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Mechanical Specific Energy Analysis of the FORGE Utah Well

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ABSTRACT

One of the key findings of the 2014 Petroleum Practices Technology Transfer Committee report led by National Renewable Energy Laboratory (NREL) was that the geothermal drilling process lacked proper data collection while drilling, data integration, and analysis of such data. The lack of this essential engineering, well planning, and construction tool seemingly adds a significant amount of time to the 12-day additional non-productive time (NPT) on average per well while drilling geothermal wells versus oil and gas wells out of the 42 wells studied of the comparable order of magnitude of construction complexity. Geothermal Resource Group (GRG) has recently been involved in the construction of a well for a unique domestic enhanced geothermal system (EGS) observation drilling project (FORGE Utah) and was able to implement a hydraulic surface torque data collection system on a mechanical rig to analyze the MSE (mechanical specific energy). This paper presents the collection, evaluation, and the post-mortem comparison of the MSE to the drilling history, parameters, and changes in general lithological structures of this well.

1. INTRODUCTION

Geothermal Resource Group (GRG) has been involved in the construction of a well for a unique domestic enhanced geothermal system (EGS) observation drilling project (FORGE Utah) and was able to implement a hydraulic surface torque data collection system on a mechanical rig to analyze the MSE (mechanical specific energy). Thie surface torque data collection system was a a hydraulic pressure gauge used to measure rotary chain tension and a conversion that was used to calculate rotary torque. The most probable reason for the scatter in the MSE data is because we did not have a more accurate method to measure rotary torque. This paper presents the collection, evaluation, and the post-mortem comparison of the MSE to the drilling history, parameters, and changes in general lithological structures of this well.

Mechanical Specific Energy has been utilized in the oil and gas industry for the past five decades in various forms and flavors. Simply stated, Mechanical Specific Energy (MSE) is conservation of energy which mandates that the amount of energy and work expended to cut a volume of rock should be equal and conserved throughout a closed system that includes top drive, circulating system, etc. However, energy to drill a volume of rock is not conserved due to several factors and therefore does not necessarily translate into the net effective rate of penetration. The use of specific energy to correlate formation characteristics has been explored by several authors, as seen in the literature. However, all these studies were related to conventional, shallower drilling applications. Today with the evolving of technologies and downhole sensors, Mechanical Specific Energy is widely used in the oil and gas industry to improve performance and provide a real-time feedback loop to the driller on downhole formation transitions. Rate of Penetration and re-engineering of technical limits that hinder performance - such as top drive limits, bottom hole design specifications, redesigning of bits to mention a few - have been performed based on specific energy measurements at the bit.

The lack of this essential engineering well planning, and construction tool in the geothermal industry, presumably adds a significant amount of time to the 12-day additional non-productive time (NPT) on average per well while drilling geothermal wells versus oil and gas wells, out of the 42 wells studied of the comparable order of magnitude of construction complexity.

2. MECHANICAL SPECIFIC ENERGY

Mechanical Specific Energy has been widely used to reduce the total days from spud to rig release by as much as 60% and therefore lower drilling costs to 30-40%. In this paper, we explore the use of MSE for hard rock – specifically application in granite and emphasize how real-time drill-off tests and qualitative trending tool can be used to reverse engineer formation properties and their variance from actual cores and log data. Data such as uniaxial and confined compressive strengths, Young's modulus, Biot's constant and pore and fracture pressures can be back-calculated from dynamic MSE values. Reacting to MSE is also a common method to reduce costs and is being widely applied to infer rock characteristics in the unconventional industry where logging might be done less frequently.

Published MSE equations have been used to keep the investigation simple and focused on hard rock drilling in a high-temperature environment. As this is an experimental well for University of Utah, most data have been analyzed on a reactive way than a proactive way to use it as a tool for improving performance in real time. With the acquisition and analysis of data, the interpretation of MSE can be a very powerful tool to provide to the driller and at least save 15-20% on drilling days (to be most conservative). This will be to be used as a real time application for the next phase of the Utah FORGE drilling program an. This paper will address the reasons why MSE is crucial for all geothermal drilling applications and how the assessment of energy expended at the bit can be translated into improved ROP. The paper will also show what properties can be inferred in a developed basin without use of highly sophisticated measurements and logging tools.

