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Interpreting Drilling Data to Inform Deep Geothermal Reservoir Rock Mass Properties

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INTRODUCTION

In deep geothermal drilling, tens to hundreds of meters are often drilled without cutting retrieval and, therefore, without insight into the encountered rock conditions. The IDDP-1 (part of the Iceland Deep Drilling Project – IDDP) well drilled at Krafla in Northeast Iceland in 2009, for example experienced significant loss of circulation and thus blind drilling, especially in the deeper parts of the well, as it approached an unexpected magma chamber (Pálsson et al., 2014). The well required two side tracks before it was concluded that magma had been intercepted. To explore and develop near-magma geothermal energy (e.g. Eichelberger et al., 2020), certainty about the conditions encountered during drilling, especially in the near-magma area will be required. Downhole data, such as wireline logs and logging while drilling, provide the ability to interpret the lithology in the absence of cuttings, whereas drilling parameters could be used to supplement these to interpret the mechanical properties of the rock mass. Recent work developing machine learning-based lithology interpretations using wireline data (e.g. Hammoud et al, 2025) highlights the potential for improving the reliability of geological modelling using down-hole geophysical data. Conversely, studies using drilling parameters (eg. Millett 2016; Wyering et al. 2017) to interpret the rock mass remain rare.

Hammoud et al. (in prep) have developed a method to link drilling parameters with wireline log data to interpret the rock mass, with particular focus on its effect on drillability and well stability. We apply the method from Hammoud et al. (in prep) to the drilling and wireline logging data from IDDP-1. We supplement this with drilling details from the drilling reports and methods developed by Villeneuve (2008) to link tunnelling boring machine parameters to rock mass conditions. Key variations in drilling parameters are used to interpret the drillability and well stability in different rock masses (e.g. poor drillability, fractured rock), aiming to determine if this method allows interpretation of the rock mass near the magma chamber. We show that different rock masses have distinct signatures of processed drilling parameter combinations, and that lithology-related effects can be differentiated from fracturing effects, and that the changes in the rock mass near the magma are identifiable in the drilling data.

1 METHODS AND RESULTS

The key drilling parameters that relate to rock mass characteristics are the rate of penetration (ROP in m/hr), rotational speed (RPM in rev/min), weight on bit (WOB in ton) and torque (T in dNm). The drilling parameters from the lower 800 m of the IDDP-1 well (see Mortensen et al., 2014) were first preprocessed according to Hammoud et al. (2026) to remove signal changes related to operations, such as adding singles to the drilling string, and then averaged over 1 m lengths (Figure 1). These were then combined with a series of electrofacies for the IDDP-1 well from Hammoud et al. (2025)., which is based on wireline logs and validated by drilling cuttings descriptions. The electrofacies descriptions were assigned to each data point in the pre-processed drilling dataset.

An approach similar to Hammoud et al. (in prep) was then used to plot the PR-WOB graphs in Figure 2, where PR is the penetration rate, which is the ROP normalized by the RPM. The data are presented according to the presence of a motor in the BHA, which affects the PR value because a BHA with a motor will have a faster drill bit rotation than one without, even for the same string rotation velocity. The figures are also colored according to the dominant electrofacies identified by Hammoud et al. (2025) over these intervals. Note that these are dominant electrofacies, and thin intervals of other electrofacies are present in the intervals. The focus of the interpretation developed by Hammoud et al. (in prep) is also applied here, where porosity, strength, drilling parameters and lithology are the key descriptors used to assess drillability.

