

Geomechanical Characterization of Core from the Proposed FORGE Laboratory on the Eastern Snake River Plain, Idaho

Rohit Bakshi, Mostafa Eskandari Halvaei, Ahmad Ghassemi

1314 Sarkeys Energy center
Boyd St. Norman, Oklahoma - 73069
E-mail: Ahmad.Ghassemi@ou.edu

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ABSTRACT

This paper presents the results of a geomechanical characterization of cores from a well in the Eastern Snake River Plain, Idaho, near a proposed FORGE EGS Laboratory. The geological and geothermics features of the area make the Eastern Snake River Plain a promising target for an EGS system. The cores tested were obtained from the INEL-1 well with core depths ranging from 1,558 - 3,160 m. According to previous geological studies, rock types present in this well are mainly rhyolite tuffs, rhyodacites, basalts and lava deposits (Miller et al). The section of core tested is mainly rhyolitic tuff or rhyodacites. These rocks are hydrothermally altered in places and are found to have varying permeability, depending upon the stress level and existence of natural fractures. The core segments from one well were plugged to obtain one inch diameter and two inch long specimens for geomechanical characterization including porosity, permeability, velocity data, elastic modulus, Poisson's ratio, tensile strength, and Mohr-Coulomb envelope as well as some acoustic emissions during triaxial tests. Pore scale characterization was also performed using thin section and Scanning electron microscope (SEM) imaging.

1. INTRODUCTION

Enhanced geothermal systems are expected to be a significant source of energy generation in the years to come. One of the most promising sites for this in the US is the Snake river geothermal Consortium's (SRGC) proposed located within Idaho National Laboratories' Geothermal Resource Research Area (GRRR), which is located along the Snake River Plain in south eastern Idaho. The presence of high underground heat flow and a large underground aquifer within the Snake River Plain makes it ideal for a geothermal energy development (Williams et. al).

EGS development relies on creation of conductive pathways for fluid flow and heat exchange. Low primary reservoir rock permeability requires hydraulic fracturing with shear and tensile fractures depending on the specific site characteristics. For a successful stimulation as well as drilling programs, geomechanical properties of the target rocks are needed. Two core sections from depths of 4874 ft and 10,365 ft, each about 4 to 6 inches, were provided by INEL. Plugs were extracted from these cores to obtain suitable samples for geomechanical testing. Mineral composition and pore scale characterization has been performed using SEM and thin sections. A variety of laboratory tests have been conducted on the plugs to determine rock strength (triaxial and uniaxial), velocity data (shear and compressional), elastic properties, acoustic emissions analysis, stress-dependent porosity and permeability, crushed porosity (low pressure pycnometer porosity).

2. MINERALOGICAL AND PETROLOGIC DESCRIPTION OF THE CORE SAMPLES

2.1 Mineralogy of the INEL Core

One inch plugs from each of the two cores were tested using Fourier transform infrared spectroscopy (FTIR). The following table shows the mineral composition of the two samples.

Spectrum Mineral	4874ft core plug (% composition)	10,365 ft core plug (% composition)
Quartz	25.55	23.13
Orthoclase Feldspar	25.48	10.87
Oligoclase Feldspar	16.25	10.06
Albite	6.07	21.30
Illite	16.78	2.85
Calcite	0.00	6.83

Dolomite	1.33	4.60
Smectite	4.21	3.04
Kaolinite	1.04	0.09
Mixed Clays	0.88	13.50
Siderite	2.38	2.98

Table 1: Mineral composition in the INEL-1 core plugs using FTIR

Feldspars (Orthoclase, Oligoclase and Albite) constitute 42-27% of the composition here followed by silica (quartz) at 24-27%.

2.2 Petrology of INEL core

Two petrographic thin section images were prepared for the two cores (from depths 4874 ft and 10365 ft respectively). The rocks have an aphanitic texture with a few interspersed large grains of sizes 1-4 mm. The core from 4874 ft is lighter in colour.

