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Review of Characterization Workflow for Geothermal Reservoirs Using High Resolution Cuttings Analysis

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ABSTRACT

For resource extraction projects, exploratory deep wells are drilled, logged and tested to validate commercial production. The collection and analysis of data from these wellbores is necessary to increase the understanding of any reservoir, including those in geothermal work. However, deep drilling is expensive and successful commercial outcomes are risky. Consequently, many operators are reluctant to invest in additional rock analyses, even when their advantages are clear.

Implementation of practical and cost-effective data collection procedures is fundamental to reduce investment associated with drilling and testing, but cost and benefit must be balanced. For instance, recording of pressure and temperature is currently a standard for any geothermal deep well. However, the use of common wireline tools and testing programs that include rock material such as cores are rare. This is not surprising considering the additional cost, technical challenges and limited coverage provided by core collection in the wellbore. For instance, a given core sample has high location accuracy (e.g., depth) but results are specific to that exact depth and may not extrapolate to larger areas of the reservoir without integration with wireline results. As a byproduct of drilling, cuttings rock material circulated up the wellbore are typically collected at discrete measured drilling depths and are commonly archived and available for subsequent research. The use of drilling cuttings as a characterization tool has had historical challenges, including lack of depth precision and insufficient accuracy of laboratory measurements. However, although lacking the depth precision of core (cuttings are typically assigned a depth range based on calculated circulation time to reach the surface from the bit), they have the benefit of being inexpensive and are arguably more representative of bulk properties within depth intervals of a reservoir than point data, such as sidewall cores.

Here we propose a workflow in support of geothermal resource characterization in deep wells using high resolution cuttings analysis. From acquisition to interpretation, the workflow takes into account unique criteria to assess heat as the source of geothermal reservoirs and its interaction with fluids. The grade of modification to current operations in geothermal wells would have to be technically adequate and perform towards decreasing risk indicators at the wellsite as rig time. Accurate continuous laboratory measurements of properties such as mineralogy, thermal conductivity, and specific heat capacity along with approximation of heat flow and other advanced measurements, would be required for adequate characterization and estimation of the geothermal resource.

1. INTRODUCTION

To identify the most appropriate tools and techniques to define the resources and reduce risk in any geothermal project, international organizations have published practical documents as guides for geothermal exploration (IGA, 2014). Throughout the type of input data for conceptual models it is common to find test drilling tools. Among those tools, laboratory measurements on drilling cuttings can be found. Drill cuttings are used for geothermal reservoir characterization in a fashion similar to oil and gas exploration, and demonstrate the value of collecting and analyzing rock material during and after drilling operations to predict reservoir properties at greater depth. Provided high resolution quality cuttings from the wellbore can be obtained, a hydrocarbon assessment study with accompanying cuttings, core, and well log data was analyzed to show the good agreements between each data set (Permata et al, 2020).

Studies involving near real-time techniques for geothermal assessment validate the large amount of data readily available from temperature logs, drill cuttings and cores to identify hot and cold stratification phenomena as seen in the Dunes in California and Marysville in Montana, among other geothermal fields (Batzle and Simmons, 1977). Rock material provided a set of physical properties, fracturing evidence and the presence of large degree of alteration to minerals as kaolinite, chlorite and montmorillonite as proof of diverse hydrothermal systems. Shallow core data at the Coso Hot Springs area in California showed open fracturing allowing minerals such as nontronite and kaolinite to be widely distributed in fractures. According to Batzle and Simmons (1977), this type of evidence indicates the existence of an interconnected network of fractures, and leads them to infer the presence of a hydrothermal circulation system at shallow depths. Therefore, using previous core data from the area, temperature logs and drill cuttings could predict possible temperature profiles that might be anticipated, and enable adjustment of drilling plans in real time.

Many authors agree that drill cuttings provide beneficial information about subsurface resources if carefully sampled, tested and interpreted. Characterization of fractured, altered, dominantly igneous and metamorphic terrains is presented in extracted sections of reports and handbooks (Hulen and Sibbett, 1981), while a description for analysis of sedimentary basins with emphasis on hydrocarbon exploration are available (Swanson, 1981).

