LWD Acquisition of Caliper and Drilling Mechanics as a New Approach on Geothermal Drilling Operation, A Case Study in Sorik Marapi Field – Indonesia

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Keywords: *Geothermal Drilling; Geothermal Formation; Geothermal Technologies; LWD; Vibration; Caliper; Case Study.*

ABSTRACT

The geothermal drilling environment presents many obstacles that limit the use of directional-drilling and logging-while-drilling (LWD) technologies, such as borehole washout, mud losses, severe vibration, and high temperature. The case study presented in this paper demonstrates a novel practice to enhance data logging in geothermal drilling by deploying advanced telemetry and LWD technologies. This operation aims for continuous improvement in geothermal drilling operations.

The case study covers the 12.25-in. hole section of well XXE-05 in the Sorik Marapi Geothermal Field. The LWD string consisted of electromagnetic (EM) telemetry, pressure while drilling (PWD), vibration (DDSr), and acoustic calliper (ACAL). Through this tool configuration, the operator acquired drilling mechanics and calliper logs in real-time and recorded mode, enabling effective monitoring and evaluation of wellbore stability.

Throughout the real-time acquisition, EM telemetry provided a data rate to the surface unit three times faster than conventional tools. Furthermore, with the integration of calliper and drilling mechanics data (vibration and equivalent circulating density), the borehole conditions became more visible to the directional driller, allowing better control of drilling parameters to minimize vibration and achieve optimum hole cleaning in washed-out or tight formation sequences. The recorded data from the calliper sensor indicated an average of 8.6% washout for the entire 12.25-in. interval. Washout intervals were compared with loss occurrence during drilling and the presence of smectite-bearing paleosols, showing that the washout zones associate with the latter, supporting the smectite-bearing paleosol model in explaining the cause of stuck pipe incidents in the Sorik Marapi field. In addition, measurements of hole ovality were compared with the interpreted fault trend, providing further insight into the existing model. In general, this LWD case study has given added value through geothermal borehole characterization, from drilling hazard identification to subsurface analysis.

Identified challenges while running LWD in this geothermal environment were addressed for future improvements, such as the effect of tool eccentricity and the impact of vibration. Perusal of both real-time and recorded calliper and drilling-mechanics data has opened various possibilities for maximizing the sensor usage in future wells.

1. INTRODUCTION

1.1 Geothermal Drilling – Sorik Marapi Field, Indonesia

The Sorik Marapi Field is one of the largest developing geothermal projects in Indonesia, part of the Geothermal Plant national strategic project targeting 35,000 MW of renewable energy located in Mandailing Natal Regency, North Sumatera Province. Since mid-2016 the project has completed numerous drilling campaigns and confirmed at least 55 MW of proven resources. A total of 39 exploration and development wells have been drilled to depths of up to 2715 m MD from eight well pads in the Sorik Marapi geothermal concession. At least 14 of these wells have confirmed the presence of a 245-325°C liquid-dominated benign chloride reservoir. The project has successfully connected 45 MW of power from Unit I to the PT PLN (Indonesia's official electric company) grid since the end of 2019 (Hidayat R., et al 2021) and has recently increased its capacity through Unit II to 90 MW. The future plan is to add Unit III with a capacity of 50 MW in 2022, unit IV with a capacity of 50 MW in 2023 and unit V in 2024. This paper discusses a trial run conducted in one of the wells in Pad XXE (**Figure 1**) of the Sorik Marapi Field.

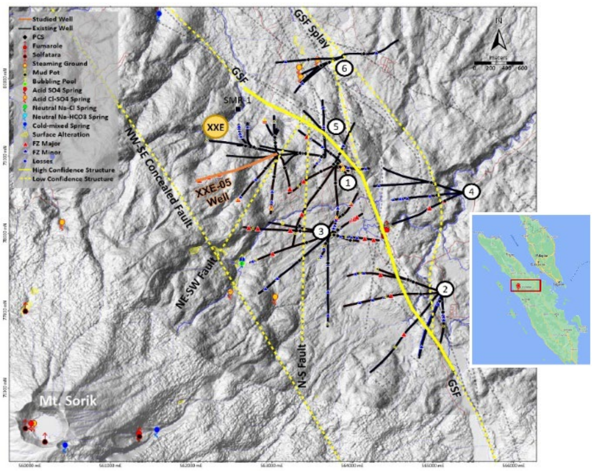


Figure 1: Map of Sorik Marapi Field concession, displaying wellbore track and fault trend of all well pads. Case study well is XXE-05 -- PAD XXE.

The geological and structural frameworks of the Sumatera Island are strongly influenced by the Australia and Euro-Asia plate movement. The collision of two plates forms a structural complex that includes the NW-SE trend of (SFZ); full apart basin (Graben); and volcanic belt (Muroaka et al., 2010). Pad XXE is situated close to the eastern flank of Mt. Sorik Marapi and immediately west of the Great Sumatera Fault System (GSF). The regional geology of the area and cross-section are

Proceedings 44th New Zealand Geothermal Workshop
23 - 25 November, 2022
Auckland, New Zealand
ISSN 2703-4275

shown in **Figure 2** below as an overview of the case study's well track stratigraphy.

The lithology sequence encountered by well XXE-05 consisted of:

- (Surface to ~900 m TVD) Quaternary-Tertiary volcanics – Interbedded andesite lavas and felsic tuffs, with varying degrees of alteration; and
- (~900 to 1800 m TVD) Pre-Tertiary metasediments and granite/schist, with 1-2 younger volcanic and/or felsic porphyry intrusions, possibly in fault contact.

Expected hydrothermal alteration zones are:

- (Surface to 225 m TVD) Unaltered zone;
- (~225 to 550 m TVD) Argillic–smectite, iron oxides, local quartz and calcite veins, local zeolite, some illite in lower parts;
- (~550 to 900 m TVD) Transitional/mixed clays, local advanced argillic–illite, sericite, chlorite, smectite, iron oxides, anhydrite, pyrite, quartz, calcite; and
- (~900 m TVD to TD) Phyllic, propylitic, phyllic/propylitic, local advanced argillic–epidote, chlorite, calcite, quartz, wairakite, illite, sericite, prehnite, pyrite, zeolite. Of the wells drilled thus far, the appearance of wairakite is the most diagnostic mineral indicating the top of the isothermal section of the reservoir.

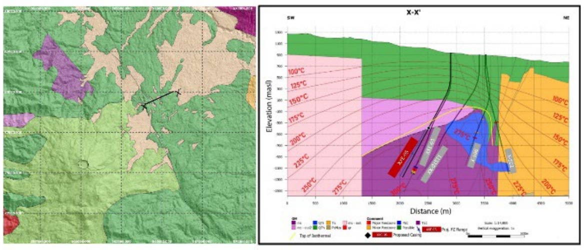


Figure 2: (Left) Regional geology of Sorik Marapi Field. (Right) Cross section X-X of case study Well XXE-05 trajectory (Geologica Study, 2021).