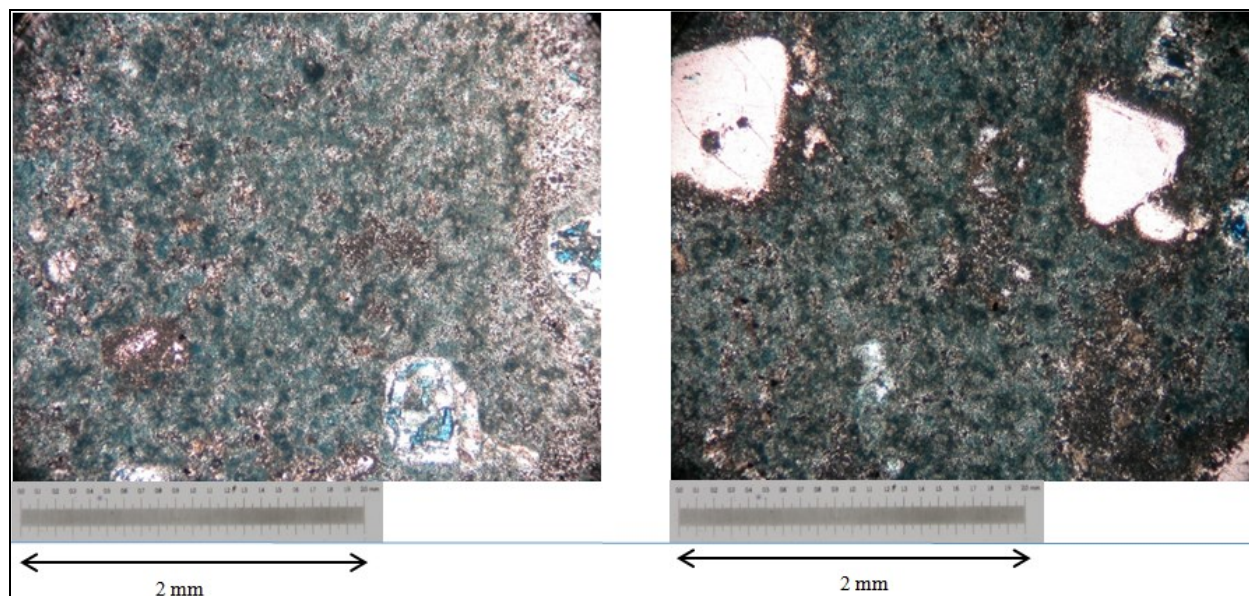


Figure 1: Thin section images of the core plugs from 4874 ft show a largely aphanitic texture with a few large quartz grains interspersed across. Porosity is not clearly observed suggesting small size pores which are described in detail in the SEM images.

