Informing deep geothermal reservoir rock mass properties from drilling data - experience from Krafla, Iceland

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ABSTRACT: During geothermal drilling it is important to know the quality of the rock mass for well completion, mud weight selection, interpreting features of interest, to characterise the subsurface in the absence of core. In deep geothermal drilling, tens to hundreds of meters are drilled without cutting retrieval and, therefore, without insight into the rock mass. Wireline logs are commonly used to interpret the subsurface, however, these data are typically collected after drilling an interval. Despite their increasing development, studies using drilling parameters and logging-while-drilling to interpret the rock mass in high-temperature, deep geothermal environments remain rare. In this paper we present a method where the drilling parameters from previous drilling at Krafla are used to assess the quality of the rock mass, with particular focus on its effect on drillability. This demonstrates how methods from geotechnical drilling and tunnelling can inform geothermal drilling.

Keywords: Supercritical fluid, drilling performance, ROP, WOB, fractures.

1 INTRODUCTION

Knowing downhole rock mass properties is important for a number of development and operational aspects of reservoir fluid extraction. During drilling for reservoir development or exploration, it is important to know the quality of the rock mass for selecting shoe placement locations and selecting mud weight (Zoback 2007; Gholami et al. 2013), interpreting whether the drilling is approaching a feature of interest, for example the Alpine fault in New Zealand (Townend et al. 2009; Toy et al. 2017) or a magma chamber at the Krafla geothermal field (Mortensen et al. 2014; Pálsson et al. 2014; Eichelberger 2019), or simply to characterise the subsurface in the absence of core. Many studies, mostly scientific drilling and some oil and gas exploration, have used wireline logs to interpret the subsurface in volcanic rocks (Jerram et al. 2019 and references therein), however direct studies using drilling parameters in these environments remain rare (eg., Millett 2016; Wyering et al. 2017). Developments of logging-while-drilling for geothermal drilling are ongoing (e.g., Radzinski et al., 2005), but challenges regarding high temperature and sensor placement close to the drill bit remain.

For geothermal well operations, identifying feed zones and high permeability zones is crucial for targeting the production intervals. Among the numerous challenges for geothermal drilling is the common occurrence of major or total loss in drilling fluid circulation, often right above major feed zones (Reinsh et al. 2017). These intervals of highly permeable, fractured rock mass appear to respond poorly to sealing by cement or recovering circulation using lost circulation materials (LCM are a mixture of materials that are pumped into the well to fill in the fractures such as walnut shells, fibrous material, cellophane flakes and diesel/bentonite (Azar & Robello Samuel 2007)). Conversely to oil and gas drilling, where it is not common practice to continue to drill in these zones (Azar & Robello Samuel 2007), in geothermal drilling dozens to hundreds of meters in crucial geological formations are drilled without cutting retrieval and, therefore, without direct insight into lithology at these depths, hence the commonly used term: blind zones.

Relating drilling parameters to rock properties can be challenging. Drilling parameters have limited precision: weight is measured in tonnes, not kg; rotary speed of the drill string, in revolutions per minute (RPM) is per minute, not per second; rate of penetration (ROP) is per hour. In addition, a multitude of drilling challenges could cause unknown side-track deviations and multiple changes in the bottom hole assembly (BHA), which includes the drill bit, motors, collars and stabilizers. In blind intervals without cuttings or wireline logs these challenges are significantly increased.

In this paper we propose a method where the drilling parameters are used to assess the quality of the rock mass. We use the drilling reports and drilling data from the IDDP-1 well drilled at Krafla in 2009 (see Mortensen et al. 2014; Pálsson et al. 2014) to develop and test this method based on recent work into relating drilling (Wyering et al. 2017) and tunnelling boring machine parameters to the rock mass (Gong et al. 2007; Frenzel et al. 2012; Villeneuve 2017).

2 METHODOLOGY

2.1 Drilling parameters

A range of parameters are recorded during drilling, at a regular frequency, e.g., 10 seconds (Archer et al., 2005; Millett et al., 2016; Wyering et al., 2017). We use drilling parameters related to drill bit advance (rate of penetration, revolution per minute, torque, weight on bit) to develop interpretations of the subsurface. Bottom hole depth (MD) is measured from the drill rig deck, in meters (m).

The ROP of the drill bit into the rock at the bottom hole, in meters per hour (m/h), is mostly affected by rock mass strength (e.g., Kahraman et al. 2003), where it is generally accepted that the stronger the rock mass, the lower the ROP (Azar and Robello Samuel 2007). The in-situ strength of the rock mass can be affected by changes in the pore pressure, as well as drilling induced fracturing, thereby also affecting the ROP. The cleanliness of the bottom hole will also affect ROP, whereby uncleared cuttings can reduce drill bit efficiency and decrease ROP.

