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Drilling Performance Improvements with High Frequency Data

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ABSTRACT

There have been significant improvements in drilling performance in petroleum operations. For example, from spud to rig release, 14,000 ft (4 267 m)wells in Wyoming have gone from 60 days to 6 days. While there were many ways in which this was accomplished, systematic analysis of the drilling data both from surface and downhole sensors was a key process.

Among the many things to analyze, large gains in drilling efficiency result from ensuring that the energy applied in the drilling system is almost entirely utilized in destroying the rock under the bit, rather than being lost through various forms of drilling dysfunctions such as bit bounce, BHA whirl, stick-slip, balling, etc. One of the greatest challenges in reducing these forms of drilling dysfunctions arises from the fact that different lithologies can drastically change how the drillstring responds with a given set of drilling parameters, making it challenging to predict which drilling parameters are optimal in reducing these dysfunctions. This paper describes the use of high frequency data acquisition and analysis to relate the lithology quantitatively to surface drilling operational measurements that characterize drilling performance.

A standard mining coring rig outfitted with a diamond impregnated core bit was used to collect core samples at the Colorado School of Mine's Edgar Experimental Mine. The formations cored are composed of hard metamorphosed igneous rocks as are often encountered during geothermal operations. The rig is outfitted with high frequency (20 kHz) vibration sensors during the operation along with force, torque, rotation, and position sensors. Data analysis in the frequency and time domains shows a clear connection to the drilling performance and the lithology as shown by the recovered cores.

The high frequency accelerometer time series data is synchronized to be spatially related with the core. An image analysis of the cores was combined with the accelerometer data to correlate lithology with drilling performance. A machine learning clustering function estimated the percent composition of a given rock matrix component. This showed confirmation of drilling observational data that indicated that lighter (in color) cuttings return was a marker of efficient performance and dark cuttings return was a marker of inefficient performance. While more work is left to be accomplished, the combination of different types of high frequency data (high definition images, accelerometers, and other drilling performance data) was shown to be a good method to optimize operational parameters with a subsequent improvement in drilling performance.

1. INTRODUCTION

Drilling performance represents a huge technical and operational challenge in the geothermal industry. Wellbore construction costs can be up to 50 percent of total project costs (Tester et al 2006). This cost has many sources; but, a significant portion of it can be attributed to an increase in non-productive time (NPT) from lost circulation events as well as less efficient rock penetration in general due to much harder rock formations associated with many viable geothermal resource plays (Visser et al). These are areas where a better understanding of drilling performance issues and root causes can help lead to better practices and faster real-time reactions.

In order to understand drilling performance, one must be able to measure relevant drilling parameters. Thankfully, industry has come a long way in improving data collection. A few decades ago, it was common to find drilling rigs equipped with crude analog sensors storing data measurements on physical media such as paper. Today, rigs are equipped with digital sensors, and due to standards such as the Wellsite Information Transfer Specification (WITS) and, increasingly, the Wellsite Information Transfer Standard Markup Language (WITSML), this data is stored in a permanent digital state that is accessible to engineers offsite, often in real-time. In addition, since the first commercial application of Measurement While Drilling (MWD) equipment in the 1970s, there is an increase in the volume, variety, and quality of measurements from the bottom hole assembly (BHA).

One benefit of incorporating better data collection practices in drilling has been the recognition of inaccurate traditional performance metrics, sensors, and human-machine interfaces. Resultant bad practices in real-time decision making can cause lagged or unwarranted reactions. Drilling operations also suffer from additional external forces and human factors that make incorporation of good data practices difficult, including scheduling issues, legal questions about data sharing between contractors, a culture of trusting experience, and a lack of motivation to upgrade field equipment. Even with these challenges, improved data practices and subsequent data exploration has led to significant value added, in the oil and gas drilling operations in particular.

While the oil and gas drilling operations are not yet quite there, true high frequency data models allow for more realistic drill string behavior and bit-rock interaction to be captured. Conventional practices collecting at frequencies orders of magnitude slower than the string rotation results in a significant lost data for any potential model. It is known that string energetics are a vast contributor to performance issues, discussed in terms of the metric mechanical specific energy (MSE).

Using high frequency accelerometer data, as performed on this project, allowed for the insight into the drill string behavior that otherwise would not be possible. Data with accelerometers was collected at 20 kHz - more than 120 times the string rotation speed while drilling. This resolution of data allowed for a much more detailed view of string behavior and bit energetics.

