" production section of a well in one of the New Zealand geothermal fields in central North Island, which is one of the most thermally active regions within the Taupō Volcanic Zone (TVZ). As detailed by Leonard et al., (2010), TVZ hosts a high-temperature, liquid-dominated geothermal reservoir within a complex assemblage of welded ignimbrites, rhyolitic lavas, and breccias, with measured temperatures reaching up to 290°C. The lithological framework of this region is shaped by caldera-forming eruptions and intense faulting – these subsurface conditions, marked by abrupt lithological transitions and fractured volcanic formations create a challenging environment for drilling operations. This often results in severe bit wear, vibration-induced malfunctions, and premature bit failure.

Given these constraints, geothermal field provides a compelling testbed for the deployment of advanced drilling technologies, including custom-designed PDC bits and embedded in-bit sensor systems. Understanding the geological and structural characteristics of the field is therefore essential for developing effective drilling strategies that enhance bit durability, ROP, and reduce operational costs. Figure 1 shows the location of Taupō Volcanic Zone.

Figure 1. Location of Taupō Volcanic Zone.

1.2 Application Description

Drilling in the Taupō Volcanic Zone presents a complex set of challenges – rapid transitions in rock strength and abrasiveness result in unstable bit-rock interactions, where harder streaks can induce lateral vibrations, torque fluctuations, and backward whirl initiation. Elevated bottomhole temperatures combined with fluctuations of mud property and full mud losses further complicate hydraulic management and contribute to inconsistent weight transfer to the bit.

An example of typical wells construction and lithological variation encountered within the Taupō Volcanic Zone is illustrated in Figure 2. The planned well trajectory where the bit was used is shown in Figure 3, highlighting the targeted 12-1/4" section and the associated inclination and azimuth variations encountered during drilling.

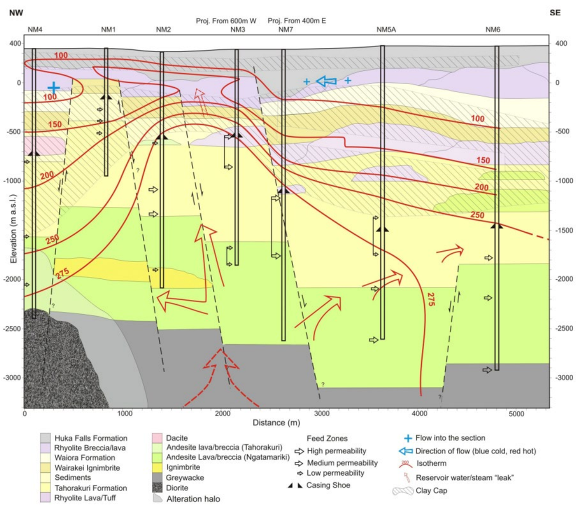

Figure 2. Nga Tamariki Lithology and wells (Boseley et al. (2010))

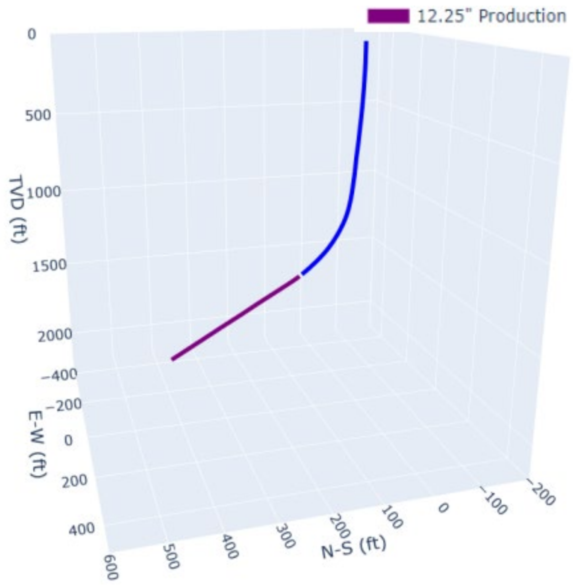

Figure 3. Planned well trajectory

The combination of complex geology, dynamic dysfunction mechanisms, and operational variables highlights the value of downhole measurements to improve understanding of energy transfer, dysfunction onset, and drilling performance optimization in this geothermal environment. These conditions contribute to accelerated bit wear and make maintaining high rates of penetration particularly challenging in this application. Additionally, the elevated natural state temperature profile, also illustrated in Figure 2, introduces further limitations for conventional measurement sensors, making standard downhole in-bit sensor systems less reliable under these high-temperature drilling conditions.

