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ANALYSIS OF BIT OPERATIONS: LAGUNA COLORADA GEOTHERMAL PROJECT, BOLIVIA

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ABSTRACT

Twenty-seven years ago the National Electricity Company of Bolivia (ENDE) drilled four wells successfully in the Sol de Mañana geothermal field. The wells confirmed the geothermal power potential of the field and with a loan, financed by the Japanese International Cooperation Agency (JICA), new wells are planned to be drilled in order to develop the project's first stage of 50 MW. Drill bit selection and operation are essential factors for getting good performance and avoiding problems during drilling activities. Multiple linear regression (also called Bourgoyne and Young method) and Mechanical Specific Energy were the methods applied on data from the Icelandic well RN-16, finding that a theoretical research could be useful in improving drilling time and better identify when problems or dysfunction is occurring. Both methods evaluate the effects of the rate of penetration (ROP), such as: rock strength and drill ability, differential bottom hole pressure, mud flow rate, weight on bit, revolution per minute. Finally, rock strength surveys were found to be a useful tool for making bit selection more efficient, especially in new fields.

1. INTRODUCTION

1.1 Location and weather description

The Laguna Colorada Geothermal Project is located on the southwest zone of Potosi-Bolivia at a high altitude (4900-4980 m a.s.l.) between the meridians 57°26´- 69°38´western longitude and 9°38´- 22°53´ southern latitude. It is inside the Occidental zone of Cordillera de los Andes, located close to the subduction zone between the South-American and Nazca Plates. The weather is relatively arid with average temperature of 0.8°C, annual rainfall between 250-300 mm and strong winds at 15 m/sec (approx.) predominantly during the afternoon.

1.2 Background

The National Electricity Company of Bolivia (ENDE) has been developing the Laguna Colorada geothermal project, which includes the Sol de Mañana field, where geoscientific exploration has been performed and five geothermal wells drilled. Four of the drilled wells have been tested, achieving an estimated power capacity of 7 MW_e per well. Through numerical reservoir simulations it has been estimated that the Sol de Mañana field is able to generate 100 MW_e with a single-flash power plant.

The reservoir evaluation indicates a high probability of the reservoir being able to sustain a 50 MW power plant, with a possible extension to 100 MW (ENEL, 1991). In light of these promising results, ENDE is planning to drill six production wells (until 2,000 m of depth) and three reinjection wells. This is an analysis of methods for optimizing the bit performance and purpose their application on these new geothermal wells. To this end, data from the Sol de Mañana drilling data was processed and analysed. Furthermore, data from drilling at Reykjanes geothermal field was analysed to apply these methods in a near future.

1.3 The geothermal field and wells (SM-1 and SM-2)

This field is located on the Miocene-Pleistocene Andin volcanic arc and is covered by an extensive dacitic ignimbrite and andesitic lava (Ramos, 2015). Geoscientific exploration was done on Sol de Mañana and volcanic rock, fractured systems, hot springs, hot water, and other factors identified.

According to geochemical studies the geothermal fluid was classified as mature water and the geothermometers indicated reservoir temperatures in the range of 280°C.

The geophysical surveys observed an intermediate conductive layer, this layer has notable variations of thickness (TERANOV-CGG, 2014). The resistivity at deep levels indicates good signals of the geothermal resource.

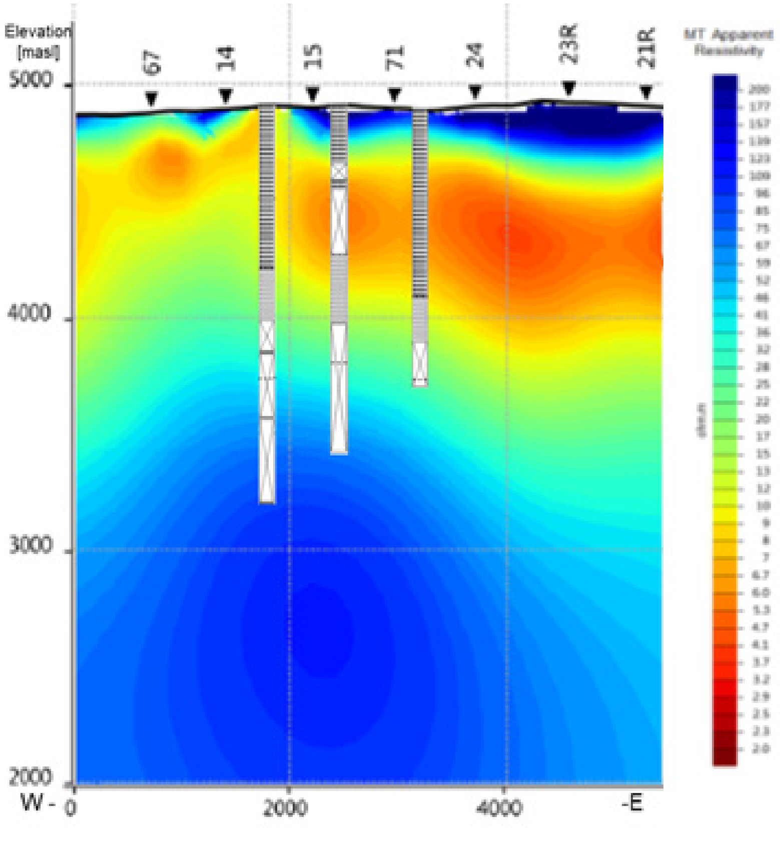

FIGURE 1: Resistivity cross-section and lithology correlation of the Wells SM-1, SM-2 and SM-5

On Sol de Mañana field five wells were drilled, four of them proved to be production wells (SM-1, SM-2, SM-3 and SM-5) finding a reservoir temperature of 245°C (West JEC, 2010). The wells were drilled with a Massarenti 7000 SP rig, with 3600 m of nominal depth capacity using 5” drill pipe. Figure 1 shows a resistivity cross-section (TERANOV-CGG, 2014) with lithological correlation (WestJEC, 2008), modified for this report.

After the surface exploration stage identified favourable conditions for geothermal power production, well SM-1 was drilled in Sol de Mañana area. The drilling began on 8th September 1988 and ended after 74 days at a depth of 1,180 m (ENEL, 1989a). Lithology information shows (Figure 2) that ignimbrite of dacite composition with variable colour, which consists of quartz crystals, plagioclase, biotite and hornblende is predominant. Three alteration zones were identified through analysis of the cuttings gathered while drilling:

1. Heulandite zone (0-400 m);
2. Quartz – chlorite zone (400-780 m);
3. Epidote zone (780-1180 m).

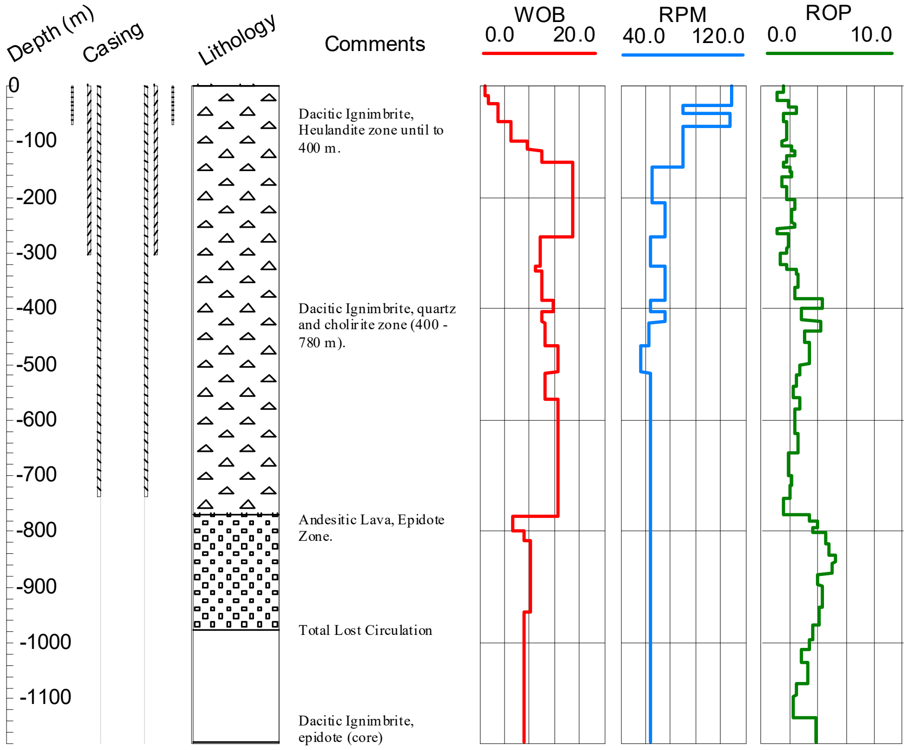

FIGURE 2: SM-1 Lithology and drilling data (ENEL, 1989a)

The well was drilled with bentonite mud down to 762 m without big losses. Successive drilling was done with water and total loss of circulation was experienced at 977 m depth. The well was drilled using hole openers for the first and second sections. As this report is focused on bit performance, Table 1 shows only the first bit used to do the first hole (without hole openers).

Well SM-2 was drilled 1100 m N-NW of SM-1, drilling began on 19th December 1988 and ended after 59.5 days at a depth of 1486.5 m, 14.5 days less than SM-1, this was attributed to lithology that was found there (ENEL, 1989b). The wells lithology is shown in Figure 3 and was similar to the lithology seen in SM-1. The alteration zones are:

1. Clay minerals zone (0-400 m);
2. Wairakite zone: (525-800 m);
3. Wairakite and epidote zone (800-900 m);
4. Epidote and adularia zone (950-1486.50 m).

Bentonite mud was used with partial losses until 242 m where total circulation loss occurred and drilling was continued with water. Similar to SM-1, well SM-2 was drilled using hole openers.

