Scratch Test Utilization to Characterize Contrasting Geomechanical Properties in Enhanced Geothermal System

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Keywords

Scratch Test, Stimulation, Rock Mechanical Properties, Enhanced geothermal system, Geothermal energy

ABSTRACT

Enhanced geothermal systems (EGS) are reservoirs that have been stimulated to efficiently extract heat from low permeability high-temperature rocks. Hydraulic fracturing treatment is one of the most efficient stimulation techniques currently utilized in heat extraction from EGS. The subsurface reservoirs including EGS, are highly characterized by heterogeneous mechanical properties and geology, which includes pre-existing natural fracture networks that are filed with mineralization. In this paper, we present how heterogeneity in rock mechanical properties and geology will impact the extraction of heat from EGS. We utilized the Scratch test method to characterize the mechanical properties of a subsurface rock from a basin of high-temperature region. Our results show heterogeneous mineral and rock strength distributions over the rock sample length. In addition, our results show that the mechanical rock response of the stimulated geothermal system will not be the same as that of a homogenous isotropic rock volume. Further, we suggest the scratch test technique for the rapid characterization of geomechanical properties in EGS. Lastly, we recommend that modeling of fracturing for EGS should include a heterogeneous rock volume with detailed mechanical characteristics of the rock properties of individual mineralized zones or mineral zonation of the rock matrix. This work provides more insights to understand how the heterogeneity of fractomechanical behavior and geomechanical properties influence EGS.

1. Introduction

Enhanced geothermal systems (EGS) are reservoirs that have been stimulated to efficiently extract heat from low permeability high temperature rocks (Nadimi et al. 2020). To improve inter-well conductivity and increase the heat extraction process, hydraulic fracturing stimulation and chemical enhancements are two major technologies utilized to achieve this feat. Hydraulic fracturing treatment is one of the most efficient stimulation techniques currently utilized in heat extraction form EGS, through the injection highly pressurized fluid into the formation to initiate fractures. Stimulated hydraulic fractures (HF) play an important role in improving the heat extraction performance of EGS (Murphy et al. 1977; Campbell et al. 1981; Zhou et al. 2018; Zhang et al. 2020). Reactivation of pre-existing natural fractures (NF) induced by injection fluid became widely accepted as an important mechanism for fracture creation and permeability enhancement in EGS reservoirs (Pine and Batchelor 1984; Mcclure and Horne 2013; Finnila et al. 2015; Sheng et al. 2018). Various EGS stimulation mechanisms have been proposed according to the field observation and laboratory works, which depend on the geology of the rock, in-situ stress, fault structures, and pre-existing natural fractures (Wang and Ghassemi 2012; Mcclure and Horne 2014).

Studies have shown that enhanced geothermal systems are characterized by heterogeneous geology, which includes pre-existing fracture networks that are filed with mineralization (Callahan et al. 2019a, b, c). It is also known that during hydraulic fracturing stimulation, propagating hydraulic fractures are known to link and connect pre-existing natural fractures (NF) (Kolawole and Ispas 2019, 2020). During this hydraulic fracturing treatment, complex fracture networks are often generated, and the HF-NF interaction significantly influences the complexity of these fracture networks created. Some of these pre-existing natural fractures includes mineralized fractures (veins), and its reactivation can result in induced seismicity of subsurface geologic materials (Kolawole et al. 2019) .

Drilling, completions, injection, and production from very deep, High-Temperature High-Pressure (HPHT) reservoirs is an expensive operation, and its success demands an understanding of the in-situ rock mechanical properties. These rock mechanical properties have implications for subsurface energy (oil and gas) exploration, recovery of high temperature fluids from geothermal reservoirs (Toth 2020), and geologic CO_2 storage (GCS).