After data collection, analysis, and visualization, instances of drilling dysfunctions such as axial, radial, and lateral vibrations, stick-slip, and whirl was identified by reviewing the data in the time and frequency domains. These instances of dysfunctions can be identified qualitatively by the frequencies excited shown in spectrograms of the accelerometer data and quantitatively using other Fourier transform methods. Being able to identify these instances of drilling dysfunctions are the first steps in determining mitigating actions in reducing these dysfunctions. But even after finding optimal drilling parameters, it's worth re-stating that these parameters change with the strength of the rock being drilled; and, thus these results change with the lithologies encountered.

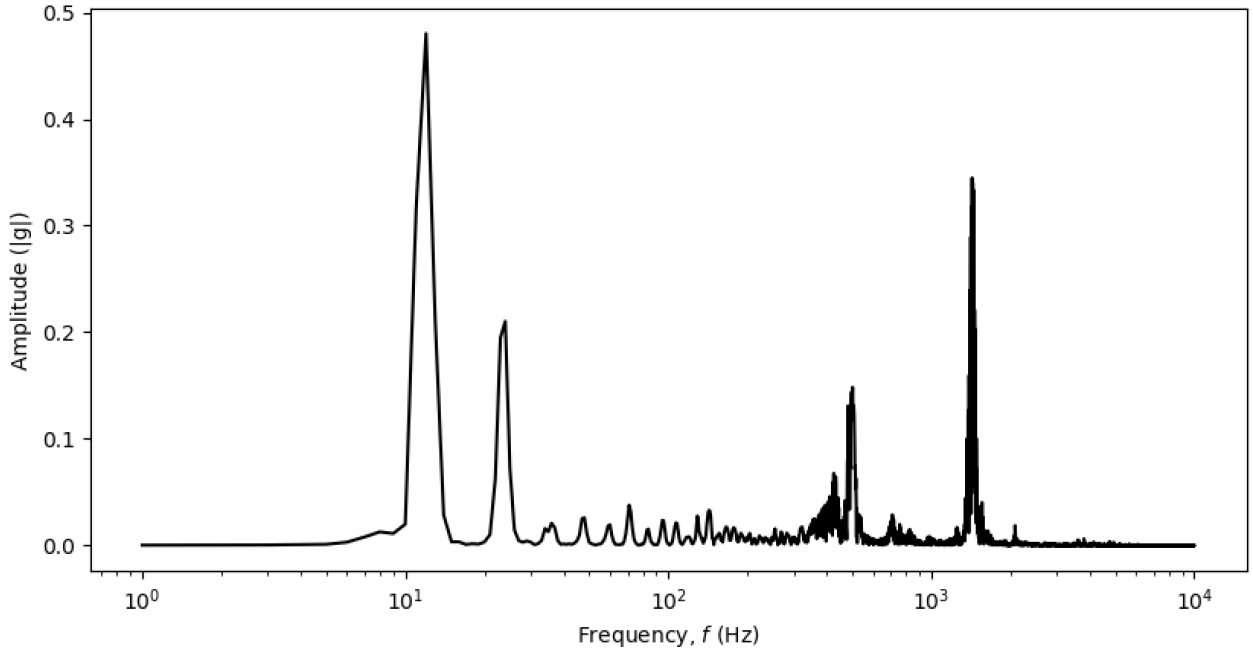


Figure 1: Lateral vibration frequency domain during the development of asynchronous forward whirl over a 1 second interval. The first mode at ~11 Hz is the rotational speed. Excitations at 500 Hz and 1.3 kHz are unique to whirl for our drilling system.

Image analysis is an increasingly viable tool in many industries because of readily available high definition imaging devices and the computing storage space and power required to work with high resolution images on a pixel by pixel basis. By treating an image as a value filled matrix of pixels, traditional and newly reapplied statistical techniques can be used to identify trends and correlate images with other data sets. This has been applied to drilling cores in a variety of ways. The mining industry has done significant work in this space; utilizing learning to identify mineralogy (Barnuevo-Perez et al), clustering with core log data to characterize lithology (Fresia et al), and identification of fracture networks using CT scans (McCall et. al). Findings from these studies can be applied and expanded upon to increase geothermal drilling performance if related to other drilling data. In particular, the correlation of lithology to performance could lead to early fracture network identification which would be useful in the geothermal industry.