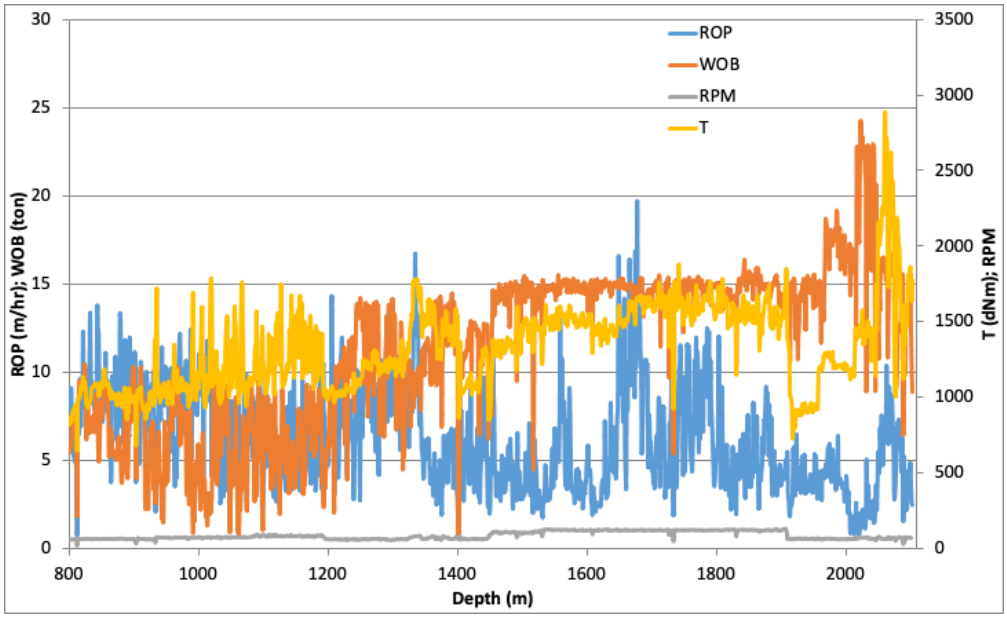


Figure 1. Drilling parameters for IDDP-1 pre-processed according to Hammoud et al. (2026).

For BHA 1 the performance is centered on WOB of approximately 8 tons (Figure 2a), decreasing to 6 tons where the drilling report (Mortensen et al., 2010) describes increasing torque, which was addressed by decreasing WOB and increasing RPM (visible at around 1000 m depth in Figure 1). Hammoud et al. (in prep) found that, for wells from Theistareykir, rocks with high porosity can have low strength, resulting in "easy" drilling. This is also evident for BHA 2 (Figure 2a), where the performance is more narrowly focused on WOB of approximately 12 tons with a clear distinction between the PR of the high porosity mafic and intermediate intervals (ranging up to nearly 4 mm/rev) and the low porosity mafic intervals (restricted to less than 2 mm/rev), highlighting more difficult drilling conditions when the porosity is lower. Similarly, for BHA 3 the WOB is very narrowly held at 15 tons (Figure 2b), with the PR in the low porosity mafic interval mostly less than 2 mm/rev and medium porosity mafic intervals with even lower PR of less than 1.5 mm/rev.

BHA 4 has two clear WOB ranges associated with a particularly difficult to drill, low porosity felsic interval directly below the contact with the low porosity mafic interval. In this interval the WOB is over 20 tons (Figure 2b) and PR is less than 1 mm/rev, differentiated from a WOB centered on 15 tons in the overlying low porosity mafic interval with PR up to 2 mm/rev, and the underlying low porosity felsic material below 2044 m depth with PR over 1 mm/rev. BHA 5 is completely in the lower low porosity felsic rock mass (Figure 2b), with a varying WOB centered on 12 tons and PR up to 2 mm/rev. The combination of increased PR and low WOB in this lower low porosity felsic interval would suggest as easy to drill rock, however the porosity and lithology descriptions do not support this, especially when compared with the overlying hard-to-drill low porosity felsic interval.