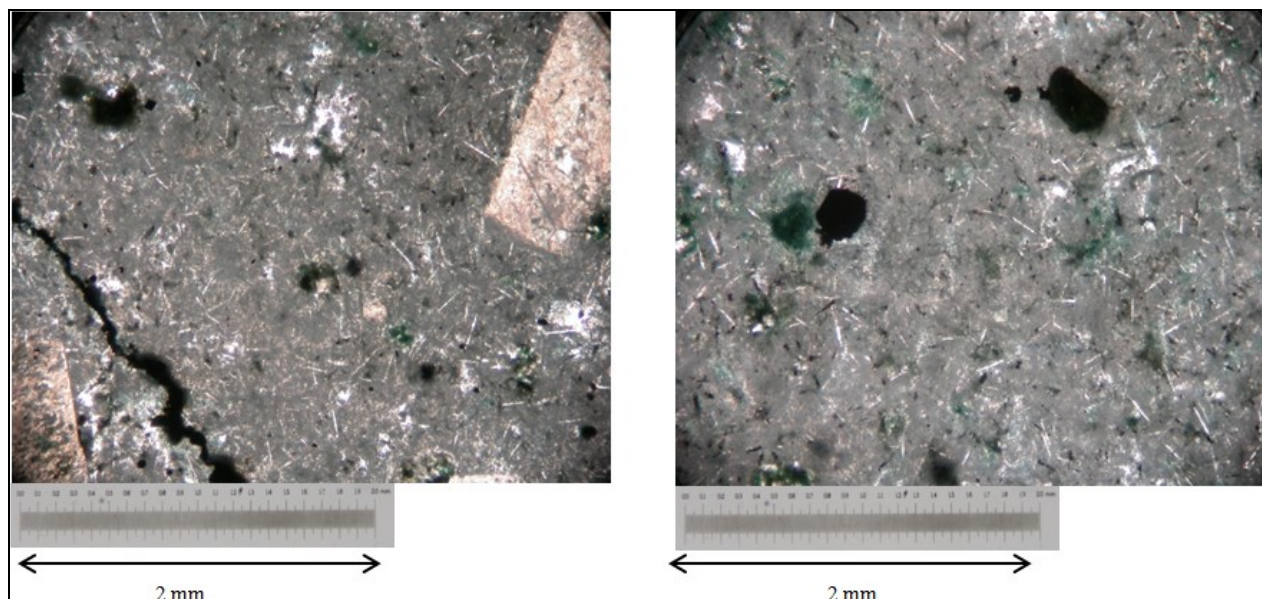


Figure 2: Thin section images of the core plugs from 10,365 ft, these also show a more aphanitic texture with a few large quartz grains interspersed across. Unconnected porosity and a micro-crack can be seen here (both black).

2.3 Scanning electron microscope (SEM) analysis

SEM imaging was used to understand the pore structure of the core – this includes mainly pore sizes, pore connectivity and presence of micro cracks. The following images show the pore structure at two different magnification levels. The core from 4874 ft shows pores of 20-100 μm at a 35x magnification. Most of the pores appear to be small though. Several large quartz grains (1-2 mm) can be seen interspersed within the sample (marked as green circles in figure 3). Pore connectivity is good. No micro cracks are seen here.

For the 10,365ft core, the structure is markedly different. No porosity is evident here in the 35x magnification. In the 240x magnified image though, a few pores can be seen with sizes less than 50 μm . A healed fracture is seen here, many more can be seen throughout the sample.