The Sorik Marapi geothermal system has been defined on the basis of a generally N-S elongated, magnetotelluric (MT), low-resistivity anomaly (~6 km2) and a wide distribution of warm to boiling temperature hot springs and fumaroles primarily centred on the GSF and extending into the summit crater of Sorik Marapi volcano. An updated conceptual model shows the reservoir elongated NNW-SSE and is bound on the east by the main strand of the GSF.

1.2 Logging While Drilling in Geothermal Field

Currently, the technology of measurement while drilling (MWD) in a geothermal environment is limited to basic telemetry, directional, PWD, temperature, and vibration sensors. The telemetry commonly used in this challenging drilling environment is an EM system (**Figure 3**), a bi-directional telemetry system where the data are encoded in an electric potential (voltage) created between the drillstring and the formation. It has the ability to transmit at up to 15 Hz and does not require a continuous liquid column in the borehole. Repeater units can be installed in the drillstring to amplify the signals. The surface configuration consists of amplifier and decoding electronics, connected to the main antenna (utilizing the rig's BOP as the main conductor) and a remote antenna (utilizing a pipe conductor grounded to the formation near the MWD unit).

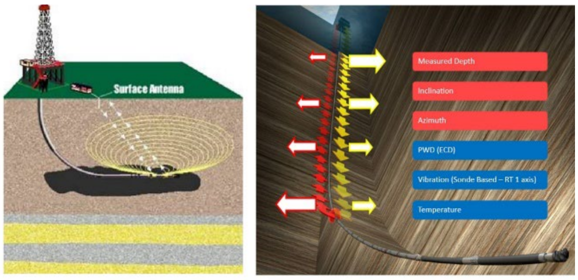


Figure 3: Basic MLWD configuration in a geothermal well: EM Telemetry system transmission.

2. CASE STUDY OF GEOTHERMAL LWD: XXE-05

2.1 Directional Drilling: Objectives, Well Planning, and Drilling Operation

The primary objective of well XXE-05 is to provide steam and hot water for the Phase III/IV power plant development in the Sorik Marapi Field. A secondary objective is to identify and test the extent of the north-western sector of the high-temperature reservoir west of Pad-1. Key reservoir information, conducted during and after drilling, is primarily obtained through rock cutting analysis, mudlogging, pressure-temperature-spinner (PTS) production logging surveys, and injection tests. Measurements include static temperature, pressure, and spinner data; fracture data, lithology, and alteration mineralogy; steam and brine flow rates; and reservoir chemistry. This information allows for further updates to the current reservoir conceptual model. Moreover, the LWD acquisition trial conducted in this well attempted to provide additional key information from the drilling-operation perspective. The LWD tool selections and telemetry program were structured to consider all probable constraints imposed by the geothermal environment, based on historical drilling runs, such as circulation temperature, total depth interval, formation conductivity, and mud column.

The XXE-05 wellhead is located near the southwest corner of the newly constructed XXE Pad. The proposed casing program and directional well plan **(Figure 4**) were primarily derived from the nearest offset wells. The trajectory kick-off point (KOP) was at ~370 m MD. XXE-05 was then directed WSW (final azimuth of 254°) towards the north-western sector of the reservoir. The 26-in. section was drilled with a basic MWD-mud-motor bottomhole assembly (BHA) and the 20-in. surface casing was set and cemented at 545 m MD. Following the well plan in the 17½-in. section, the well final inclination was successfully built to 30° with the 13⅜-in. production casing set at 1399 m MD. Subsequently, 775 m of 12¼-in. open hole was drilled by maintaining the trajectory angle of ~30° and setting the 10¾-in. perforated liner at 2175 m MD – shallower than the original well plan.

From the initial model, the 12¼-in. section was expected to intersect extensions of one of the projected fractures imaged in Pad-3 wells. Based on the geomechanical model of a complex faulted pull-apart, XXE-05 had been predicted to intersect multiple undiscovered faults and fractures with a range of possible orientations, primarily NNW-NNE-striking. Intersection of these faults led to total lost circulation (TLC), hence the perforated liner was set earlier to cover this potential resource of geothermal reservoir whilst maintaining borehole stability and securing the loss zone.

Drilling then continued with a newly planned 9⅞-in. section, overcoming partial lost circulation (PLC) to TLC conditions until successfully drilling 315 m MD past the original plan to maximize the reservoir coverage of fractured interval and reaching TD at 2715 m MD, followed by setting an 8⅝-in. perforated liner on bottom. The well became the deepest well in Sorik Marapi as of the year 2021.

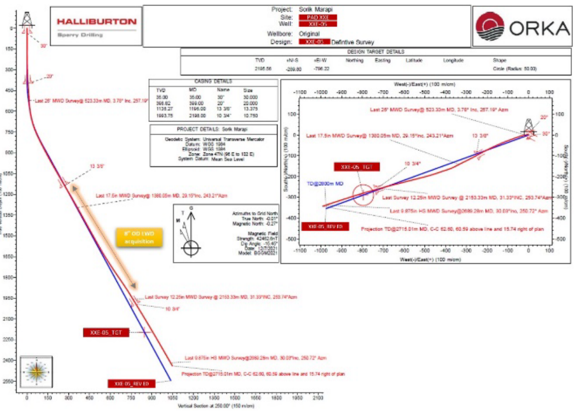


Figure 4: Directional drilling of XXE-05: initial well plan (blue line) vs actual well trajectory (red line). The well consisted of 26, 17½, 12¼, and 9⅞-in. sections.

2.2 LWD BHA: Tools Set-Up and Preparation

The trial run of LWD in XXE-05 was successfully executed in the 12¼-in. section. The LWD system was deployed in the depth interval of 1710-2178 m MD, providing both real-time and recorded data. LWD sensors, in 8-in. OD collars, were arranged as shown in FIGURE 5, with the ACAL closest to the bit, followed by PWD, vibration (DDSr-HCIM), directional (PCDC), and telemetry (EM). This configuration enabled the LWD system to provide an upgrade to the telemetry system; instead of the common basic decoding, the EM telemetry was able to be set to Pulse-Position-Modulation (EM-PPM) decoding.

The ACAL is an ultrasonic caliper sensor, featuring three transceivers mounted at 120° intervals around the tool collar. The hole size and shape are determined by measuring the travel time between the firing of a transceiver and detection of the reflected signal from the borehole wall. A temperature measurement is also available from this sensor.