Figure 1 in Appendix I shows the drill bit data for SM-1 and SM-2. Table 1 shows the drill bits used to drill SM-1 and SM-2. Neither hole-openers nor core bits are included in the table as such drilling techniques are outside the scope of this report. Table 1 shows that several bit changes were performed in both wells, some in conjunction with tripping operations related to coring, logging or testing, all of

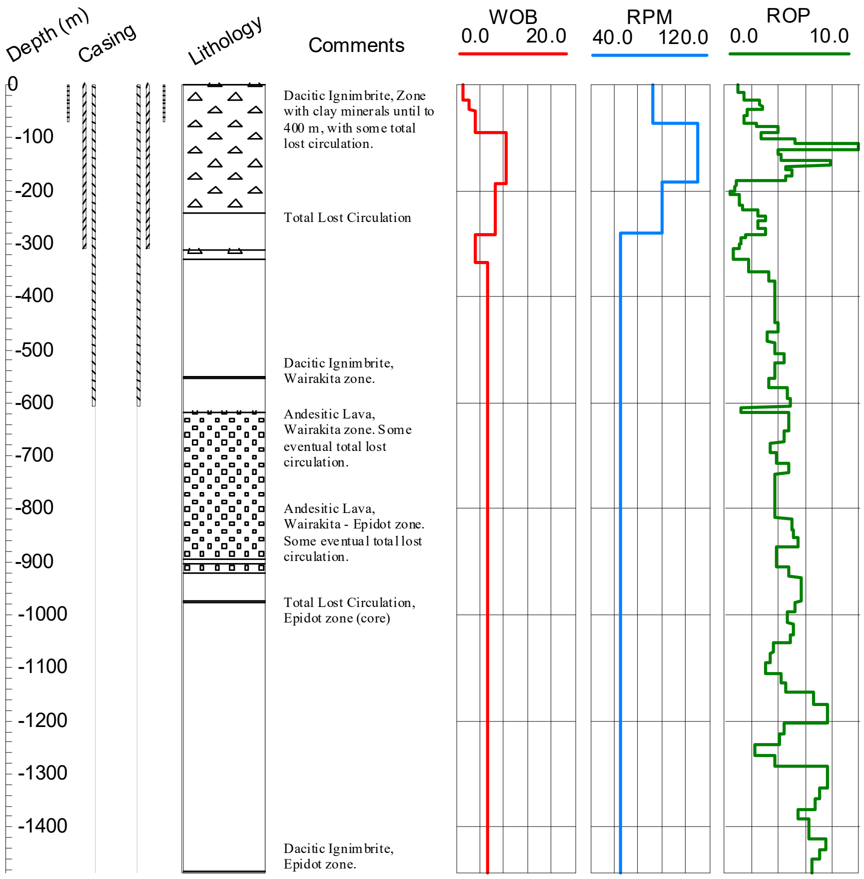

FIGURE 3: SM-2 Lithology and drilling data (ENEL, 1989b)

which are common during drilling of exploratory wells. The rate of penetration (ROP) is relatively low and according to the IADC Code (Table 1), a long steel tooth bit was used in shallow layers and a short tooth TCI bit from 300 m to bottom. Some exceptions during drilling below 300 m in SM-2, a medium steel tooth bit was used and the recorded ROP was slightly lower that for same size TCI bits.

TABLE 1: Bit record of wells SM-1 and SM-2 (ENEL, 1989a; ENEL, 1989b)

SM-1						**SM-2**					
IADC Code	**Bit diameter ["]**	**Section**	**Depth start [m]**	**Depth end [m]**	**ROP [m/hr]**	**IADC Code**	**Bit diameter ["]**	**Section**	**Depth start [m]**	**Depth end [m]**	**ROP [m/hr]**
1-3-1u	17 1/2	0	0	26.0	2.50						
1-3-1u	17 1/2	0	26.0	75.0	1.75	6-3-7	12 1/4	0	12.7	74.0	2.70
1-3-1	17 1/2	1	75.0	94.5	1.62	1-1-1u	17 1/2	1	74.0	85.0	2.50
1-3-1	17 1/2	1	94.5	195.0	1.58	1-1-4	17 1/2	1	85.0	209.0	1.70
1-3-1	17 1/2	1	195.0	255.0	1.71	1-1-1	17 1/2	1	209.0	240.0	2.00
6-1-7	12 1/4	1	255.0	307.0	1.30	6-3-7	12 1/4	1	240.0	311.0	1.70
LH2J	12 1/4	2	307.0	316.0	1.63	2-3-1	12 1/4	2	311.0	328.0	0.95
6-1-7	12 1/4	2	317.5	411.0	2.20	6-1-6	12 1/4	2	328.0	617.0	3.84
6-1-7	12 1/4	2	411.0	614.0	2.40	2-5-1	8 1/2	3	634.0	851.0	4.50
6-3-7	12 1/4	2	614.0	762.0	1.57	6-2-7	8 1/2	3	851.0	943.0	4.70
7-3-1	8 1/2	2	762.0	786.0	6.00	6-2-7	8 1/2	3	943.0	973.0	6.00
6-2-7	8 1/2	3	786.0	963.0	4.04	6-2-7	8 1/2	3	976.0	1052.0	5.30
6-2-7	8 1/2	3	963.0	1029.0	2.73	6-3-7	8 1/2	3	1052.0	1198.0	4.80
6-2-7	8 1/2	3	1029.0	1114.0	2.38	2-3-1	8 1/2	3	1198.0	1264.0	3.20
6-2-7	8 1/2	3	1114.0	1178.5	5.38	6-3-7	8 1/2	3	1264.0	1485.0	6.14

where: Section 0 with safety casing 20" on hole 26"
Section 1 with safety casing 13 $^{3}/_{8}$" on hole 17 ½"
Section 2 with safety casing 9 $^{5}/_{8}$" on hole 12 ¼"
Section 3 with on open hole 8"

2. LITERATURE OVERVIEW

2.1 Bit selection

Unfortunately, the selection of the optimal drill bit and operational parameters can only be achieved by trial and error. In the absence of bit records or if bit records are poor, several rules and methods can be applied. One method is based on collecting available drilling data in previously formations drilled (Bourgoyne et al., 1991). In addition to lithology information, the drillability and abrasiveness are the theoretical concepts to describe the formation drilled:

- Drillability: is a calculated parameter for estimating how easy or hard it is drill a specific formation and is inversely proportional to the compressive stresses of the rock formations.
- Abrasiveness: is relative to the tooth wear rate of the drill bit during operation in a specific formation. Abrasiveness tends to increase when the drillability decreases.

The drill bits are classified into Roller Cone and Drag bits (Figure 2 in Appendix I). The roller-cone has been more widely used (Ngugi, 2008) and is the bit type used on the wells that are studied in this report. Usually roller cone bits (parts of the bit are shown in Figure 3 in Appendix I) have an IADC code that consist of three digits (Tables 2 and 3):

- First digit – cutter structure (1-8): used to describe the type (Steel tooth or Tungsten Carbide Insert tooth TCI) and application of drill bit (Bourgoyne et al., 1991):
- Second digit – subdivision (1-4): is a subdivision inside to each class, where 1 is the softest formation inside each series and 4 is the hardest formation.
- Third digit – Bearing description (1-7): describe the bearing system and whether the bit is gouge protected or not.
- Optional letter could be show to describe other characteristics.

TABLE 2: IADC Code, First Digit

First digit	Type	Application
1	Steel tooth cutting structure	Soft formations with low compressive strength or high drillability.
2		Medium to medium hard formations with high compressive strength.
3		Hard formations and semi-abrasive to abrasive formations.
4	Tungsten carbide insert tooth cutting structure	Soft formations with low compressive strength or high drillability.
5		Soft to medium formations with low compressive strength.
6		Medium hard formations with high compressive strength.
7		Hard formations and semi-abrasive to abrasive formations
8		Extremely hard and abrasive formations

TABLE 3: IADC Code, third digit

Third digit	Bearing description
1	Standard roller bearing
2	Roller bearing air cooled
3	Roller bearing gauge protected
4	Sealed roller bearing
5	Sealed roller bearing – gauge protected
6	Sealed friction bearing
7	Sealed friction bearing gauge protected

In order to do guidelines to select the drill bits, it is possible to mark off the next points as some general rules according with their performance and cost (for roller cone bit):

1. Rules to use to choose the size of bit tooth (Bourgoyne et al., 1991):
   a) Use the longest tooth size possible;
   b) Allow small amount of tooth breakage rather than selecting a shorter tooth size;
   c) When enough weight cannot be applied economically to a steel tooth bit to cause self-sharpening tooth wear, a longer tooth size should be used;
   d) When the rate of tooth wear is much less than the rate of bearing wear, select a longer tooth size (improvements with a better bearing design or apply more weight on bit).
2. Rules to choose the bearing and gauge:
   a) Bits with roller bearings can be run at a higher speed than bits with journal bearings;
   b) Bits with sealed bearings have a longer life than bits with open bearings;
   c) Bits with journal bearings can be run at higher weights than bits with roller bearings. For geothermal drilling sealed bearings are recommended specially for high temperature intervals.
3. Rules to choose the journal angle: Bits with relatively small journal angles are best suited for drilling in softer formations, and those with larger angles perform best in harder formations.

2.2 The main drilling parameters

Below is a brief description of the main drilling parameters being analysed:

Hook load is the total force pulling down on the hook. This includes the weight of the drill string, the drill collars and any ancillary equipment in air, less any force that reduces that weight. Example of forces that might reduce the weight include friction along the wellbore wall (especially in deviated wells) and, importantly, buoyant forces on the drill string caused by its immersion in drilling fluid.

WOB: Weight On Bit represents the weight applied on the bit i.e. the force to overcome the compressive strength of the rock. The actual measurement of the weight is made with a hydraulic gauge attached to the dead line of the drilling line (as tension increases in the drilling line, more hydraulic fluid is forced through the instrument, turning the hands of the indicator. This sensor measures a unique value, which is the overall weight (hook-load) of the drill string including the weight of the block and top drive system, therefore a correct calibration is required in order to have proper reading for the actual WOB.

RPM: Revolution Per Minute represents the rotational speed of the drill string. It is measured at the top drive system or rotary table and is read directly from the respective electronic unit. The measurement for this parameter is considered accurate as long as the acquisition system has been properly set up. If a down hole motor (DHM) is included on the bottom hole assembly (BHA), the real RPM should be calculated and include on the drilling data record.

ROP: Rate of Penetration, is measured through the relative change of the position of the block in time. Accurate calibrations are important in order to have a representative ROP parameter.

Bourgayne et al. (1991) explained the response of the ROP with changes in WOB and RPM, which is shown in Figure 4. ROP increases with increased WOB (a to c). At higher WOB increases start to show only slight improvement in ROP (c to d). In some cases a decrease in ROP is observed at too high values of WOB for a given scenario (d to e), this type of behaviour is often called bit floundering. As shown in Figure 5, ROP usually increases with rotary speed RPM (a to b). At certain RPM, ROP stops increasing linearly with increased RPM and the ROP response becomes poor (b to c).

Torque: This parameter is the torque applied to rotate the drill string. It is measured by means of a top drive system or a rotary table and its monitoring is important for detecting wellbore cleaning issues and problems related to highly deviated wellbores. If a DHM is included on the BHA, the torque of the motor can be calculated based on hydraulic parameters.

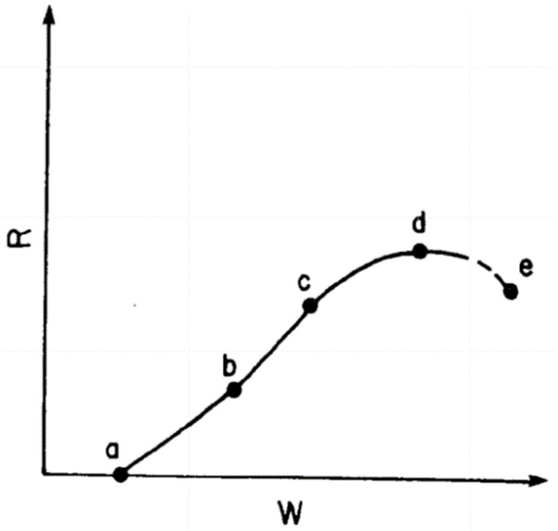

FIGURE 4: Typical response of ROP(R) with increasing WOB (W)

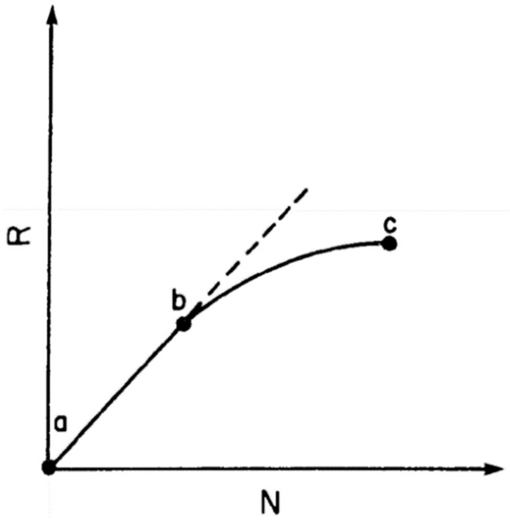

FIGURE 5: Typical response of ROP(R) with increasing RPM (N)

Pump rate represents the pump rate of the of the mud pumps. The pump rate is determined by the liner size in use and number of strokes. In case there are two pumps working simultaneously, the pump rate is the total combined flow rate of the two pumps. Use of flow meters could also be adapted for accurate flow rate measurements.