The combined effects of these drilling conditions result in progressive damage to PDC cutters, particularly on the shoulder and nose areas, often presenting as chipping, cutter loss, and, in more severe cases, full spiral cutter row failures, commonly referred to as ring-out (Figure 4). In this failure mode, entire rows of cutters along multiple blades are gone, leading to uneven load distribution, elevated stresses on remaining cutters, and rapid progression of additional cutter failures. Ring-outs can be initiated by insufficient diamond volume in critical high-stress regions of the cutting structure, excessive weight on bit (WOB), or inadequate selection of cutter material properties relative to the formation hardness and abrasiveness.

Figure 4. Old PDC Bit design run in NZ geothermal field

Both the gauge and shoulder regions of the PDC bit require reinforcement to prevent undergauge hole conditions, which can lead to erratic torque response, stick-slip, stabilizer hanging, and inefficient weight-on-bit (WOB) transfer. The observed dull pattern on bits run within the TVZ resembles the wear typically seen when drilling hard basement formations, such as granite. This suggests that localized hard inclusions within the Taupō Volcanic Zone may contribute to cutter overload and accelerated wear in these zones.

2. BIT DESIGN PROCESS

2.1 New drill bit design

Hard volcanic formations present specific drilling challenges due to the tendency for cutter over-engagement, often resulting in erratic torque response and the onset of dynamic dysfunctions such as stick-slip, shocks, and severe vibrations. Under these conditions, impact-related damage becomes the dominant failure mechanism for PDC cutters, rather than conventional wear, consistent with observations from previous geothermal drilling applications. Based on the dull condition observed on bits pulled from the production section of the Taupō Volcanic Zone, mitigation strategies for the newly developed PDC bit focused on increasing diamond volume through a 7-blade configuration, reduced cutter spacing, extended shoulder geometry, and smaller cutter diameters - with particular emphasis on enhancing bit stability.

The optimized design also incorporates Depth-of-Cut Control (DOCC) elements positioned strategically within the cone section to minimize cutter over-engagement when drilling through interbedded or highly variable lithologies. Additional enhancements include larger chamfered edges to improve chipping resistance and smoother back rake transitions to minimize torque fluctuations and promote consistent drilling performance. Furthermore, cutter grade, toughness, and geometry were carefully selected to maximize durability and minimize the risk of impact-induced cutter loss under the severe dynamic loading conditions encountered in geothermal applications. Based on this design approach, the new 12-1/4” HD75DMF bit was developed, as shown in Figure 5.

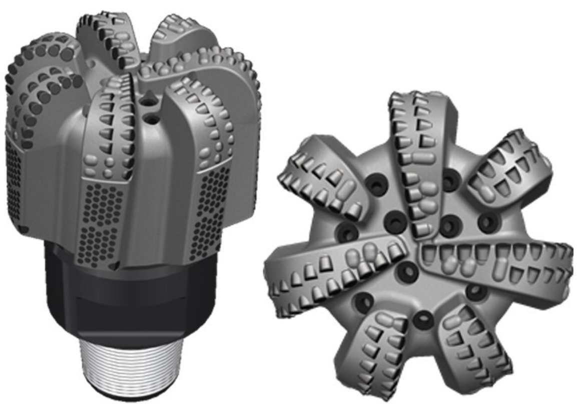

Figure 5. 12-1/4” HD75DMF bit picture

This new design concept incorporates reduced cutter force in critical areas by cutter spacing and a smoother back rake (BR) adjustment in critical wear zones, as illustrated in Figure 6.

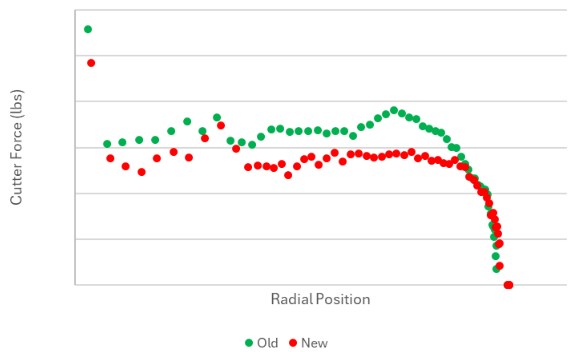

Figure 6. New bit vs previous design Cutter Forces comparison (Green- old design configuration; Red - new design version)

The new 12-1/4” HD75DMF design demonstrated improved modelling results in terms of rate of penetration (ROP), durability, and directional response compared to the previous bit design, as illustrated in Figure 7. Additionally, to minimize the risk of ring-out based on previous experience in this application, a new generation of cutters with improved material properties - including higher impact and abrasion resistance, enhanced thermal stability, and thicker diamond tables (Figure 8) - was incorporated into the HD75DMF bit design. This modification is intended to delay the initial PDC cutter wear, allowing the cutters to maintain a sharper cutting edge over extended drilling intervals.

