PROCEEDINGS, 46th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 15-17, 2021
SGP-TR-218

Common Practice of Formation Evaluation Program in Geothermal Drilling

Vicky R. Chandra[1], Ribka F. Asokawati[2], Dorman P. Purba[3]

[1]PT Geo Dipa Energi, Jl. Warung Buncit Raya No.75, Jakarta, Indonesia

[2]PT Rigsis Energi Indonesia, Equity Tower, 49th Floor, Jl. Jend. Sudirman, Jakarta, Indonesia

[3]PT Enerka Bhumi Pratama, Kawasan Komersial Cilandak Gudang 410, Jakarta Selatan 12560, Indonesia

vickyraychandra@gmail.com

Keywords: technique, petrography, xrd, methylene blue, formation evaluation, cutting, coring, pressure, temperature, spinner, rock pH, borehole image, drilling, mudlogging, geothermal

ABSTRACT

Formation evaluation program in drilling operation, particularly geothermal drilling, is very much determined by the purpose and objective of drilling itself. During early exploration phase, the formation evaluation program is carried out by collecting as much subsurface information as possible. This was applied because of available subsurface data to support the development geothermal project are very limited. On the other hand, the program is very influenced and directly involve to the drilling operation that might risks the drilling operation, in term of well stability and well cost perspective. Thus, the effective and efficient techniques are highly required in the making of proper formation evaluation program.

The main purpose of formation evaluation is to get a better understanding of subsurface geology and developed geothermal system so the best future strategy of field development can be determined. By doing this evaluation while drilling, it will give an advantage to the drilling operation itself. Knowledge of the real-time drilled formation, in term of its behavior, characteristic, and composition, will help the improvement of drilling performance and increase the well success ratio.

This paper will present the available technical guidelines that can be applied to evaluate the formation during drilling operation, completed by the pros and cons. Those techniques including drill cutting examination and analysis, drilling data interpretation, rock coring analysis, both conventional and sidewall coring, and well-logging, including PTS logging, acoustic and electric borehole imaging, also other logging activity. All those techniques expected to enhance the better understanding of subsurface geology and improve the drilling operation.

1. INTRODUCTION

Formation evaluation program holds an important role in drilling campaign as the program to get a better understanding of subsurface geology and developed geothermal system so the best future strategy of field development can be determined. Formation evaluation can be divided into two different condition, the first one is for exploration drilling. During early exploration phase, the formation evaluation program is carried out by collecting as much subsurface information as possible. This was applied because of available subsurface data to support the development geothermal project are very limited. The purpose of formation evaluation in exploration drilling is to help looking for the upflow zone, prove the prospect area and target the permeable zone (structure, lithology, and contact lithology).

The other condition of formation evaluation program is for development drilling. In development drilling, we already know some data and by drilling, we can collect more data and complete our subsurface modelling of the field. The formation evaluation will provide information to characterize the reservoir and quantifying reserves in current production area and new undrilled area, to delineate the border top of reservoir, bottom of reservoir, and to map the steam cap of reservoir.

By doing formation evaluation program while drilling, it will give an advantage to the drilling operation itself. Knowledge of the real-time drilled formation, in term of its behavior, characteristic, and composition, will help the improvement of drilling performance and increase the well success ratio. The success ratio will also include from the well stability and well cost perspective. Thus, the effective and efficient techniques are highly required in the making of proper formation evaluation program.

2. METHODOLOGY

The methodology used in this paper both from literature and practical experiences from Authors and other expertise. This paper provides optional program for evaluating the subsurface formation during drilling activity. The mentioned techniques completed by workflow, efficiency, including pros and cons.

Integrated of all mentioned techniques gives us the comprehensive interpretation about subsurface condition in order to make an improvement related to drilling activity and development strategy.