The ability to link the rapidly changing subsurface structure in geothermal drilling to the performance data at a higher resolution than the general lithology in real-time or near real-time would be beneficial to operational decisions. While the general idea of the differences between drilling through a metamorphic formation and a sedimentary one is well understood, the innate heterogeneity of the former introduces a significant amount of uncertainty into the model of what exactly is happening downhole. This paper explores several different preliminary methods of identifying that link, including image analysis and time-frequency analysis.

2. BACKGROUND AND METHODS

Rig Setup

The Edgar Experimental Mine in Idaho Springs, Colorado was a commercial silver mine that has been owned and operated by the Colorado School of Mines for training and research purposes for nearly a century. In 2015, the Apache Corporation donated a large grant for the purposes of drilling engineering education that enabled the purchase of a Sandvik DE130 coring rig. This coring rig has been used in a variety of research projects at CSM, and in addition, the rig has been used in the undergraduate drilling engineering curriculum to allow students hands on experience in observing the mechanics of drilling and analysis of data collected. A paper given at the 2019 Society of Petroleum Engineers Annual Conference outlines the educational merit of the drill system (Eustes et. Al. 2019)

The drilling rig was initially equipped with a selection of analog measurements. This included an analog flow-meter for flow rate from the triplex pump. As the rig is a hydraulically powered rig, various analog gauges measuring hydraulic pressure provide proportional measurements for such parameters as force on bit and torque.

For the work described in this paper, the rig was augmented to include multiple three-axis accelerometers with nine degree of freedom gyros collecting measurements at high frequency (20 kHz) and high acceleration [>100g (>981 m/s^2)]. While not able to send data in real time, the data is instead recorded to an on-board 8 Gb drive. The gyrometers can measure angle and rotation rate in relative or absolute modes. Multiple sets of these accelerometer packages were attached directly to the drill pipe to measure drill pipe axial, tangential, and centripetal acceleration directly. Other commonly recorded drilling parameters such as rate of penetration (ROP) and depth had to be collected using somewhat crude manual methods at this time. However, the rig is the processes of being upgrade for the collection of all the drilling parameters one would commonly encounter on a drilling rig digitally via a National Instruments CompactRIO Data Acquisition System (DAQ) and suite of high frequency, direct measurement sensors. Future work will be performed in automating the drilling function of the rig which will enable the rig for research in advanced drilling robotics.

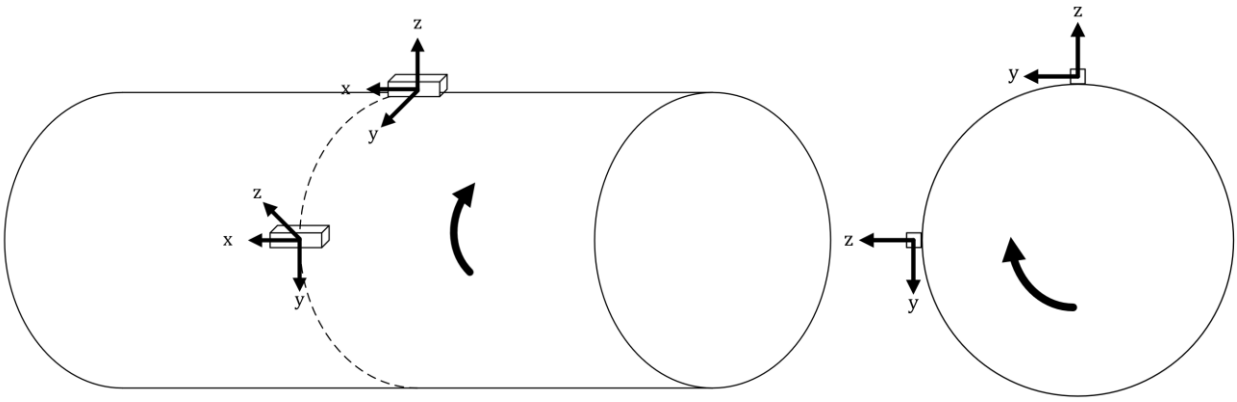


Figure 2: The side view and cross-sectional view of the accelerometer placement and each axis local to the accelerometers. The pipe is rotating clockwise with the bit in the direction to the left of the figure.

The core rig drills 1.874 in (47.6 mm) diameter cores up to 3,000 ft (914 m) of depth and at inclinations from -90° to +90°. The hard, metamorphic gneiss environment of the Edgar Mine requires diamond impregnated coring bits. The diameter of the cored hole is 2.98 in (75.7 mm); however, the rig has drilled up to 6 in (152 mm) diameter holes for research and exploration at the mine.