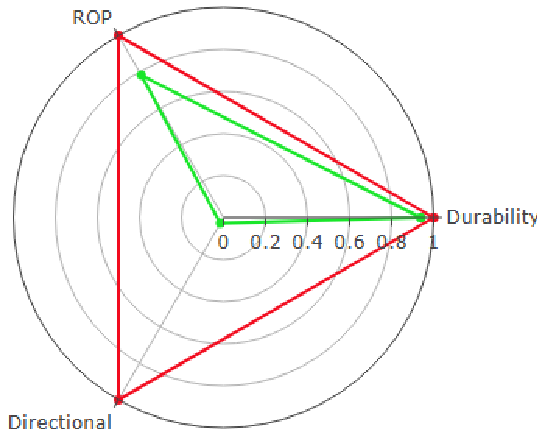

Figure 7. PDC Bit Design Modeling Results (Green- old design configuration; Red - new design version)

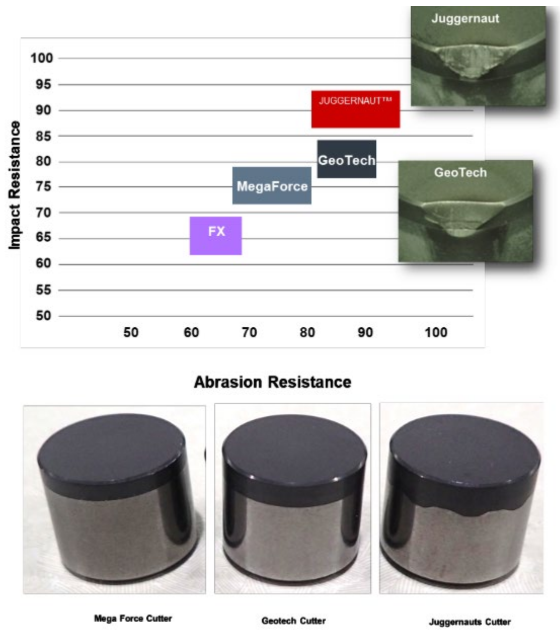

Figure 8. HD75DMF uses Juggernaut cutters

2.2 Mechanical Specific Energy

Teale (1965) was the first to introduce the concept of Mechanical Specific Energy (MSE), which quantifies the energy required to fail a unit volume of rock during drilling. Over the years, Teale’s equation has been widely adopted and modified to better estimate the energy input needed for efficient rock removal. In his formulation, two primary energy components are considered: the axial force applied to the bit, represented by weight on bit (WOB), and the rotational energy applied through torque and rotational speed. The original form of the MSE equation includes surface-measured WOB as the axial term, and a rotational term consisting of the system torque and surface-measured rotations per minute (RPM), normalized by the rate of penetration (ROP), which defines drilling advancement.

However, in applications involving positive displacement motors (PDMs), additional considerations must be considered when applying Teale's MSE equation. With PDM assemblies, a significant portion of the rotational energy is generated downhole by the motor itself, rather than being delivered entirely from surface RPM. As a result, surface RPM may no longer accurately reflect the total rotational speed at the bit, potentially leading to an underestimation of the actual rotational energy input. For accurate MSE calculations in motor-driven systems, the true bit RPM (combined surface and motor output) must be captured to properly quantify the rotational term in the equation. This highlights the added value of downhole measurements, such as those obtained from in-bit sensor modules, which directly record bit RPM, torque, and WOB at high frequency, allowing more accurate MSE determination and better evaluation of drilling energy efficiency.

2.3 Downhole Measurement at bit

Downhole measurement tools capable of capturing vibrations and drilling parameters have been available to the industry for several years; however, these sensors are typically positioned far above the drill bit, limiting the ability to directly capture dynamic responses at the bit-rock interface. In this study, in-bit strain sensors were installed within the shank of the PDC bit, operating in memory mode with a high-frequency sampling rate of 1024 Hz. This configuration enabled direct measurement of weight on bit, torque, and multi-axis bit motions at the cutting structure level, allowing for correlation between energy transfer efficiency and dysfunction mechanisms that strongly influence overall bit drilling performance, rate of penetration (ROP), and well delivery timelines.