There is a real opportunity to improve performance in granitic formations and understand how real-time drill-off tests and qualitative trending tools can be useful for improving performance. This paper goes one step further. Ideally, the analyst should be able to use the bit as a laboratory and determine, at the least, a formation's mechanical properties (El-Biblawi et al., 2007, Detournay and Defourny, 1992; Detournay and Chan, 2002; Shewalla and Smith, 2015; …). It should be possible to reverse engineer formation properties and assess their variance from actual core and log data.

To calculate MSE, you only need certain appropriate input data. However, to understand WHY it changes and HOW to improve your response (for example, adjustments to WOB) and design going forward, you need all the data you can get. Pump pressures, differential pressures, temperatures, MWD vibes, GR and other logs, even auto driller settings such as ramp rate can be important. It really depends on the situation and dysfunction encountered in a particular interval.

3. FORGE UTAH WELL

With increasing interest in Enhanced Geothermal Systems, EGS, efficient and informative drilling becomes essential. A recent drilling program provided an opportunity for back analysis; this drilling operation has been part of the United States Department of Energy's FORGE program. The acronym FORGE stands for Frontier Observatory for Research in Geothermal Energy. "The FORGE Utah site is located 350 km south of Salt Lake City and 16 km north northeast of Milford, Utah, in an unpopulated area that is predominantly used for renewable energy, including wind, solar, and geothermal generation. The site lies 5 km west-northwest of the Blundell geothermal power plant, which produces 35 MWe from flash and binary units." (Simmons et al., 2018).

"Well 58-32 was spudded on July 31, 2017 and was drilled vertically to 7,536 ft (2,297 m) depth in 57 days. The well penetrated layered alluvium deposits down to 3,176 ft (968 m), where it crossed the contact with underlying crystalline basement rocks, which make up the rest of the stratigraphy to the bottom of the hole. Drill cuttings were collected every 10 ft and samples of core were collected from two intervals at 6,800-6,810.25 ft (2,073-2,076 m) and 7,440-7,452.15 ft (2,268-2,272 m). The cores were logged for their physical and lithologic properties, photographed, CT-scanned and plugged for mechanical testing. A complete suite of geophysical logs was run (7,536 to 2,172ft (2,298 to 662 m), and the hole was then lined with 7-inch casing down to 7,375 ft (2,248 m)." (Simmons et al., 2018)

Diagnostic Fracture Injection Testing (DFIT) was performed in the barefoot section of the hole to determine in situ stresses, permeability and reservoir pressure. Figure 1 shows a cross-section of the FORGE site. Notice the plans for two future wells to be interconnected with hydraulic fractures.

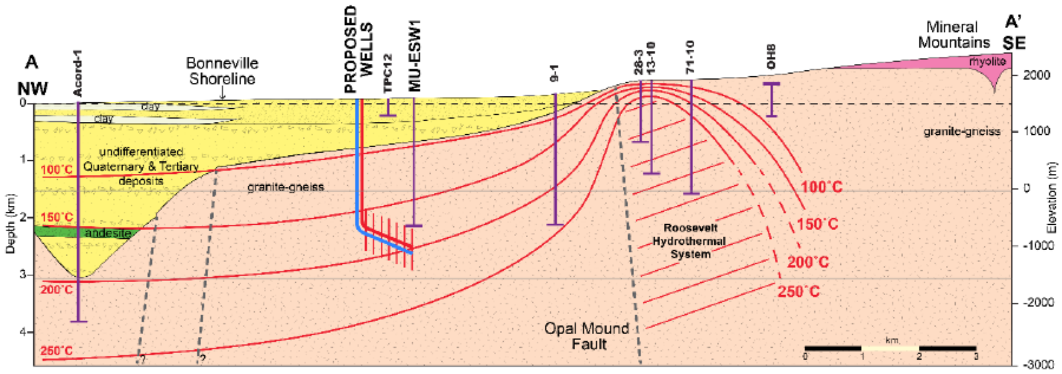

Figure 1: This a NW to SE (A to A') cross-section showing the top of the crystalline basement rocks in the Milford Basin in the vicinity of the FORGE site. Precambrian gneiss and Tertiary plutonic rocks are undifferentiated. The Roosevelt Hot Springs hydrothermal system lies east of the Opal Mound fault. Isotherms are interpreted from well measurements. The figure shows the proposed FORGE injection and production wells and the vertical 2134 m deep test well (originally MU-ESW1, now referred to as 58-32) drilled (after Moore et al., 2017).