Image Analysis and Computer Vision

The variability of lithology and the geomechanically properties of the rock influence drill bit and drill string behavior. In oil and gas drilling operations, correlations between drilling behavior and geology is done at the large scale by formation. In reality, lithologies composed of many different components. Generally, it is not sufficient to approximate each formation as a homogeneous matrix. These heterogenous components all have unique geomechanical and petrophysical properties that affect drilling significantly within a given formation. In a geological environment such as found at the Edgar Mine, changes within the same formation from point-to-point can be very significant in terms of composition, orientation, fractures, and so forth. Sufficiently large datasets collected at high frequencies are able to tease out these subtleties.

Over the course of multiple experiments at the Edgar Mine, it was noted that the color of the circulated cuttings is indicative of drill string behavior in terms of both efficiency (as characterized by ROP) and energetics (as qualitatively noted by changes in acoustics and ROP). Darker cuttings return appeared to be correlated with decreased ROP and drilling efficiency in general; but, this cannot be sufficiently quantified and confirmed from circulation returns alone. An image analysis of core taken and synchronized with drilling rate and depth was used to test this theory.



Figure 3a: Image of the Core in RGB Space

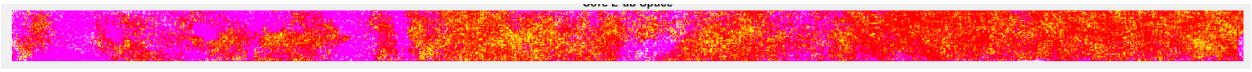


*Figure 3b: Image of Core in L*a*b* Space*

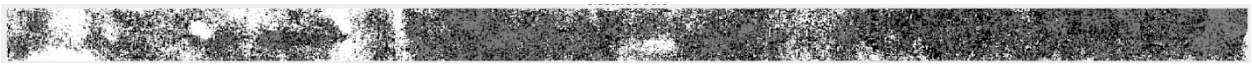


Figure 3c: Core Pixels Clustered into 3 Groups

Figure 3: The same 5 ft (1.7 m) core image decompiled from the original image (a) to the L*a*b* space statistical clusters.

As any good geologist would confirm, color alone is a poor indicator of exact mineralogy. In terms of an indicator of change in mineralogy, however, it can be a useful metric. The formation being drilled into ranged from black to white in color, and thus could be categorized based on the full range of the visible electromagnetic spectrum. It should be noted that Figure 3 is not fully representative of the actual core; the image is series of photos from a single side of the core spliced together as a panoramic for the

length of the core. The image was taken on the mine floor and the boundaries were cropped to ensure the mine "soil" didn't alter the computer analysis. This also meant that the core was being categorized based only on the superficial features facing the camera. Based on the analysis done, however, the picture appeared to serve as a representative proxy.

The images are then analyzed by converting them from the standard Red-Green-Blue (rgb) space to the Luminosity-Chromaticity (L*a*b*) space. The L*a*b* space contains three values representing a given pixel. One is for luminosity, and two represent chromaticity measurements: one quantifies where the pixel falls on the red-green axis, and one quantifies where the pixel falls on the blue-yellow axis. This allows for color differences to be quantified and operations performed on them more easily than in the RGB space (by coupling the X and Y axes and giving each point a magnitude). This discretization of image data to matrix form can be a very powerful tool for data analysis.

High definition images contain a large volume of spatial data. For something such as a core, this can be very useful in examining it at a macro-grain scale. Clustering is a means by which groups of objects (in this case, pixels) can be distinguished from one another. This function assumes the objects in question have a location in space and partitions off similar objects in distinguishable groups, optimizing the clusters by a combination of maximizing distance between groups and minimizing differences within groups. Since the dataset has a location in space (defined by the pixel matrix) and is quantified by color, for this analysis, the algorithm separated out areas of the rock matrix by dominant color and proximity. The number of types of clusters desired is specified by the user. In this case, a k-means clustering function was used; three clusters were specified. These clusters represented the two-color extremes (white and black) and a third category to allow for algorithmic determination of ambiguous intermediate material via different intersections of color and proximity. In this way, the dominant mineralogy throughout the core could be spatially approximated and aligned with the performance data.