The high-frequency high temperature memory-based motion sensors provided detailed insight into multiple vibration modes occurring directly at the bit, offering valuable diagnostics to evaluate bit stability and dysfunction severity under varying downhole conditions that are critical to drilling performance. Figure 9 displays the schematic representation of the in-bit sensor system installed within the bit shank, capturing high-frequency strain, torque, and multi-axis motion measurements directly at the bit-rock interface.

Figure 9. Shank-Based In-Bit Sensor Schematic

As summarized in Table 1, the memory-based in-bit sensor system captures high-frequency measurements across multiple parameters, including weight on bit, torque on bit, bit RPM, and multi-axis vibrations. These data enable detailed post-run analysis of bit dysfunctions and facilitate the calculation of at-bit Mechanical Specific Energy (MSE).

By comparing the downhole MSE derived from direct sensor measurements with the conventionally calculated surface MSE, a more accurate assessment of energy transfer efficiency and system losses can be achieved. This comparison provides valuable insights for optimizing drilling parameters, improving bit performance, maximizing rate of penetration (ROP), and enhancing overall BHA efficiency.

Table 1. In-Bit Sensor Specifications

Vibration	Axes	3
	Range	+/- 8g
Shock	Axes	3
	Range	+/- 200 g
Magnetometer	Axes	3
	Range	+/- 16 gauss
Accel/Mag RPM	Axes	3
	Range	0 to 1200 rpm
Gyro RPM	Axes	3
	Range	+/- 666 rpm
Strain	Axes	WOB/TOB

3. NEW BIT DESIGN RUN RESULT

The new 12-1/4" HD75DMF bit was deployed in the production section of the Taupō Volcanic Zone (TVZ), utilizing a conventional motor BHA equipped with a 0.78° bent housing. Drilling operations were conducted using aerated water, a fluid system that inherently increases drag forces and lateral vibration tendencies. The objective of the run was to drill through the Tahorakuri pyroclastic formation and reach the targeted South Production Fault.

Post-run dull analysis indicated excellent bit condition, with the majority of PDC cutters remaining intact. Only a limited number of cutter failures were observed: one broken cutter on the shoulder, one on the main cutting row, and one on a secondary row located in the lower shoulder region, as shown in Figure 11. The field dull grading for the bit was recorded as 1-1-BT-S,N-X-I-NO-TD, indicating that the bit remained in a condition suitable for continued drilling. Based on the dull condition, the bit demonstrated the capability to drill significantly greater footage in the 12-1/4" production section. Observations from this run confirmed improvements in gauge, shoulder, and cone durability, with all gauge cutters remaining in excellent condition. Drilling operations conducted in accordance with the recommended Roadmap allowed the bit to maintain high performance while minimizing wear.