Balamir et al., 2018, describe drilling operations for this well. 20" conductor pipe was cemented with the casing shoe at 83.5 ft (25.5 m). in advance of the arrival of the drilling rig. The rig completed mobilization and rig up on July 30, 2017, and drilling commenced on July 31, 2017. The 17-1/2" hole was drilled to 342 ft (104 m). (relative to Kelly Bushing Height (RKB) of 21.5 ft (6.55 m)) and 13 3/8" casing was cemented to 338 ft (103 m) on August 2, 2017. Drilling of the 12-1/4" hole commenced the next day and continued to August 6, when the casing point was reached at 2,180 ft (664 m). 9-5/8" casing was set and cemented at 2,172 ft (662 m) MD on August 7. Drilling 8-3/4" hole commenced on August 8, and total depth of 7,536 ft (2297 m) MD was reached on Sept 14, 2017. Two cores (totaling 35 ft (10.7 m) in length) were collected; one starting at 6,800 ft MD (2073 m) and the second starting at 7,440 ft MD (2268 m). A supplementary extensive logging, injection, testing and measurement program has provided an excellent opportunity for evaluating mechanical specific energy principles in a strong, high temperature (297°C), high modulus environment. Figure 2 is the mud log from the well, showing the ROP record in Track 1 (about 10 feet per hour).