RESULTS

Time Frequency Domain

The accelerometer data, in addition to rough time vs. depth data, was collected for a 5-foot depth interval. For the interval mentioned in this paper, drilling for the first 30 in (762 mm) went poorly with a meagre rate of penetration and apparent drilling dysfunctions, as evident in Figures 4 and 5. The latter half of the drilling interval drilled with greater efficiency as evidenced by the ROP.

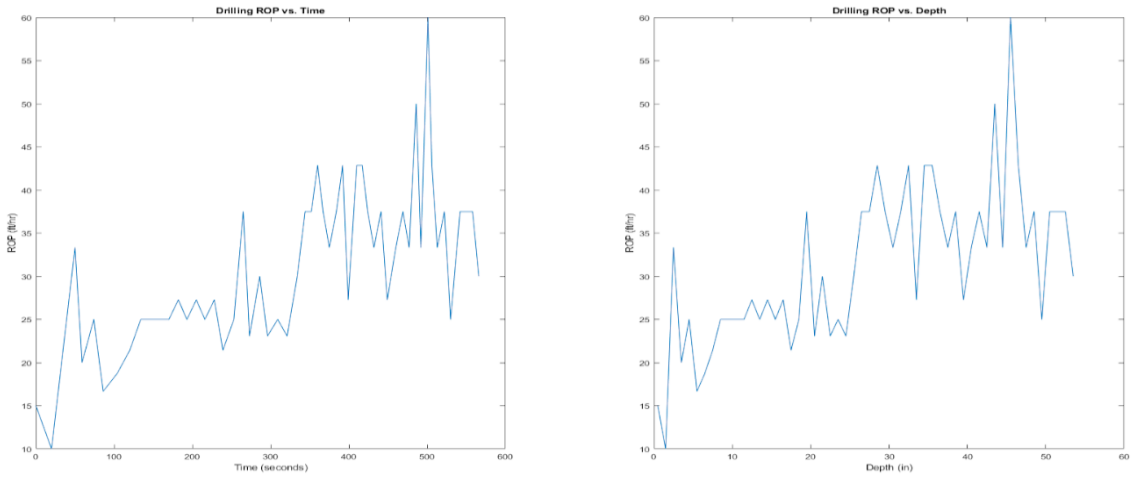


Figure 4: Rate of Penetration plotted vs. Time and Depth

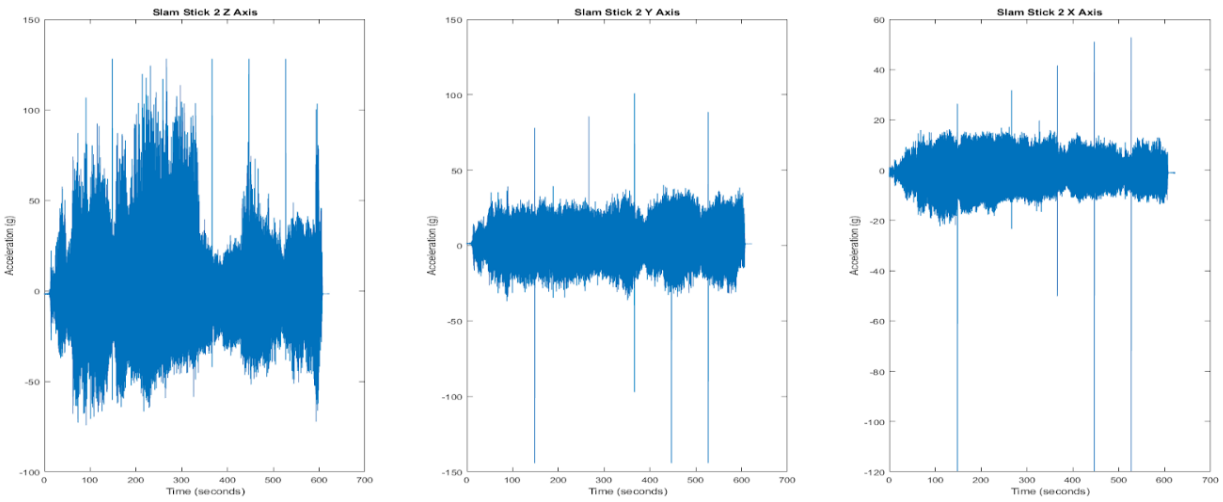


Figure 5: 20,000 Hz Accelerometer data collected while drilling

Figure 6 then presents this data in the frequency domain over time. The spectrogram is a fast Fourier transform taken from 5 second Hamming windows that sequentially overlap every 4 seconds. During the period of peak vibrations, called here as drilling dysfunction, many frequencies throughout the 0 – 5 kHz range are excited in the radial axis. When there are less drilling vibrations, the drilling is smoother with a higher rate of penetration. From the 6 to 10 minute mark during low dysfunction and "softer" mineral content, the rig drills faster and the peaks of vibration trend to increasing frequency. This is represented by the upward trend in the yellow colored peaks. While the data here is preliminary, the correlation between minerology, drilling performance, and drilling dysfunction shows promise for future research.