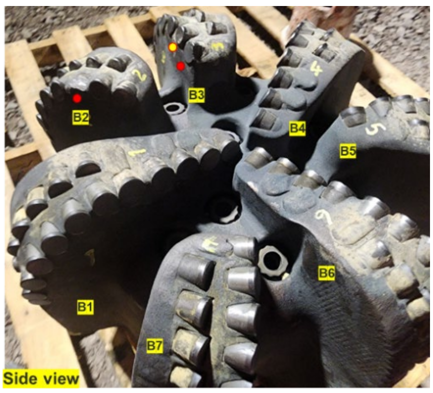

Figure 10. HD75DMF bit dull condition after run

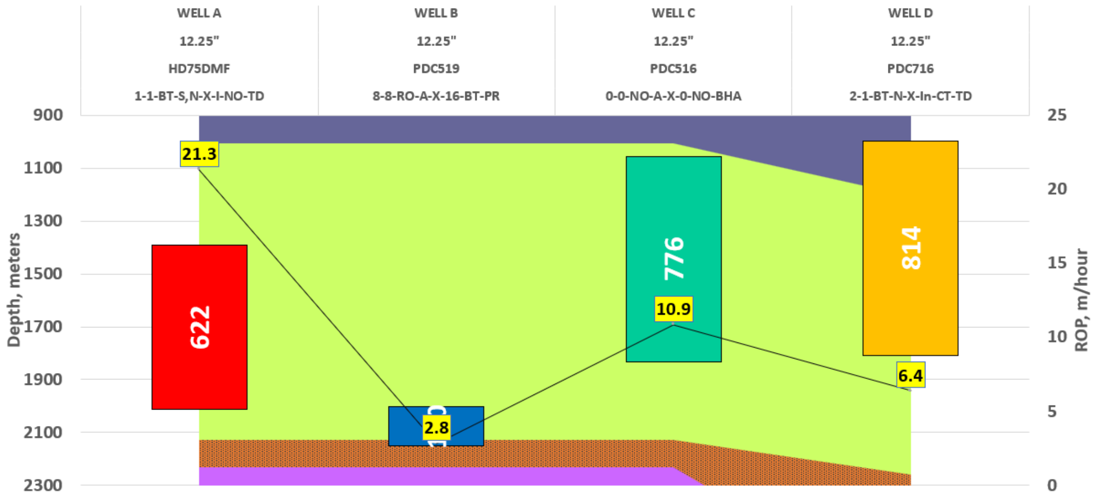

Figure 11. Current well outperforms all other offset well bit performance

To further enhance bit performance, a specifically developed Roadmap drilling strategy was implemented for this section. As a result, the bit successfully drilled the entire 622-meter production interval in a single run. When compared to offset well performance, this run established a new ROP benchmark for the field, achieving an average ROP of 21.3 m/hr as seen in Figure 11.

For future applications, it is anticipated that higher WOB could be applied while drilling through the Tahorakuri formation using the same BHA configuration to further improve ROP without compromising bit life.

4. IN BIT SENSOR RESULTS

A preliminary review of the vibration data obtained from the bit sensor indicated smooth drilling conditions with consistently low vibration levels maintained throughout the entire run, even prior to advanced post-run analysis (Figure 12). The 12-1/4” HD75DMF PDC bit was equipped with an in-bit memory sensor module, which recorded axial, lateral, and torsional vibrations, along with downhole weight on bit (DWOB), downhole torque (DTOR), and gyro-based RPM measurements at a sampling rate of 1024 Hz. The advanced analysis of the acquired downhole data is presented in the following section of this paper.

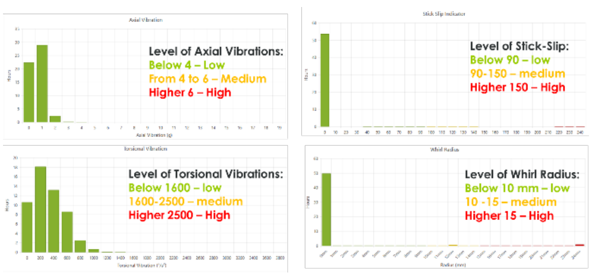

Figure 12. Vibration Summary from the Bit Sensor

4.1 Methodology of bit sensors data analysis

The methodology applied in this study builds upon previous field-proven applications of in-bit sensor technology in harsh drilling environments, such as those described by Witt-Doerring et al. (2023), where embedded sensors enabled identification of dysfunctions including poor weight transfer, string buckling, and lateral vibration - reinforcing the value of memory based and load measurements directly at the bit. The sensor data provided several actionable insights throughout the run, including:

- DWOB vs. SWOB comparison across drilling intervals to assess weight transfer efficiency,
- Surface torque vs. downhole torque correlation for torsional load analysis,
- Spectrogram-based identification of backward whirl frequency,
- Evaluation of hookload taring inconsistencies and off-bottom rotation effects.

In addition to the bit-based sensor module, MWD sensors positioned within the BHA captured supplemental string-level vibration data, allowing cross-validation and correlation between bit and drillstring dynamics.

4.2 Post-Processing and Data Synchronization

Following completion of the run with the HD75DMF bit configuration, the high-frequency downhole data were retrieved from the memory-based in-bit sensors. The original 1024 Hz recordings were down sampled to 1 Hz to allow for synchronization with surface-acquired drilling parameters and enable precise depth-time correlation. Similar data processing approaches were previously described by Kouzaiha et al. (2023, SPE-215976-MS), where high-frequency in-bit measurements were utilized to evaluate dysfunction signatures and energy transfer efficiency in lateral drilling applications. In this study, vibration data covering axial, lateral, and torsional modes were processed and plotted against measured depth, as illustrated in Figure 13.