In 2017, well 58-32 located in Milford, Utah and part of Forge project, included a core and drill cuttings analysis as part of its testing program. Drill cuttings were collected and described at 10-foot intervals; thermal conductivity, density, X-ray diffraction, magnetic susceptibility, and spectral gamma ray measurements were performed at least every 100 feet. Analyses showed the basement rock consisted of a suite of intrusive rock types, primarily granitic. Other lithologies were also identified as monzodiorite and diorite.

Mineralogy, thermal conductivity and specific heat capacity measurements from drill cuttings provided data that was critical not only to characterization of the rock types but also to understanding the thermal regime of the geothermal system (Gwynn et al, 2019). Efficient methodologies to identify hydrothermally altered minerals using infrared spectroscopy, have been developed and applied to geothermal fields testing programs (Calvin et al 2010).

The analysis of fluids extracted from drill cuttings in assessment of geothermal fields is not a new approach. An applicable example in the Coso geothermal field shows the use of fluid inclusion stratigraphy (FIS) to correlate responses from multiple boreholes and categorize them from producing to non-producing wells (Dilley et al. 2004; Dilley and Norman, 2004; Norman et al. 2004; Dilley et al. 2005). Following the hypothesis that selected gaseous species and their ratios can differentiate groundwater and fluid in fractures, drill cuttings are carriers of selective pore fluid making them one of the best materials from which to extract and analyze fluid chemistry. Techniques like fluid inclusion stratigraphy (FIS) along with 3D models become a strong tool in determining target areas for future geothermal drilling.

In addition to and equally important, maximizing the use of rock material recovered from drilling activities is extremely beneficial to the continuous efforts in minimizing volumes of drilled cuttings as part of Environmental, Health, and Safety Guidelines that regulate drilling activities.

2. DRILLING CUTTINGS ANALYSIS

Extensive documentation has been published regarding analysis performed using drill cuttings to measure physical and chemical properties of borehole rocks. In this section we will summarize some of the property definitions, common reported units, description of analytical techniques and estimations proposed to assess properties related to geothermal resources.

2.1 Elemental and Mineral Composition

Elemental composition from rock material can be measured by X-ray fluorescence (XRF). Over 40 elements can be evaluated including Ca, Si, Al, K, and Thorium (Th) and Uranium (U) trace elements. Major elements are generally reported in weight percentage (wt%) units and trace elements in parts per million (ppm). The method is fast, accurate and usually requires only a minimum amount of sample preparation. XRF spectrometer systems are of two types: Energy dispersive (EDXRF) and wavelength dispersive (WDXRF). The wavelength dispersive method has a higher energy output and a more efficient detector compared to the energy dispersive method (Figure 1). The WDXRF precisely focuses on specific regions in the intensity-spectrum, properly measures the intensity of the peaks and therefore quantifies the elemental compositions more accurately. As a widely used instrument, EDXRF allows for a quick calculation of elements but is less accurate. EDXRF is not fully suitable for trace element quantification, but offers advantages in portability. WDXRF equipment is used to obtain chemical data and a complete geochemical profile of the rock samples measured.

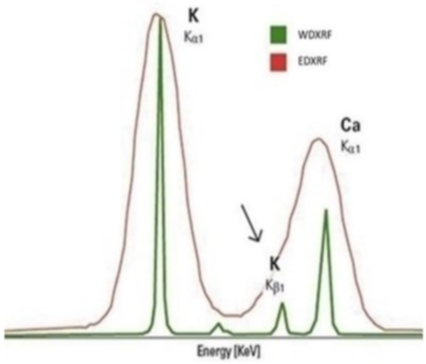

Figure 1: Example of EDXRF and WDXRF measurement spectrum comparison in potassium and calcium elements (Permata et al, 2020)