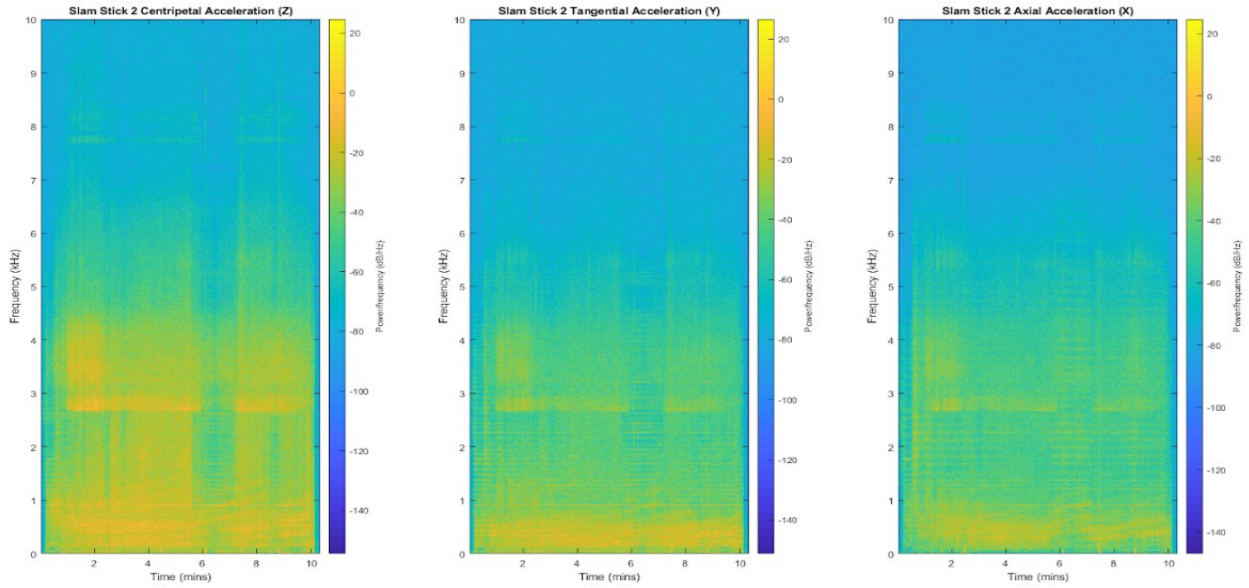


Figure 6: Accelerometer data collected while drilling in the frequency domain

One aspect conclusively determined from analysis in the frequency domain is the actual rotational speed, given that two of the accelerometers in the tri-axial accelerometer package were rotated more or less perpendicularly to the gravity vector. This was useful in identifying and characterizing torsional vibration modes such as "stick-slip." Often magnetometers can be used for such a purpose as well, given that the rotational direction is not likely parallel with the local magnetic field vector. In many circumstances, this may be preferred given the fact that magnetometers are less susceptible to noise while in motion. However, in practice, the magnetometer data proved to be unusable while rotating.

It is also worth mentioning that as a redundant method of depth correlation, the drill pipe was struck with a small hammer with every 10 in (254 mm) of depth drilled. These impulses were used to synchronize the ROP, depth, and accelerations data rather like the movie industry does when they slam the clapper at the beginning of a scene to synchronize the sound and visuals. This resulted in some of the periodic spikes evident in Figure 5.

Core Image Analysis

Along and intact core was chosen for our analysis. This was done so that severe fracturing or breakage in the core could be ruled out as having had a significant effect on the accelerometer data collected at that time. The panoramic image taken of this core was key in trying to correlate performance with rock matrix changes. By aligning accelerometer data with the image, performance was correlated with an estimation of lithology. It would have been impossible to determine exact lithology from an image; but in this case, lithology change was what was of value. This was tracked by observing changes in the pixel properties across the core image (color, brightness, et cetera).