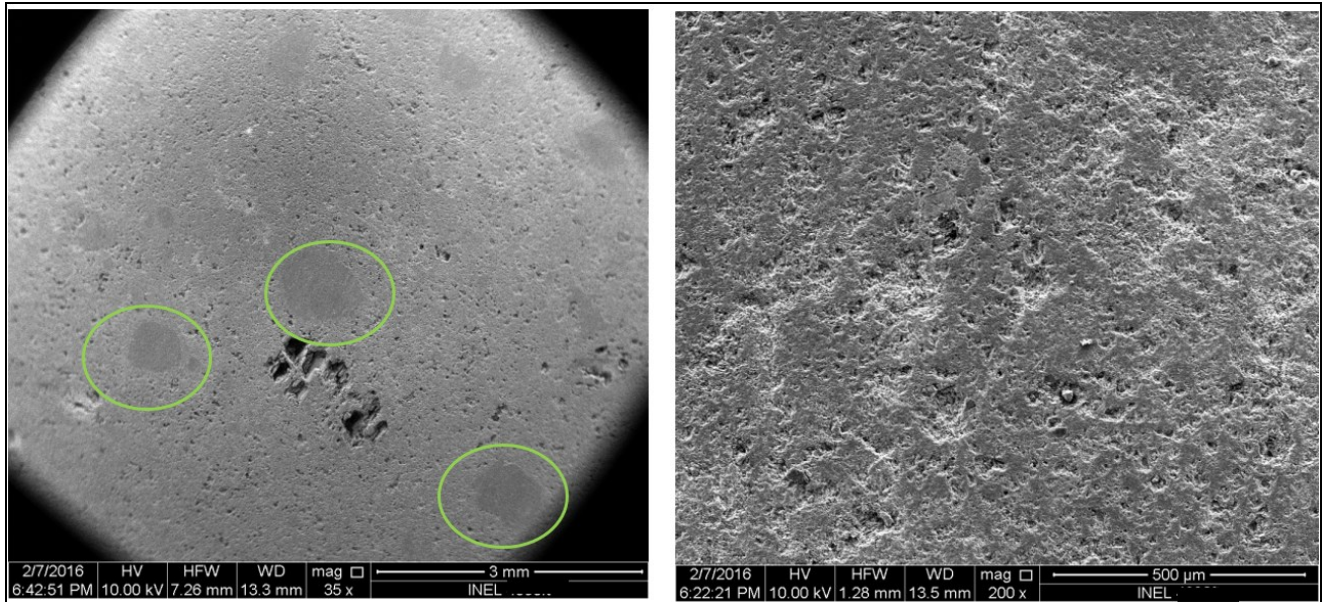


Figure 3: SEM images of the 4874 ft core

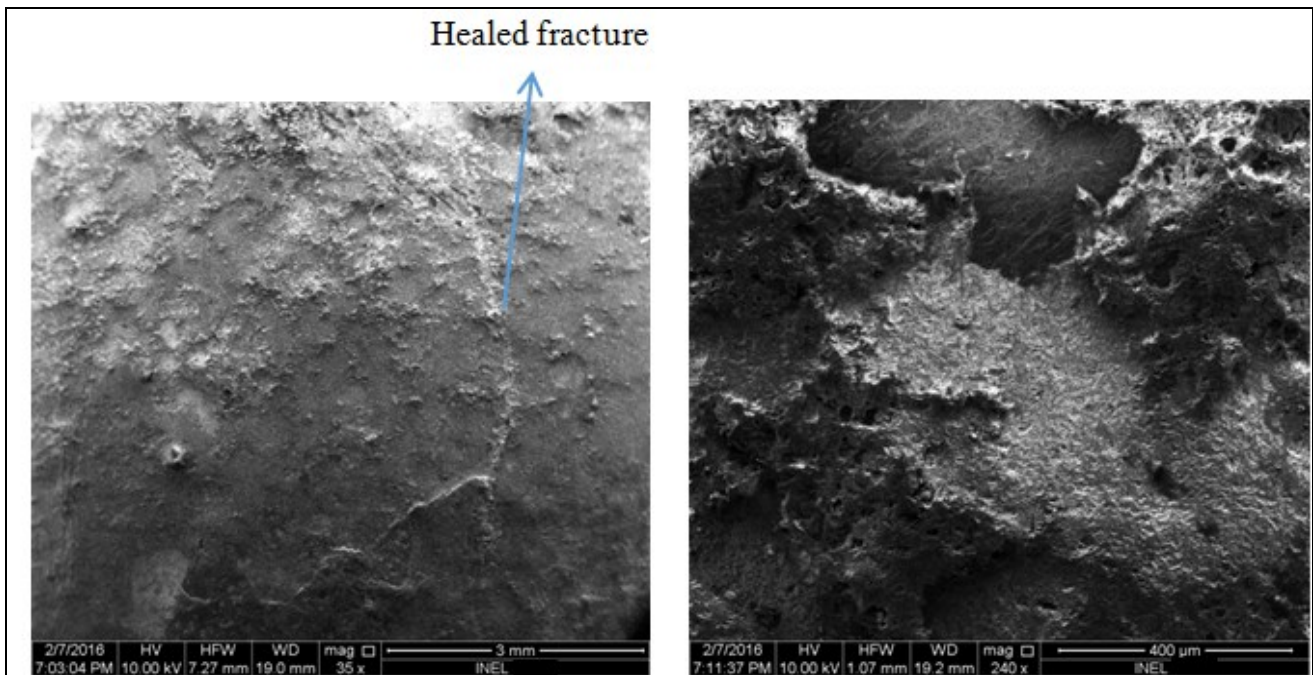


Figure 4: SEM images of the 10,365ft core

2.4 Porosity and Permeability

Porosity and Permeability were measured for all samples before triaxial testing using an automated Porosimeter-Permeameter. The Porosity was measured first using Boyle's law technique using Helium expansion at different confining pressures. Helium was injected at both the ends of the core sample to achieve equilibrium faster. Below plot shows the variation of porosity (0.5%-11%) with confining pressure, the deeper core from 10,365ft depth was found to have very low porosity.