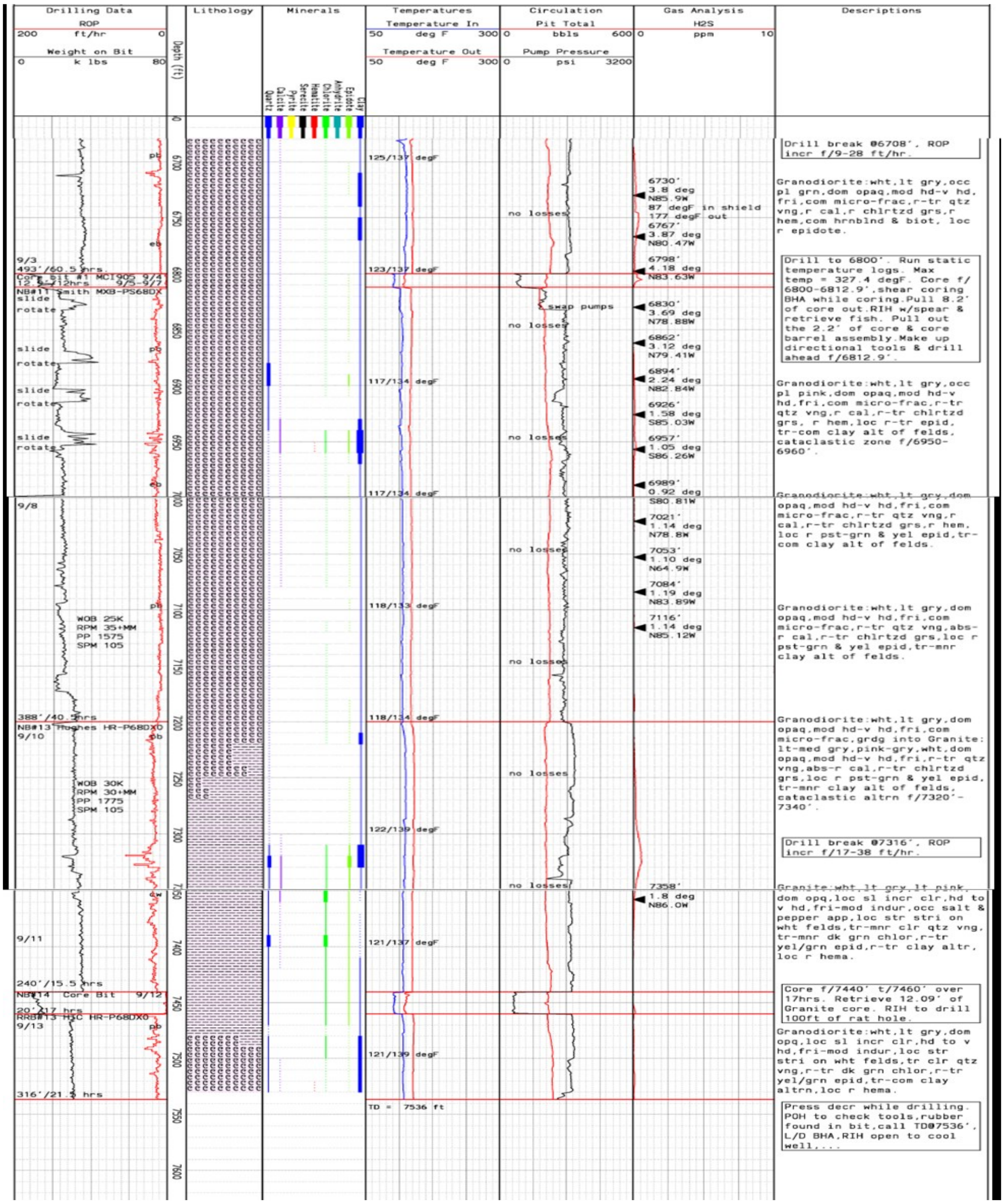

Figure 2: Mud log from Well 58-32. At the extreme left is the rate of penetration, approximately 10 ft/hr.

3.1 Analysis

Standard core analysis was used to determine mechanical properties (Young's modulus, Poisson's ratio and Mohr-Coulomb failure parameters. Figure 3 is an example. Standard logging interpretation was used to infer stresses and dynamic mechanical properties. These predictions were calibrated using DFIT and microhydraulic fracturing and laboratory modulus measurements.

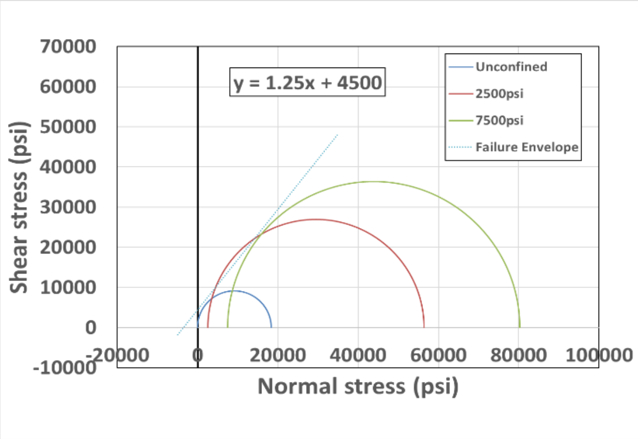

Figure 3: One of eight Mohr-Coulomb failure envelopes for samples plugged from core from Well 58-32. All the envelopes are characterized by strong, brittle rock.

A post-mortem BHA and modeling study were carried out. Well 58-32 was drilled with 22 BHAs from spud to TD, including two core runs. These evaluations focused on three to four BHAs used near the top of the core runs, one PDC bit run, and depths where real-time drill-off tests were carried out. All the evaluations were in the 8 ¾-inch hole sections.

The components of the BHA were analyzed using Landmark's WellPlan® software to evaluate the critical speed, torque and drag to predict the torque of the actual well drilled. This predicted torque was seen to be extremely low in the 8 ¾" hole section. However, the actual torque that was estimated from rotary table pressure was very high. This suggests that severe helical and sinusoidal buckling had occurred. To confirm this, photographs of the bits (Figure 4is an example) were analyzed on every face, blade and shoulder following the International Association of Drilling Contractors' specifications. The results demonstrated excess wear on the face of the blades and cutters (broken teeth, dull gauge) rather than at the core of the bit. When severe buckling occurs, there is more torsional vibration in the drill string. This will result in:

1. The observed higher torque occurred since the buckling tends to amplify vibrations. When sinusoidal and helical buckling occur, the effect is a four-time amplification of the initial vibrations. This results in sixteen times less energy translating downhole to the bit.
2. Energy losses through high vibrations
3. Lower Rate of Penetration
4. Damage to the bits on the gauge, shoulders of the blades of PDC bits and broken bit teeth.

Figure 4: Pulled bit, showing excessive wear, including broken teeth and dull gauge.

3.2 MSE calculations

MSE was first defined by Teale, as the Input Energy divided by the Output ROP. This ratio is likely to be constant for a given rock strength and hold down pressure (Figure 5). This implies that the numerator is the net energy that is input into the rock below the bit – corrected for operational losses associated with torque, drag, vibrations and other losses. Knowing and understanding the MSE will allow real-time decision-making to adjust the drilling system for the current rock strength (Balamir et al., 2018). Over the years, this basic relationship has gone through numerous improvements or refinements.