The PWD tool is a pressure measurement tool that comprises quartz transducers that measure the internal or bore pressure and the external or annular pressure. The annular gauge measures the pressure differential in the annulus between the sensor measure point and the surface. The internal pressure gauge can be thought of as measuring the pressure drop from the internal measure point to surface, via the BHA below the tool, the bit, and the annulus.

The DDSr-HCIM sensor responds to changes in acceleration in the X, Y, and Z-axis directions which occur in response to impact between the BHA and the borehole wall. Accelerometers are the primary source of vibration data acquisition, while magnetometers and gyroscopes are used for rotational speed measurements, known as stick-slip indicator measurements. The X and Y axes are oriented in a lateral direction, perpendicular to each other and to the tool axis. The Z axis is aligned with the axis of the tool.

The PCDC sensor consists of accelerometers and magnetometers for directional measurement purposes, providing measurements of total gravity, magnetic field, and dip angle. The surface computer calculates and converts raw PCDC measurements into directional survey data, comprising inclination, azimuth, and toolface.

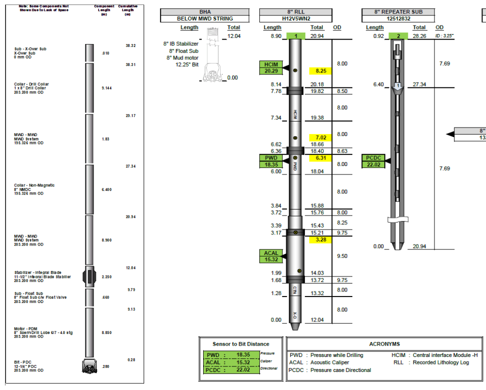


Figure 5: 8-in. OD LWD configuration deployed in the 12¼-in hole section.

3. GEOTHERMAL LWD ACQUISITION FOR DRILLING OPERATIONS

3.1 Caliper Data Analysis (Real-Time & Recorded Data)

During the run, real-time communication between the MWD surface equipment and downhole LWD tools was a success. To begin the caliper measuring process downhole, a calibration process was required to be conducted inside casing during a shallow pulse test (SPT). Real-time caliper and drilling mechanics data were used throughout drilling to aid the directional driller.

From the caliper real-time result, BHA centralization had been known to have a major impact on caliper signal acquisition. The ACAL tool uses the standoff measured at each of the three transceivers to define a circle that represents the borehole diameter. If a good echo is not identified from one or more transceivers, the triplet is considered a bad detect and not used in the calculation of the equivalent borehole diameter. A small number of bad detects for a sample can be expected, however, the quality of the caliper log may be compromised if there is a consistently large number of bad detects over an interval.

As would be expected, the standoff values spread out as the tool moves off-centre, giving smaller values on one side of the hole and larger values on the other. However, many of the echoes are missed due to the signal being reflected obliquely away from the transceivers rather than coming straight back to them. The apparently large standoff causes the calculated borehole diameter to appear larger than it really is.

This off-centre effect was clearly identified after extracting the recorded caliper data from the downhole tool after the BHA had returned to surface. Advanced travel-time filtering was performed on the recorded data, by restricting the valid range of travel time that is used to calculate the hole size, and yielded a proper calibrated caliper result (**Figure 6**). The recorded caliper data is explored in more detail in the next section.

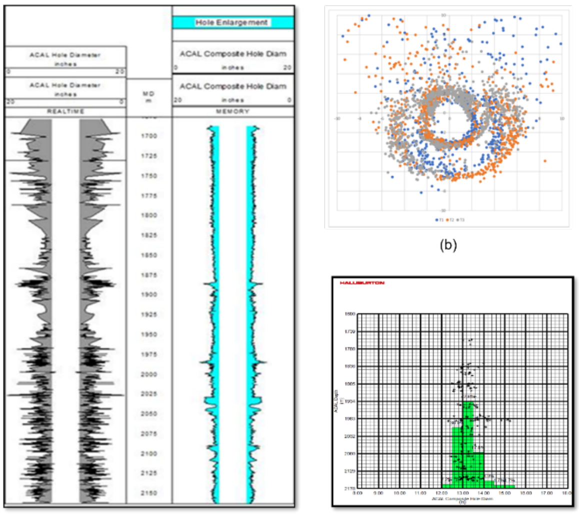
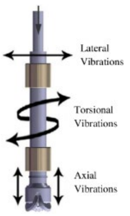


Figure 6: (a) Real-time (left) vs recorded (right) caliper plot. (b) Travel-time filtering process for recorded caliper data. (c) Recorded caliper statistics indicate the hole is enlarged in some depth intervals, with an average diameter of 13.3 inches.

3.2 Drilling Mechanics Data Analysis (Real-Time & Recorded Data)

Vibration data is monitored as it is collected, using a vibration display in a real-time plot. Vibration monitoring is especially important in terms of operating limits. Quick and appropriate changes to drilling parameters can help to reduce vibration and extend the life of all downhole tools, and also avoid subsequent borehole issues in a geothermal environment, such as buckling, ledging, stuck pipe, hole pack-off, BHA failures, or inefficient hole cleaning.

The use of surface parameters and vibration data can help engineers identify the type of vibration that is occurring downhole. There are three main types of vibration modes: Axial (longitudinal) motion along the drill string; torsional motion with twist and torque; and lateral (transverse) motion. Theoretically, within those three modes, vibration are broken down into nine mechanisms (**Figure 7**).



Mechanisms	Primary Vibration Mode	Secondary Vibration Mode	Frequency
Stick-Slip	Torsional	Axial	0 – 5 Hz
Bit whirl	Lateral	Torsional	5 - 100 Hz
BHA Whirl	Lateral	Torsional	5 – 20 Hz
Bit bounce	Axial	Torsional	1 – 10 Hz
Modal Coupling	Axial, Lateral, Torsional		0 – 20 Hz
Bit Chatter	Lateral	Torsional	20 – 350 Hz
Torsional Resonance	Torsional	Lateral	20 – 350 Hz
Parametric Resonance	Axial, Lateral		1 – 10 Hz

Figure 7: Classification of Vibration (Foster, 2005)

PWD data consist of measurements of annular and internal pressure. Annular pressure is commonly calculated and displayed as an equivalent circulating density (ECD) in units of ppg. With the combination of advanced LWD sensors and EM-PPM telemetry being deployed, this run was able to gather data more rapidly than the previous runs, which was limited to utilizing basic PWD and EM telemetry (**Figure 8**). With denser real-time data acquired in the 12.25-in. section, more detailed hydraulics information was available, such as swab-surge indications due to pipe movement and pumps-off annular data for static hydraulic information. All these features captured through ECD progression were able to be monitored closely and compared against cuttings volume to ensure good hole cleaning throughout the run.