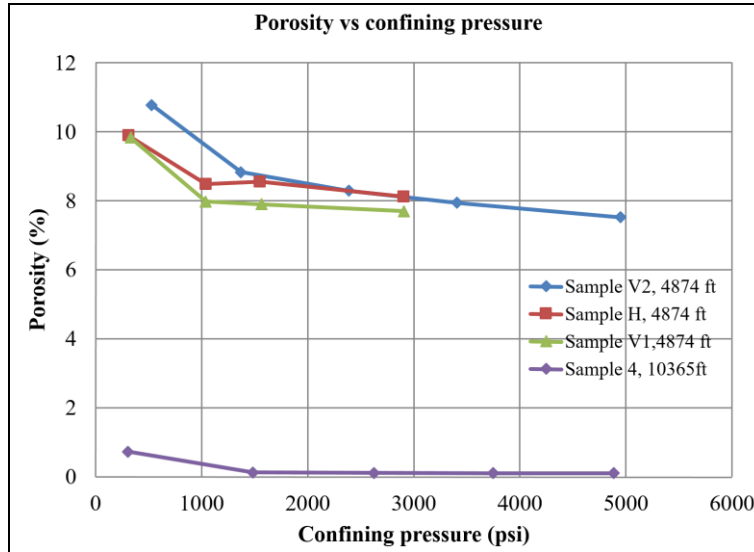


Figure 5: Porosity vs confining pressure for four core plugs from the INEL-1 core, sample depths are provided

Total porosity (crushed) was also measured using the displaced fluid method by taking a piece of core and crushing it to obtain grain density and total porosity values for both the core depths. These are shown below:

Sample	Bulk density (g/cc)	Grain density (g/cc)	Total porosity (%)
10365 ft	2.53	2.66	4.67
4874 ft	2.30	2.63	12.49

Table 2: Density and total porosity for INEL core plugs

The values of crushed porosity are very different from the connected porosity for the deeper core section; this indicates that it possibly has lots of unconnected pores.

Permeability was measured using the standard unsteady state pressure decay technique. The data is used to determine the equivalent liquid permeability, slip and turbulence factors. An equivalent air permeability at a defined confining pressure can also be calculated. Both these tests were done before triaxial testing of the sample.

To evaluate the permeability of the sample during triaxial testing, two precision syringe pumps are used to maintain a small pressure differential of 100 psi across the sample under a given confining pressure. Although any fluid can be used for permeability measurements, nitrogen gas was used in these experiments. Klinkenberg corrections were applied to correct for slippage. One way to avoid the need for corrections is to use higher pore pressure (>2000 psi). The confining pressure must be adjusted to maintain the required effective confining pressure during the test. Then, sample is left for achieving steady state – this is achieved when the flow rate in both the upstream and downstream pumps becomes approximately the same (figure 6).

The time period to achieve steady state varied – for Tuff or shales of nano-darcy permeability, 6-12 hours are needed (if using gas only, liquids can take a week or more). Hence for all samples with ~ micro-darcy or lower permeability, gas was used.

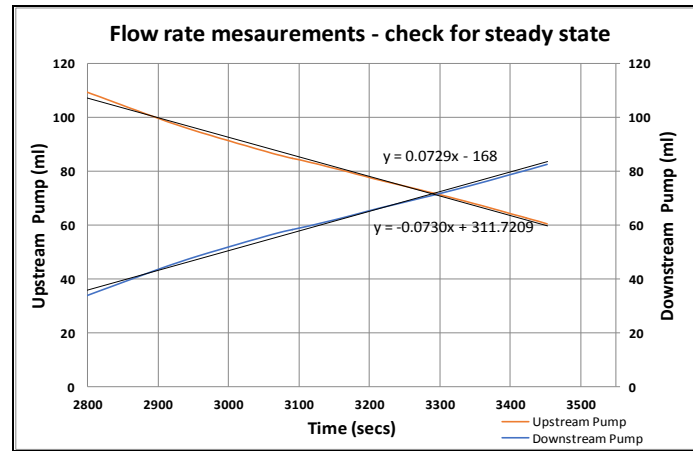


Figure 6: Plot shows steady state equilibrium between upstream and downstream pumps for measuring permeability.