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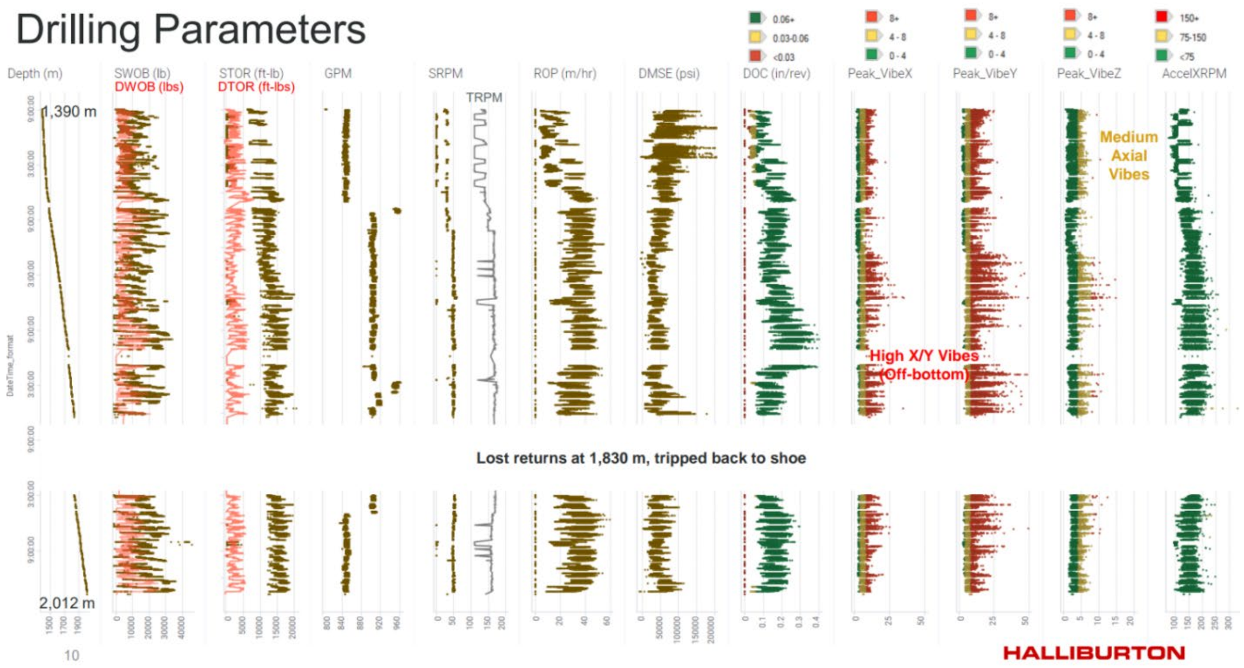

Figure 13. Drilling parameters and downhole dysfunctions plots during the drilling

Vibration severity levels were color-coded to aid interpretation: green indicating stable drilling with low vibration severity; yellow representing moderate vibrations with potential implications for bit wear and BHA component fatigue; and red highlighting severe vibration intervals where elevated dynamic loads may contribute to cutter damage, reduced drilling efficiency, or downhole tool failures. This post-run analysis framework enabled clear identification of dysfunction intervals and facilitated correlation between observed downhole dynamics, energy transfer losses, and overall drilling performance. Some of these observations expand on the earlier in-bit sensor-based dysfunction analysis by Rebrikov et al. (2021), where sensor modules were utilized to measure drilling parameters directly at the bit, significantly improving drilling performance and reducing well construction time in Eastern Siberia (SPE-206437-MS). These findings further highlight the value of in-bit sensor data for correlating downhole dysfunction signatures with subtle geological variations and complex lithological transitions encountered during geothermal drilling operations.

4.3 Hookload Taring during the run

The sources of taring errors have been extensively documented in the literature (Dupriest et al., 2022; Watson et al., 2022; Neufeldt et al., 2020) and will not be discussed in detail in this paper. However, during this study, consistent challenges were encountered with taring SWOB. In a vertical well, the Hookload Tare value is expected to incrementally increase as more DP is added to the well and the TVD is increasing. During this run generally fair rig taring practices observed in which the Hookload Tare is within 10klb of the calculated off bottom rotating weight (Figure 14). The comparison of SWOB and DWOB reveals a consistent weight transfer dysfunction exceeding 10 klb throughout the run. As illustrated in Figure 15, this dysfunction was present during approximately 36% of the total drilling interval. Downhole weight rarely exceeded 24–25 klbf despite stacking WOB.