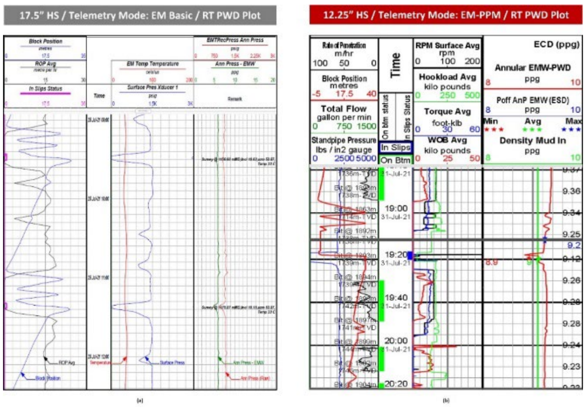
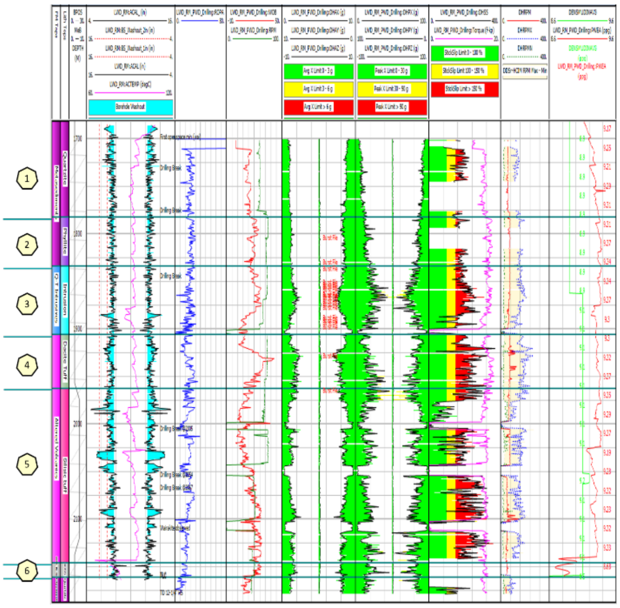


Figure 8: Real-time, time-based PWD plot (a) PWD with basic EM telemetry from previous run in 17.5-in. HS. (b) PWD with advanced EM-PPM telemetry, showing a more active curve of ECD, allowing identification of drilling features as higher data density was transmitted from downhole.

The overall drilling performance in XXE-05 is summarized in **Figure 9.** The recorded data showed a low level of lateral vibration (X and Y directions), as shown in tracks 7 and 8, where the accelerometer measurements mostly remain within the green limit area (0-3 g for average vibration and 0-30 g for peak) and only a few points in the yellow limit area (3-6 g and 30-90 g). In contrast, the stick-slip measurement in track 9 from the magnetometer shows that almost throughout the entire drilling section, the red limit (>150%) was exceeded. The caliper in track 4 shows washouts in several areas that are in sync with drilling break records, particularly in formation interval no 5, comprising altered volcanic silicic tuff. With current available data, the occurrence of washouts appears to be more related to formation properties than to drilling practices. In a geothermal operation, a drilling break, as shown through an increase in the rate of penetration (ROP) and losses of drilling muds into the formation, indicates a zone of natural fracturing and permeability in the rock. In contrast, for formation intervals 1, 2 and 3, the drilling break occurs several times yet does not correspond to caliper washouts. This shows that the borehole stability in these intervals is good. In general, it is also observed that hole cleaning seems to have operated optimally; the torque (track 9) and ECD (track 11) show no significant or sudden gain that might indicate bad cuttings transport.



Additional Information on Study Area	Depth (m MD)	PLC/TLC	Loss Rate (BPH)	Remarks
6	2159	TLC	No Return	TLC pumping 900 GPM
	2162	PLC	90-138	After circulation 3 hours
	2178	PLC	40-180	

Figure 9: Recorded LWD caliper and drilling mechanics plot display of XXE-05 in 12.25-in. HS, showing the interval divided into several study areas.

As mentioned in the beginning, the main objective for this trial LWD run was to define the actual borehole condition in a geothermal environment drilling operation. Drilling efficiency is often characterized by the output of drilling speed (ROP), where the ROP in this case is measured in meters drilled per hour (m/hr). Another drilling output which may compromise drilling efficiency is the occurrence of vibration. Several input parameters contribute towards these outputs of ROP and vibration, such as weight on bit (WOB), bit rotational speed (RPM), mud flow (GPM), BHA design, bit wear, and rock strength (Hareland et al. 2007a). With drilling efficiency analysis as the final target, this case study attempts to compose a methodology framework to unravel vibration mechanisms in each geothermal facies in the Sorik Marapi Field, based on the LWD data acquired in the trial run (**Figure 10**).

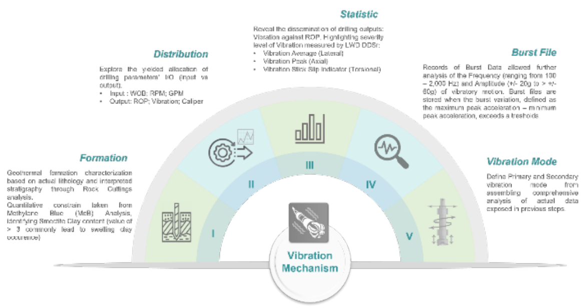
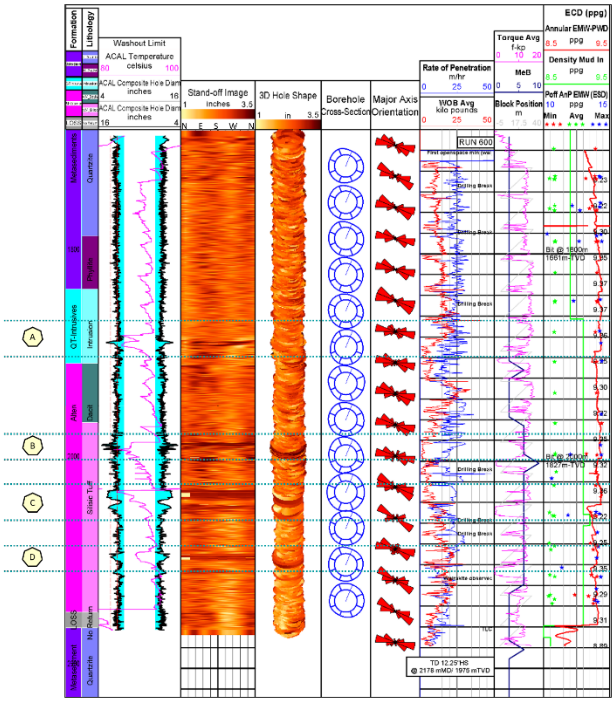


Figure 10. Methodology framework to acquire vibration mechanism information in each lithology layer of geothermal formation in the Sorik Marapi Field. (Designed by Authors for purposes of this study.)