3. DYNAMIC VELOCITY MEASUREMENTS

Both Compressional and shear velocities were measured using 500 kHz crystals at hydrostatic pressure of 3500 psi before triaxial testing. The following table shows these values for the respective samples:

Sample	P-wave velocity (m/s)	S-wave velocity (m/s)	Dynamic Elastic Modulus (GPa)	Dynamic Poisson's ratio (unitless)	Vp/Vs
V1	4089.46	2633.74	36.36	0.15	1.55
V2	3872.02	2516.81	32.64	0.13	1.54
H	5292.86	3425.12	59.40	0.14	1.55
Sample 4, 10365 ft	4648.65	3286.62	55.14	-	1.41

Table 3: Dynamic measurements on the INEL core plugs

As can be seen, both Compressional and shear velocities increase with depth. There is significant difference between velocities measured between vertical and horizontal plugs from the 4874ft depth. This indicates anisotropy between vertical and horizontal properties. As can be seen in the static measurements section later, this translates into a higher strength for the horizontal core plug as compared to a vertical plug as expected. Ratio of Compressional to shear velocities varies between 1.4-1.5.

A comparison between the static and dynamic measurements (Elastic modulus and Poisson ratio) is provided in the summary table below.

4. STRENGTH AND MODULUS MEASUREMENTS

4.1 Multistage triaxial and triaxial-injection testing

Triaxial testing normally involves taking several samples from the same depth (or close depths) and then subjecting them to triaxial tests at varying confining pressures to define the strength envelope. However, limited sample availability and sample heterogeneity can result in variations in strength and other parameters resulting into difficulties in defining a meaningful envelope. Multistage triaxial testing (Kovari and Tisa in 1975) has been used increasingly in defining strength envelopes (Wang et al., 2016). Use of multistage triaxial testing involves subjecting the sample to varying confining pressures and applying deviatoric stress to levels which won't cause irreversible damage. The range of confining pressures can be defined depending upon the expected stress levels in the reservoir. Prevention of permanent damage can be ensured by using a criterion to define when to stop applying deviatoric (see Tran et al (2010), Kovari and Tisa (1975), Kovari et al. (1983), Kim and Ko (1979), Crawford and Wylie(1987)). For the purpose of this paper, the experiments which were carried out have used the volumetric strain deflection in conjunction with AE information to define the stopping point.

In a triaxial test combined with injection (to replicate in-situ stimulation practice) the sample is loaded to the point of dilatancy where the volumetric strain curve shows a deflection. Then, the pore pressure is increased to induce rock failure.. The test provides useful data for stimulation treatment design. We performed two variants of this test. In the first case, the sample was stressed axially to a pre-determined level (close to failure based on analysis of reservoir stress data) with a certain confining pressure, then the pore pressure was

increased and the sample deformation was observed. If the sample did not fail, a higher pore pressure and/or differential stress was applied to induce failure. In the second case, the sample was loaded until the deflection in the volumetric strain was observed. Then, the pore pressure was increased to bring the sample to failure. In each case, the principal stresses at failure were measured.

Two multistage triaxial compression tests, two injection tests, and five Brazilian tests were carried out to determine the geomechanical properties and the Mohr-Coulomb failure envelopes. Also, permeability before and after tests was measured for all the triaxially tested samples.

Figure below shows the four core plugs used for triaxial and injection tests. All samples are one inch in diameter and have a length to diameter ratio of 2:1 with the exception of sample H, which had a ratio of 1.92:1. It can be observed that, the three core plugs from 4,830ft had no visible fractures and looked very similar in appearance. However, the core plug from 10,365 ft depth had several healed fractures.