The clustering function used was a basic "nearest neighbors" function. In this case, three clusters were chosen. Qualitatively, it was difficult to determine exactly how many distinctive visual regions the cores had; what was obvious was that light and dark cuttings were indicative of differing levels of drilling efficiency. The three clusters were meant to distinguish between light, dark, and intermediate core composition. The analysis was run multiple times so that a stochastic estimation of the model could be generated, since any given execution of the function would be different. Figure 9 shows the resulting estimate of mineral composition across the length of the core.

As shown in the figure, there is a significant variation between categories in the core. Qualitatively comparing this to the original image (Figure 3) shows a matching variation. The initial length of core varies between very dark components, lighter components, and large grains. The end of the core transitions into what appears to be a mostly lighter rock matrix. Figure 10 compares the tracked ROP and estimated percent composition of the darkest matrix cuttings across the core:

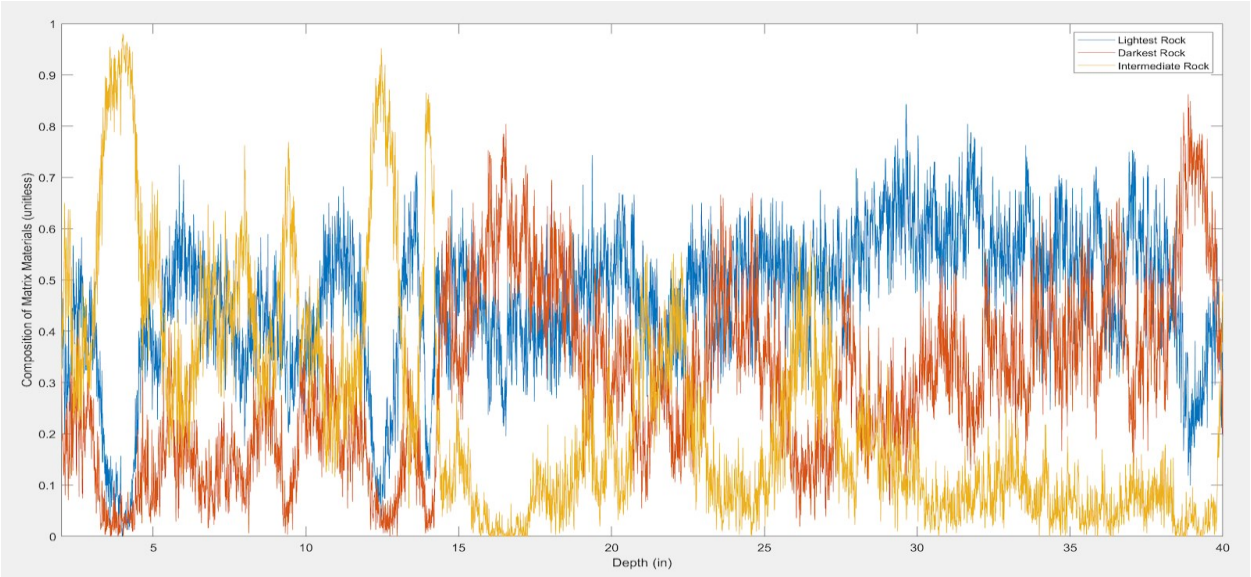


Figure 7: Estimated Composition of Rock by Depth

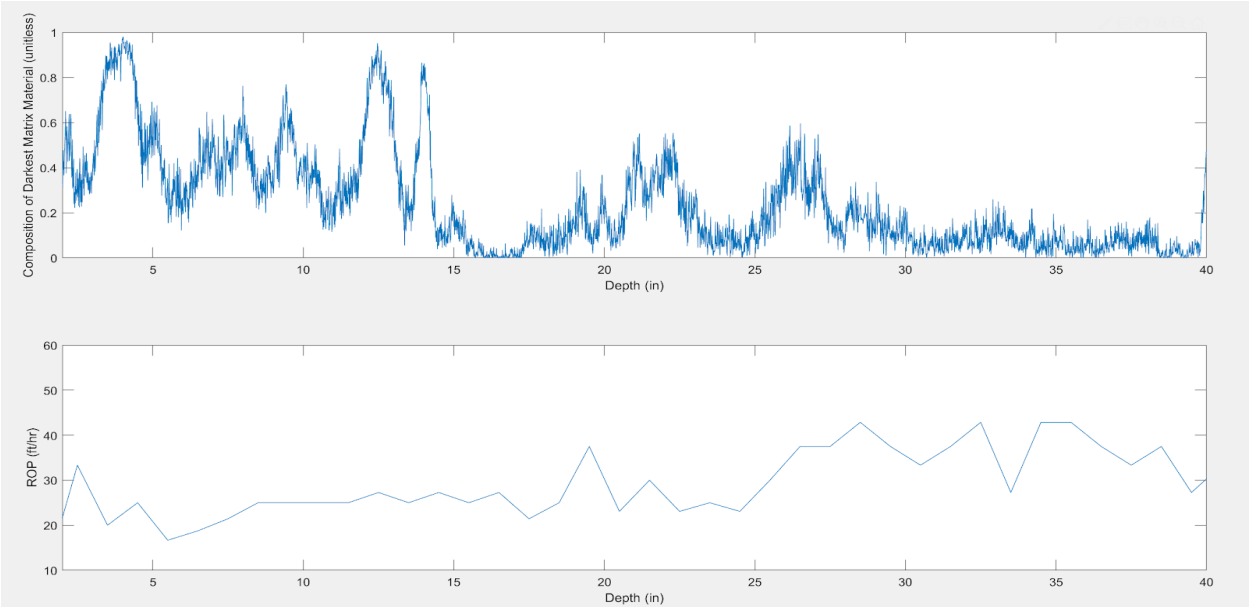


Figure 8: ROP as a Function of Estimated Darkest Cuttings Composition

The data corroborates what was observed; once the drill broke through the portion of rock with a significant amount of darker matrix material, around 25 to 28 in (635 to 711 mm), the ROP profile increased. During the initial drilling phase with material change and darker materials mixed in, the ROP was in general, slower.

Drill String Behavior