By implementing the above methodology framework, a vibration characterization was generated, using all available data from the LWD sensors throughout the 12.25-in. HS interval (**APPENDIX 1**)

4. GEOTHERMAL LWD ACQUISITION FOR SUBSURFACE

4.1 Caliper Data Analysis correlated to Subsurface Data



Study Area	Washout Limit	Washout Interval (m MD)			Temperature Drop (°C)			Formation	Lith	Increase in Torque
A	2 in.	1883	1890	7	93	86	7	Q-T Intrusives	Intrusion	N
B	2 in.	1982	1990	8	94	87	7	Altered Volcanics	Silicic tuff	N
C	2 in.	2027	2052	25	93	86	7	Altered Volcanics	Silicic tuff	N
D	2 in.	2089	2097	8	93	89	4	Altered Volcanics	Silicic tuff	N

Figure 11: Recorded caliper data plot, highlighting washout measurements in the study area. Utilized for subsurface analysis, plot showing caliper average, stand-off image, and borehole cross-section measurement results.

In **Figure 11**, track 3 of the recorded caliper data identifies washout areas as listed in the table. Washouts seems to appear mostly in study areas B, C and D (altered volcanics/silicic tuff formation) and lightly in study area A (Q-T intrusive formation). The washout intervals are in sync with the drop in temperature, an increase in the methylene blue (MeB) measurement, and several drilling breaks. These findings can be an indirect indicator of in-situ fractures in the area to be furthered analysed. Commonly in geothermal wells, injection tests (IT) and PTS (pressure, temperature, spinner) logging are utilized to locate outflow and inflow zones in wells and the spinner log is used to quantify the flow in and out of the feed zones and determine the relative contribution of each of the feed zones to the flow pattern in the well. Hence, IT/PTS will most likely only be able to detect the general area of the natural fracture network. A dedicated logging tool, such as a borehole imager would be more effective to detect individual fractures. One of the techniques to identify the smectite clay content in rock cutting is MeB analysis. MeB is an organic dye that shows high selectivity for adsorption by smectite clays. The dye also is adsorbed by the smectite component of mixed layer clays but is largely unaffected by other (even electrically conductive) common clay minerals. This selectivity permits it to be used to estimate on a semiquantitative basis the amount of smectite present in alteration mineral assemblages (Chandra, V., et al. 2021).

From the drilling operation perspective, the presence of caliper measurements may aid in highlighting borehole instability that arises from the applied drilling parameters. This might be the case in study area A (Q-T intrusive formation). However, when a comprehensive analysis also considers the formation properties, an increase in MeB value that occurs in study area B, C and D (altered volcanics/silicic tuff formation) seems to give a major effect in the caliper measurement, confirming that the washout came from the swelling of smectite. High values of MeB (> 3) indicate the presence of an altered layer in the geothermal stratigraphy, hence providing an unstable formation. This LWD trial run has revealed warning indicators for formation layers that have the potential for drilling hazards such as stuck pipe or pack-off. To support this notion, caliper measurements in loss intervals have shown a good in-gauge measurement. This may indicate that though a geothermal reservoir is often fractured, the stratigraphic and structural geology are confirmed to be stable. Problematic intervals come in formations that stratigraphically are altered layers.

The LWD caliper can also record stand-off measurements as an image (tracks 4 and 5). Transducer standoff is the distance in inches between the transceiver and the borehole wall, calculated from the arrival time and plotted as a discrete point. In a good data set the standoff values should be roughly constant, with any variation being due to either lateral movement of the tool or changes in borehole size and shape. This image came from the recorded measurement of 8 azimuthal bins extracted from the three transceiver. Data should exist in all azimuthal bins during periods of rotation. During sliding intervals, only one bin will be populated. The image is coloured so that large standoff values appear as dark colours and smaller standoff values as light colours. This azimuthal capability has enabled the plotting and analysis of borehole cross-sections and the major axis direction (tracks 6 and 7), which show that in this XXE-05 case study the hole ovality direction is towards NW-SE.

The combination of the updated geologic model with existing geophysics and well temperature data has supported extending well from Pad 4 to the N-NW between strands of the Sumatran fault zone. Wireline image logs have been successfully collected in six Sorik Marapi wells thus far. Open and partially open fractures are observed in association with most of the observed minor and major feed zones in these wells. It is likely that these open and partially open fractures are a combination of tensile fractures and shear fractures (faults) and have variable strike lengths. The completely open fractures associated with feeds (5 total) dip consistently S-SW to SW, similar in orientation to the deepening trend of permeability and the low permeability cap rock in the Pad 1, 2, and 3 area. The partially open features associated with feeds in these wells (28 total) have more widely distributed orientations with dips SE, SW, and NW.

As taken from actual drilling cuttings analysis in this case study well XXE-05, decreases in MeB values had provided the most consistent marker for the top of the reservoir in this area, coupled with the appearance of chlorite replacement of phenocrysts; this is typical of the argillic to transitional/mixed clay transition. By adding analysis of LWD caliper measurement result in the 12.25-in. drilling section from this case study, hole ovality information has been able to validate the fault extended direction towards NW-SE.

5. CASE STUDY PERFORMANCE SUMMARY

Contrary to some initial expectations, adding the LWD string in the BHA of this XXE-05 case study did not hinder the drillstring performance (**Figure 12**). Other than being the deepest well in the Sorik Marapi Field at 2,715 m MD, Well XXE-05 is also one of the fastest wells with 94 m/day overall ROP. The data provided by the LWD utilized in the 12.25-in. hole section will be referenced for future offset wells to ensure the performance in this well can be repeated.

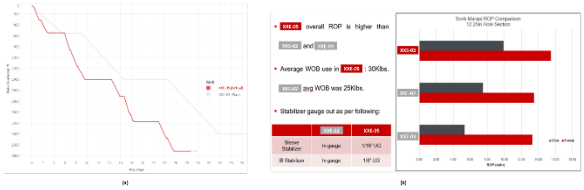


Figure 12: XXE-05 well 12.25-in. hole section BHA performance summary. (a) Drilling-time curve summary of actual vs plan. (b) Drilling parameters comparison to offset wells.

Nonetheless, the challenges and limitations that occurred in this LWD trial run require to be handled for improvements when operating LWD in future geothermal wells. Specifically on tool configuration, analysis of BHA positioning (**Figure 13**) reinforces the requirement for additional stabilization to prevent degradation of the travel-time measurements in the LWD caliper acquisition (as elaborated in previous section of this study).