The scratch test is a quasi-non-destructive method made up of pushing a tool across the surface of a weaker rock and tracing the groove at a given penetration depth. The uniaxial or unconfined compressive rock strength (UCS) which is the ultimate stress a rock can withstand before undergoing failure, is characterized by rock confining pressure, stress-strain relationship, and pore-fluid pressure. The estimation and prediction of the in-situ rock failure behavior as a function of rock type, pore pressure, spatio-temporal stresses, and fault-reactivation potential provides critical information for proactive decision-making to achieve successful energy production and heat extraction operations. Reservoir rocks with higher UCS will exhibit greater stiffness, which will influence the fracture geometry and how the fracture nucleates. The rock mechanical properties of EGS reservoirs adopted in hydraulic fracturing modeling, Discrete Fracture Network (DFN) modeling, and Finite Element Modeling (FEM), are most often overestimated and the effects of pre-existing NF and geology are often not fully accounted for.

Although several researchers have attempted to model and predict the hydraulic fracturing process in EGS, the mechanical rock response of the stimulated geothermal systems remains an important issue. In this paper, we present how heterogeneity in rock mechanical properties and geology will impact extraction of heat from EGS. We utilized the Scratch test method to characterize the mechanical properties of a subsurface rock from a basin of high-temperature region. Our preliminary results show heterogeneous mineral and rock strength distributions over the rock sample length. In addition, our results show that the mechanical rock response of the stimulated geothermal system will not be the same as that of a homogeneous isotropic rock volume. Further, we suggest the scratch test technique for rapidly characterization of geomechanical properties in EGS. Lastly, we recommend that modeling of fracturing for EGS should include a heterogenous rock volume with detailed mechanical characteristics of the rock properties of individual mineralized zones or mineral zonation of the rock matrix. This work provides more insights to understand how the heterogeneity of fractomechanical behavior and geomechanical properties influence EGS exploitation and production.

2. The Scratch Test Method

2.1 Merits of Scratch Test Method

The advantages of the scratch test method over other conventional methods in estimating rock strength and other geomechanical properties are (Mitaim et al. 2004; Coudyzer et al. 2005; Dagrain and Germay 2006; Dagrain et al. 2006; Richard et al. 2012; Germay et al 2015, 2018):

a. It is quasi non-destructive, and the post-test core samples remain intact which can be utilized for other destructive or non-destructive tests.
b. It provides direct equivalent measurement with the rock's UCS.
c. It requires limited and minimal level of sample preparation.
d. It is simple, quick, and highly repeatable.
e. It can be conducted on any dimension of rock, as the results are not affected by the core sample geometry.
f. It provides precise continuous profile of rock strength over the scratch interval.

2.2 The Mechanics of Rock Scratching

In the scratch testing method, continuous trace of the groove of the rock surface is conducted with a stronger cutting tool, while the cutter penetration depth (d) and the velocity (v) between the cutter and the rock are held constant. In Fig. 1, the horizontal force (F_T) which is parallel to the cutter velocity, and the vertical force (F_V) which is normal to the cutter velocity; are measured. The rock cutting configuration is also characterized other parameters such as: the back-rake angle ($\emptyset$); the cutter/probe geometry; the contact surface between the cutter and the rock surface which is represented by l; the friction coefficient (μ) beneath the wear flat of the cutter.

The mechanisms of rock scratching are evident in the linear relationship between cutter penetration depth (d) and F_T.

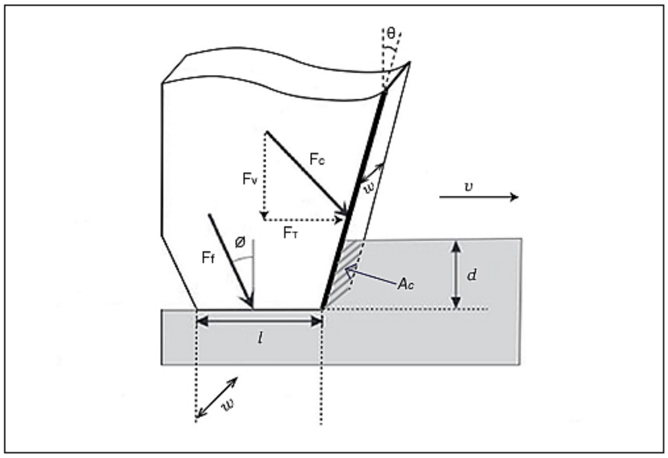

Figure 1: Rock scratching configuration

The two rock failure mechanisms (Fig. 2) depending on the cutter penetration depths are (Schei et al. 2000; Richard et al. 2012):

a. Ductile failure mode: Also known as "plastic flow". The ductile failure mode occurring at shallow penetration depth (d), is characterized by the rock shearing ahead of the cutter. As the rock matrix and the grains are dislodged, the rock grains and powder accumulate continuously ahead of the cutter, and they are removed by the moving cutter.