The RPM, and the weight on bit (WOB) can be controlled from the surface to achieve the desired ROP. For efficient drilling (higher ROP) in a rock unit with consistent (constant or uniform) strength, either higher WOB or higher RPM are needed. Comparing WOB, ROP and RPM provides basis for interpreting drill bit-rock interaction.

Torque (T), applied by the drill rig to rotate the drill string at the desired RPM, in decinewtonmetre (dNm), is influenced by drill configuration and operation, such as hole size, depth, BHA, drill pipe, RPM, and mud properties, as well as rock mass properties (Azar and Robello Samuel 2007). Typically, with constant WOB and RPM, a change in rock mass properties causes torque to vary.

Loss of circulation of drilling fluids into the rock mass, in litres per second (L/s), is considered total when 50 L/s is reached (Azar & Robello Samuel 2007). This could be an indication of a fractured rock mass, representing a feed zone or potential for wellbore instability. When the cuttings are no longer being returned to the surface, the operations are referred to as blind drilling.

2.2 Drilling parameter analysis

Many studies that use drilling data, usually ROP, and cuttings to interpret the subsurface compare these parameters to each other along a depth profile (Archer et al. 2005; Millett et al. 2016). Time profiles allow rock/drill interactions to be observed when the drill bit is stuck at a particular depth, which would otherwise be overprinted on the depth profiles (Figure 2). Because the parameters are interrelated, and their response could be due to a number of geological or operational changes, simply using one parameter to interpret the rock mass may not provide the best interpretation. Similarly, to make the drilling data comparable at different intervals and for different projects, where the operator may be selecting different drilling parameters or using a different bottom hole assembly (BHA), specific penetration rate (PRs), specific weight on bit (WOBs) and specific torque (Ts) should be used. Bingham (1964) provides a detailed argument for normalising ROP and WOB. These, and the normalisation for torque, are obtained as follows:

$$PR_{\mathrm{S}} = \frac{ROP}{RPM} \tag{1}$$

$$WOB_{\mathrm{S}} = \frac{WOB}{drill\ bit\ diameter} \tag{2}$$

$$T_{\mathrm{S}} = \frac{T}{RPM} \tag{3}$$

For the analyses in this research the units for PR_S, WOB_S and T_s are mm/rev, tonne/mm and dN/rev/min, respectively. More complex drilling logs can be made by combining these normalised data. In tunnel boring machine (TBM) studies, one means to quantify the ease of excavation is the Penetration Index (Villeneuve, 2017 and references therein), which is the specific penetration rate normalised by the normalised force applied by the TBM to achieve this rate. For drilling, we propose that the Penetration Index is calculated as follows:

$$PI = \frac{PR_S}{WOB} \tag{4}$$

The PI has units of mm/(rev.tonne) and can be computed either instantaneously using the normalised values, or using data averaged over discrete length scales (for example 1 m) or timescales (for example 60 seconds). Drilling is efficient (easy) when PI is high, whereas drilling is inefficient (tough) when it is low (Villeneuve 2017).

To quantify the impact of unstable rock masses on TBM utilisation, Villeneuve (2008; 2017) developed the net advance rate (NAR) in length/time, which takes into account the distance travelled during any time that the TBM head is turning. NAR can be derived for drilling data on a selected length scale, for example 1 m. In this case, for every 1 m of advance, the time taken to achieve that advance (including time when the WOB is 0 but RPM is > 0) is used to compute a net advance rate. This provides three end member scenarios: NAR is high because the rock is easy to excavate, NAR is low because the rock is tough to excavate, NAR is low because the utilisation is low for drilling or excavation reasons (i.e. drill bit balling, bottom balling, vibrations, poor hole cleaning, or bottom hole instability such as fractured rock; e.g., Tveit and Berg, 2016). In particular, we are interested in distinguishing between strong and weak, as well as fractured rock masses.

To determine the NAR and PI along a borehole, the data from the data acquisition system must first be processed to remove data confounded by operations, such as adding string, pulling out of hole (POOH), running into hole (RIH), fishing for lost BHA components. In general, data can be processed in a spreadsheet using filters, however some aspects must be processed manually by observing indicators such as height of drive changes (adding string). Once operational confounders have been removed, filters remove occurrences when RPM is ≤ 0. For NAR, Pivot Tables in Excel extract the total time required to excavate our length scale of interest, for this research 1 m. NAR is then calculated as the length, in mm, divided by the time extracted by the Pivot Table. For instantaneous PI, a second filter removes all occurrences when WOB = 0 and ROP = 0. A second Pivot Table then determines average PI over the same length scale as for NAR. NAR and PI can then be plotted along the borehole depth (Figure 1) or as a cross-plot against each other (Figure 2).