Mineral composition is measured at the laboratory by analytical techniques such as X-ray diffraction (XRD). Recently, portable XRD units have been developed for use at wellsites. Results are reported as weight percentage (wt%) of minerals present in the sample. This measurement provides diffraction intensities reflected from the crystal structures of minerals. Recent developments for XRD instruments add special detectors to boost a lower limit of detection, eliminate background from fluorescence, and improve the accuracy of measurements. Commercially available or in-house analysis software is used to calibrate the equipment and reference specific minerals to quantitatively measure the mineral percentages in the rock samples. Current software packages are able to automatically perform interpretations based on thousands of diffraction patterns which enable a quick turn-around time and reduce human error. XRD is a well known technique used widely for assessing mineral content for ore minerals evaluation, hydrocarbon exploration and material science characterization. The identification of minerals in a geothermal reservoir provides valuable information about the type of rock, mineral distribution, presence of hydrothermal minerals, and possible indication of fractures. In Calvin et al (2010) a successful identification of layered silicates, zeolites, opal, calcite, iron oxides and hydroxides in drill cuttings using optical and infrared spectroscopy methods was described. Rapid information opens the door to quick recognition of geothermometer mineral distribution and potential fracture zones.

For the techniques described above, sample preparation involves crushing the material and requires less than 30 grams to perform the analysis so unconsolidated rocks and drill cuttings material are suitable for analysis. Instruments are commercially available and automated analysis has increased notably in the last decade. In addition, WDXRF and XRD measurements are not affected by wellbore fluid, so cuttings from any fluid type can be tested and provide quality information useful in log response reconstruction (e.g. gamma ray, photoelectric factor) when wellbore logs are not available. For example, commercial spectrometers are used to measure emitted gamma radiation from whole cores or large amounts of drill cuttings (mostly combined from a large depth interval >100 ft) and the data quality depends on the duration of measurements. One noteworthy alternative is the reconstruction of a gamma ray log using the spectral response from Th, U, and K measured during WDXRF analysis (Permata et al, 2020).

2.2 Thermal Properties

2.2.1 Thermal Conductivity

Thermal conductivity (K), is defined as the ability of a material to conduct heat. For rocks and minerals it is an intrinsic property reported usually in the International Systems of Units (SI) as watts per meter-Kelvin (W/(m°K)), also known as the k value. Several authors have compiled reported measured values or some common rocks and minerals (Figure 2 and Figure 3). A complete description of a standard method to determine the thermal conductivity (K) of cylindrical rock cores is presented in Blackwell and Spafford (1982). The methodology is applicable to hard rocks in the temperature range 5-95°C using a steady state divided-bar technique. The use of a divided-bar technique has been commonly used as part of the exploration set of methods in geothermal characterization when core material is available.

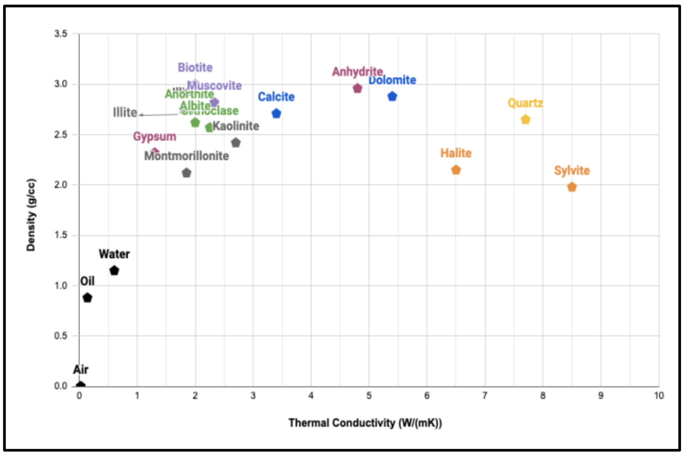

Figure 2: Density vs Thermal Conductivity measured for common minerals and fluids. Modified from Fuchs and Forster (2013).

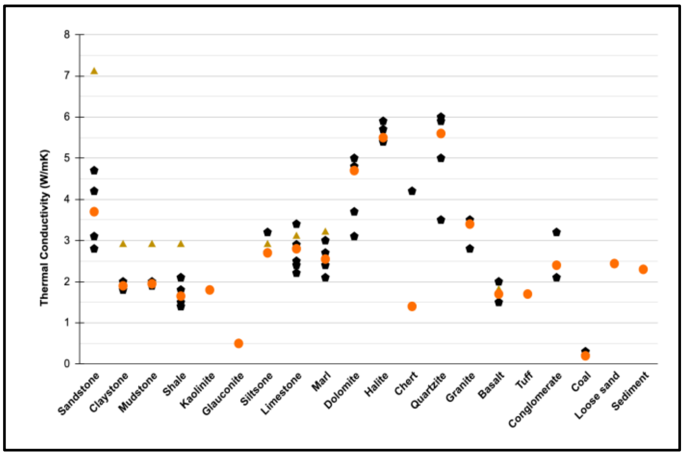

Figure 3: Thermal conductivity measurements for some common rocks. Yellow triangles are matrix thermal conductivity measurements. Black pentagons are bulk thermal conductivity measurements from multiple authors and orange circles are the median values of the bulk thermal conductivity values. Reproduced from Beardsmore et al (2001).