For Well 58-32 the formula to calculate MSE is as shown:

$$MSE = \frac{480 \times T \times RPM}{d_{bit}^2 \times ROP} + \frac{4 \times WOB}{\pi d_{bit}^2}$$

where:

MSE……………..Mechanical Specific energy (psi)

T………………… Torque (ft-lb_f)

RPM……………..Revolutions per minute (1/minute)

d_{bit}………………………… Bit diameter (inch)

ROP……………… Rate of penetration (ft/hr)

WOB……………..Weight on bit (lb_f)

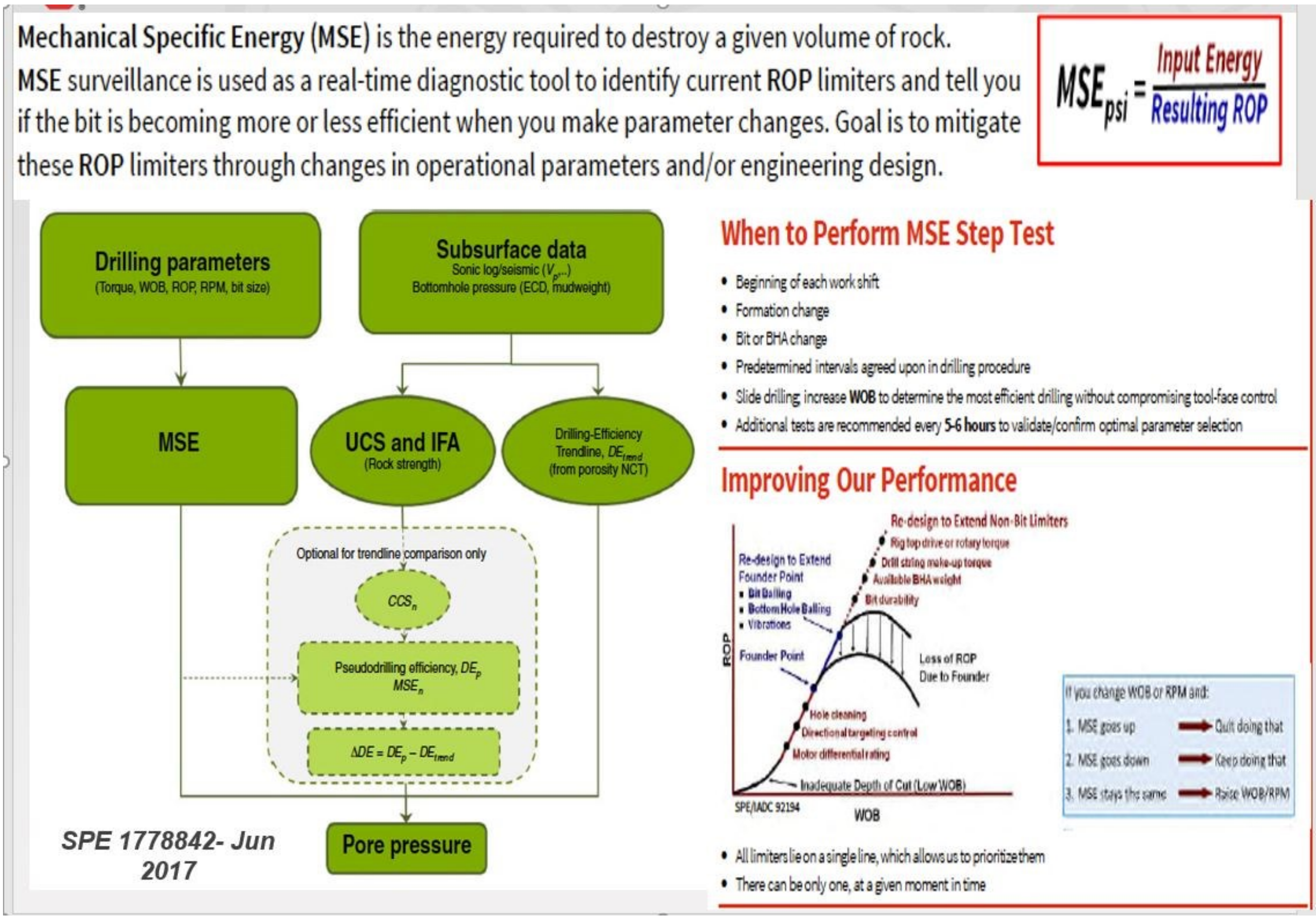

Figure 5: Mechanical Specific Energy definition and equation (Noynaert, 2019)