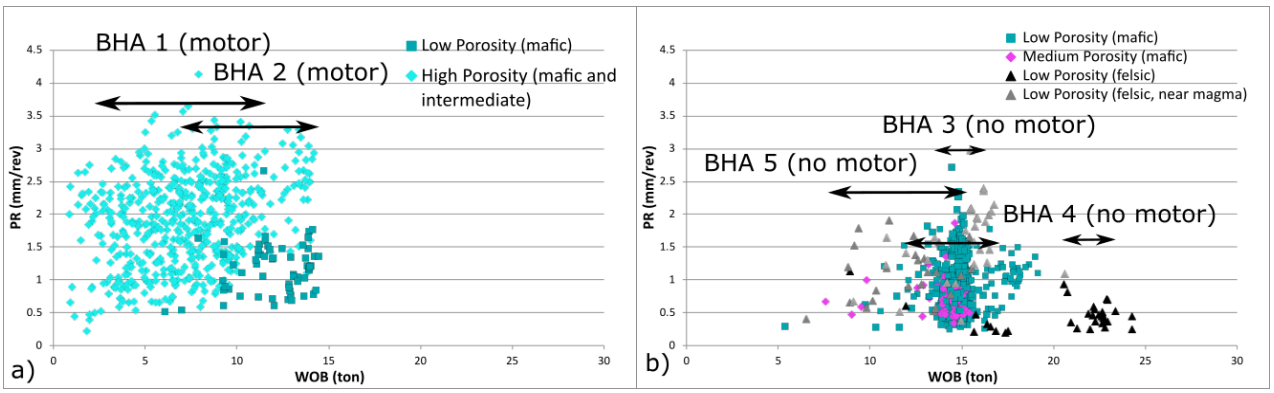


Figure 2. Penetration rate (PR) for the IDDP-1 well, divided into different borehole assemblies (with and without motor) and into the different electrofacies from Hammoud et al (2025). a) upper portion of the well (800-1400 m depth) dominated by high-porosity mafic rocks and BHAs using a motor; b) lower portion of the well (1450-2102 m depth) dominated by low-porosity mafic and felsic rocks and BHAs without a motor.

The interpretations using the PR-WOB graphs are supplemented by two performance indices developed by Villeneuve (2008) for tunnel boring machines, and a third index developed for well drilling. These indices allow comparison of drilling performance for different operating conditions (changes in RPM or WOB) and, to some extent, for different borehole assemblies (BHAs). The first index is the penetration index (PI):

$$PI = \frac{PR}{WOB} = \frac{\mathrm{ROP}}{RPM \cdot WOB} \quad (1)$$

The second index is the net advance rate (NAR) which is the drilling speed averaged over 1 m length, including times when ROP is 0, but RPM is > 0 (see Villeneuve et al. (2023) for details)

A third index, first introduced in Villeneuve et al. (2023) is the torque index (TI):

$$TI = \frac{T}{RPM} \quad (2)$$

In Villeneuve et al. (2023) these indices were plotted together to highlight how bit-rock interaction affects drilling performance. In this work we provide a refined interpretation of the impacts of rock mass conditions on drillability based on the advances made by Hammoud et al. (in prep).

Figure 3 provides two types of graphs of the performance indices. In the first set (Figure 3a and b), the PI is plotted versus the NAR, while in the second set (Figure 3c and d), the TI is plotted against the NAR.

The solid lines highlight the ideal relationship for each BHA between the two plotted indices, where PI and NAR both increase together as drilling becomes easier, whereas TI remains constant regardless of NAR. Each BHA has a slightly different ideal relationship based on its efficiency in terms of penetration and torque. The data points that deviate from the ideal relationship are interpreted as representing changes in either operations or in geological conditions. In Villeneuve et al. (2023) the interpretation in the upper portion of the well (1266-1399 m depth) and the lower portion of the well (1907-2102 m depth) was that stoppages due to unstable well conditions were causing the low NAR-high PI deviations from the ideal relationship.