The divided-bar laboratory method can be tedious, time consuming and has specific requirements for material shape. When a well shaped core from the borehole is not available for reliable thermal conductivity measurements it is almost impossible to obtain by a divide-bar method. A comparison of the divided-bar method and needle-probe thermal conductivity measurements for a group of samples is presented in Combs et al (1977). Samples ranging from 2 to 25 p.u. were measured using the divided-bar apparatus while crushed material and drill cuttings were tested using a divided-bar cell technique and the needle-probe technique. Thermal conductivity measurements of drill cuttings from the needle-probe showed an excellent agreement when corrected for water saturations with differences less than a few percentage points on average. Quantification of thermal conductivity by field techniques with the needle-probe method provides an opportunity to incorporate unconsolidated, highly fractured cores and drill cuttings material and provide a reliable and quick measurement of their thermal conductivities with a reasonable precision.

Labus and Labus (2018), measured bi-directional thermal conductivity in fine-grained sedimentary rocks using a C-Therm analyser. The study had relevant findings for sedimentary rocks as the anisotropy of thermal conductivity in shale rocks was highly connected to the presence of organic matter or sheet-silicate minerals. Additionally, the study revealed how the presence of organic matter reduces thermal conductivity. It also confirmed samples with high quartz content show the highest values of thermal conductivity.

It is known that thermal conductivity in rocks and minerals are affected by composition, porosity, water content, pressure, and temperature. Robertson (1988), published a complete compilation of data on common igneous, metamorphic and sedimentary rocks and minerals. The document contains graphs to show the relationships of thermal conductivity to solidity (one minus decimal porosity), water or air pore content, content of certain highly conducting minerals, and temperature. The report describes calculations of thermal conductivity, specific heat, diffusivity and thermal inertia of a rock from its mineral composition. Theoretical models have been used to calculate rock intrinsic thermal conductivities from fractional volume of mineral components. In rocks with parallel arrangement (grains parallel to the heat flow direction), conductivity is:

$$Kp = n1K1 + n2K2 + n3K3 \ldots \tag{1}$$

Where Kp is the parallel bulk rock conductivity, n1, n2, n3 are fractional volumes of minerals 1,2,3 and K1, K2, K3, are conductivity of minerals 1,2,3. While rocks with perpendicular or layered arrangement (layers perpendicular to the heat flow direction), the series conductivity (Ks) is defined:

$$1/Ks = n1/K1 + n2/K2 + n3/K3 \ldots \tag{2}$$

Models used to predict the effective thermal conductivity of porous materials defined for parallel arrangements (Equation 3) and for perpendicular arrangement (Equation 4). Where Keff is the effective thermal conductivity, Kf is the fluid thermal conductivity, Θ is porosity, and Km is the matrix thermal conductivity (Zeb et al, 2020)

$$Keff = \Theta Kf + (1 - \Theta)Km \tag{3}$$

$$Keff = 1/[\Theta/Kf + (1 - \Theta)/Km] \tag{4}$$

Empirical models have been proposed and discussed by several authors in the last decades. These models often compare measurements from outcrops or core material along with additional corrections applied such as thermal impedance. Thermal conductivity value is part of the heat flow definition as shown in Equation 5:

$$Q = K\, dT/dz \tag{5}$$

where Q is Heat flow, K is thermal conductivity and dT/dz is thermal gradient. Heat flow is one of the main thermal parameters for the evaluation of a geothermal resource assessment.