Stand pipe pressure is the total pressure pumped to the well, this pressure must be sufficient to overcome the total pressure losses in the well. Pressure losses are the sum of pressure losses in the annulus, across the bit, in the bottom hole assembly and drill string. The monitoring of this parameter helps in determining downhole problems.

The pump rate and stand pipe pressure should be determined before the start of drilling in order to select the appropriate jet bit nozzle size, determine the effective flow rate of the cleaning fluid and to ensure efficient cleaning of a wellbore. Rheological models can be used to determine the effective standpipe pressure and pump rate in a wellbore during drilling. In geothermal drilling the Newtonian Model and Bingham Plastic Model are often used.

Depth: The depth refers to the bit position. Usually it is linked to the position of the block, by means of a sensors located at the crown block.

Fluid properties: Rheological properties and the density of the drilling fluids are important parameters to be recorded for optimization purposes. Physical, chemical and rheological properties are measured in the laboratory.

2.3 Optimization of drilling parameters

Optimization of drilling parameters has a long history (Eren, 2010) through objective analysis and research in oil fields (Bourgoyne and Young, 1974) and laboratory tests (Eckel, 1968). The parameters that have been studied and found to affect the rate of penetration (ROP), include bit type, formation characteristics, drilling fluid properties, weight on bit (WOB), rotational speed (RPM), bit tooth wear and bit hydraulics. This report focuses on the methods to find the optimum WOB and RPM combinations with regards to ROP and bit life. Methods to find the optimum WOB and RPM combination include a step test and drill off test to give a starting point, which will be monitored to maintain optimum parameters.

2.3.1 Step test

A step test involves increasing the WOB at constant RPM to find the most effective WOB for a given RPM. An example is shown in Figure 6 where WOB is increased by 5,000 pounds at a time at constant RPM. The ROP responds by increasing 25 ft/hr with each step until 15,000 tons are reached, then the next ROP increase is less 10 ft/hr. The founder point is defined at the WOB after which the ROP increases are no longer a linear (IADC, 2014). This method is also called an active drill off test.

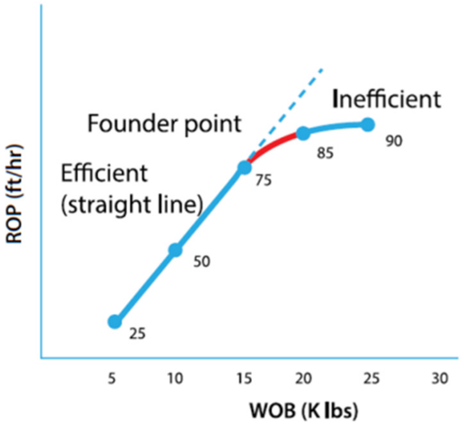

FIGURE 6: Step Test (IADC, 2014)

2.3.2 Drill off test

A drill-off (passive) test is performed in order to determine the combination of WOB and RPM which maximizes the rate of penetration (Figure 7). In geothermal drilling it could be good to do this test where a section where uniform lithology is expected or when large changes in ROP or Torque are observed. Following the recommendations of Bourgoyne et al. (1991), this test consists of the following steps:

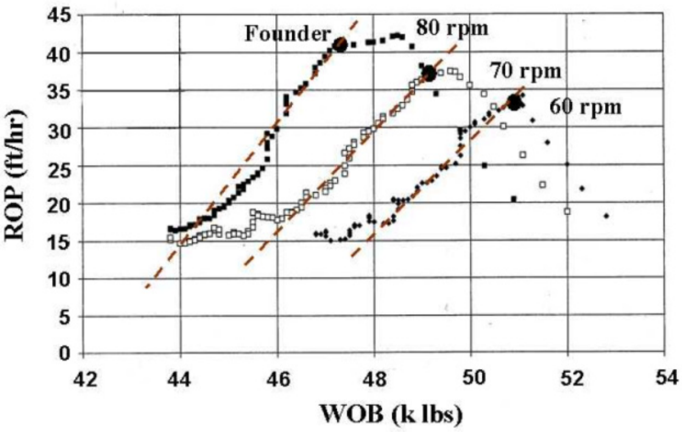

FIGURE 7: Drill off test (Guerrero, 2007)

1. While drilling with the bit weight currently in use, lock the bake and determine the time required to drill off 10% of this weight. This is called the characteristic time.
2. Increase the bit weight to the initial value of the drill off test. This initial value should be at least a 20% increase in bit weight over the bit weight currently in use.
3. Drill at this bit weight long enough to establish the new bottom hole patterns of the bit. The time allowed is usually one characteristic time per 10% increase in bit weight, an interval of twice the characteristic time would be used for a 20% increase in bit weight.
4. Lock the brake and maintain a constant rotary speed. Record each time of bit weight falls off 4,000 pounds. Continue the test until at least 50% of the initial bit weight has been drilled off.
5. Make a plot of ROP versus WOB. A straight line should result having a slope that is equal to the bit weight exponent a_5 (on a log-log plot).
6. These steps should be repeated at different RPM. Could be applicable to choose the maximum ranges recommended by manufactures.

The application of this method should not take more than five minutes. Modern drilling data acquisition allow for fast analysis, using for example an excel sheet. The ROP can be calculated using the Equation 1:

$$ROP = 0.95\,\frac{L_{DP} * \Delta WOB}{E * A_S \Delta t} \tag{1}$$

Find the ROP, a_5 and a_6 can by calculated with Equations 2 and 3:

$$ROP = K * \left(\frac{WOB}{d_B}\right)^{a_5} N \tag{2}$$

$$ROP = K * N^{a_6} \tag{3}$$

Then the optimum WOB and RPM are found using Equations 4 and 5:

$$\left(\frac{WOB}{d_B}\right)_{opt} = \frac{a_5 * H_1 \left(\frac{WOB}{d_B}\right)_{max} + a_6 \left(\frac{WOB}{d_B}\right)_t}{a_5 * H_1 + a_6} \tag{4}$$

$$N_{opt} = 60 * \left[\frac{\tau_H}{t_B} \frac{\left(\frac{WOB}{d_B}\right)_{max} - a_6 \left(\frac{WOB}{d_B}\right)_{opt}}{\left(\frac{WOB}{d_B}\right)_{max} - 4}\right]^{1/H_1} \tag{5}$$

where WOB = Weight on bit [lb];
N = Revolutions per minute;
d_B = Bit diameter [in];
ROP = Rate of penetration [ft/hr];
L_{DP} = Length of drill pipe [ft];
E = Young's modulus;
A_S = Cross-sectional area of drill pipe [in^2];
Δt = Differential of elapsed time [hr];
τ_H = Formation abrasiveness constant [hr];
t_B = Optimum bit life [hr];

$\left(\frac{WOB}{d_B}\right)_t$ = Threshold weight on bit per inch applied in the drill off test
$\left(\frac{WOB}{d_B}\right)_{max}$ = Maximum weight on bit per inch applied in the drill off test
K = Constant of proportionality

2.3.3 Multiple linear regression

In statistics, a regression or linear adjustment is a mathematical model used to approximate the dependency relationship between a dependent variable y_i and the independent variables x_i. Using this method, Bourgoyne and Young (1974) presented an approach to get a ROP model, which can be optimized through variables which are controllable during drilling, such as weight on bit (Equation 4) and bit rotation speed (Equation 5), to obtain maximum ROP. This method is based on statistical analysis of past drilling data where a mathematical model of ROP is made through multiple linear regression analysis to find the a coefficients. Equation 6 shows the mathematical ROP model:

$$\text{ROP} = \frac{df}{dt} = e^{(a_1 + \sum_{j=2}^{8} a_j x_j)} \tag{6}$$

where a_1 to a_8 are the constant coefficients; and x_2 to x_8 are the variables by different effects.

Formation strength function: a_1 primarily represents the effect of formation strength on ROP. It is inversely proportional to the natural logarithm of the square of the drillability parameter (Maurer, 1962). The coefficient a_1 includes also the effects of parameters not mathematically modelled such as the effect of drilled cuttings. Other factors which could be included for future consideration but known to be under this function could be drilling fluid details, solids content, efficiency of the rig equipment/material, crew experience and service contractors' efficiency (Bourgoyne et al., 1991).

The function f_1 is has the same unit as rate of penetration, for this reason it is called the apparent formation drillability and is defined by Equation 7:

$$f_1 = e^{a_1} \tag{7}$$

Formation compaction function: The functions f_2 and f_3 are models of the rock compaction due to depth. f_2 is an effect of normal compaction trend which is defined by Equation 8:

$$\begin{aligned} f_2 &= e^{a_2(10{,}000-D)} \\ x_2 &= (10{,}000 - D) \end{aligned} \tag{8}$$

The function f_3 assumes an exponential increase in penetration rate with pore pressure gradient. That means that for over-pressured formations, the ROP will increase (Murray, 1955). This function is defined by:

$$\begin{aligned} f_3 &= e^{a_3\, D^{0.69}(g_p-9)} \\ x_3 &= D^{0.69}(g_p - 9) \end{aligned} \tag{9}$$

where D = True vertical well depth [ft];
g_p = Gradient of pore pressure [lb/gal].