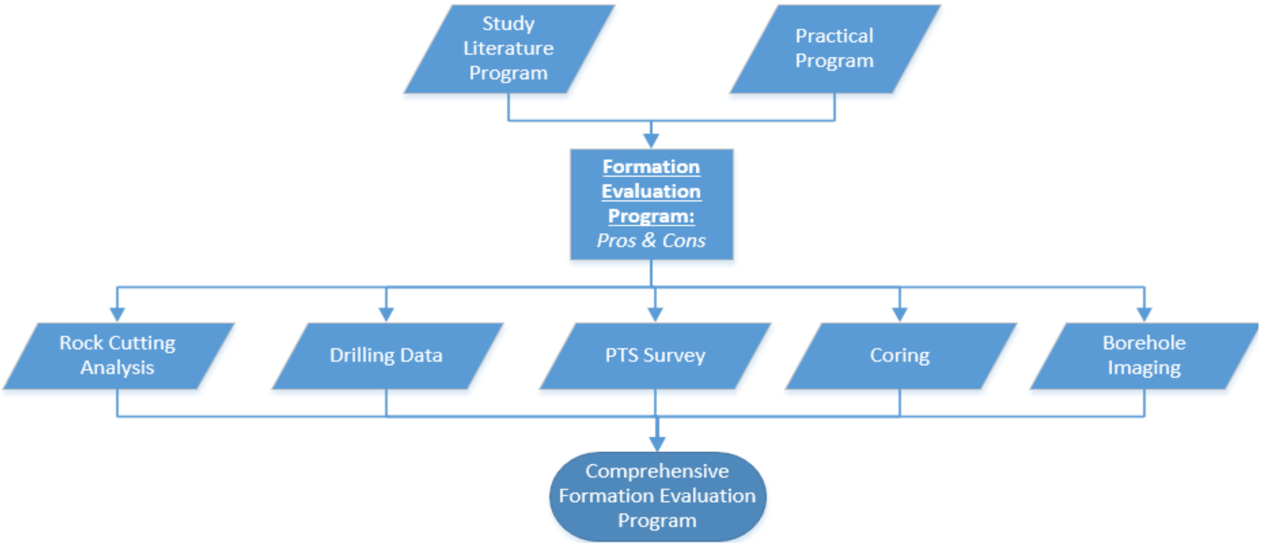

Figure 1: Methodology chart utilized in this study.

3. TECHNIQUES

3.1 Rock Cutting Analysis

Rock cuttings will bring the information of lithologies, depth base of the clay cap-rock, smectite content from Methylene Blue (MeB) analysis, first epidote, and continues epidote, evidence of veining and fracturing and monitoring the complete set of drilling parameters.

Drill cutting is a real time and on-site evaluation, the cuttings usually collected at every 3 m (10 ft) intervals (as specified by the well site geologist. The sample is available when drilling with returns.

The information of sample depth and time at shale-shakers is important, and detail microscope rock analysis is needed to conduct by the well site geologist (WSG).

3.1.1 Microscopic Analysis

Drilling cutting produced while drill a formation is not always contained of rocks and minerals, sometimes it contains steel junks as the result of drill string friction, it can also contain strange materials such as fiber, pieces of wood, $CaCO_3$ grains and so on depends on the type of used drilling fluids and many more. The first step to evaluate the drilling cutting is to differentiate which one is the formation and which one is not. There are many ways and styles on how to describe the lithology of the cutting. It usually starts from very prominent features which is color of the rock, followed by hardness, texture, structure, composition, and other significant features such as secondary minerals included grade and intensity of alteration, degree of crystallinity, vein mineralogy, paragenesis, and rare alteration minerals with its behaviors.

The steel junk found in cutting indicates the drilling string scrub the surrounding surfaces, it can be friction with casing or formation. Finding the steel junk in big amount in cutting could be a sign that the drilling string is intensively washed out. This can be happened within high dog leg interval, high vibration drilling, and during hard drilling of an abrasive formation such as silica-rich formation.

The advantage of microscopic analysis is we can observe the real mineral composition of the formation directly fresh from the drilling data (real-time data). The first notification of certain zone beneath the surface can be captured through the cutting. The analysis then transmits to the office-based geologist so the geothermal system interpretation could be updated directly. The wellsite geologist who will be in charge the analysis also will inform the other drilling crew about the zonation progress of drilling. Thus, will improve the drilling operation (identification hole problem such as tight spot, sloughing, loss zone, fill, caving, or reservoir zone).

Table 1: Example of cutting description worksheet.

DEPTH (mMD)	HYDROTHERMAL ALTERATION											DESCRIPTION
	Alteration Intensity: 1 - Rare 2 - Weak 3 - Moderate 4 - Strong											*Include colour, hardness, texture, composition, lithology and other significant features (e.g., crystallinity of secondary minerals, vein mineralogy, paragenesis, relict, etc.). Identify formation name when applicable. Reminder: Comment on rare alteration minerals in text.*
	Hm/ Lim	**Cal**	**Qtz**	**Pyr**	**I**	**Chl**	**Epi**	**Mt**	**Smc**	***Veins***	***Shearing***	
1245	0	1	3	1	3	2	1	1	0	1	0	Mostly white and transparent colour. Moderate hard and brittle formation. Fragmented texture with composition dominated by crystal tuff and whitish rhyolitic tuffaceous matrix. Moderate intensity and medium grade of alteration. Dominated by silicification which is amorphous quartz sometimes semi crystalline. Epidote in crystalline form but remain rare. Chlorite in dark greenish in weak to moderate amount. illite exhibit specks embedded in crystal. Calcite in semi crystalline form. Vein filled by crystalline epidote at 1245 incipient epidote observed start at 1251 **Name: Rhyolitic Tuff**
1248	1	2	3	1	2	1	1	1	0	0	0	
1251	0	1	2	1	2	1	1	1	0	0	0	
1254	0	1	2	1	2	1	1	1	0	0	0	
1257	1	1	2	1	2	2	1	1	0	0	0	
1260	1	1	2	0	2	1	1	0	0	0	0	
1263	1	1	2	0	2	1	1	1	0	0	0	
1266	0	2	2	1	2	1	0	0	0	0	0	
1269	0	1	2	1	2	1	0	0	0	0	0	
1272	0	1	2	1	2	1	0	0	0	0	0	
1275	1	1	2	1	2	1	0	0	0	0	0	

3.1.2 Petrographic Analysis

Petrographic analysis will be applied usually after few days or not necessarily analyze during the drilling campaign. Usually, the analysis will be performed on certain laboratory with specific microscope. The samples will be chosen for further analysis. The petrographic sample usually is used to get better understanding of the subsurface rock composition which will be affect the geothermal system modeling, such as delineating the border top of reservoir, bottom of reservoir, or the steam cap of reservoir. Although, thin section preparation could be conducted at rig site or site laboratory if there are tools available.