b. Brittle failure mode also known as "chipping", The brittle failure mode occurring at large penetration depth (d), is characterized by macroscopic fractures generating from the tip of the cutting tool and propagates upwards towards the rock surface ahead of the cutter. The chips and fragments formed are removed by the cutter.

The brittle failure mode is dependent on fracture toughness (K_{IC}), while the ductile failure mode on UCS, and the transition between ductile and brittle failure modes is dependent on the cutter penetration depth (d).

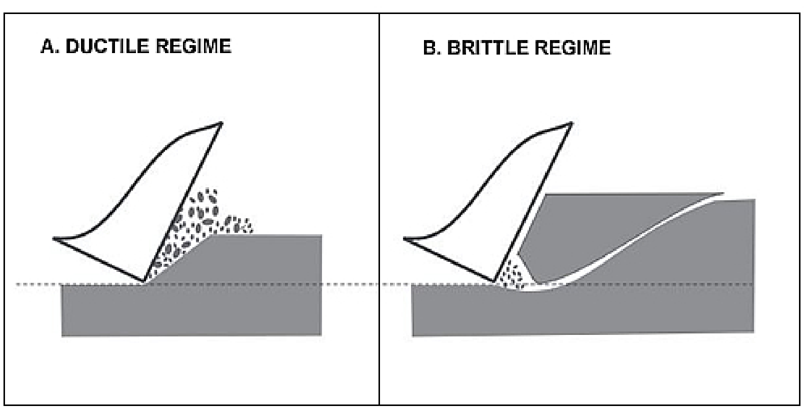

Figure 2: Rock failure regimes (Modified after Richard et al. 2012)

2.3 Estimation of Rock Strength Through Scratch Test

The scratch test can be resourceful in estimating reservoir geomechanical and petrophysical properties (Onwumelu et al. 2020). The concept of obtaining rock strength information from rock cutting tests was proposed by Adachi et al. (1996), and this approach was dependent on phenomeno-logical model of continuously cutting of rock with blunt cutter. This cutter/rock interaction model in ductile failure mode was developed based on three assumptions, irrespective of the cutting tool wear. These assumptions are that (Detournay and Defourny 1992): (i) the forces acting on the cutter face, averaged over a distance higher than the penetration depth, is directly proportional to the cross-sectional area (A_c) due to horizontal force; (ii) the inclination of the average force acting normal to the cutter face is constant; (iii) friction force at the wear-flat rock interface exists. The above developed model is composed of three major parameters:

a. the intrinsic specific energy (ε) applicable to the rock cutting process.
b. the inclination (ζ) of the average force acting on the face of the cutter.
c. the coefficient of friction (μ) on the wear flat/rock interface.

The model assumptions and its application to estimate rock strength is summarized in Eqns. 1-4 as:

$$F_T = \varepsilon A_c = \varepsilon w d \quad (1)$$

$$F_V = \zeta \varepsilon A_c = \zeta \varepsilon w d \quad (2)$$

Where: *w* is the width of cutter.

Combining Eqn. (1) and Eqn. (2) gives:

$$F_T = \varepsilon(1 - \mu\zeta) w d + F_V \quad (3)$$

Where:

$$\mu = \tan \phi \quad (4)$$

In Schei et al. (2000), the researchers investigated 35 sandstone and 24 carbonate samples to assess the rock strength and Young's modulus (stiffness) of sedimentary rocks through scratch testing as shown in Fig. 3. The values of intrinsic specific energy (ε) obtained in their results agree with the UCS, which further validates the efficiency of scratch test for quick and effective estimation of UCS and other geomechanical properties in rocks. Thin layer of weakness or heterogeneity along rock core can be captured through scratch testing, and this was showed in the rock strength estimation experiment conducted by Mitaim et al. (2004). The rock strength estimation results from Ferreira et al. (2017) scratch test on Brazilian limestone cores with high heterogeneity was presented by the researchers. Their results validated the use of scratch testing to estimate UCS and Young's modulus in rocks such as limestone.