Item #	Description	Gauge (in)	Length (m)	Total (m)	Location (m)
1	NOV	12.250	0.280	0.280	0.000
2	8" SperryDrill Lobe 6/7 - 4.0 stg (1.15° bend)		8.850	9.130	
	Bottom Stabilizer	12.125			1.480
3	8" Float Sub c/w Float Valve		0.660	9.790	
4	11 1/2" IB Stabilizer	11.500	2.250	12.040	10.810
5	8" DDSr - PWD - ACAL		8.900	20.940	
6	11 3/4" Inline Stabilizer (ILS)	11.750	1.524	22.464	21.702
7	8" NMDC		6.400	28.864	
8	8" EM Repeater Sub		0.920	29.784	
9	8" EM Antenna Sub		0.910	30.694	
10	1 x 8" Drill Collar		8.730	39.424	
11	X-Over Sub		0.980	40.404	
12	5 x 6-1/2" Drill Collar		45.560	85.964	
13	7 x 5" HWDP		64.460	150.424	
14	6-1/2" Sledgehammer Jar		6.390	156.814	
15	22 x 5" HWDP		200.000	356.814	
16	5" Drill Pipe		2043.186	2400.000	

Additional stabilizer (ILS) may required to centralize the calliper sensor.

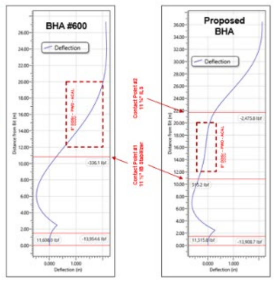


Figure 13: BHA configuration analysis. Adding a stabilizer may mitigate the real-time noise that occurs in caliper acquisition.

The next finding is on LWD tools programming procedure. Compared to conventional MWD tools used in previous geothermal wells, the new technology tools require additional time during laydown of the BHA to extract the recorded data. In this trial run, the team required ~1.5 hours to conclude the procedure on the rig floor. This data extraction required a large amount of time due to the extensive memory data recorded in this trial run, due to the high data density acquired by this LWD configuration. Hence, to enable faster data extraction and optimize rig operation hours, options for LWD hardware compatibilities (processor, memory board, battery, data compression capability, etc.) need to be explored in detail during the pre-job stage, utilizing this trial run as a reference for future programming.

6. SUMMARY AND FUTURE POTENTIAL

The methodology framework applied to this case study, as extracted from LWD caliper and drilling mechanics data, has initiated the first step in acknowledging the borehole conditions during geothermal drilling operations:

- Drilling parameters review (inputs & outputs);
- Vibration facies characterization;
- Subsurface insight into the possibility of in-situ fractures and confirmation of smectite clay presence;
- Insight into problematic geothermal formation intervals, which has enabled the bridge between drilling and subsurface evaluation.

These first steps of analysis may open future studies to improve geothermal borehole learning and future planning:

- Composing a comprehensive drilling parameters roadmap for the geothermal environment;
- Constructing and deploying an effective real-time display for monitoring vibration and PWD, directly mitigating real-time issues during drilling;
- Sharpening the vibration methodology framework by detailing each step, i.e., adding bit and BHA analysis utilizing LWD sonic/density measurements to acquire the quantitative analysis of geothermal rock strength properties, and fine-tuning drilling parameters by acquiring more trial data;
- Improving the borehole drilling strategy to combat problematic geothermal intervals discovered in this case study, particularly altered volcanics (dacite and silicic tuff). Mitigation strategy may be explored around the specific adjustment on drilling parameters, borehole fluid, BHA design, and so on.
- Potential study on generating machine learning or AI (artificial intelligence), focusing on geothermal drilling behaviour. Many studies have begun to explore this area, enhancing the usage of drilling parameter inputs and outputs for various automated drilling purposes, e.g., mitigation of drilling hazards (Sarwono, 2022), optimization of ROP and MSE (mechanical specific energy) (Abdelaal, K., et al 2021), and creating a real-time drilling advisory system (Bailey, J. R., et al 2017).

From the subsurface perspective, this paper has shown that caliper data can be a validator for fracture and fault trends. Deploying advanced LWD such as high-resolution borehole imaging may increase the LWD measurement function as a leading indicator in a hidden/blind geothermal system (where formation character is unseen from surface seismic measurements).

7. CONCLUSION

The LWD trial in well XXE-05 has given a good result for both real-time transmission and recorded acquisition. Many lessons have been learned from this trial. Real-time data from the EM-PPM telemetry configuration provided very dense data from the rapid transmission capability. However, for better real-time acquisition, improved BHA centralization and travel-time filtering are needed for caliper acquisition in the next run. Recorded data was able to be comprehensively analysed in this paper for both drilling operation review and subsurface analysis.

In addition to being one of this trial's key highlights, examination of the LWD-recorded data has led to the discovery of the associated geothermal formation's problematic interval. Cost-wise, using LWD in a geothermal BHA string may result in the increase of operational cost up to hundreds of thousands of dollars. However, with the series of analyses being revealed through this case study that can be extracted from both real-time and recorded LWD data, it is more feasible to mitigate hazards and save on cost from potential stuck pipe or even lost-in-hole incidents that might reach hundreds of millions of dollars in geothermal operations.

ACKNOWLEDGEMENTS

The authors wish to thank Halliburton Indonesia and KS ORKA for permission to publish this paper. They are also grateful for the collaboration between Sperry Drilling's Solutions Engineering and KS ORKA Drilling and Subsurface departments for the case study. Internally, authors would like to convey gratitude for the Field Team (Ramadhan Jarekson, Benny Pernando, and Bey Hafid Aulia) and Geologica study team for all the dedication and support poured into this technical paper