Following Dupriest and Koederitz, 2005, efficiency factors (0.35 is common) may be applied to the calculated specific energy. Vibrations, torque and drag corrections and modifications for mud motors are usually applied to determine the energy that is reaching the rock. It is also well known that the ability to break rock beneath a bit is a function of the so-called "chip hold down" pressure (Balamir et al., 2018). It follows that the MSE should incorporate this in terms of a difference between the bottom hole pressure and the formation pressure ahead of the bit (wellbore pressure minus pore pressure). Majidi et al., 2016, provided a method (DEMSE – Drilling Efficiency and Mechanical Specific Energy) where drillability and MSE were used to estimate the pore pressure. These authors indicated that the energy expended at the bit to remove a unit volume of rock is a function of the pressure difference between the mud weight and the formation pressure ahead of the bit – another MSE application.

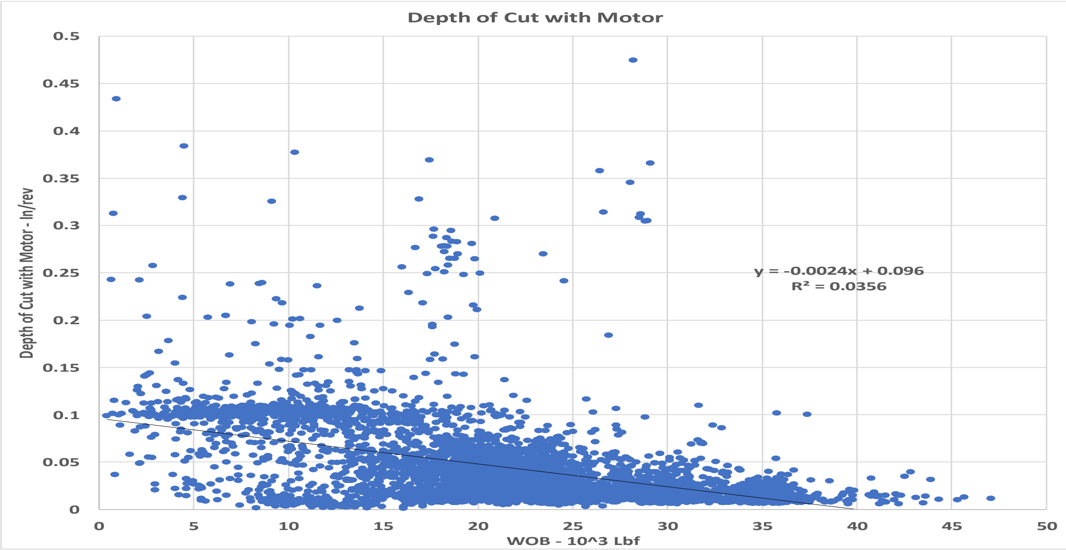

Figure 6: Cross plot of WOB vs. depth of cut (in/rev) – depth of indentation by shearing and grinding action of the bit. Motodepth of cut considers cut with a motor with hydraulic action.