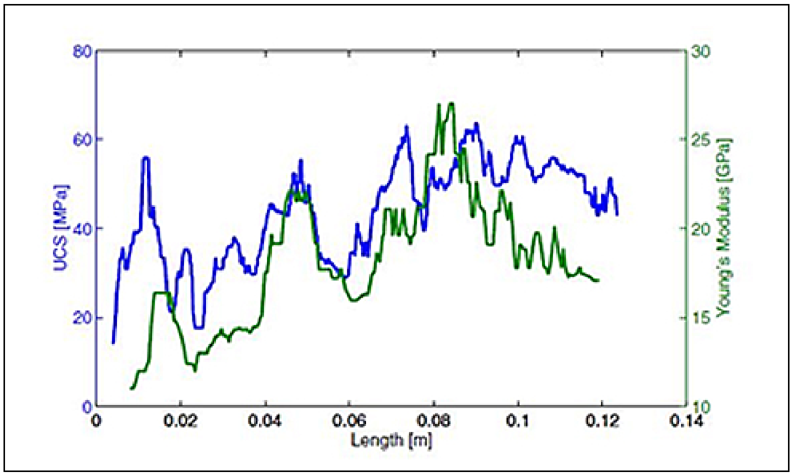

Figure 3: Rock strength and Young's modulus over the scratch length. (After Schei et al. 2000)

3. Methodology

In this study, we used a core sample of 1 ft. length and cut perpendicular to the bedding plane. The core sample was obtained at reservoir depth from a basin of High-Pressure High-Temperature (HPHT) region. Due to the proprietary nature of the data, we cannot disclose the location of the core sample.

We utilized the scratch test technique to measure the mechanical properties of the subsurface core sample. The scratch test has shown to be efficient in estimating the mechanical properties of reservoir rocks. The scratch test technique provides continuous properties for the entire length of a core material. At varying penetration depths (depth of cut) (d) of 0.05 mm, 0.08 mm, 0.11 mm, 0.14 mm, 0.17 mm, 0.20 mm, 0.23 mm, 0.26 mm, and 0.29 mm; we conducted 9 scratch tests on the core sample using the Wombat scratch machine (Epslog S.A. 2019) (Fig. 4) at the Rock Mechanics Laboratory of Bob L. Herd Department of Petroleum Engineering, Texas Tech University. The cutter properties are sharp, flat, width (w) of 10 mm, and inclination (ζ) of 0.67.

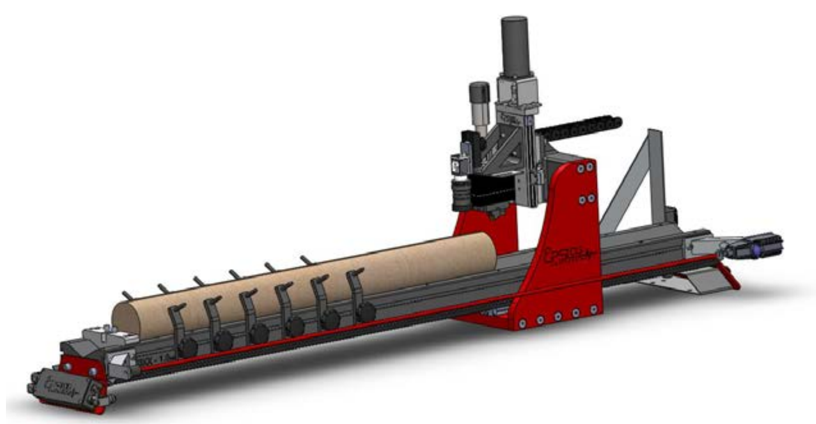

Figure 4: The Wombat Scratch Machine. (Image Courtesy of Epslog S.A.)