Bottom hole differential pressure function: (Also called overbalance pressure). This function has a value equal to 1 when the overbalance is zero. This function shows a reduction in ROP with increased overbalance (Bourgoyne et al., 1991). If the overbalance is expressed in terms of equivalent circulating density (ECD) and pore pressure gradient, the function f_4 is defined by:

$$\begin{aligned} f_4 &= e^{a_4 D(g_p-ECD)} \\ x_4 &= D(g_p - ECD) \end{aligned} \tag{10}$$

where ECD = Equivalent circulation density [lb/gal]

As example, for turbulent flow of Newtonian fluids, the ECD can be calculated using Equations 11-13:

$$\Delta P_{annulus} = \frac{{\rho_m}^{0.75} v^{1.75} \mu^{0.25}}{490\,(D_2 - D_1)^{1.25}}\, \Delta L_S \tag{11}$$

$$v = \frac{1000\,Q}{(D_2^2 - D_1^2)} \tag{12}$$

$$ECD_{SI} = \rho_m - \frac{\Delta P_{annulus}}{10.2\ D} \tag{13}$$

where ECD_{SI} = Equivalent circulation density on SI units [kg/m^3]
$\Delta P_{annulus}$ = Frictional pressure losses through to annulus [kPa]
ρ_m = Mud density [kg/m^3]
v = Velocity [m/s]
Q = Flow rate [l/s]
μ = Viscosity [Pa-s]
D_1 = Outside diameter, drill pipe or drill collar [in]
D_2 = Inside diameter, open hole or casing [cm]
ΔL_S = Length of conduit [m]

Weight on bit and diameter function: The WOB and bit diameter are considered to have direct effect on the penetration rate. This assumes that the penetration rate is directly proportional to WOB per bit diameter (Graham and Muench, 1959). The $(WOB/d_B)_t$ is the WOB threshold and the reported values for this term is between 0.6 to 2.0. The WOB threshold can be estimated from drill off test performed using low WOB. This function has an upper limit corresponding to the floundered point, which must be estimated from drill off test (Cheraghi, 2013):

$$f_5 = \left[\frac{\left(\frac{WOB}{d_B}\right) - \left(\frac{WOB}{d_B}\right)_t}{4 - \left(\frac{WOB}{d_B}\right)_t}\right]^{a_5} \tag{14}$$

By properties of natural logarithmic, the x_5 is equal to:

$$x_5 = \ln\left[\frac{\left(\frac{WOB}{d_B}\right) - \left(\frac{WOB}{d_B}\right)_t}{4 - \left(\frac{WOB}{d_B}\right)_t}\right] \tag{15}$$

where $\left(\frac{WOB}{d_B}\right)_t$ = Threshold weight on bit per inch of bit

Rotary speed function: this function assumes that the ROP is directly proportional to rotary speed of the bit, RPM or N (Graham and Muench, 1959):

$$\begin{gathered} f_6 = \left[\frac{N}{100}\right]^{a_6} \\ x_6 = \ln\left(\frac{N}{100}\right) \end{gathered} \tag{16}$$

It should be highlighted that a_5 and a_6 can be determined from a independant of this method as described in Section 2.2.1.

Tooth wear function: The tooth wear function is calculated by fractional tooth height h (adimensional). In order to calculate the respective tooth height, a bit record for a similar bit type that has been used within the same formation is necessary. For practical purposes, this report assumes zero tooth wear, that is valid when the drill bit is starting to do the hole (Bourgoyne and Young, 1974).

$$\begin{gathered} f_7 = e^{a_7(-h)} \\ x_7 = -h \end{gathered} \tag{17}$$

Hydraulic function: It is based on microbit experiments performed by Eckel (1968). The hydraulics function represents the effects of the bit hydraulics. Jet impact force was chosen as the hydraulic parameter of interest with a normalized value of 1.0 for f_8 at 1,000 lbf.

$$\begin{gathered} f_8 = e^{a_8\left(\frac{\rho\, Q}{350\, \mu\, d_n}\right)} \\ x_8 = \frac{\rho\, Q}{350\, \mu\, d_n} \end{gathered} \tag{18}$$

where:
ρ = Mud density [lb/gal]
Q = Mud flow rate [gpm]
μ = Apparent viscosity at 10,000 s^{-1} [cp]
d_n = Diameter of bit nozzle [in]
h = Fractional tooth height worn away

2.3.4 Mechanical specific energy

Mechanical specific energy (MSE) surveillance is another method for determining drilling performance. Teale defined the MSE as the energy being used per volume of rock drilled (Teale, 1965):

$$MSE = \frac{TOTAL\ ENERGY\ INPUT}{VOLUME\ REMOVED} \tag{19}$$

where the total energy input is the vertical energy plus the rotational energy.

Then the vertical energy, or work done, is the vertical force (WOB) times distance (ROP). The rotational energy, or work done, is the bit rotation (RPM) times torque. The volume of rock removed is the area of the bit times ROP. Therefore, the MSE can be expressed by:

$$MSE = \frac{WOB \cdot ROP}{A_b \cdot ROP} + \frac{2\pi \cdot RPM \cdot T}{A_b \cdot ROP} \tag{20}$$

Introducing the mechanical efficiency factor, the final MSE equation is given by (Bevilacqua, 2013):

$$MSE = EFF_M \cdot \left(\frac{4 \cdot WOB}{\pi d_B^2} + \frac{480 \cdot RPM \cdot T}{d_B \cdot ROP} \right) \tag{21}$$

where

			Field units	SI units
MSE	=	Mechanical specific energy	[psi]	[kg/cm^2]
WOB	=	Weight on bit	[lb]	[kg]
RPM	=	Rotary speed	[rev/min]	[rev/min]
T	=	Torque on bit	[lb-ft]	[kg-m]
d_B	=	Bit diameter	[in]	[cm]
ROP	=	Rate of penetration	[ft/hr]	[m/hr]
EFF_M	=	Mechanical efficiency		

Currently this equation it is called the Teale MSE model, and is valid under atmospheric conditions. The torque could be an erratic measure affected by the torque and drag of the drill string along the well. Pessier (1992) defined a coefficient of sliding friction μ to express the torque as a function of WOB as shown in Equation 22:

$$T = \frac{\mu \cdot WOB \cdot d_B}{36} \tag{22}$$

The TOB (torque on bit) is used to compute the MSE in the absence of reliable torque measurements.

Then the mechanical efficiency of rock destruction is defined by:

$$EFF_M = \frac{CCS}{MSE} \tag{23}$$

In theory, at perfect drilling efficiency, the value of the MSE is equal to the rock strength. In the experience of oil and gas companies, the bits are typically 30-40% efficient at peak performance (Guerrero, 2007). In field practice, MSE is primarily used as an indicator of drilling efficiency and thus it is not necessary to know the rock strength (IADC, 2014). The rock strength can be evaluated by:

- Unconfined compressive strength (UCS) represents the force applied to a defined area necessary to deform the rock at atmospheric pressure, whose value is characteristic and fixed for each type of formation and represents the minimum value of the relative mechanical resistance.
- Confined compressive strength (CCS) is the force on a defined area needed to deform a volume of rock which is subjected to pressure in a confined medium. CCS measures the maximum value of the resistance for each rock.
- The real compressive strength (RCS), of a defined formation, will be an average value within UCS and CCS. Experience of oil drilling engineers recommend maintaining the MSE value as close as possible to RCS. Unexpected changes in MSE may indicate changes in the rock formation, or drilling inefficiency, or both.

The MSE value could be plotted by the data-acquisition tools on the rig. Modern systems can provide relatively high definition with a sampling rate typically at 1 Hz, or sometimes even higher at 10 Hz. Then as the driller makes a change he can observes the MSE to see if rock cutting efficiency improves or declines. Mainly, WOB, RPM and flow rate are the parameters to operate and change when looking for efficient ROP, then while the driller is operating he can change one parameter, holding the others constant until the best combination is found.

An increase in MSE value can be caused by (IADC, 2014):

- Bit balling: build up of material on the bit that interferes with depth of cut.
- Interfacial severity: formations with hard inclusions or layers that cause axial shocks and break cutters.
- Bottom hole balling: layer of ground cuttings held to the bottom of the hole by differential pressure.
- Whirl vibrations: lateral motion of the string and bit.
- Stick-slip vibrations: torsional motion in which the bit speed oscillates periodically.
- Axial vibrations: axial motion in which the bit depth of cut oscillates periodically.
- Changes on Overbalance Pressure: increases of mud pump pressure or decreases on the gradient pressure.

When MSE information is combined with other information, it could be useful to determine the cause of the problem.

Figure 8 shows an example of a drill off test with a MSE record. The drill off test was done when a new formation was entered and a MSE increase was noted. If the MSE remains close to the baseline value while increasing the WOB until the floundered point, then the bit is as efficient at the high load as in the previous formation.

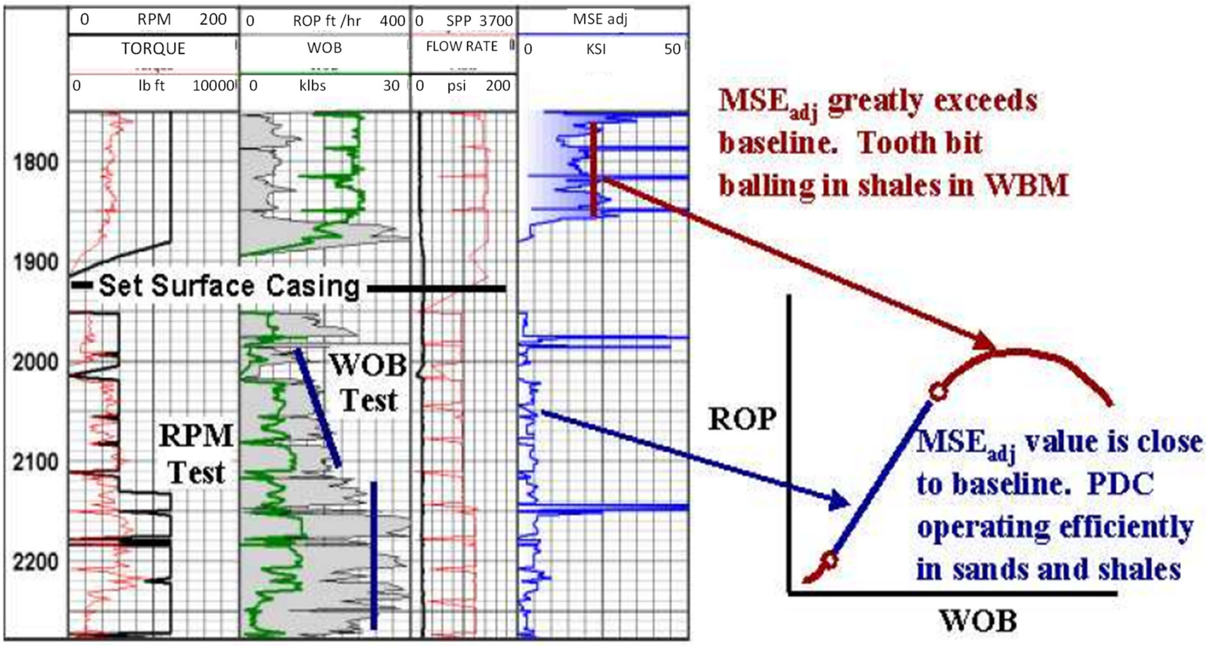

FIGURE 8: MSE analysis on a drill off test (Guerrero, 2007)

3. DATA AND RESULTS

3.1 Icelandic data – RN-16

Data from well RN-16 in Reykjanes, Iceland, is shown in this report with the purpose of trying the methods used to evaluate the drilling performance. Well RN-16 is located in Reykjanes at the south western tip of Iceland. This well was completed on May 6 of 2004 at 2627 m. The raw data was provided by ISOR and measurements were recorded with a sampling rate of 0.2 Hz (one set data per 5 seconds). It was necessary to filter the data and to delete the measurements done on connections, tripping, and other stops. After filtering, smoothing was done to get data with a width of 1 m of intervals (approx.) as is presented on Table 4.