3.1.3 Methylene Blue (MeB) Analysis

Comprehensive analysis of rock cutting strengthens the interpretation of subsurface condition and gives a lot of advices in drilling operation, especially to avoid the most common geothermal drilling problem, which is stuck pipe due to swelling clay (Smectite clay). One of the techniques to identify the smectite clay content in rock cutting is Methylene Blue (MeB) Analysis. MeB is an organic dye that shows high selectivity for adsorption by smectite clays. The dye also is adsorbed by the smectite component of mixed layer clays but is largely unaffected by other (even electrically conductive) common clay minerals. This selectivity permits it to be used to estimate on a semi-quantitative basis the amount of smectite present in alteration mineral assemblages. The technique is rapid, requires little sample and can readily be carried out by the rig geologist under relatively unsophisticated field conditions. (Gunderson, 2000).

For the analysis of geothermal drill cutting the MeB dye is essentially “titrated” into a suspension containing powdered drill cuttings until the rock is saturated with the MeB molecule. By measuring how much MeB is required to saturate the rock, the quantity of smectite clays in the rock can be calculated. The method involves the incremental addition of a known concentration of MeB solution into an acidified suspension containing a known quantity of powdered rock sample. The MeB is adsorbed by the smectite until the point where the smectite is saturated. Beyond this point there is free MeB in solution, which can be easily recognized by blotting the fluid onto standard filter paper. (Gunderson, 2000).

The advantage of MeB analysis, we can obtain direct result of the clay content from the drilling cutting samples. The result will be a first caution for the drilling team if the smectite content exceed the procedure limitation. The drilling team then will prepare the mitigation to prevent the tight hole and stuck pipe occurrences. It will also help the subsurface team to delineate the clay zone of field geothermal system. The cons of MeB analysis are MeB samples only represent certain spot of the well. Therefore, we need to analyze several samples in one time to conclude the clay content result.

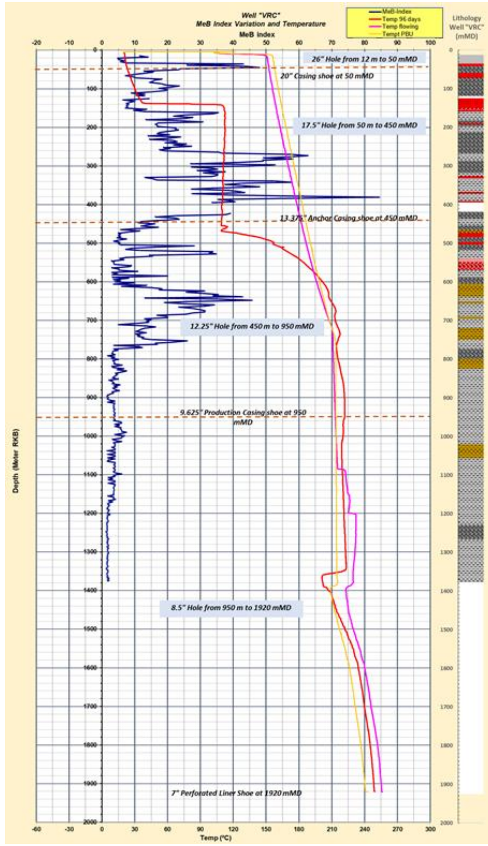

Figure 2: Correlation of MeB value with Subsurface PT and lithology of Well "VRC"

3.1.4 X-Ray Diffraction Analysis

X-ray diffraction is based on constructive interference of monochromatic X-rays and a crystalline sample. These X-rays are generated by a cathode ray tube, filtered to produce monochromatic radiation, collimated to concentrate, and directed toward the sample. One of the crystalline samples are the clay minerals. Clay minerals have certain structure, composition, properties, and occurrences which have a specific characteristic that can be distinguished from the other mineral in wavelength pattern (Moore and Reynolds, 1989). The XRD unit nowadays have a record database of X-ray diffraction patterns of clay mineral so after the sample has put in the chamber and tested, the tools will automatically search the fittest X-ray diffraction pattern on the database and give the results.

In the drilling campaign, the pros of this analysis are it can generate the mineral composition name, especially clay mineral accurately. It would help the subsurface team to update the conceptual modelling and help the drilling improvement. The cons of this analysis are the tools is so big and unable to move. The samples needed is also in a little amount, so whether the samples represent the borehole is questionable. Therefore, the samples should be prepared carefully.

Nowadays, there is another alternative of XRD instrument, called halo mineral identifier. This is a full-range VIS-NIR-SWIR spectrometer measuring the visible, near-infrared and short-wave infrared regions (350-2500 nm) that produces immediate on-instrument results using a non-destructive contact measurement. The instrument includes internal references to allow for easy operation and data management also features proprietary, state-of-the-art mineral identification software for fast data capture in the field and easy data management back in the lab or core shack. It would be a hand-held instrument (portable) so we can use it in the field immediately. The cons of this instruments is the database limitation because the input mineral database cannot be inserted manually and limited so sometime the result will be missed.