Afterwards, we estimated the UCS and the fracture toughness (K_{IC}) of the full core.

4. Results and Discussion

Our result presented in Fig. 5 shows the continuous rock strength (UCS) log profile and the ultra-high-definition panoramic photography of the full core sample over a 1 ft. scratch length.

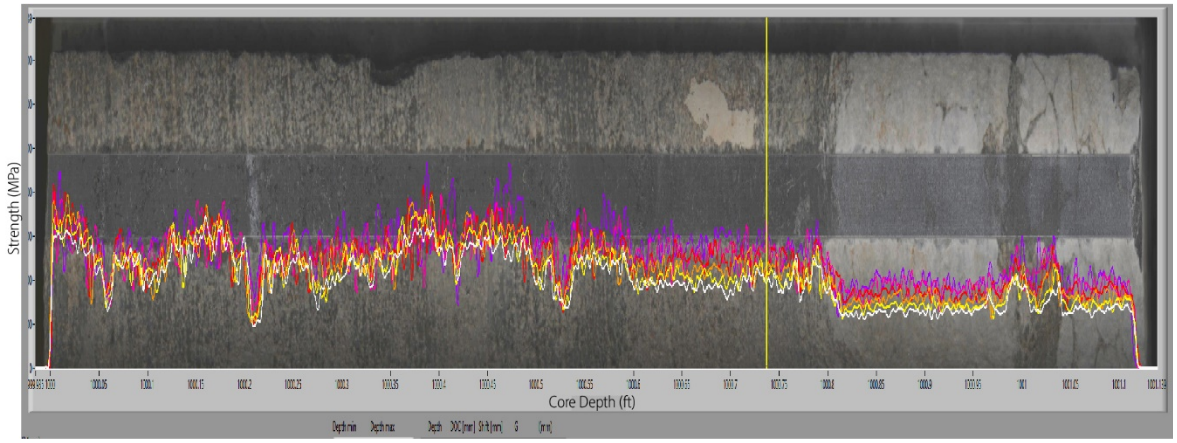

Figure 5: Full core length showing continuous log profile of rock strength and ultra-high-definition panoramic core photography.

In Fig. 6, the high-strength regions of the core sample are labeled as X, while the low-strength regions of the core sample are labeled as Y. Our observations from Fig. 6 show that the X regions correlates with the absence of pre-existing natural fractures (NF), while the Y regions correlates with the presence of NFs and are zones of weaknesses. In Fig. 6c, the extremely-low strengths observed are due to the presence of multiple pre-existing micro-fractures or veins across the entire core section.

Our observations from results in Fig. 6 shows varying mineralized zones, with the X regions having dark coloration, while the Y regions have much lighter coloration. We suspect that the Y regions in Fig. 6 are composed of mechanically-weaker mineralized zone relative to the X regions, and the X regions are composed of composed of mechanically-stronger mineralized zone relative to the Y regions.

Our result presented in Fig. 5 and Fig. 6 shows the heterogeneous distributions of the geologic and mechanical properties over the rock sample length, and how these parameters are impacted by NFs and variation in minerology. Therefore, from our results, we can envision that the mechanical rock response of a stimulated geothermal system will not be the same as that of a homogenous isotropic rock volume. Furthermore, modeling of fracturing for Enhanced Geothermal Systems (EGS) should include a heterogeneous rock volume with detailed mechanical characteristics of the rock properties of individual mineralized zones or mineral zonation of the rock matrix.