TABLE 4: Data based by depth interval

MD [M]	**WOB [ton]**	**RPM [rev/min]**	**ROP [m/h]**	**TORQUE [dN*m]**	**Flow Rate [l/s]**	**SPP (bar)**	**ECD [kg/l]**	g_p **[kg/l]**
881.99	13.02	200.46	20.20	155.21	56.37	81.29	1.016707	0.869910
883.08	15.91	193.39	8.05	185.77	56.20	84.64	1.016728	0.869846
884.10	16.27	195.79	6.10	155.70	56.34	83.58	1.016747	0.869785
885.29	15.87	195.28	6.54	149.27	56.43	82.79	1.016770	0.869715
886.51	16.38	194.77	7.40	157.77	56.32	85.12	1.016793	0.869643
889.64	16.40	195.35	16.54	137.82	55.37	80.79	1.016852	0.869458
890.94	16.21	195.98	11.05	147.97	55.43	80.80	1.016877	0.869382
892.19	16.10	195.89	12.53	149.41	55.46	80.86	1.016900	0.869308
893.49	16.05	195.69	12.24	151.99	55.38	80.62	1.016925	0.869231
894.86	15.69	195.71	13.54	150.95	55.14	79.92	1.016951	0.869150
898.76	15.59	196.08	13.19	144.15	55.13	79.79	1.017025	0.868919
900.11	14.63	194.25	12.40	140.23	55.20	80.58	1.017050	0.868839
901.41	14.34	194.32	13.33	138.97	55.25	80.16	1.017075	0.868762
902.93	13.73	194.30	12.90	139.53	55.28	79.88	1.017104	0.868672

The lithology is mostly basalt tuff, tuffs and pillow lava. The secondary minerals found are shown in Table 5.

TABLE 5: Secondary minerals

Secondary mineral	**Minimum temperature**	**RN-16**
Quartz	100	880
Epidote	105	1074
Wollastonite	290	1050
Amphibole	290	2010
Garnet	290	1248
Calcite	300	>2532

The production casing 13 3/8" (K-55 98.46 kg/m) was set down to 870 m. The last section between 879 and 2627 m of depth was made with two TCI drill bits, 12 ¼" with nozzles 32/32", using fresh water as drilling mud. The interval from 879 to 1923 m was drilled using one 12 ¼" TCI drill bit, a 5" drill string and a bottom hole assembly including a downhole motor 9 ½" M1XL, 9 drill collar 8", drilling jar, shock absorber (Kristjánsson et al., 2005). The drill operation was made combining the rotation of the drill string and DHM, the raw data collected included the corrections of the RPM. Appendix I shows the raw data filtered and smoothed (Table 1 and Figure 4 in Appendix I). Specifically, Table 1 in Appendix I presents a sample of the data used to show the drilling optimization methods.

3.1.1 Application of multiple regression analysis

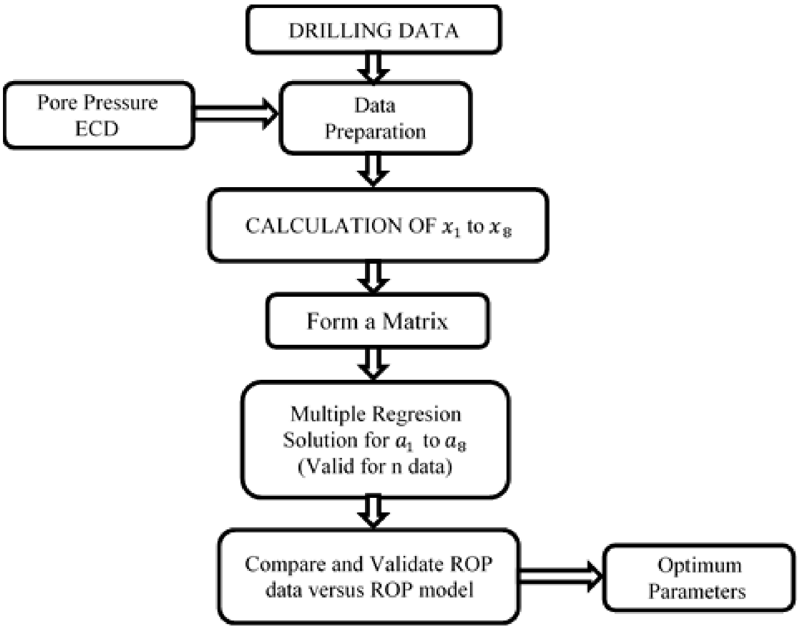

FIGURE 9: Steps of multiple regression

Figure 9 shows a flow chart of the multiple regression steps. Visual basic and Excel were used to apply the ROP model described in Section 2.2.3, by taking the following steps.

The data was collected from 124 data set points (drilling parameters) form the interval between 882 to 1116 m. This section was drilled with a tricone insert bit starting at 879 m and as the wear of the bit is assumed to be minimal the value of x_7 was assumed to be equal to zero, as was explained in Section 2.3.3.

Equations 7-10 are used to find the values x_1 to x_8. Using the x values and the ROP data, a matrix was formed which was solved using multiple linear regression. To do this Equation 6 is modified by taking the logarithmic on both sides, such that the ROP is expressed by:

$$\ln ROP = a_1 + \sum_{j=2}^{8} a_j x_j \tag{18}$$

With the ROP data base and the x values found, the multiple regression was run getting the a coefficients shown in Table 6:

TABLE 6: "a" coefficients

a1	a2	a3	a4	a5	a6	a7	a8
12446.21	-1.15	24.12	0.86	-0.1	-6.91	0	0.84

After the coefficients a_1 to a_8 are obtained, the model for the drilling rate or ROP is calculated and the results are shown in Figure 10 where they are compared with the measured ROP data. The square residuals are also displayed in Figure 10 and are considered acceptable.

The model introduced could be useful for another well in the same area, if the well prognosis, lithology, pore pressure, bit structure, drilling mud, operation, and the depth, are similar. Data from each additional well drilled in the area can be used to update the model for each interval. It is, however, necessary to validate the results by comparing the logged ROP to the ROP from model.

The a_5 and a_6 coefficients are used with Equations 4 and 5 in order to get the optimum WOB and RPM.

The optimal values are 8.5 tons and 194.7 rev/min for the WOB and RPM respectively. In other words, as an interpretation, the model helps to find the efficient point which was described in Section 2.3.1. in the literature overview. Figure 11 shows the data for the WOB versus ROP. The optimum WOB (8.5 tons) versus ROP (13.8 m/hr, average from model) is highlighted in the figure.

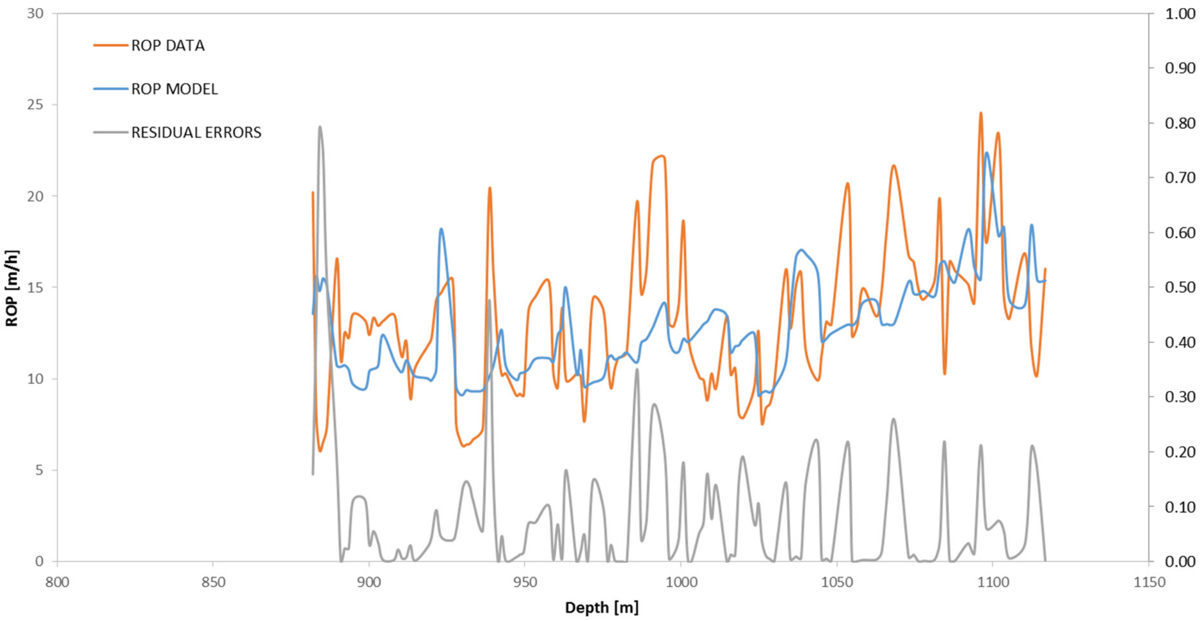

FIGURE 10: ROP data and ROP model

3.1.2 Application of mechanical specific energy

As explained before, the MSE is an indicator of the drilling performance. The log plot Figure 12 shows the drilling parameters and the behaviour of MSE calculated with Equation 21. The WOB and ROP data is plotted alongside the log plot with the aim of showing how the MSE could be a useful indicator while drilling.

As was indicated in Section 2.3.4, it is recommended to maintain the MSE value as close as possible to the estimated rock strength. For this report, it was assumed to be 24,000 psi for basalt and tuff rocks (Figure 5 in Appendix) as a relative indicator for high MSE value.

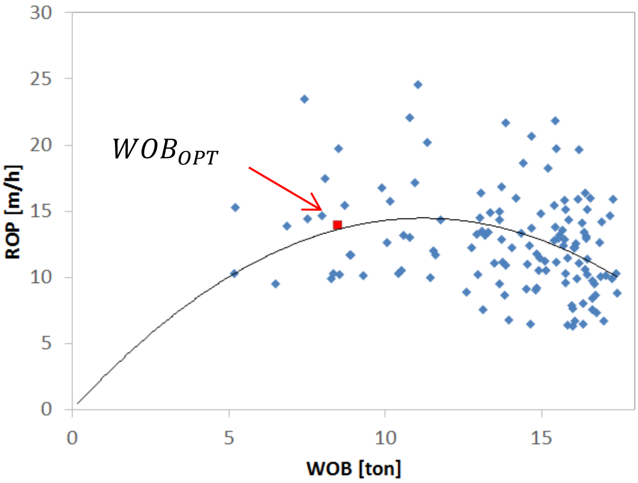

FIGURE 11: Response of the ROP at 882-1116 m (grey line is the smoothed line)

Intervals of similar lithology were selected. In Figure 12 the drilled layer Coarse Basalt (890-925 m) shows on Figure 13 that the ROP response is similar at 8, 12 or 16 tons without dependence of the depth, the low MSE is at 8 tons with a ROP response of 15 m/hr. The drilling performance on Fine-Mid Basalt (with some intercalations of Basaltic Tuff) is shown on Figure 14 where 12-16 tons have high MSE and 8-12 tons have low MSE, both scenarios have variable ROP with similar range.

Figure 15 shows intervals of Fine-Mid Basalt. Figure 16 shows that the WOB was close to 16 tons, when the driller reduced it to 12 tons and got a better ROP with lower MSE. Below this interval the same situation was repeated. Figure 17 shows a good example of optimum ROP found between 4 to 8 tons with low MSE. The lowest MSE is 8,000 psi, but it should be highlighted that a good estimation of CCS is an important factor to get a MSE baseline.