Attempts were made to determine string behavior on each subsequent rotation since the data was at a high enough resolution. Post drilling surveys indicated that a slight dog leg developed over the course of operations. This would be expected to show up in energetics data since the force distribution downhole could not be equal for this to occur. Figure 11 shows the change in acceleration from collection point to collection point tracked and displayed in polar coordinates. A slight skew at higher change magnitudes can be seen in the 270 to 360-degree range (orientation staring up the string at the top drive). The dog leg experienced matches the direction of skew:

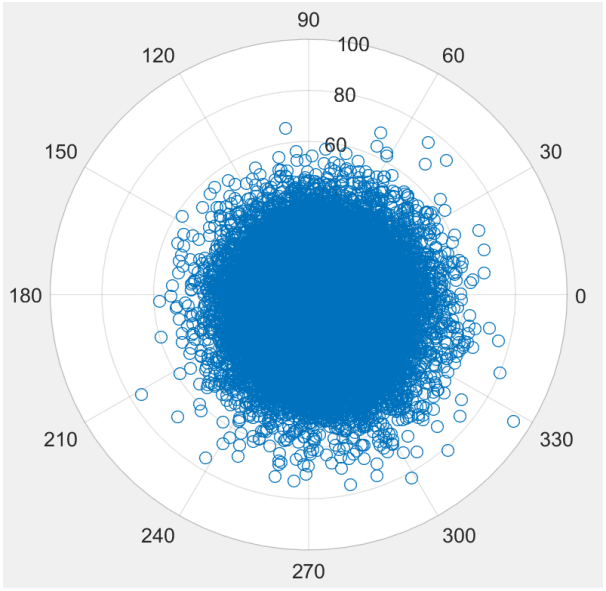


Figure 9: Y and Z Acceleration Change in Polar Coordinates

CONCLUSIONS

Changes in mineralogy can be reasonably detected and correlated using only data generated while drilling. The geology has direct effects on the bit-rock interaction and the drill string behavior such that it is possible to determine lithology, albeit crudely, from drilling parameters measured with high frequency sensors. The preliminary research currently shows a correlation enabling geological characterization from drilling data. While it can be quite simple to recognize instances of drilling dysfunction in the data presented here by looking at the accelerometer data in the time domain, either qualitatively by looking at the data over time, or by statistical quantification of acceleration averages and standard deviation, future work is needed to exactly quantify these empirical correlations. Even though correlations between rock mechanics and drilling dynamics remains empirical, this area of research opens the door for development of advanced artificial algorithms for control and optimization of drilling for oil and gas, geothermal, mining, space exploration, and any drilling application.

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