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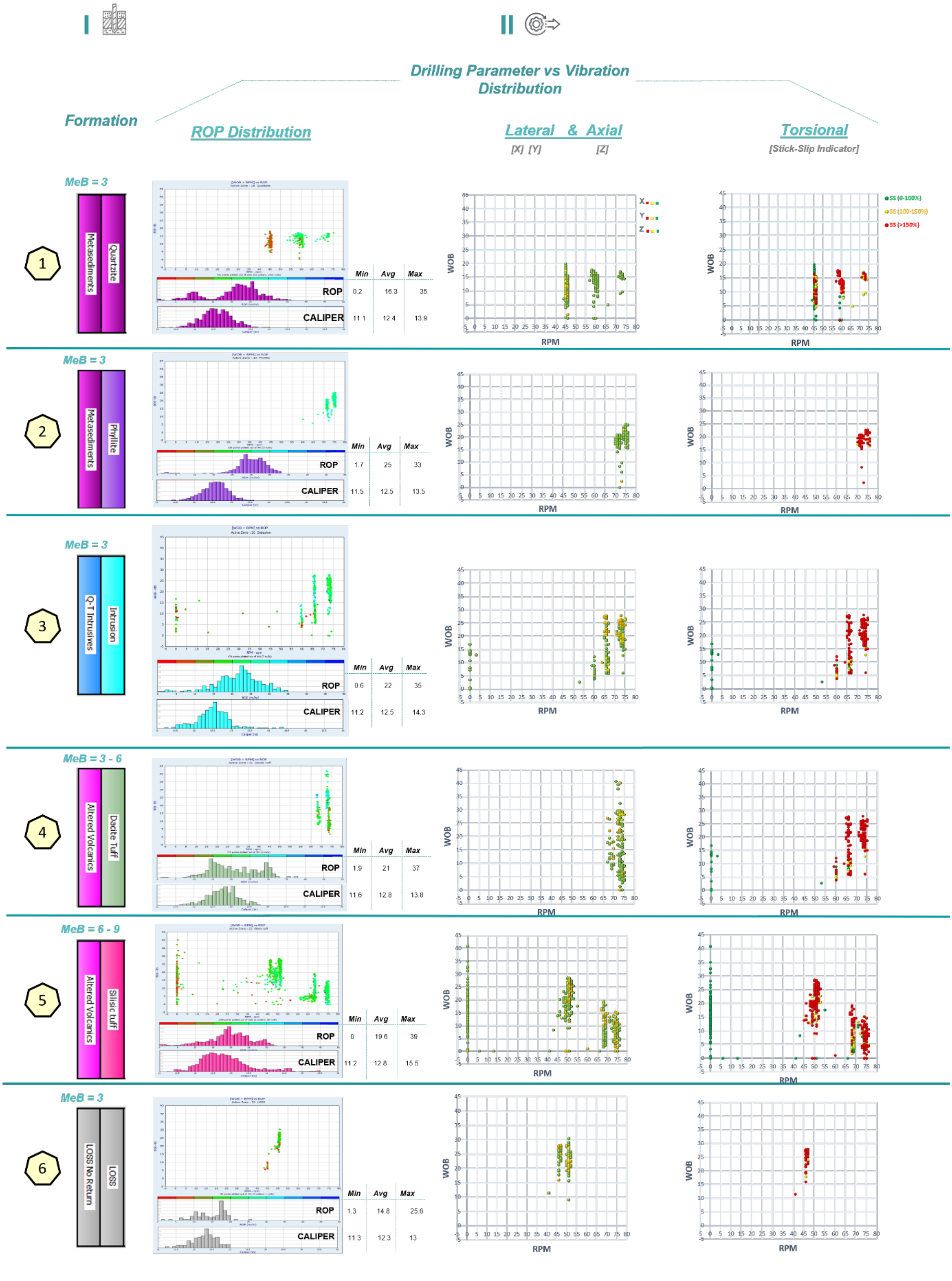
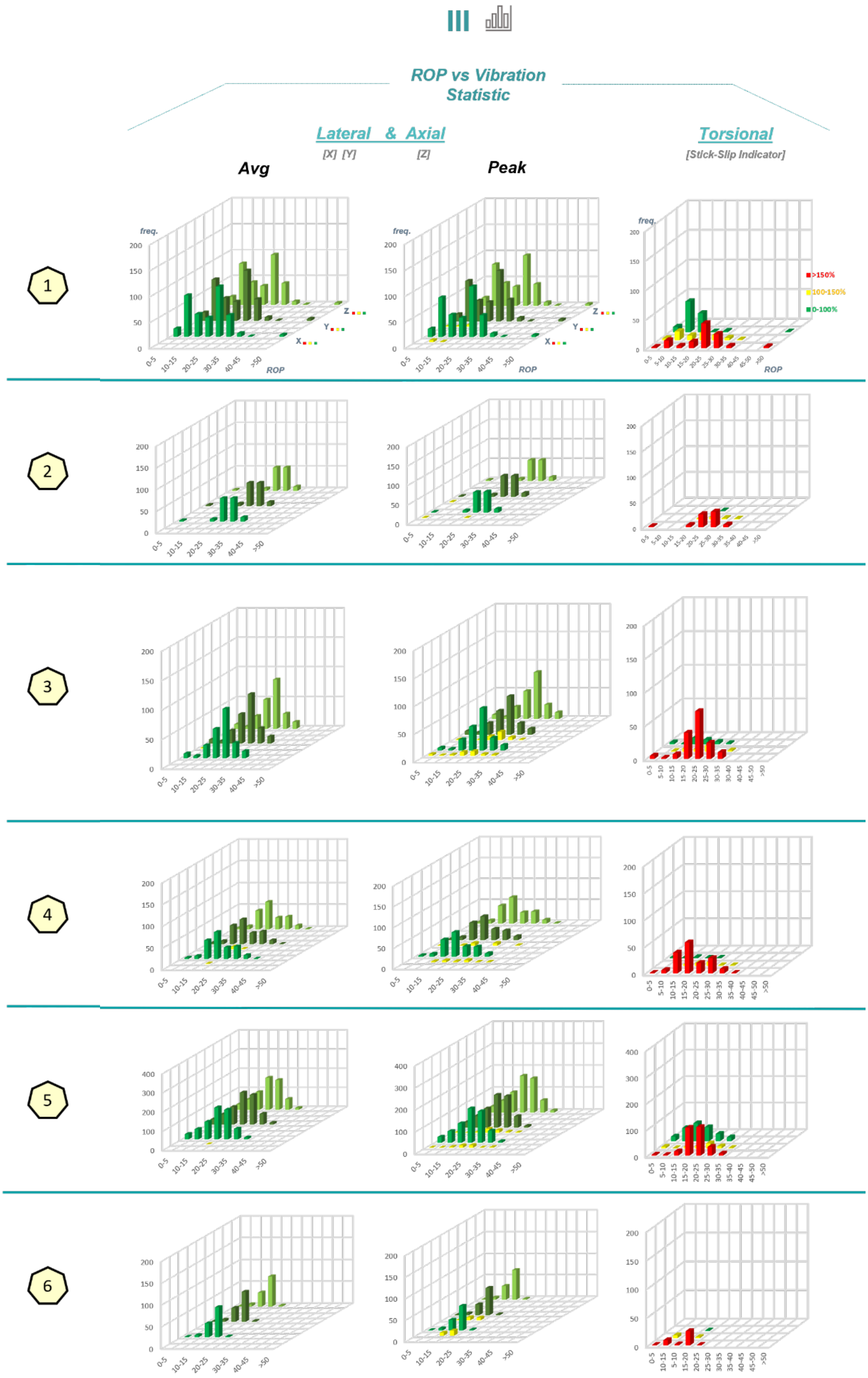
APPENDIX 1