With the addition of data from the upper portion of the well and a better understanding of the geology via the lithofacies from Hammoud et al. (2025) we can now interpret the NAR-PI deviations in Figure 3a as being the result of particularly drillable intervals in the highly porous mafic and intermediate rocks, resulting in lower WOB for the same ROP and RPM, thus dramatically increasing PI. In these intervals, the TI does not significantly deviate from the ideal relationship except for a few data points (each represents a 1 m interval).

The interpretation from the lower part of the well remains consistent with the interpretation from Villeneuve et al. (2023). Of particular interest is the comparison of the data from BHA 3 and those from BHAs 4 and 5. The data for PI and TI from BHA 3 nearly all fall on the ideal relationship line, suggesting that the BHA was ideally suited to drilling in these rocks and no issues occurred, which is also reflected in the drilling report (Mortensen et al., 2010). For BHAs 4 and 5, there is considerable deviation from the ideal relationship for both PI and TI, especially in the low porosity felsic material below 2044 m depth. Here the PI is high compared to the resulting NAR due to frequent stops. This is also reflected in the TI, where the torque increases, likely due to increased resistance at the drill bit from a fractured rock mass, the switch from drilling mud to water and hole inclination. The drilling report (Mortensen et al., 2010) notes that fractured zones are present with loss of circulation, along with a twist-off without warning between BHAs 4 and 5, suggesting that some of the stops are associated with clearing of fragmented rock from the hole bottom. The combined interpretation from the PR-WOB graphs and the NAR-PI and NAR-TI graphs supports the interpretation of decreasing rock mass strength arising from fracturing, leading to a combination of easier drilling (low WOB with high PR) and higher resistance to rotating the drill bit and string (high TI). This differentiates the low porosity felsic interval which, while easier to drill because of fracturing, causes operational issues, from the high porosity mafic interval, which was also easy to drill, but did not lead to operational issues.