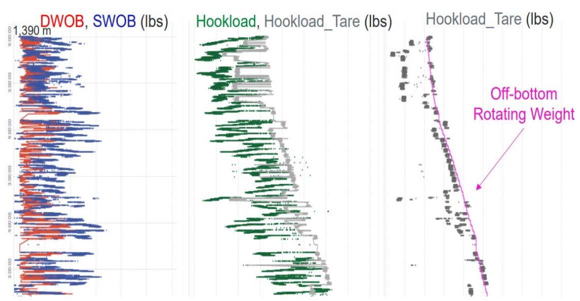

Figure 14. DWOB, SWOB comparison with Hookload tare

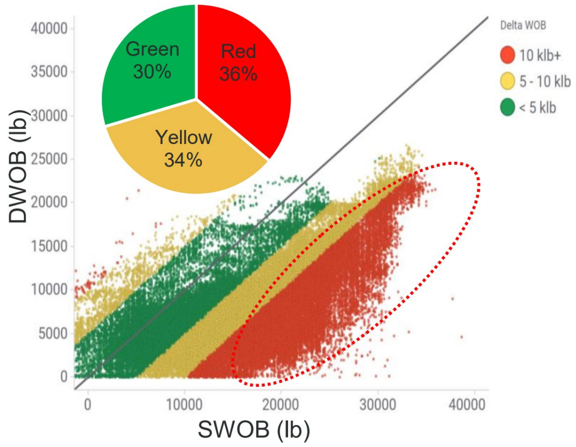

Figure 15. DWOB vs SWOB transfer dysfunction

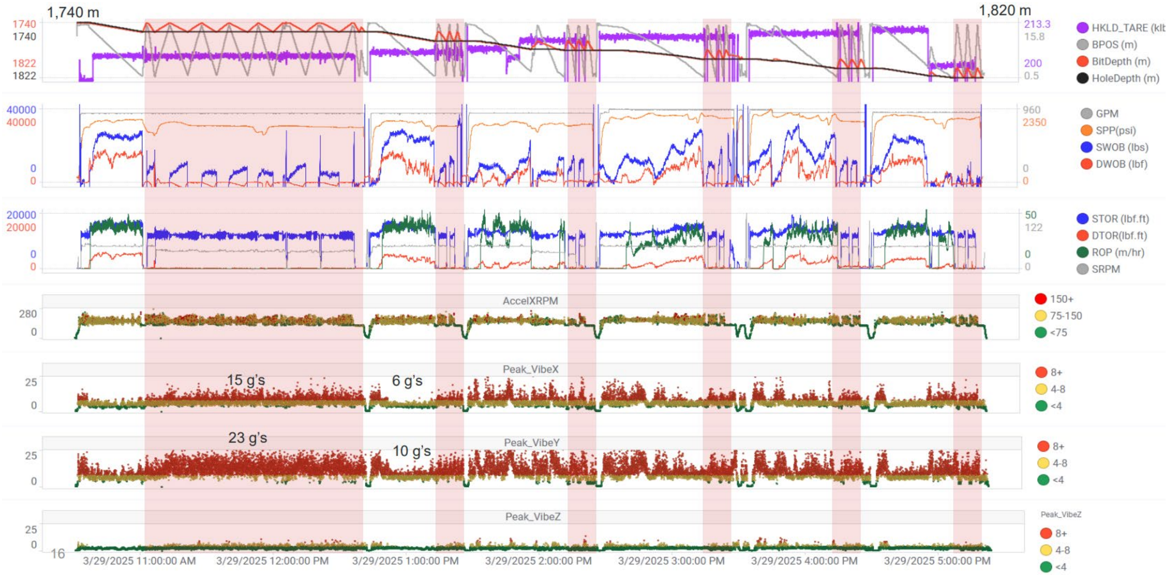

Figure 16. High Lateral/Torsional Vibes Off-bottom (backreaming)

4.4 Vibration identification

High-magnitude off-bottom lateral and torsional vibrations were observed during the run, reaching levels of over 50 g lateral and 23 g torsional acceleration. As shown in Figure 16 below, these vibrations occurred predominantly during backreaming operations. In backward whirl, the whirling frequency is typically related to the bit rotation speed (RPM) but occurs opposite to the rotation direction. In backward whirl (especially for fixed cutter PDC bits), the number of blades influences the contact frequency, because as the bit whirls, multiple blades strike the borehole wall during one whirl revolution. Backward whirl contact frequency (*f_{BW}, Hz*) was estimated using a kinematic model where:

Equation 1 Backward Whirl Contact Frequency

$$f_{BW} = (N_{blades}+1)\, x\, RPM/60$$

Where:

- N_{blades} – number of blades on the bit
- *RPM* - Rotational Speed (RPM)

Based on this approximation, spectrogram analysis identified indications of backward whirl for off-bottom, characterized by elevated harmonic responses in the ~14–16 Hz range, as shown in the Figure 17.