3.1.5 Rock pH Test

The mineral itself will be altered after interacting with hydrothermal fluid. It would lead to specific characteristics including temperature and pH, such as epidote represents above 200°C fluid temperature with benign pH, or kaolinite represents 100 – 200 °C fluid temperature with acidic pH. The specific minerals will represent the surrounding pH environmental. But sometimes, when the fluid equilibrium shifting to different pH, the mineral alteration will not represent the fluid condition anymore. But the recent pH of the rocks from the cuttings ideally should be match to the reservoir fluid. Therefore, it should be rechecked through rock pH test.

The cuttings should be crushed into powder, dissolved into aquadest (with comparison 10 mg powder needs 50 ml aquadest), then check the pH. Next, let stand 5 – 6 hours, and measure the pH again. If there was not much difference, we can use the result. The pro of this method is it is quite easy to apply at the field, but it will be cons too because the human error is probably very easily interfered in this analysis.

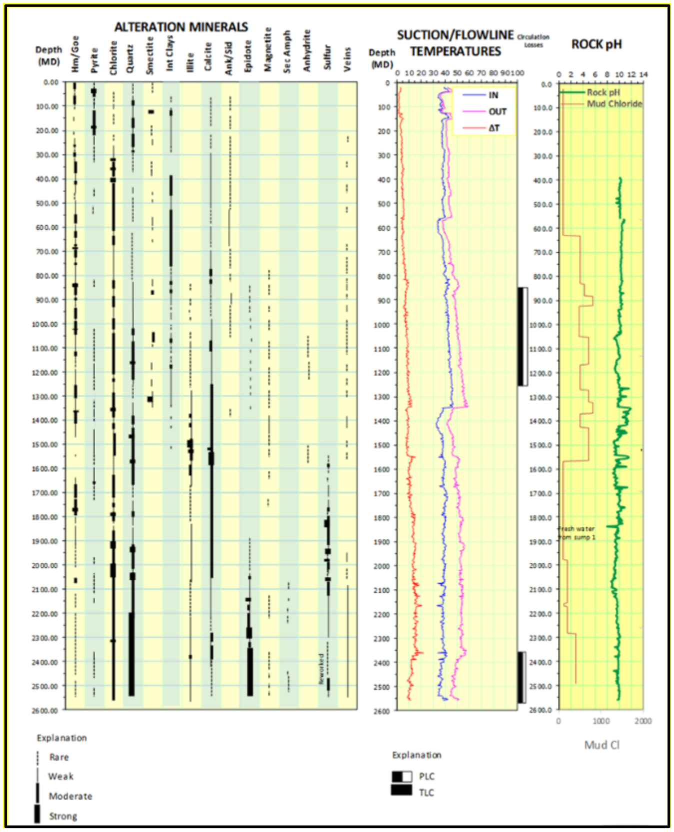

Figure 3: Rock pH analysis in Well "RA"

3.2 Drilling Data

3.2.1 Mudlogging

Mud-Logging systems of modern drilling rigs provide numerous data, directly extracted from rig sensors systems which usually mounted to Rotary system, Circulation system, and Hoisting system. The real time drilling parameter data directly collected from the sensors and calculated by Mud-Logging system with certain formula. Regular calibration and inspection of the sensors are highly required to maintain the quality of the data. Parameters from drilling activity used in interpretation of subsurface condition showed in Figure 4.

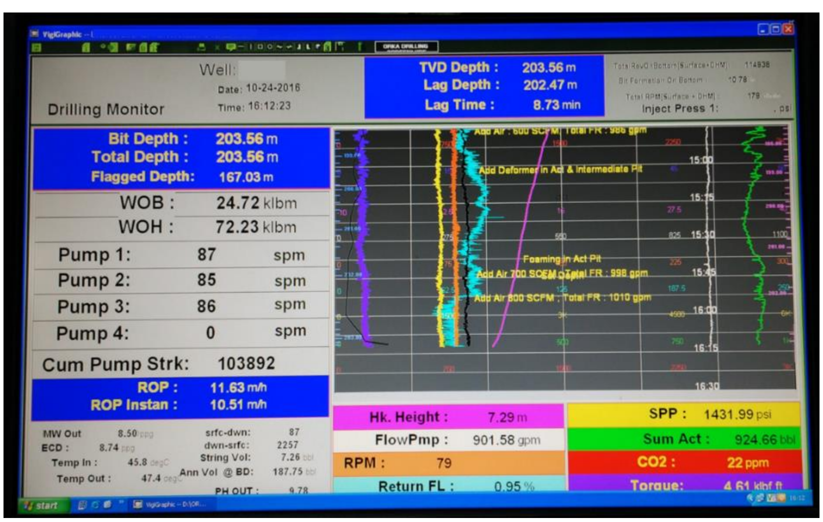

Figure 4: Real time drilling parameter data.