2.2.2 Specific Heat Capacity

The specific heat capacity (Cp) is defined as the amount of heat energy needed to change the temperature of one gram of a substance one degree of temperature (C or K), therefore the SI units are joules per kilogram per Kelvin degree (J/kg°K). Specific heat capacity values of non-porous rocks between 700 to 1300 J/kg°K have been reported (Figure 4). Specific heat capacity is measured in rocks with a calorimeter usually calibrated with water and fused quartz standards. A common measurement procedure for drill cuttings consists of a calibrated calorimeter instrument. The rock sample is heated to 72°C and immersed in water at room temperature, then the temperature rise is measured and reported (Gwynn et al, 2019). Another calorimetric method consists of dropping cooled rock fragments into a double-walled flask of water, then the temperature is recorded. This simple and rapid method, described in Scharli and Rybach (2001), was developed and tested to determine matrix heat capacity on drill cuttings at room temperature. Effects of pore fluids could be calculated if the porosity is known.

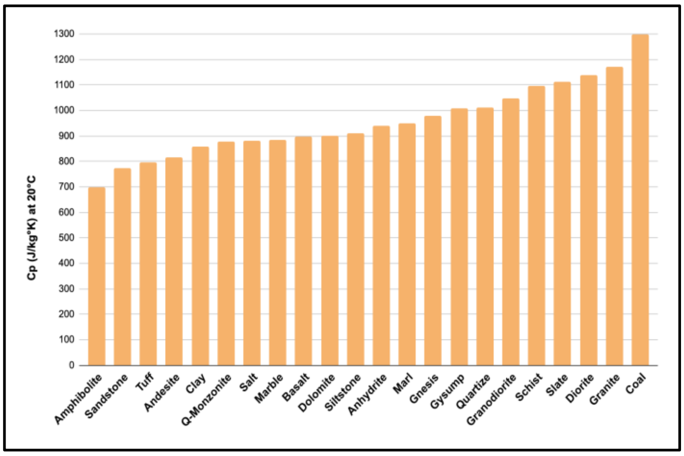

Figure 4: Specific thermal capacity measured at 20°C, for some common non-porous rocks. Modified from Waples and Waples (2004).

Specific heat capacity for rocks can be obtained from data on rock-forming minerals. The calculation of specific heat capacity (Cp) of a rock at a selected temperature from its modal mineralogy in volume percent can be made using the parallel composite model in Equation 6 as following:

$$Cp = (xn\,Cn) = x1C1 + x2C2 + x3C3\ldots \quad (6)$$

Where xn is the volumetric decimal fraction of the content of minerals 1, 2, 3.... and Cn is the specific heat per unit volume of the corresponding mineral constituent at constant pressure at a selected temperature. Other thermal parameters such as thermal capacity and thermal diffusivity are calculated from thermal conductivity, specific heat capacity and densities. Thermal properties such as specific heat capacity of rocks and minerals are used practically for geothermal resource appraisals and radioactive waste management.

2.3 Fluids Composition Analysis

For geothermal plays, mapping fluids and stratigraphic distribution across multiple boreholes is possible due to mass spectrometry performed on drill cuttings (Dilley et al. 2004; Dilley and Norman, 2004; Norman et al. 2004; Dilley et al. 2005). Gaseous and hydrocarbon species are plotted as a function of depth. The results were able to support the distinction and interpretation of different fluids in a geothermal field located in California. For example, $N2/Ar > 200$ and $CO2/CH4 > 4$ is indicative of magmatic fluids while crustal fluids will have lower ratios of the same compounds. Steam heated waters, mixed fluids and gas caps are also interpreted based on sulfur components and gas-water ratios. Dilley et al, in 2006, added to the same study by plotting the relative change in CO2/N2, thus distinguishing permeable zones. Studies have been completed to understand and improve the performance of injection wells in two Enhanced Geothermal Systems (EGS) fields located in California and have determined the effects of fluid injection on reservoir rocks. Through examination of drill cuttings samples from original and redrilled injection wells, mineral characterization and geochemical changes were captured as a possible result of injection. Fluid inclusion ratios as gas/water decreased significantly while the water amount was about the same. Changes were more pronounced in high fluid flux intervals with silica scale. Results of these investigations were employed to build a numerical modeling of fluid-rock interactions and predict changes in the near wellbore (Moore, 2007).

Another approach to volatile analysis from drill cuttings involves an identification of helium anomalies as fault indicators or from possible release of radiogenic helium from the reservoir rocks. Helium in geothermal fluids is normally thought to have originated from the atmosphere, since waters were in contact with air before infiltration; however, higher than expected concentrations may be due to the release of radiogenic helium from the reservoir rocks (Barragan et al 2006) or from deeper migration.