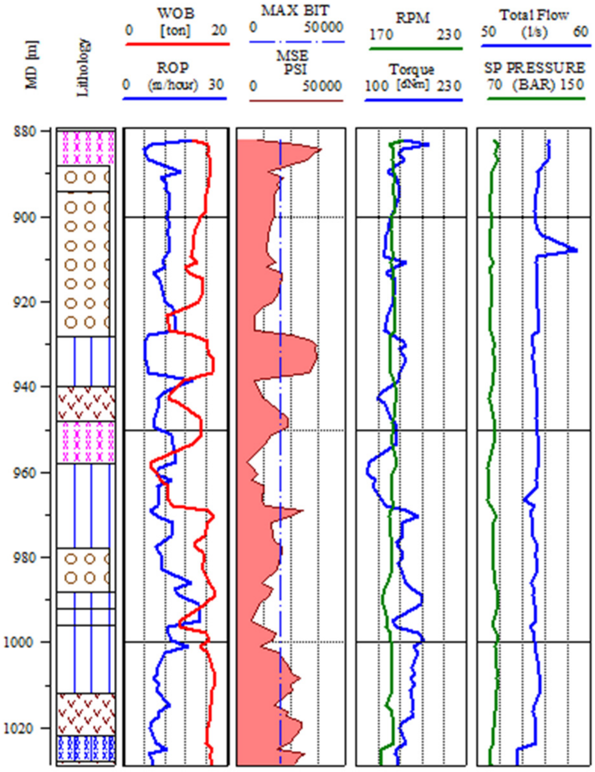

FIGURE 12: Log Plot drilling data 890-1030 m

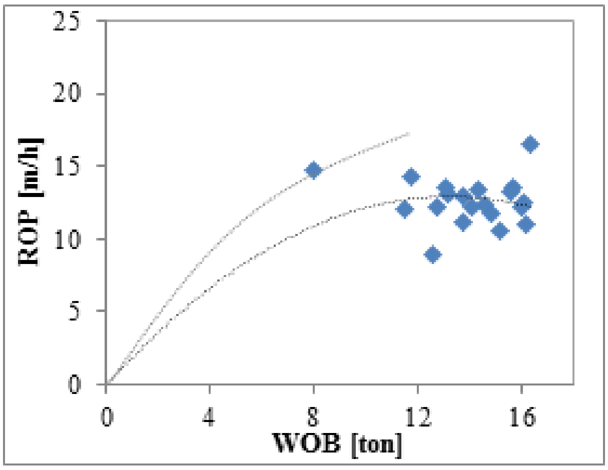

FIGURE 13: Response of ROP at 890-925 m

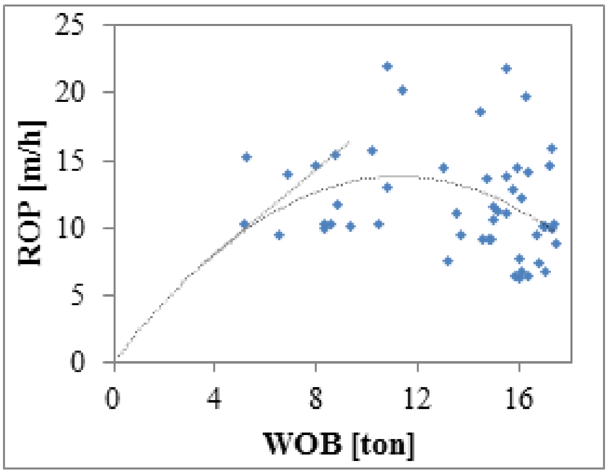

FIGURE 14: Response of ROP at 925-1010 m

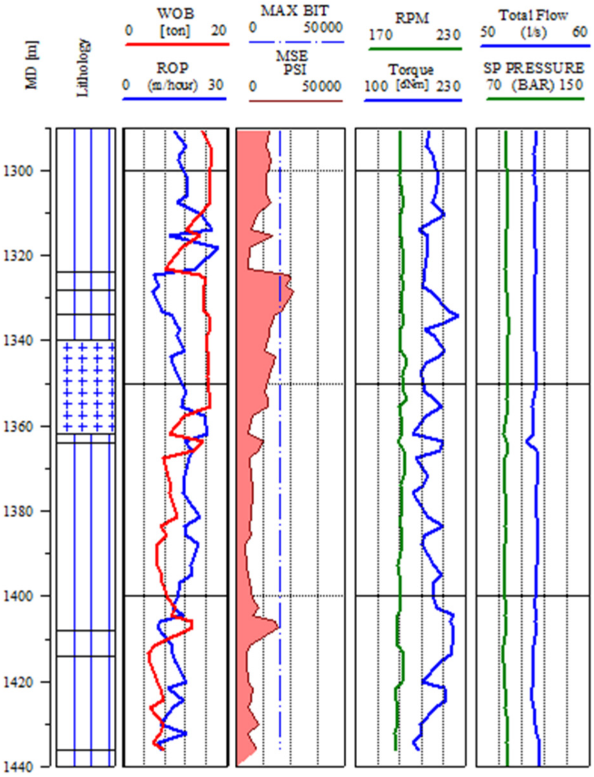

FIGURE 15: Log Plot drilling data 1290-1440 m

In Figure 18 the combination WOB versus RPM shows the ROP performance, where the changes of these three parameters were cyclical along the interval from 890-1,500 m. At first glance it is possible to see where the lowest ROP and the highest MSE are.

Looking at the same lithology, two intervals were selected to show the difference on their operation behaviour and MSE indicator. As Figure 19 shows the WOB-RPM combinations in range A (WOB 5 to 11 tons and RPM 195 to 200) are less likely to result in low ROP (1.68-8.26 m/hr) and more likely to result in high ROP. Further, this combination results in the lowest MSE zone, which means that the drilling is efficient. It is worthy of attention to observe that the results from multiple linear regression, MSE and statistical analysis shows that high values of WOB (more than 12 tons) could be resulting in inefficient drilling. WOB in the 8-10 tons range seems to be most efficient, RPM in this section of the well does however not change significantly.

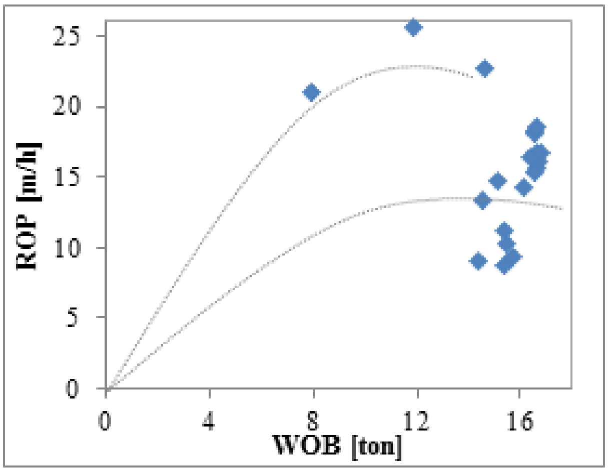

FIGURE 16: Response of ROP 1290 - 1338 m

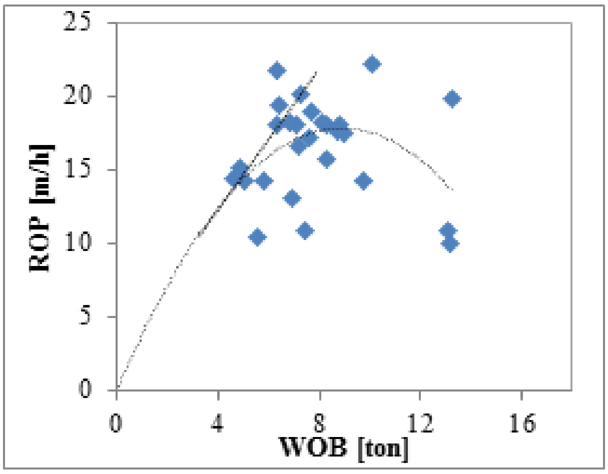

FIGURE 17: Response of ROP 1365 - 1436 m

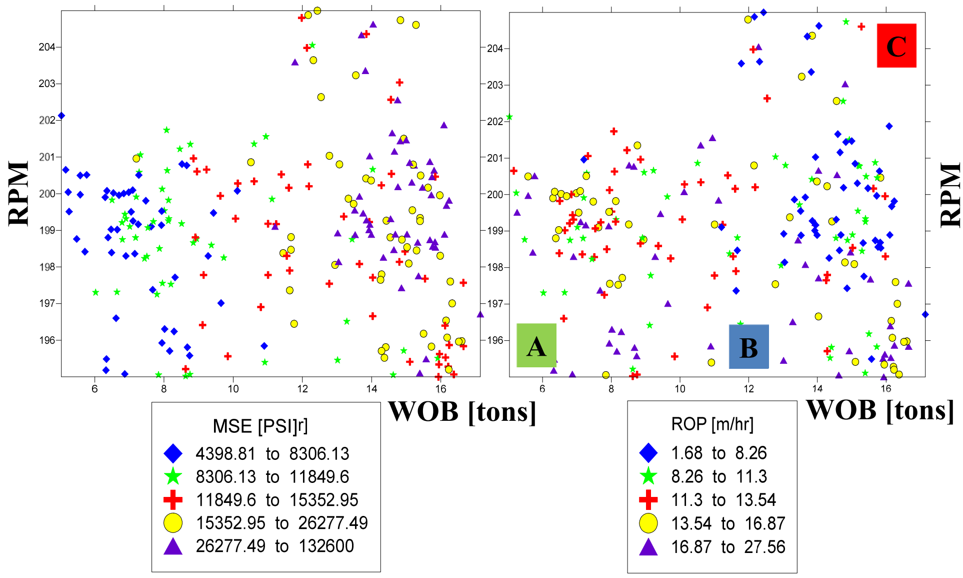

FIGURE 18: Distribution of MSE and ROP, 890-1500 m

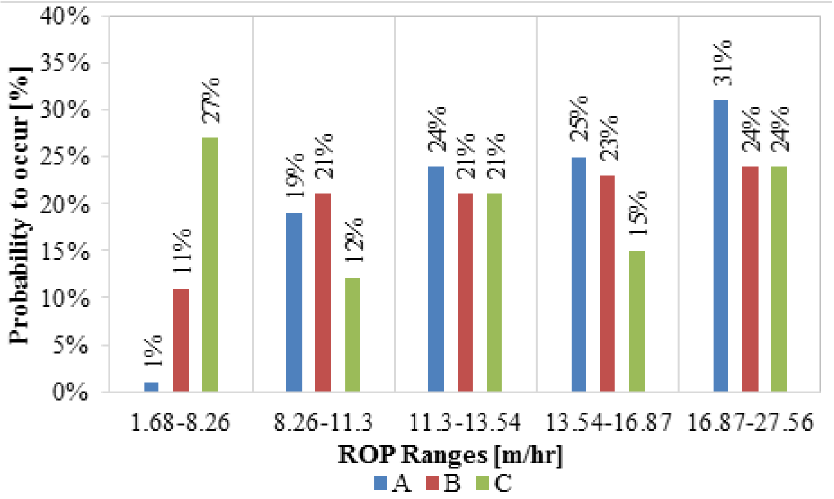

FIGURE 19: ROP probability distribution for WOB and RPM combinations

3.2 Bolivian data and results

As the raw drilling data from SM-1 and SM-2 was not available for analysis, it was not possible to apply the methods presented above. The summary in Table 7 was made from the available data, shown in Figure 2, 3 and Table 1; doing a comparison from the use of different kind of bits shows that drill bits with a long steel tooth were often used on shallow layers and short tooth TCI bit on sections 2 and 3. It is interesting that the steel bit with medium tooth was used on sections 2 and 3, and that the performance was similar to TCI bit on same section.