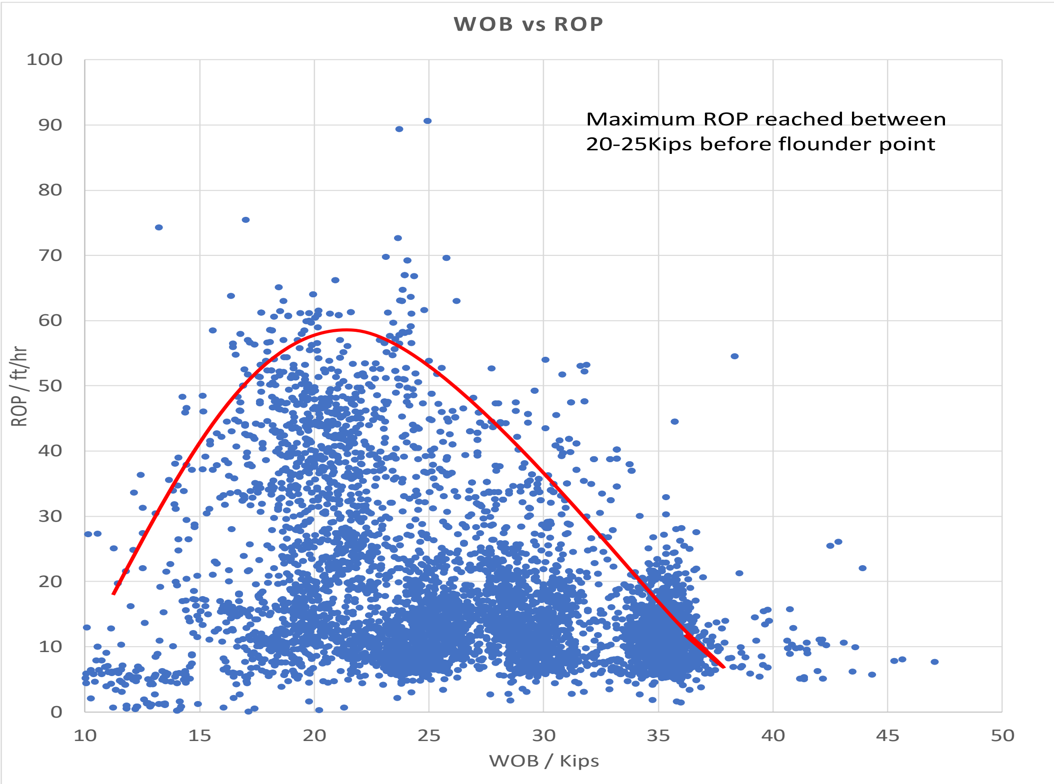

Figure 7: This demonstrates Dupriest's (2005) flounder point curve with an ROP limitation. Weights greater than 25,000 lbf correlate with a diminishing ROP, due to buckling. In the future, BHA design must be investigated to reassess drilling any well.

4 Conclusions

The post-mortem comparison of the MSE recollected at Well 58-32 provides helpful data interpretation to improve future drilling for the FORGE project and the Geothermal Industry as a whole:

- When using a downhole motor (mud motor) it is possible to use the differential pressure across the motor and the pump rate to calculate the torque right at the bit and the actual downhole bit speed.
    - This is also called the Bit MSE and it's become the preferred practice over the last 3-4 years.
    - It is planned to compare this with the surface MSE data in future wells, to validate the difference.
- Plan to use higher weight on bit with a packed BHA design will help to keep the hole straight and prevent bit whirl dysfunctions that will prevent pulling out the bit green.
    - A modern PDC bit does not wear in the traditional sense.

- Any wear you see in bit Figure 4 is due to whirl, stick slip, or interfacial severity, this bit was damaged by whirl.
  - Running a higher WOB it would have caused less wear on the bit, because there would have been less whirl.

- PDCs bit have a higher friction coefficient and only drill slower than an insert bit if you run less WOB (as proven in this well).
- The wear equations found in the literature for insert bits are inappropriate. The wear rate is highly dependent on whirl and is not reflected in laboratory work. The insert bit picture (Figure 4) shows broken inserts on the shoulder. These are indicative of lateral impact from bit whirl. The other teeth are worn, and the bit was ready to be pulled. However, if the whirl had been minimized the bit would have gone much further before it arrived at this level of damage and wear. Like the PDC, this bit needs more WOB.
- Critical speeds cannot be calculated accurately because true configuration lengths for the BHA components are rarely known. It's much better to just run RPM step tests as soon as you drill out of casing and watch MSE to see when whirl is higher or lower. At critical speeds, the higher BHA whirl will cause more stabilizer drag and the MSE will rise because of the higher torque without a proportionate increase in ROP (meaning the torque is not at the bit).
- Torsional vibration does not cause stabilizer wear because it does not increase the force acting normal to the face of the stabilizer; whirl does. If there's accelerated stabizer wear it's due to whirl.
- Since the depth of cut (DOC) is a function of WOB and does not change with RPM, DOC does not change for a motor. However, the higher RPM of a motor should always result in more ROP for the same DOC. ROP is linear with both WOB (indention) and RPM (sliding distance per minute at the indentation depth). If a motor does not drill as fast as envisioned, it is because the driller chose to run less WOB on it, or an insert was used instead of a PDC (less DOC for given WOB).
- The results of the DOC plots shown in the figure 4 and figure 5 above, are distorted by decisions the driller is making. Drillers are generally keeping their WOB below 20-35k lb_f. The only time they go above this is when the ROP falls (harder rock, more whirl, or dull bit). The lower DOC is not a product of the higher WOB; the higher WOB is a product of them seeing a lower DOC (ROP) and responding with higher WOB.

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