3 DRILLABILITY ANALYSIS

Key variations in both normalised (PR_s, WOB_s, T_s) and processed (PI, NAR) parameters are used to interpret the drillability in different rock masses. Major variations highlighted on these large-scale drilling logs vs depth can be combined with the drill cuttings to determine the impact of lithology changes on drillability, as well as other indicators of down-hole conditions, such as circulation loss and feed zones, interpreted from in flow rate changes (Figure 1). Of particular interest is the link between areas over which the drilling analysis indicates “blocky ground” with circulation loss and feed zones.

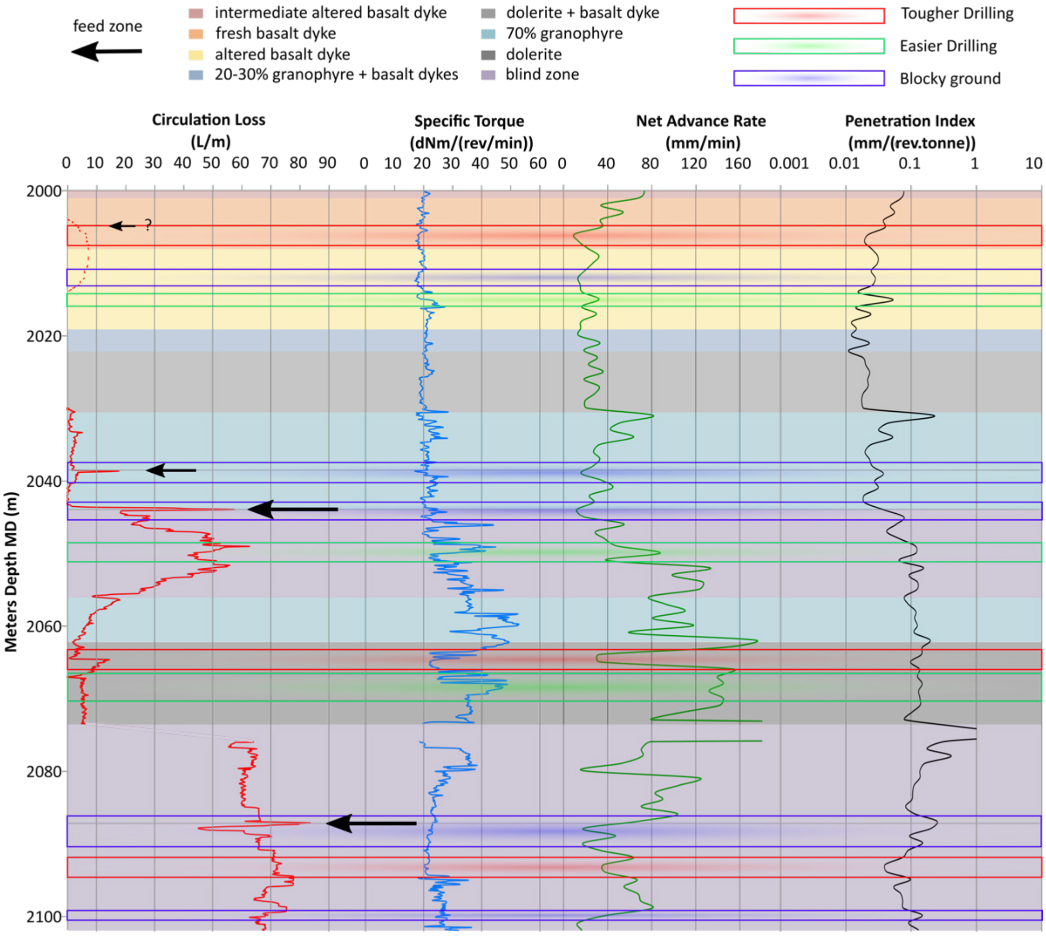

Figure 1. Depth log of processed drilling data, with lithology from cuttings, circulation loss and feed zone interpretations from Mortensen et al. (2010) to interpret drillability in the bottom 100 m of IDDP-1 leg 1.