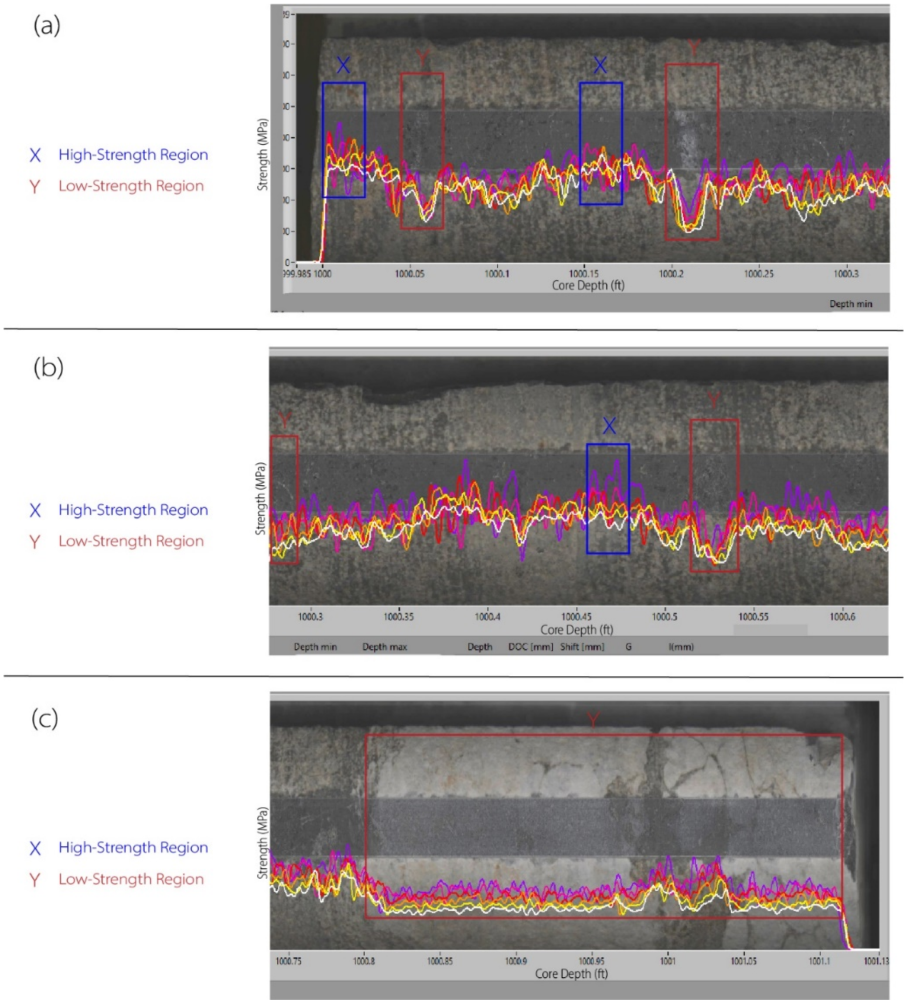

Figure 6: Core length showing continuous log profile of rock strength and ultra-high-definition panoramic core photography. (a) Core depth from 1000–1000.35 ft.; (b) Core depth from 1000.25–1000.65; (c) Core depth from 1000.70 – 10001.12 ft.

Table 1. Estimated Fracture Toughness

Core Length (cm)	Core Scratch Length (ft)	Maximum Penetration Depth (d)[mm]	Fracture Toughness (K_{IC}) [Mpa.√m]
30.5 cm	1 ft	0.29	2.02 ± 0.03