2.4 Advanced Analysis

2.4.1 Petrology

Petrology is a fundamental technique to define origin, texture, microstructures, fractures and diagenesis for rocks. For cuttings, pieces a few millimeters in size are enough to observe textures, cementation, the presence of hydrothermal alteration and other qualitative information. This data becomes valuable in combination with depth control to distinguish physical features of the reservoirs. In Libbey et al (2013) drill cuttings from the Wairakei Geothermal Field in New Zealand were analyzed using SEM imaging to determine the morphological distribution of hydrothermal clays (Figure 5). Images showed that illite-smectite morphological changes with depth, accompanied analytical measurements of rock and fluid chemistry. These are helpful tools to understand the reservoir and its permeability evolution in geothermal systems.

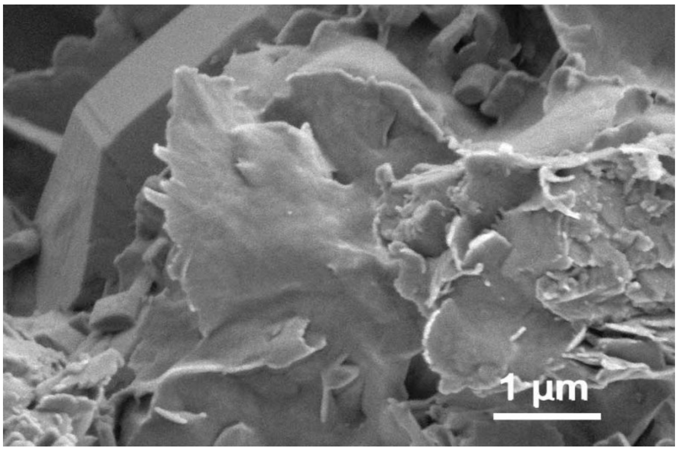

Figure 5: Example of a SEM image showing flakes of illite ribbons from the Wairakei Geothermal Field in New Zealand (Lybbey et al 2013)

2.4.2 Deoxyribonucleic Acid (DNA) sequencing

Living extremophilic bacterial species have been found thousands of feet below the surface thriving in high pressure, high salinity and high-temperature environments. Extremophilic bacteria can be categorized as acidophilic (thrive at low pH), halophilic (thrive in an environment with high concentrations of salt), thermophilic (thrive at high temperature), and hyperthermophilic (optimally survive extreme high temperature, usually well above 80 °C). There are tens or even hundreds of various bacterial/archaean species that live in the subsurface. Therefore, bacterial species are perfect biomarkers that can be used as living tracers. Thanks to recent advancements in Deoxyribonucleic Acid (DNA) sequencing technology and bioinformatics applied to sequence studies from boreholes, the geothermal industry can greatly benefit from bacterial speciation from novel innovative techniques including unique sample collection, preservation, and DNA extraction protocols. It is important to note that bacterial species vary with changes in environmental conditions (temperature, pressure, fluid types, dissolved minerals fluids, and rock mineralogy/elemental composition). Hence, once conditions change, bacteria/archaea change as well. This allows using bacteria for production allocation (to identify the water source), reservoir continuity, well to well communication, and fault identification purposes.

2.4.3 Mechanical Properties

Orientation of the current stress field has an impact on fluid flow along faults and ultimately on the permeability anisotropy in fractured geothermal reservoirs. In addition, the stress field plays an important role in Enhanced Geothermal Systems (EGS) development where creation of artificial fractures is the final objective to increase permeability. The growth and orientation of the fractures are controlled by stress field and geomechanical rock properties. Rock mechanical properties are measured in the laboratory using typical load frames and rock samples with a specific measurable shape. It is extremely challenging to obtain reliable mechanical properties measurements in the laboratory from unconsolidated rock samples or drill cuttings. Studies in the estimation of mechanical behavior of rocks from drill cuttings have been completed for unconventional oil and gas reservoirs in horizontal sections where advanced wellbore logs and core material are absent (Prioul et al, 2016). A valid estimation of mechanical properties will allow a full characterization of a geothermal system and the identification of parameters that control the stress field. New successful techniques apply rock physics modeling to find optimal theoretical bounds then implement them to predict mechanical properties using mineral composition from cuttings samples (Permata et al, 2020).