Below graphs of (a) (b) (c) are each broken-down's steps of Methodology framework (**Figure 10**), plotted to observe vibration characterization in 12.25-in. HS of XXE-05 by also cross-referencing it to geothermal formation's study area of Sorik Marapi Field:



(a)


ROP vs Vibration
Statistic
Lateral & Axial
[X] [Y]
[Z]
Torsional
[Stick-Slip Indicator]
Avg
Peak
freq.
ROP
>150%
100-150%
0-100%
1
2
3
4
5
6

(b)

	IV Burst File Detected	V Vibration Mode	Vibration Mechanism
1		❑ Torsional ❑ Lateral	Torsional Resonance
2	see table (2)	❑ Torsional	Torsional Resonance
3	see table (3)	❑ Torsional ❑ Lateral	Torsional Resonance / Bit Chatter
4	see table (4)	❑ Torsional ❑ Lateral	Torsional Resonance / Bit Chatter
5	see table (5)	❑ Torsional ❑ Lateral	Torsional Resonance / Bit Chatter
6		❑ Torsional ❑ Lateral	Torsional Resonance

(2)

Burst Depth (ftMD)	Maximum Mag (g^2/Hz)	Freq at Max Mag (Hz)
1804	X Mag = 0.24 [Low]	0.5 – 35 Hz
1830	X Mag = 0.46 [Low]	0.5 – 200 Hz

(3)

Burst Depth (ftMD)	Maximum Mag (g^2/Hz)	Freq at Max Mag (Hz)
1837	X Mag = 0.18 [Low]	0.5 – 30 Hz
1851	X Mag = 0.21 [Low]	0.5 – 3 Hz
1854	X Mag = 0.59 [Med] Y Mag = 0.65 [Med]	0.5 – 3 Hz 70 – 150 Hz
1856	X Mag = 0.70 [Med]	0.5 – 20 Hz
1859	X Mag = 0.86 [Med]	0.5 – 200 Hz
1864	X Mag = 0.93 [Med] Y Mag = 1.33 [High]	0.5 – 3 Hz 150 Hz
1865	X Mag = 0.96 [Med] Y Mag = 1.50 [Med]	0.5 – 150 Hz 150 Hz
1867	X Mag = 0.87 [Med] Y Mag = 0.53 [Med]	0.5 – 150 Hz 150 Hz
1871	X Mag = 0.52 [Med]	0.5 – 100 Hz
1874	Y Mag = 1.64 [High]	150 Hz
1877	X Mag = 0.14 [Low]	0.5 – 20 Hz
1886	X Mag = 0.13 [Low]	0.5 – 250 Hz
1891	X Mag = 0.22 [Low]	0.5 – 20 Hz
1893	X Mag = 0.15 [Low]	0.5 – 20 Hz
1898	Y Mag = 0.11 [Low]	1 – 150 Hz

(4)

Burst Depth (ftMD)	Maximum Mag (g^2/Hz)	Freq at Max Mag (Hz)
1928	Y Mag = 1.11 [High]	150 Hz

(5)

Burst Depth (ftMD)	Maximum Mag (g^2/Hz)	Freq at Max Mag (Hz)
1965	Y Mag = 0.23 [Low]	150 Hz

(c)

Respectively to each geothermal formation of the Sorik Marapi Field, below is the vibration analysis summary:

- ***Metasediment / Quartzite.*** Vibration mechanism mainly considered to be torsional resonance. In achieving maximum ROP of 30-35 m/hr, lateral vibration was within green limit, but stick-slip exceeded the red limit. Lowering the RPM and WOB 10-20% (to around 60 RPM and 5-10 klbs) seemed to help reduce this torsional issue. The caliper was mostly in-gauge, with several ~1.5-in. washouts.
- ***Metasediment / Phylite.*** Vibration mechanism mainly considered to be torsional resonance, with several burst files recorded but showing only low magnitude of lateral mode. ROP achieved was quite moderate at 20-30 m/hr with lateral vibration all within the green limit, but stick-slip exceeding the red limit. Lowering the WOB 10-20 % (to 10-15 klbs) seemed to help to increase the ROP to ~33 m/hr in this formation interval. The caliper was mostly in-gauge.
- ***Q-T Intrusives / Intrusion.*** Vibration mechanism is inclined towards torsional resonance and bit chatter, with ~15 burst files recorded in the time-span of this interval. ROP achieved was quite moderate at 20-30 m/hr with lateral vibration all in the green limit, but stick-slip exceeded the red limit. The optimum RPM and WOB were found at 65 RPM and 15-20 klbs, where ROP reached 30-35 m/hr maximum, and lateral vibration was in green limit. Increasing the WOB & RPM seemed to reduce ROP and increase lateral vibration towards the yellow limit. The caliper is moderately in-gauge, but having several drastic washouts of ~1.5-2.5 in.
- ***Altered Volcanics / Dacite Tuff.*** Vibration mechanism is inclined towards torsional resonance and bit chatter, with burst files showing high magnitudes in the Y direction. ROP achieved was quite moderate at 20-30 m/hr with lateral vibration all in the green limit, but stick-slip exceeding the red limit. The optimum RPM and WOB were found at 70-75 RPM and 25-30 klbs, where ROP reached ~35 m/hr, with minimal lateral vibration and stick-slip. In contrast to other formations, lowering the WOB and increasing the RPM seemed to reduce ROP to ~10-15 m/hr, and increase lateral vibration towards the yellow limit and severe stick-slip. The caliper is rarely in-gauge, with multiple occurrences of ~1.5-in. washout.
- ***Altered Volcanics / Silicic Tuff.*** Vibration mechanism is inclined towards torsional resonance and bit chatter, with burst files showing low magnitudes in the Y direction. ROP achieved was mostly moderate at 20-25 m/hr with much of the lateral vibration being in the yellow limit, but stick-slip mostly exceeding the red limit. The optimum RPM and WOB were found at 65-70 rpm and 10-15 klbs, where ROP reached a maximum of 30-35 m/hr, and lateral vibration fell within the green limit and stick-slip decreasing to within the yellow and green limits. Raising or lowering the WOB and RPM seemed to reduce ROP and increase vibration. This interval had the most frequent washout occurrence detected by the caliper, with drastic washouts around 1.5-2.5 in.
- ***Unknown / Loss interval.*** Vibration mechanism detected to be torsional resonance, with no burst file recorded. The ROP achieved was low to moderate at 10-20 m/hr with moderate lateral vibration in the yellow limit and stick-slip exceeding red limit. Increasing the WOB 10-20% (25-30 klbs) seemed to help to increase the ROP to ~25 m/hr in this formation interval. The caliper is mostly in-gauge. The overall character resembles that of metasediment/quartzite.