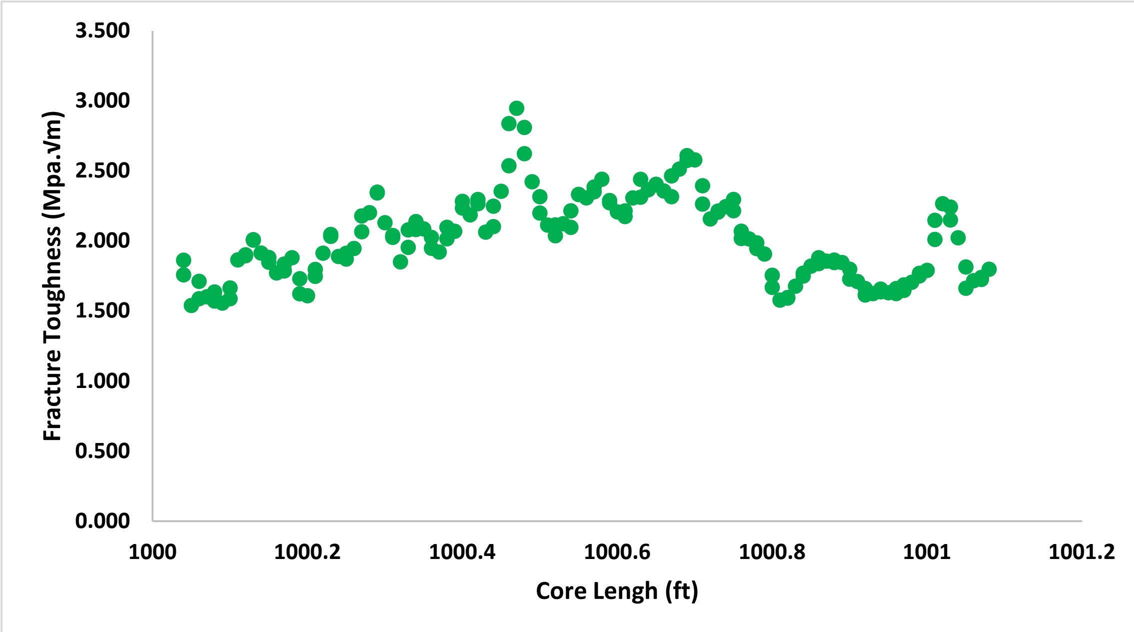

Figure 7: Estimated Fracture toughness of the full core length.

The results of the estimated fracture toughness are presented in Table 1 and Fig. 7. The mechanically-weaker mineralized zones (1000.05 ft., 1000.2, 1000.525, and 1000.8) observed in Fig. 6 correlates with the core depths having the lowest fracture toughness values as shown in Fig. 7. The observed contrasting values of fracture toughness across the full core length in Fig. 7, provides further insight on the how heterogeneous geomechanical properties will impact fluid extraction from enhanced geothermal systems.

The continuous profile of mechanical properties and mineralized zones distributions in the rock sample shows that this technique can provide a reliable measurement of the scale and distribution of the heterogeneous properties along the tested core sample.

Calcite minerals ($CaCO_3$) will precipitate in higher temperature conditions and dissolve more in lower temperature conditions. Therefore, nucleation of new fracture systems and linkage of pre-existing natural fractures during hydraulic stimulation of EGS will naturally expose the hot reservoir fluids to previously un-intruded regions in the reservoir. As a result, hydraulic stimulation of EGS may not only lead to the flow of the hot fluids through open fractures, but may be associated with precipitation of minerals (occlusion of fractures) and/or dissolution of pre-existing mineral veins (opening of fractures). In this context, hydraulic fracturing models should consider the time-dependence modification of the heterogenous mechanical rock properties in response to the hydraulic stimulation treatment.

5. Conclusions and Recommendations

In this study, we first introduced the mechanics of rock scratching and the estimation of rock strength (UCS). Secondly, we performed scratch tests on a subsurface core from a basin of High-Pressure High-Temperature (HPHT) region, and estimated the UCS and fracture toughness (K_{IC}) of the full core.

Our major findings from this study are that:

a. The scratch test provides continuous properties for the entire length of a subsurface core material.
b. The scratch test is suitable for rapidly characterizing the geomechanical properties of an EGS reservoir.
c. Heterogeneity in rock mechanical properties and fracture-mechanical behavior will impact extraction of heat from Enhanced Geothermal Systems (EGS).
d. The hydraulic fracturing stimulation modeling and simulations should incorporate the time-dependence modification of the heterogeneous mechanical rock properties in response to the hydraulic stimulation treatment.

Further, we recommend that modeling of fracturing for EGS reservoirs should include a heterogeneous rock volume with detailed mechanical characteristics of the rock properties of individual mineralized zones or mineral zonation of the rock matrix.

This work provides more insights to understand how the heterogeneity of fractomechanical behavior and geomechanical properties influence extraction of heat from EGS reservoirs.

Acknowledgement

We wish to acknowledge EPSLOG S.A. for offering guidance and support to obtain some of the results presented in this study.

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