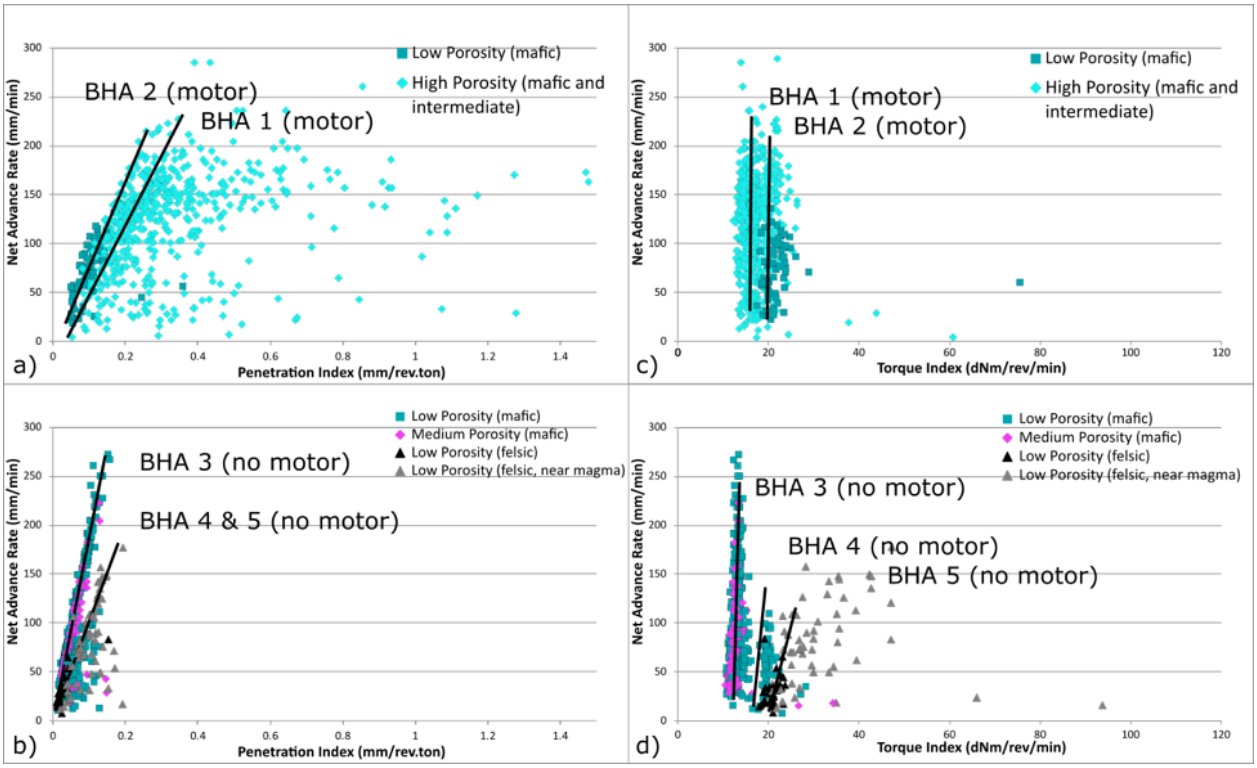


Figure 3. Net advance rate (NAR) versus penetration index (PI) and torque index (TI) for the IDDP-1 well, divided into different borehole assemblies (with and without motor) and into the different electrofacies from Hammoud et al (2025). a) and c) upper portion of the well (800-1400 m depth) dominated by high-porosity mafic rocks and BHAs using a motor; b) and d) lower portion of the well (1450-2102 m depth) dominated by low-porosity mafic and felsic rocks and BHAs without a motor.

2 DISCUSSION AND CONCLUSION

This work demonstrates how drilling parameter indices can complement interpretations of drilling data to differentiate between intervals of difficult vs easy to drill rock, intervals of particularly drillable rock, and intervals of fractured rock. The data from BHAs 1 and 2 shows the role of porosity in the drillability of a rock mass, where high porosity lithofacies are easier to drill than low porosity lithofacies (as also shown in Hammoud et al., in prep). Similarly, BHA 4 highlights how an interval of low porosity felsic rock was very difficult to drill, requiring high WOB for relatively low PR compared to overlying low porosity mafic rock.

The data from BHA 3 highlight a 450 m thick interval of rock that was reasonably consistent: very little variation in the PI, TI and WOB, with PR likely affected by the strength of the material. It is not clear why the medium porosity mafic material has lower PR than the low porosity mafic, although this might arise from the generalization of the lithofacies classes used in this paper, or some physico-mechanical reason that requires more investigation. Further work is required to more precisely correlated lithofacies to drilling performance indicators.

Finally, the data from BHAs 4 and 5 reflect the impact of fractures on drilling by lowering the WOB required, even for the same lithofacies (in this case the low porosity felsic rock). The key differentiator between easy to drill intact rock (as observed in the high porosity mafic rock) and a fractured rock mass (as observed in the low porosity felsic rock near the magma) is the increase in torque in these intervals associated with high PR and, thus, high PI.

The combinations of performance indices PI, NAR and TI, along with PR and WOB and the lithofacies from wireline logging allow a mechanical interpretation of the lower part of the IDDP-1 well nearest the magma chamber. It provides an additional source of evidence to interpret the rock mass below 2044 m as being fractured. The causes of the fracturing range from magma emplacement processes (as proposed by Kennedy et al., 2021) to quenching and dilation of the hot rock mass by cold drilling fluids (as shown experimentally by Siratovich et al., 2015). More near-magma drilling is necessary to truly understand the nature of a rock mass near a magma chamber, but this work highlights the tools that could be deployed to interpret this rock mass, and possibly eventually anticipate the arrival of the drill bit at the rock-magma interface.

The impacts of this research reach beyond understanding the magma encounter at IDDP-1. The combined geological interpretation from the wireline logging and cuttings descriptions as well as drilling data, can provide detailed models of the subsurface for exploration, drilling optimization, well completion and reservoir operation. This research also shows that care is needed to understand the operating conditions and not only preprocess the data (as in Hammoud et al., 2026) and only compare data collected under similar conditions (as in the separation according to BHA and according to the presence of a motor).