TABLE 7: Average performance of the bits in well SM-1 and SM-2

Bit type	Section	ROP average	Avg. drilled [m]	Avg. time used	Sum quantity
Steel bit with large tooth	0	1.77	56.86	34.80	3
	1	0.95	17.00	17.89	6
Steel bit with medium tooth	2	0.95	17.00	17.89	1
	3	3.85	141.50	34.42	2
TCI bit with short tooth	1	1.50	61.50	40.88	2
	2	2.94	127.75	51.02	5
	3	4.61	106.39	24.56	10

It is to be expected that the first wells drilled in a new field will take longer to drill than a well in a developed field. This is due to continuous improvement as the developer and personnel involved, gain a better understanding of the field and its geology. As mentioned in Section 1.3, it took 74.0 and 59.5 days to drill the SM-1 and SM-2 to 1,180 and 1,486 m of depth respectively. Figure 20 shows how the drilling time is divided between different activities on both wells, with drilling and cementing taking longest, as is usual. The aim of this report is drilling optimization that can result in reduced need for bit changes, help avoid drilling problems and mitigate non-productive time, all points that could result in reduction of cost.

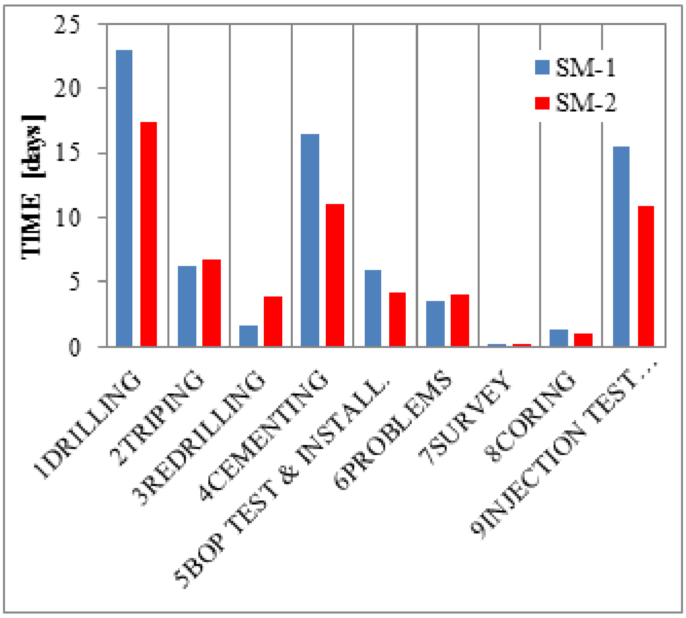

FIGURE 20: Distribution of working time on SM-1 and SM-2

The drill bit selection, for the new wells, will be done by a team studying the lithology, rock strength, fractures, drilling mud, temperature and others specific drilling needs. Below an attempt is made to provide an initial bit selection, by using the rules presented in Section 2.1 which can be thought of as an initial starting point for a selection of the drill bits:

- 26” hole (until-70 m): Steel Bit with long tooth hard formations and bearing gauge protected with the aim to drill with one trip (series 1-4-3 to 2-4-3). Due to a possible lack of WOB it might be necessary to use a bit 17.5” first and after that a 26” hole opener. Series 1-1-1 to 1-2-6 could provide more RPM with WOB reduction.
- 17 ½” hole (70-400 m): Similar to the last hole, steel tooth bit with long tooth for hard formation and bearing gauge protected with the aim to drill with one trip (series 1-4-3 to 2-4-3).

- 12 ¼” hole (400-850 m): in this section the angle will be built with KOP (kick-off point) planned at 450 m and an end of build at 30º of inclination. At least two changes of the drill bit should be planned. As it is possible to find high temperatures, a sealed bearing to journal friction bearing is recommended. Steel bit with middle tooth was used at similar depths on wells SM-1 and SM-2, thinking on the bit life and operation with down hole motor (DHM) TCI bit with longer to medium tooth could be useful (series 4-3-4 to 6-3-7).
- 8 ½” hole (850 – 2000 m): section holding 30° of inclination at high temperatures. At least two drill bits should be considered for this section. The use of DHM could improve the RPM on the bit resulting on more ROP (recommendable series 5-1-4 to 6-3-7).

The bit selection for the 12 ¼” and 8 ½” sections should be aimed at getting good ROP and bit life to avoid unexpected trips. Notice that a drilling program with estimated down hole temperatures and coring are very important to be able to choose the correct drill bit. Also for this section, the uses of PDC and hybrid drill bit should be considered.

It is recommended to analyse the rock core and do well logs such as compressional / shear travel time (Sonic log), bulk density (Density log), shale content (Gamma log) (Shrivastava et al., 2013) at least for the first wells. These results are very useful to find the unconfined compressive strength (UCS) and the confined compressive strength (CCS) which provide a better criterion for choosing a drill bit (Shrivastava, 2013). These surveys can also be useful for describing the characteristic of each formation.

4. CONCLUSIONS AND RECOMMENDATIONS

The drilling optimization methods explained in this report show similar results at the interval studied. The main points that can be highlighted are:

- Multiple linear regression model is able to predict the ROP and provide corrections especially for Weight on Bit (WOB). The model’s reliability depends on data quantity and quality. When drilling in a new field, it is more reliable to find a_5 and a_6 through a drill off test, because of the reduction in the uncertainly of variables such as the drillability.
- Mechanical specific energy (MSE), was found to be a good indicator for efficient drilling and drilling rate (ROP). By including this indicator on the drillers monitor, it can facilitate the processing and analysis of drilling performance. Knowing the rock strength is valuable and provides added guidance to the driller in the form of a better established MSE baseline.
- Both methods can help improve the drilling operation by identifying the optimal ROP, reduce unexpected trips, accelerate the drilling related learning curve, reduce drilling risks and thereby mitigating NPT (nonproductive time), resulting in reduced costs per meter drilled. Both could be applied in real time while drilling.

Finally, a good drilling program and carefully selected materials and equipment should help in achieving optimum drilling time and total cost reduction. It is highly recommended to invest in scientific surveys such as well logging and coring laboratory studies to expedite knowledge build up when drilling in new fields.

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APPENDIX I: Additional information and raw data