Plotting PI and NAR against each other provides the ability to interpret the drillability of a rock interval for a given BHA more clearly than using depth profiles. Villeneuve (2008) proposed zones on PI versus NAR graphs for TBMs and we apply a similar interpretive framework for drilling. The linear PI-NAR relationship in the 1450-1907 mD interval represents a continuum of easier to tougher drilling related to the efficiency of cuttings generation at the drill-rock interface (Figure 2a). During easier drilling, the drill bit efficiently generates and propagates fractures, creating chips, and is associated with rock low strength and brittle rock (Villeneuve, 2017), and the ROP, and therefore PI and NAR, are high (Figure 2a). During tougher drilling the drill bit does not efficiently generate and propagate fractures, resulting in grinding of very strong rock, drill bit balling, bottom balling or poor hole clearing, and the ROP, and therefore PI and NAR, are low (Figure 2a). This relationship will be different for each unique BHA configuration (different depth intervals and solid and dashed lines in Figure 2). Intervals that plot off the linear relationship are interpreted as areas of increased fracture density or short intervals of weaker rock. In these intervals the ROP is high for a given WOB (high

PI) because pre-existing fractures aid in chipping or weaker rock excavates more easily, but the time required to advance the bit is also high (overall low net advance rate, Figure 2b) because of decreased utilisation dominated by stoppages. These graphs highlight changes in conditions, for example that drilling over the interval before (1266-1339 mD) a feed zone at 1339 mD is easier than the drilling over the interval after (1340-1399 mD) the feed zone.

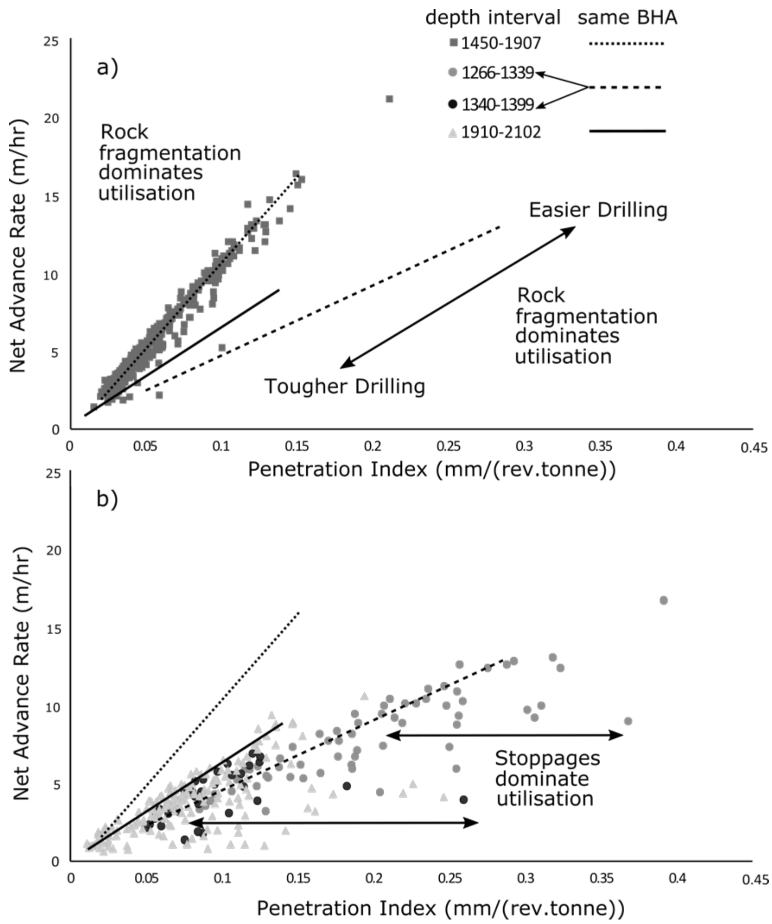

Figure 2. PI versus NAR graphs at 1 m intervals for the a) 1450-1907 m depth interval of IDDP-1 leg 1, showing a clear linear relationship where rock fragmentation processes at the drill bit – rock interface dominate utilisation; b) 1266-1399 m depth (split into before and after a feed zone at 1339 m depth) and 1959-2102 m depth intervals of IDDP-1 leg 1, showing both a clear linear relationship where rock fragmentation processes at the drill bit – rock interface and stoppages dominate utilisation.

4 CONCLUSIONS AND RECOMMENDATIONS

We present a methodology for analyzing well drilling data using methods developed for evaluating performance of tunnel boring machines. The approach of characterizing drilling data by the drillability index (DI), which relates penetration to applied force, as well as net advance rate (NAR), which relates penetration rate to duration of active drilling, allows an assessment of the interaction of the drill bit with the rock mass. Based on previous work regarding interaction of tunnel boring machines with rock masses, we provide interpretations of the rock masses encountered by the drill bit. We have shown that the DI and NAR combination, along with torque, can provide insight into the locations of fractured rock masses, as confirmation for feed zones that also show increased loss of circulation. Ongoing work is aimed at validating this method with geological characteristics obtained from cuttings, wireline logs and geological models. The development of logging-while-drilling technologies for high-temperature wells also presents the possibility to interpret drilling and wireline log data simultaneously, during drilling.

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