3.2.2 Rate of Penetration

Hardness of the formation usually reflected by the Rate of Penetration (ROP), the softer formation, the higher of ROP and it works in other way. Despite there are factors that known to have effect on ROP are listed under two general classifications such as controllable and environmental. Controllable factors are the factors which can be instantly changed such as WOB, RPM, hydraulics. Environmental factors on the other hand are not controllable such as formation properties, drilling fluids requirements. (Mahasneh,2017). The hardness of formation controlled by several factors, such as composition of the lithology, texture and structure, porosity and permeability, faults and joints, and secondary mineral intergrowth in the lithology as product of rock and hot fluid interactions. These natural properties of the lithology affect the ROP. By analyzing the ROP, thus we can interpret the changing strength of the subsurface formation, for example, the drilling breaks noticed from sudden jumping ROP can indicate penetrating the different lithology (contact of formation and contact of fragment-matrix), can also indicate the Bottom Hole Assembly (BHA) is passing through the faulted formation.

Figure 5 shows the trend of ROP while passing through the formation. Seen at 900 mMD the ROP is high when drilling Tuff Breccia and at 2000 mMD the ROP is low when drilling Diorite Intrusion although both WOB is in consistent amount. The hardness comparison of those formations shows that the Tuff breccia is softer than Diorite Intrusion.

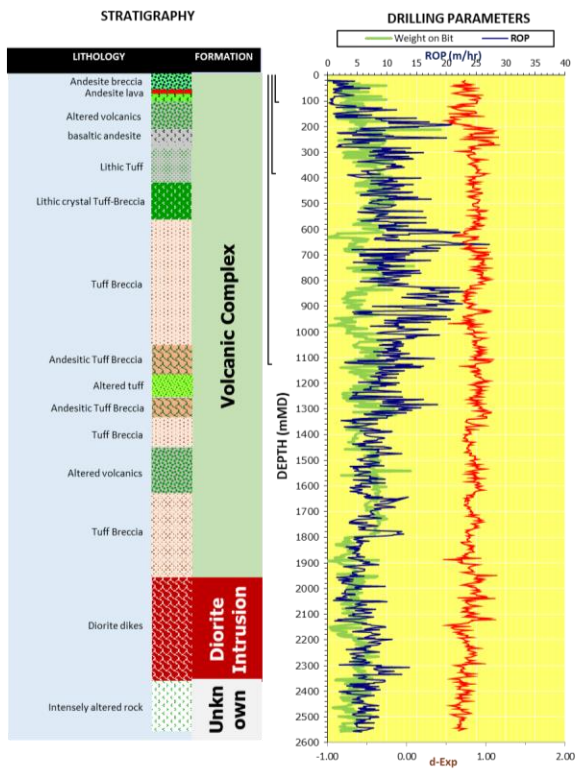

Figure 5: Stratigraphy and ROP trends of Well "X"

The permeability of subsurface formation can be adjusted as fractures developed to improve the permeability and at the other side it can be decreased as well as intergrowing of secondary minerals fill the spaces. Porous formation can be detected during drilling operation by noticing loss circulation event and gaining fluid (kick). Loss circulation or loss of returns is defined as the drilling fluids into the formations which are usually lost to natural or induced formation fractures (Whitfill 2008 in Rahmanifard 2014). It happens due to the hydrostatic pressure is more than formation pressure in over balanced condition. Loss circulation event characterized by sudden drop of Standpipe Pressure and fluid level drop in active mud tank while there is partially and even no return to surface. Gain or kick is an event where the formation fluid flow into the wellbore due to the pore pressure is higher than hydrostatic pressure known as underbalanced condition. The primary method of detecting a kick is to compare measurement of the drilling fluid inflow and outflow, if outflow the greater then there is a kick. It also can be detected by monitoring the increased fluid level in mud pits. The other indicators of impending flow from the well are influx of gas, rapid rise in the temperature of returning fluids and encountering rapid drilling, particularly if associated with a loss of returns (Finger, 2010).

3.2.3 Directional Drilling Tendency

Directional drilling activity with angle trajectory influenced by the rock formation especially the hardness. The bit will tend to look for soft formation than hard formation. The directional drilling trend will give subsurface depiction of lithology beneath. It also will give us the information of bit walk when operation. The cons of this analysis is we need to comply with other analysis to find the better result of this analysis.

3.3 PTS Survey

Pressure, temperature and spinner (PTS) logging is used worldwide to study geothermal wells during drilling. PTS logs locate outflow and inflow zones in wells and the spinner log is used to quantify the flow in and out of the feed zones and determine the relative contribution of each of the feed zones to the flow pattern in the well. The pressure logs show the pressure conditions (including the water table) in the wells and give valuable information on the permeability structure around and in the vicinity of the wells and the hydrologic connection of the wells to the geothermal reservoir (Gudmondsdottir and Steingrimsson, 2018).

3.4 Coring

Spot cores are often taken in geothermal drilling especially in exploration phase to improve understanding of subsurface condition. There are two type of cores could be taken, which are conventional (continuous) core and side wall core.

Skinny et al (2010) suggests important notes to improve the coring operation which could be applied in both type of coring jobs. That notes should be considered are the percentage of core recovery, bit grading and performance, core barrel handling and coring tools temperature limitation since the interest formation usually related to high temperature zones.

3.4.1 Conventional Coring

Conventional cores, also known as whole cores are continuous sections of rock extracted from the formation in a process similar to conventional drilling. The two operations differ chiefly in the type of bit used: Instead of a conventional drill bit, coring uses a hollow bit and core barrel in the Bottom Hole Assembly. (Varhaug,2015).