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REFERENCES

Eichelberger, .J, Kiryukhin, A., Mollo, S., Tsuchiya, N., Villeneuve, M. Editorial: Exploring and Modeling the Magma-Hydrothermal Regime *Geosciences Special Issue Exploring and Modeling the Magma-Hydrothermal Regime* **10(6)**, (2020), 138.

Hammoud, A., Villeneuve, M., Caspari, E., Mortensen, A.K.: From logs to layers: Framework for interpreting subsurface facies in Iceland geothermal reservoirs. *Geothermics*, **133**, (2025).

Hammoud, A., Villeneuve, M., Caspari, E., Mortensen, A.K., El Kasti, K.: The Overlooked Foundation: The Crucial Role of Preprocessing in Enhancing Rock Unit Characterization, *Proceedings,* 8th World Geothermal Congress, Calgary, Canada (2026).

Hammoud, A., Villeneuve, M., Caspari, E., Mortensen, A.K., El Kasti, K.: Electrofacies-Guided Interpretation of Drilling Responses for Volcanic Facies in Theistareykir Geothermal wells. (In prep).

Kennedy, B.M., Heap, M.J., Burchardt, S., Villeneuve, M.C., Tuffen, H., Gilg, H.A., Davidson, J., Duncan, N., Saubin, E., Gestsson, E.B., Anjomrouz, M., Butler, P.: Thermal impact of dykes on ignimbrite and implications for fluid flow compartmentalisation in calderas. *Volcanica*, **5(1)**, (2022) 75–93.

Millett, J.M., Wilkins, A.D., Campbell, E., Hole, M.J., Taylor, R.A., Healy, D., Jerram, D.A., Jolley, D.W., Planke, S., Archer, S.G., Blischke, A.: The geology of offshore drilling through basalt sequences: Understanding operational complications to improve efficiency. *Mar Petrol Geol,* **77**, (2016), 1177–1192.

Mortensen, A.K., Egilson, þ., Árnadótti, S., Gautason, B., Sigurgeirsson, M.Á., Ingimarsdóttir, A., Tryggvason, H., Gunnarsson, H.S., Jónsson, R.B., Sveinbjörnsson, S., Þorsteinsson, E. Krafla – IDDP-1. *Drilling completion and geology report for drilling stage 3*, Prepared by Iceland GeoSurvey (ÍSOR) for Landsvirkjun, (2010).

Mortensen, A.K., Egilson, þ., Gautason, B, Àrnadóttir, S., Guðmundsson, À. Stratigraphy, alteration mineralogy, permeability and temperature conditions of well IDDP-1, Krafla, NE-Iceland. Geothermics **49**, (2014), 31-41.

Pálsson, B., Hólmgeirsson, S., Guðmundsson, Á., Bóasson, H. Á., Ingason, K., Sverrison, H., and Thórhallson, S.: Drilling of the well IDDP-1. *Geothermics*, **49**, (2014), 23-30.

Siratovich, P.A., Villeneuve, M.C., Kennedy, B.M., Cole, J.W., Begue, F.: Saturated Heating and Quenching of Three Crustal Rocks and Implications for Thermal Stimulation of Permeability in Geothermal Reservoirs. *International Journal of Rock Mechanics and Mining Science*, **80**, (2015), 265-280.

Villeneuve, M.C.: Hard rock tunnel boring machine penetration test as an indicator of chipping process efficiency. *Journal of Rock Mechanics and Geotechnical Engineering*, **9(4)**, (2017), 611-622.

Wyering, L.D., Villeneuve, M.C., Kennedy, B.M., Gravley, D.M.: Using drilling and geological parameters to estimate rock strength in hydrothermally altered rock–A comparison of mechanical specific energy, R/NW/D chart and Alteration Strength Index. *Geothermics,* **69**, (2017), 119-131.