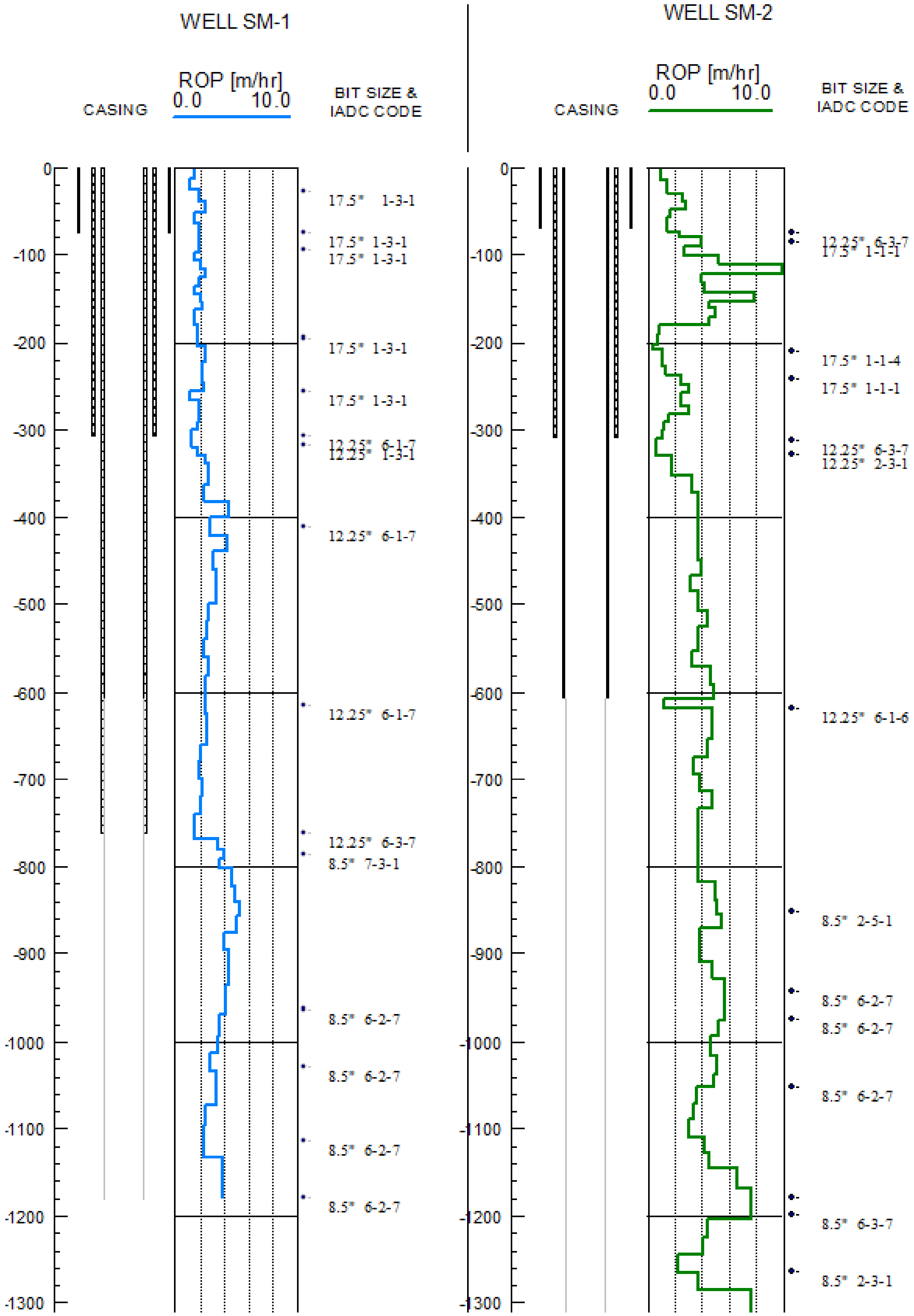

FIGURE 1: Drill bit data SM-1 and SM-2

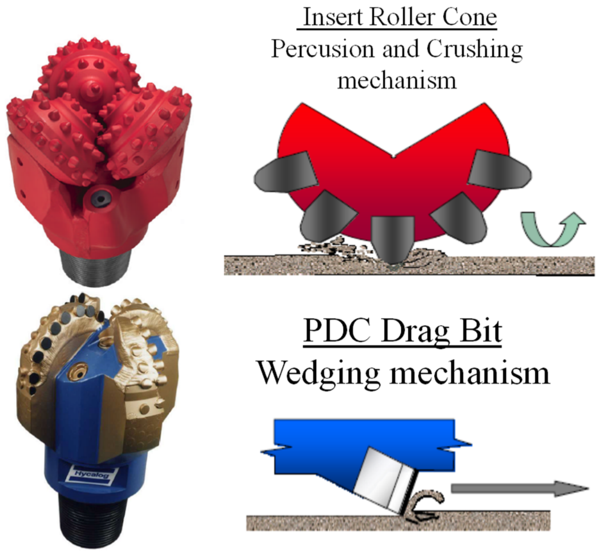

FIGURE 2: Drill mechanism of roller cone and PDC bit

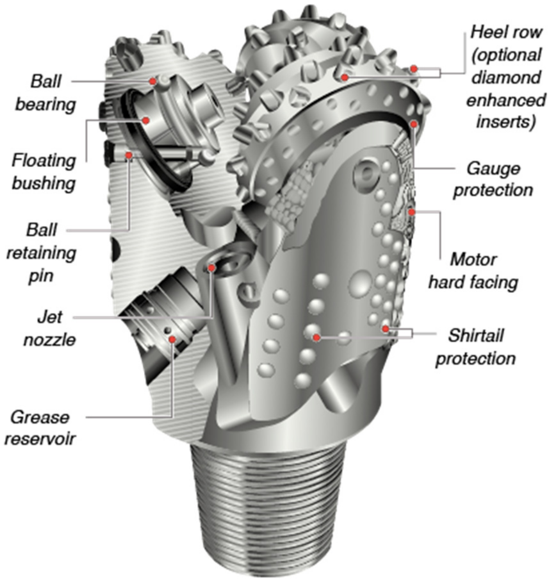

FIGURE 3: Parts of roller cone drill bit

TABLE 1: Sample of the raw data used

Data time	Depth of well	Mudpump1	Mudpump2	Mudpump3	TotalFlow Rate (l/s)	LOC (l/s)	SPP (bar)	Temperature, mud-pit (down)	Temperture, flowline (up)	Height of kelly (m)	Total Weigth	WOB (ton)	RPM	TORQUE (dN m)	ROP (m/hr)
21/04/2004 21:22:15	885.52	28.05	28.16	0	56.22	0	85.14	10.21	16.09	3.01	30.81	16.11	39.8	157.18	7.02
21/04/2004 21:22:20	885.54	28.08	28.27	0.02	56.36	0	85.11	10.21	16.09	2.99	31.05	15.87	39.8	156.77	7.00
21/04/2004 21:22:25	885.54	28.06	28.37	0	56.43	0	84.94	10.21	16.09	2.99	31.21	15.71	39.9	155.39	6.98
21/04/2004 21:22:30	885.55	28.12	28.06	0.02	56.2	0	84.71	10.21	16.09	2.98	31.05	15.87	40	152.54	6.98
21/04/2004 21:22:35	885.55	28.06	28.14	0	56.2	0	84.53	10.21	16.09	2.98	31.53	15.4	40.1	152.86	6.97
21/04/2004 21:22:40	885.55	28.16	28.3	0	56.47	0	84.35	10.21	16.09	2.98	31.84	15.08	40.1	151.48	6.92
21/04/2004 21:22:45	885.56	28.06	28.16	0.02	56.24	0	84.1	10.21	16.07	2.97	32.08	14.84	40.1	151.32	6.87
21/04/2004 21:22:50	885.58	28.14	28.24	0.02	56.4	0	84.49	10.21	16.09	2.95	32	14.92	40.2	151.24	6.83
21/04/2004 21:22:55	885.58	27.98	28.43	0	56.41	0	84.41	10.21	16.09	2.95	32.24	14.69	40.2	151.64	6.79
21/04/2004 21:23:00	885.58	28.18	28.27	0.02	56.47	0	83.95	10.21	16.09	2.95	32.24	14.69	40.6	145.87	6.32
21/04/2004 21:23:05	885.60	28.18	28.15	0.02	56.35	0	83.68	10.21	16.09	2.94	32.47	14.45	40.6	144.56	6.26
21/04/2004 21:23:10	885.60	28.07	28.36	0	56.43	0	84.07	10.21	16.07	2.93	31.84	15.08	40.5	145.7	6.21

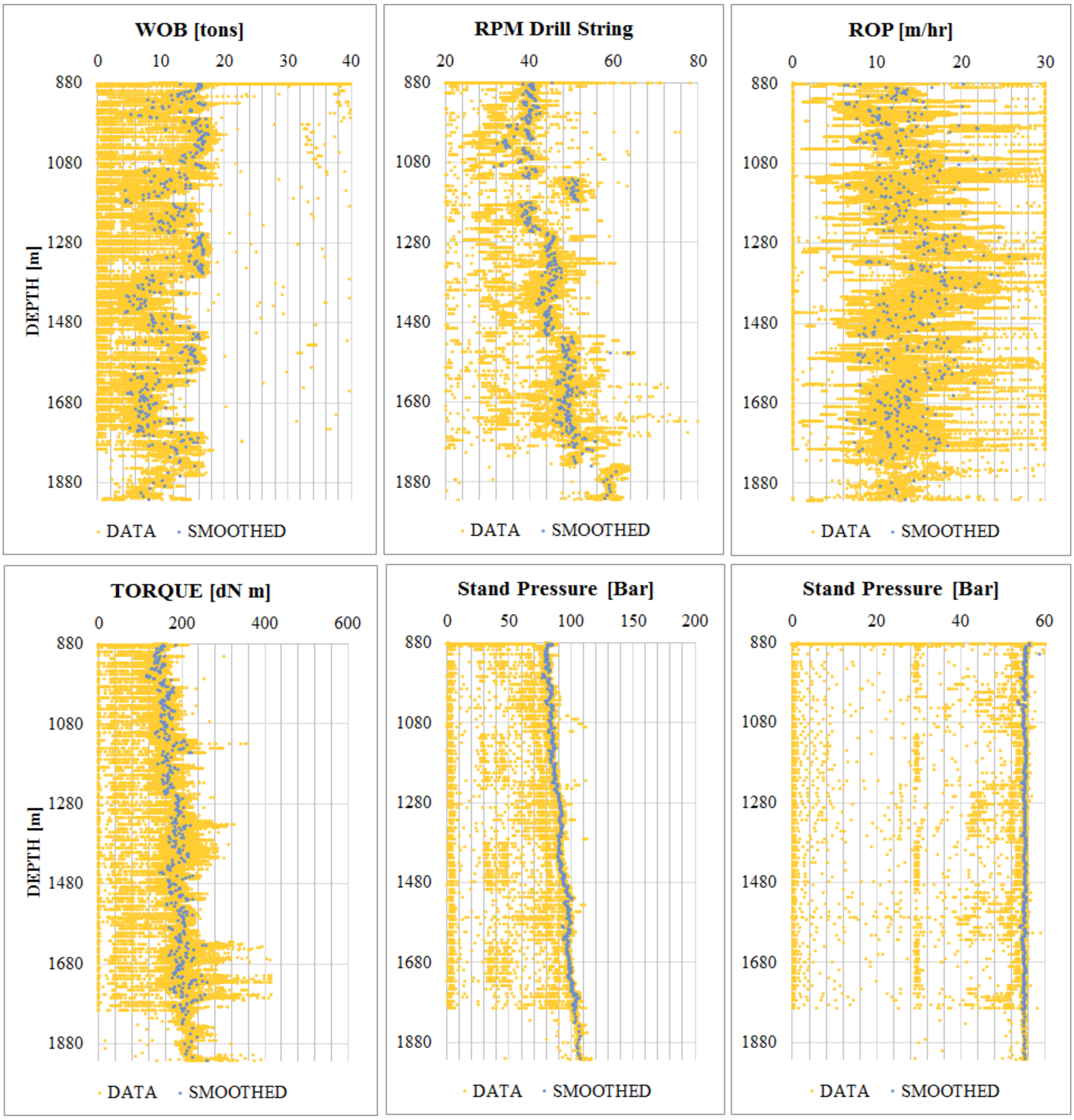

FIGURE 4: Raw data, filtered and smoothed

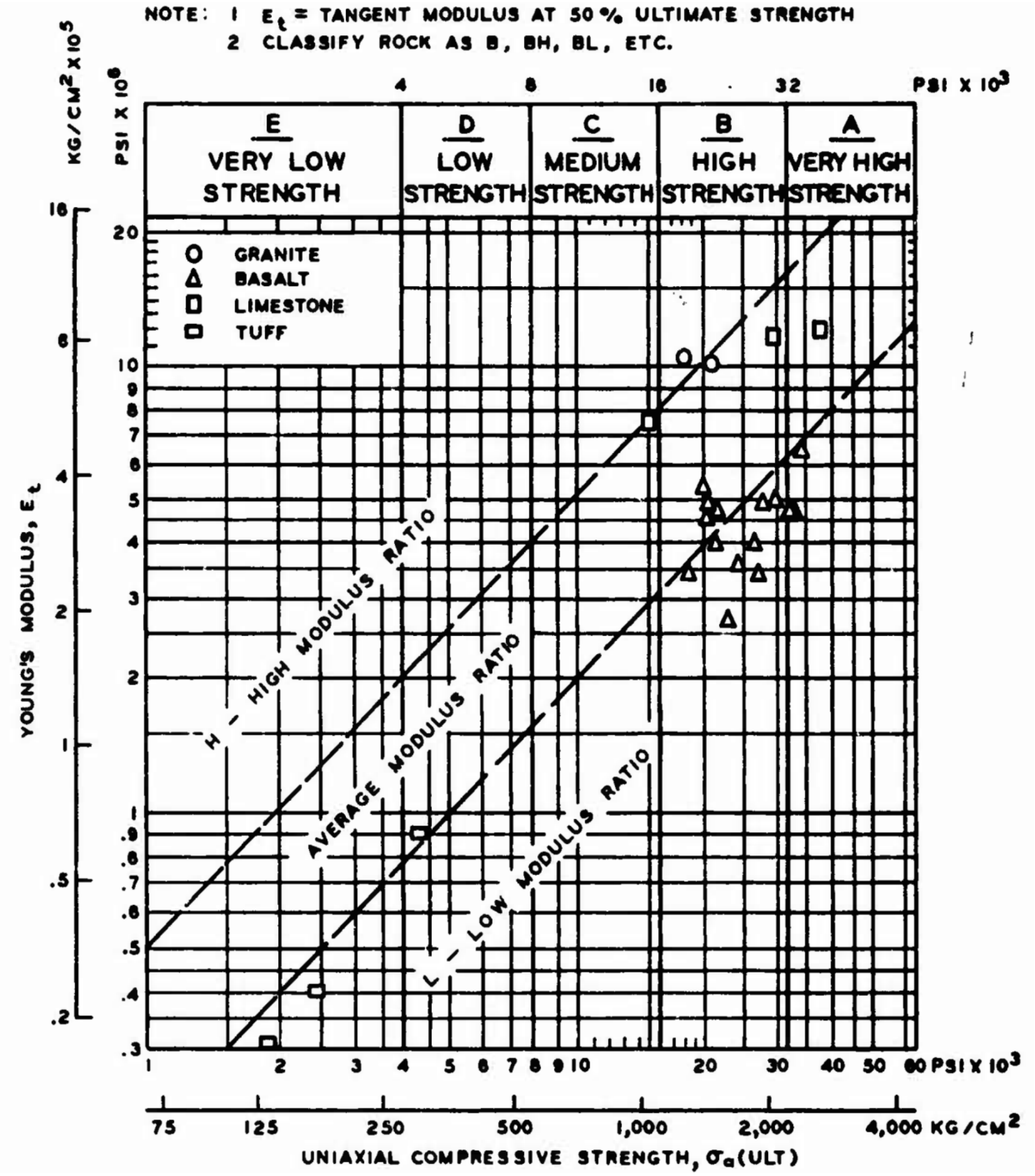

FIGURE 5: UCS for intact basalt at different loading rate (Stowe, 1969)