Figure 5: Core sample on faulted formation in particular depth of "DP" Well.

Continuous coring sample reflected stack of formation like in natural state, it provides information accurately to present the subsurface condition. Fractured formation obviously seen in cores, but the orientation of the structures is hardly determined. The tool face orientation technology could be applied in this case.

3.4.2 Sidewall Coring

Sidewall cores (SWCs), plugs of rock taken from the wellbore wall, may offer a cost-effective alternative to conventional cores. The SWCs are usually acquired by wireline tools, and a single wireline descent can recover SWCs from multiple zones of interest (Varhaug,2015). The updated technology of sidewall coring offers two ways to extract the samples, one is by applying percussion sidewall coring gun and the other using rotary coring bit. Both tools are run with wireline after the hole reach TD and while the hole is still open.

The cores extracted spotted in various depth within such interval. In-term of the operation, the tripping time is not as much as conventional coring, due to utilization of wireline technology instead of drill-pipe. Although, the success ratio of SWCs to catch the samples remains low while coring the side wall hole even more the formation is massive and solid.

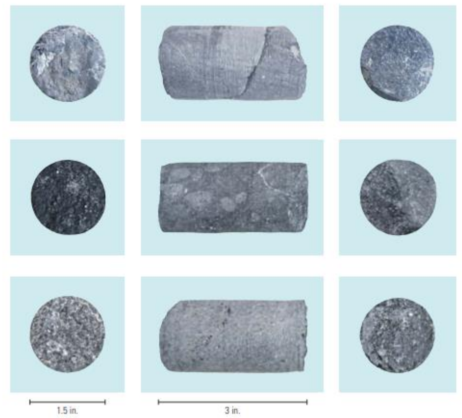

Figure 6: Side wall core sample, borehole end (left), side view (middle), and rock end (right). (Photographs courtesy of William Murphy in Agarwal 2014).

3.5 Bore-hole Imaging.

The common borehole imaging technique used in geothermal drilling to evaluate the formation is open hole logging using both electrical resistivity and acoustic reflectivity measurement. Those techniques used to be focused on identification of formation permeability usually indicated by structural framework and lithological properties (porosity and lithological contact).

Acoustic imaging tools are mandrel devices that consist of a rotating (4-12rps) piezoelectric transducer that operates in a pulse-echo mode at an ultrasonic frequency. The transducer, which acts as both transmitter and receiver, measures the travel-time and amplitude of an acoustic pulse reflected off the borehole wall or casing as the transducer scans the borehole with each rotation. Acoustic energy does not travel in a gas, it can be applied in both conductive (water-based) and non-conductive (oil-based) muds (Prensky,1999). The primary applications of acoustic imaging are identification and evaluation of fractures (e.g. Dudley 1993) and breakouts, borehole geometry, and cement evaluation. The image is displayed with the convention that light colors represent highly reflective formations, while low reflective formations are in darker colors (longer travel time). Variations in lithology, bedding, lamination or physical rock features such as fractures and vugs consisting of varying impedance that can be seen on the reflectance amplitude image. Any borehole intersection of planar geological features (foliation planes, faults, joints) will be shown as sinusoid on the images. In this area the following features are distinguished: several types of natural fractures (open, partially open, closed, discontinuous), foliation planes, faults. Other features, deriving from drilling are recognized: tensile induced fractures, breakout and compressional centerline fractures. A manual interactive picking point-to-point correlation technique was used in order to provide classified orientation data that are as accurate as possible (Berto, 2002).

Electrical imaging devices are electrode-type resistivity devices that measure resistivity and require a conductive borehole fluid. These are pad-type resistivity devices comprised of multiple, generally independent arms (four, six, and sixteen and so on) each of which has one or more pads and each pad contains several or an array of closely spaced microelectrodes. The pads inject current into the formation and the microelectrodes measure the current density across the pad which is kept at a constant potential relative to the return electrode. Variations in current density are due to variations in local formation resistivity (Prensky,1999).

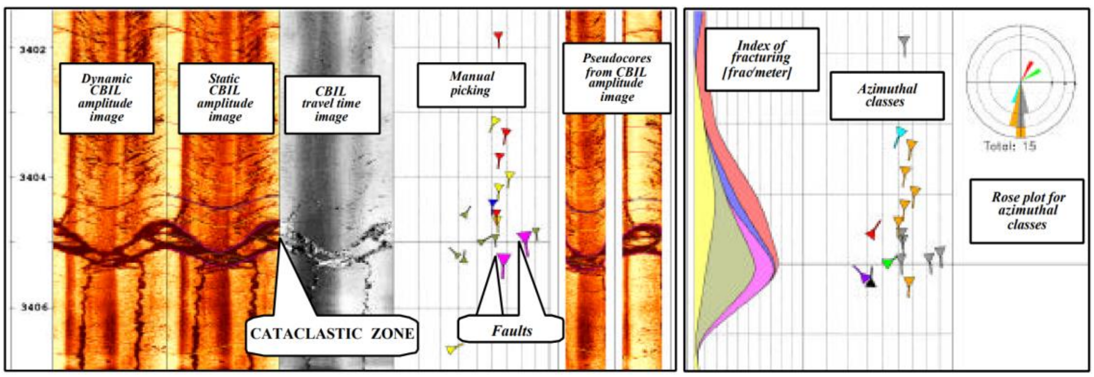

Figure 7: Acoustic image recorded using CBIL® shows structural interpretation in a cataclastic zone observed in the Palazzaccio 2 well, at depth 3404.8-3405.2m (Berto, 2002).