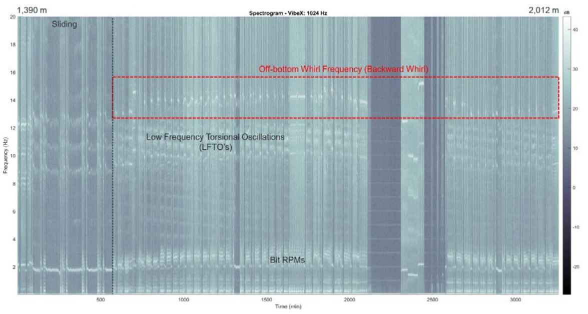

Figure 17. High Frequency spectrogram analysis showing indications of backward whirl

4.5 Key findings and insights based on the advanced analysis

The majority of observed dysfunction during the run were not driven by bit aggressiveness, but rather by off-bottom system behaviour and limited weight transfer to the bit. Backward whirl was detected consistently during backreaming operations on each stand, contributing significantly to observed shoulder and gauge wear.

- The bit exhibited stable drilling performance with minimal dysfunction when sufficient depth of cut (> 0.16 in/rev) was maintained.
- Lateral vibration was primarily observed off-bottom, representing a critical damage mechanism that often goes undetected using surface-only monitoring systems.
- Spectrogram frequency-magnitude mapping confirmed the presence of BHA whirl and backward whirl signatures during backreaming intervals.
- High off-bottom vibrations are damaging even when the bit is not actively drilling.
- Cutter damage can occur without elevated surface torque or other obvious surface indicators.
- Hookload taring requires routine verification to ensure accurate surface-to-downhole WOB transfer measurements.

5. CONCLUSION

This study successfully demonstrated the application of advanced in-bit sensor modules for measuring real-time downhole dynamics to improve PDC bit drilling performance in challenging geothermal environments. The combination of complex lithology, severe dynamic dysfunctions, and operational limitations within the Taupō Volcanic Zone highlights the need for direct at-bit measurements to fully capture dysfunction onset mechanisms that are often undetectable by conventional surface or BHA-level tools. The deployment of the newly developed 12-1/4” HD75DMF bit design, combined with optimized operational parameters and a roadmap-based drilling strategy, resulted in the successful completion of the entire 622-meter production interval in a single run. This run established a new field ROP benchmark of 21.3 m/hr while achieving excellent dull condition with minimal PDC cutters wear. Post-run analysis of in-bit high-frequency sensor data confirmed that the primary sources of dysfunction were not related to bit design aggressiveness but rather to off-bottom lateral dynamics, limited weight transfer, and backward whirl occurring predominantly during backreaming. Backward whirl contact frequencies were identified in the range of 14–16 Hz, consistent with kinematic models incorporating bit blade count and rotation speed. Hookload taring challenges further contributed to WOB transfer dysfunction, with a consistent 10+ klb discrepancy observed between surface and downhole weight measurements. Importantly, maintaining sufficient depth of cut (DOC > 0.16 in/rev) was shown to suppress lateral vibrations and stabilize drilling performance. Spectrogram analysis provided direct evidence of vibration modes that otherwise would remain undetected using surface-only diagnostics.

The insights gained from this study directly support several key recommendations for future geothermal drilling applications:

- Reduce backreaming frequency and limit surface RPM during backreaming to minimize off-bottom whirl.
- Apply WOB immediately upon rotation to improve bit stability and constrain lateral movement.
- Reinforce hookload taring procedures to improve WOB transfer accuracy.
- Incorporate real-time downhole data analysis to enable proactive dysfunction mitigation.
- Maintain current bit design while allowing for further aggressiveness adjustments if additional WOB can be applied.

The integrated approach of customized PDC bit design, targeted drilling strategy, and advanced in-bit sensor measurements has proven effective in extending bit life, improving drilling efficiency, and reducing dysfunction risks under the complex geological and dynamic drilling conditions of the Taupō Volcanic Zone. The methodologies and lessons learned from this work provide a valuable foundation for future geothermal drilling optimization efforts.

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