3. HIGH RESOLUTION WORKFLOW

High quality cuttings are crucial for extracting valuable and useful information. When properly acquired, prepared, and analyzed drill cuttings have the power to capture wellbore vertical and lateral heterogeneity. Defining high resolution workflows to characterize geothermal reservoirs from drilling cuttings will require a modification from the current constant sampling intervals used during drilling activities. Enhancing the data acquisition resolution, intervals from 20, 10, 5, or even 2 ft would be required to obtain sufficient representation of the reservoir. Higher frequency samples must be located in the target units or where heterogeneity is expected to be higher. To recognize heterogeneity as part of the methodology in the field, availability of trained experts to interpret changes in drilling logs becomes relevant. As an alternative to enhanced sample collection based on reservoir heterogeneity, the use of prior petrophysical data at the area, if available, is recommended. The dense sampling frequency allows for high-precision depth-matching which ensures data trends are not lost. When wellbore logs such as gamma ray are available, depth shifts validation using proprietary algorithms are suggested.

Elemental and mineral composition of the drill cuttings plus thermal properties are suitable measurements to be performed at the wellsite, therefore values can be reported in near-real time. Results can be displayed as a field composite log based on observations, analysis of drill cuttings and drilling logs at the wellsite. Splits of the drill cuttings are transported to the laboratory to perform a full set of measurements and to reconstruct fluid inclusion stratigraphy (FIS) profiles. The material is cleaned, only if it is necessary, then crushed in a vacuumed system. In general terms, the released volatiles are pumped through a quadrupole mass spectrometer where they are ionized and separated by mass/charge. Results are added to the existing field log to complement those analytical tracks. According to the geothermal systems, standards ratios tracks would be defined as well as flags for identifying producing intervals. Additional high precision fluid analytical techniques, such as laser ablation ICP-MS could be rapidly adapted to the laboratory stage. Additional tests targeting reservoir and/or intervals of interest could be added to the results. This would include, but not be limited to DNA sequence measurements and petrology observations.

Finally, a precise combination of wellsite observations, laboratory analyses and integration tools would be required to ensure the full characterization of the geothermal reservoir. The integration of temperature logs, pressure logs, drilling logs, logging while drilling (LWD), continuous drill cuttings logs plus reconstruction of spectral and total gamma ray, calculations of thermal parameters such as heat flow and estimation of mechanical properties would create a full picture of the heat capacity for the geothermal reservoir. Interpreters and decision makers would then be presented with defined producible intervals and zones of interest as a score of reservoir quality, in other words, flagged intervals with high thermal potential and high flow units. Standard and customized flag parameters would be defined according to the category of geothermal plays.

CONCLUSIONS

Drill cuttings are considered a low cost material at the wellsite, often available and easy to recover relative to core. This material carries immense and valuable information about the reservoir units throughout the wellbore that cannot be ignored. High quality cuttings are crucial for extracting that valuable and useful information versus depth. When properly acquired, prepared, and analyzed, cuttings have the power to capture wellbore heterogeneity. The geology of geothermal systems can abruptly change and the characterization of small units could be missed, for example the precise identification of hydrothermal alteration. In this document, we present a workflow that will support the characterization of resources in geothermal wells by using high resolution cuttings analysis. From the collection of drilling data at the wellsite, to quick and precise rock and thermal analysis in the field, to material transported to the laboratory for fluid analysis. All of the effort in the field and the laboratory is complemented with reconstruction of spectral and total gamma ray, calculations of thermal parameters such as heat flow and estimation of mechanical properties fundamental to geothermal plays development. The estimation of mechanical properties will introduce basic parameters about the stress regime, a necessary dataset for the development of EGS completion planning. Thanks to continuous innovation in detection instruments for rock, minerals and fluids, the workflow proposed could adapt easily to new developments as well as specific needs for different geothermal systems. Drill cuttings have been underutilized for many years. They hold vital information that when properly acquired and analyzed can contribute ground-truth knowledge to optimize well performance, a definition applicable to all categories of geothermal plays exploration.

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