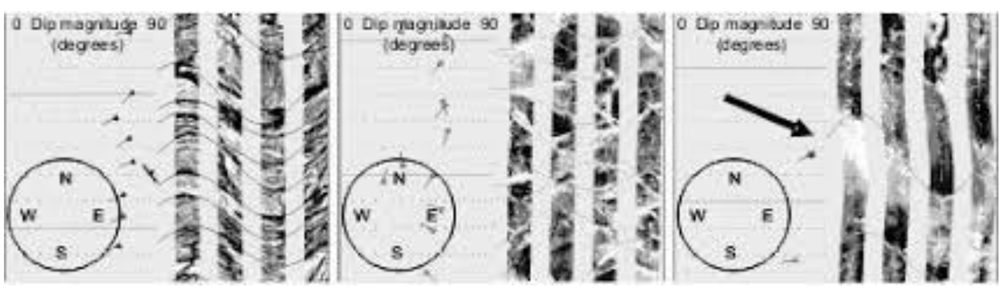

Figure 8: Left: conductive (dark) open fractures over interval 1,551-1,553 m. Middle: resistive (light) healed fractures. Right: fault at 1,100 m flows 8,900 BWPD into the borehole. (Netherwood,2008)

Fractures that appear conductive (dark on Figure 9) on the electrical borehole image can be open (invaded by drilling fluid) or clay filled. They are abundant and, although not exclusively so, tend to be concentrated in more resistive and, therefore, more brittle (cemented) rock. Resistive (light on Figure 9) fractures are healed by electrically resistive minerals such as quartz or calcite, are less extensively developed and, may be concentrated in both resistive and conductive rock. Faults (Figure 9) were identified based on evidence for movement, including truncation of bedding and changes in lithofacies or lithology across a fault plane (Netherwood,2008).

By doing the analysis of anisotropy resistivity value of a wellbore formation (electric image) and analysis the travel-time and amplitude of acoustic wave (Acoustic image), those techniques can give a guidance in permeability analysis in-term of structural frameworks and lithological permeability control. It is important to be considered that both electrical and acoustic borehole imaging techniques have its own advantages/disadvantages, in term of data quality and data acquisition (See Table-2).

Table 1 Comparison Electric and acoustic borehole imaging technique (Modified from Kubik et al 1992 in Prensky,1999)

Technique	Advantages	Limitations/disadvantages	Guidelines
Microresistivity	High-resolution	Requires conductive muds	use interpretation windows of 4 and 30 ft
	Good strike/dip quantification of natural and induced fractures	Limited borehole coverage on single pass of 4-pad tool may result in poor fracture ID	Make multiple passes with a 4-pad tool, or use 6-pad 0r 8-pad devices for higer borehole coverage
	Thin-bed detection	Joint ID dependent largerly upon degree of borehole spalling	cross-correlate with core and/or other tools
	Data routinely corrected for borehole deviation and magnetic declination	large spalls difficult to identify as joints and to quantify	many stuies indicate accoustic tecniques image fewer (undersample) fractures compared with microresistivity techniques
	Low operational sensitivity	Resolution decreased by pad standoff	
		irregular logging speed (stick/pull) causes laye misalignment	
Acoustic	Essentially full borehole coverage	reduced effectiveness in heavy muds; can't operate in air/gas-filled holes	take all precautions possible to minimize eccentering nd tool noise
	Good strike/dip quantification of natural and induced fractures	Rugosity, eccentering, and motor noise may locally limit effectiveness borehle coverge	use directionally corrected tool package if availabel
	Breakout detection and orientation (stress tensor)	Joint identification dependent largely upon degress of borehole spalling	cross-correlate with core and/or other tools
	high-resolution borehole caliper (geometry)	large spalls difficult to identify as joints and to quantify	
		Some tools are not routinely corrected for borehole deviation and magnetic declination	

4. CONCLUSION

There are many techniques available on how to evaluate the formation during drilling activity. Every technique has its own limitation, risks, costs, benefits, and pros/cons. The election of a particular technique depends on the purpose of the drilling itself and should consider the parameter mentioned earlier.

The technology rapidly developed on these days, it might impact the formation evaluation strategy on minimizing the risk and cost and maximizing the result and positive impact on future strategy. This table 3 below provides subjective conclusion on formation evaluation technique.

Table 3 Subjective conclusion of formation evaluation techniques

Techniques		Benefit			Execution		Cost
		Drilling Target Monitoring	Next Well Targeting	Drilling Operation Adjustment	Time	Risk	
Rock Cutting	Microscopic Analysis	Very High	Very High	Very High	Low	Very Low	Low
	Petrographic Analysis	High	Very High	High	High	Very Low	Medium
	Methylene Blue Analysis	Very High	Very High	Very High	Low	Very Low	Very Low
	X-Ray Diffraction Analysis	High	Very High	High	High	Very Low	Medium
	Rock pH Analysis	High	High	High	High	Very Low	Very Low
Drilling Data	Mud Logging Data Analysis	Very High	Very High	Very High	Very Low	Very Low	Very Low
	Rate of Penetration Analysis	Very High	Very High	Very High	Very Low	Very Low	Very Low
	Directional Drilling Tendency	Very High	Very High	Very High	Very Low	Very Low	Very Low
PTS Logging		Very High	Very High	Medium	High	High	Medium
Coring	Conventional Coring	Very High	Very High	Low	Very High	High	Very High
	Side Wall Coring	High	High	Low	Very High	Very High	Very High
Borehole Imaging	Electrical Imaging	High	Very High	Medium	Very High	Very High	Very High
	Acoustic Imaging	High	Very High	Medium	Very High	Very High	High

5. ACKNOWLEDGEMENT

This paper is written based on literature study, author's experiences, and informal discussion with expertise. The support of all the parties involved on this paper are gratefully acknowledged.

REFERENCES

Agarwal, Abhisek, Robert Laronga, and Larissa Walker. "Rotary Sidewall Coring - Size Matters." *Schlumberger*. 2014. https://www.slb.com/-/media/files/oilfield-review/03-rotary-side (accessed August 9, 2020).

Arnaout, Arghad, Rudolf K. Fruhwirth, Bilal Esmael, and Gerhard Thonhauser. "Intelligent Real-time Drilling Operations Classification Using Trend Analysis of Drilling Rig Sensors Data." *Society of Petroleum Engineers Kuwait International Petroleum Conference and Exhibition.* Kuwait City: SPE Kuwait, 2020.

Berto, Roberto, Fabio Brambilla, Michele Casini, and Adolfo Fiordelisi. "Advanced Well-log Analysis in Geothermal Wells for Fracture Identification." *EAGE 64th Conference & Exhibition.* Florence, Italy: European Association of Geoscientists, 2002.

Finger, John, and Doug Blankenship. *Handbook of Best Practices for Geothermal Drilling.* Albuquerque, New Mexico: Sandia National Laboratories, 2010.

Florence, Fred, and Fionn Petter Iversen. "Real-Time Models for Drilling Process Automation: Equations and Applications." *IADC/SPE Drilling Conference and Exhibition, 2-4 February.* New Orleans, Louisiana, USA: Society of Petroleum Engineers, 2010.

Gudmundsdottir, Valdis, and Benedikt Steingrimsson. "Geothermal Well Logs: The Role of Spinner, Temperature and Pressure Logging During Drilling in Locationg Feed Zones in Wells." *SDG Short Course III on Geothermal Reservoir Characterization.* Santa Tecla, El Salvador: UNU-GTP and LaGeo, 2018.

Gunderson, Richard, William Cumming, Doddy Astra, and Colin Harvey. "Analysis of Smectite Clays in Geothermal Drill Cuttings by the Methylene Blue Method: For Well Site Geothermometry and Resistivity Sounding Correlation." *Proceedings World Geothermal Congress.* Kyushyu - Tohoku: World Geothermal Congress, 2000.

Mehaysen, A., and AL-Mahasneh. "Optimization Drilling Parameters Performance During Drilling in Gas Wells." *International Journal of Oil, Gas and Coal Engineering*, 2016: 19-26.

Moore, D. M., and R C, Jr Reynolds. *X-ray Diffraction and the Identification and Analysis of Clay Minerals.* Oxford: Oxford University Press, 1989.

Netherwood, Richard E., et al. "Characterization of Flow Zones in Geothermal Well Using Electrical Borehole Images and Production Logs: An Example from South Sumatra, Indonesia." *New Zealan Geothermal Workshop.* Taupo: New Zealand Geothermal Workshop, 2008.

Prensky, Stephen E. "Advances in borehole imaging technology and applications." In *Borehole Imaging: Applications and Case Histories*, by M. A. Lovell, G. Williamson, & P. Harvey, 1-43. London: Geological Society London, 1999.

Rabia, Hussain. *Oilwell Drilling Engineering : Principles and Practice.* London: Graham & Trotman, 1985.

Rahmanifard, H., A. R. Rasouli, N. Mayahi, A. H. Amouri, and M. Mafreshi. "Best Practice in Managing Lost Circulation Challenges during Drilling and Cementing Operations in Azar Oil Field." *2nd International Conference Of Oil, Gas And Petrochemical.* Tehran: International Conference Of Oil, Gas And Petrochemical, 2014.

Skinner, Alister, Paul Bowers, Sverrir Thorhallsson, Gudmundur Omar Fridleifsson, and Hermann Gudmundsson. "Coring at Extreme Temperatures, Design and Operation of a Core barrel for the Iceland Deep Drilling Project (IDPP)." *Proceedings of World Geothermal Congress 2010.* Bali, Indonesia: World Geothermal Congress 2010, 2010.

Varhaug, Matt, and Tony Smithson. "Downhole Coring." *Schlumberger.* 2015. https://www.slb.com/-/media/files/oilfield-review/defining-coring.ashx (accessed August 9, 2020)