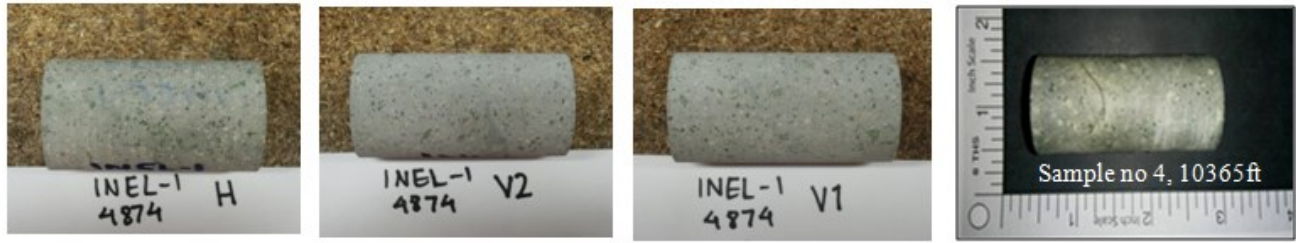


Figure 7: Pictures of samples before the triaxial or injection tests

Two samples – both from the well INEL-1, were subject to multistage triaxial tests; four to five different confining pressure stages were used for these tests and the samples were taken to failure using gas injection in the last loading stage. The axial stress was applied using a strain control mode at a rate of 5×10^{-6} strains/sec. The following procedure was followed:

1. Sample is jacketed with a thin copper jacket (0.003" thickness) and 8-12 acoustic crystals are added on the jacket at fixed locations.
2. Sample is hydrostatically loaded to a confining pressure slowly while monitoring strain.
3. Sample is then loaded deviatorically until volumetric strain deflection is observed, at this point sample is unloaded. Confining pressure is changed for the next stage. This is repeated until the last stage.
4. In the last stage, failure is initiated using injection while the sample is under a confining pressure of 3500 psi and an axial load which causes a negative change in volumetric strain. This has been described earlier.

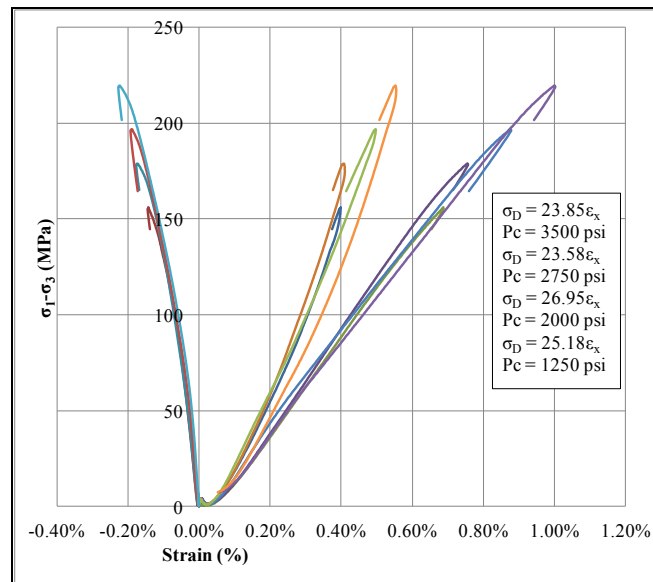


Figure 8: Stress strain response at four stages of multistage triaxial test for INEL-V1 (4874 ft depth) sample. Volumetric deflection point increases with increase in confining pressure signifying higher strength; Young's modulus also increases slightly at higher confining pressures.

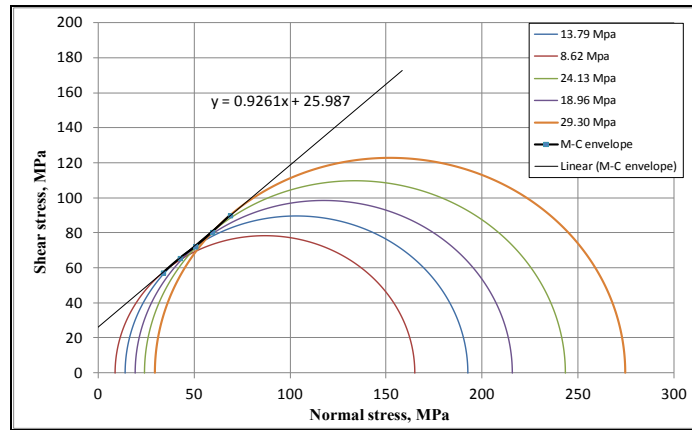


Figure 9: Mohr-Coulomb plot for INEL sample V1, depth 4874 ft.

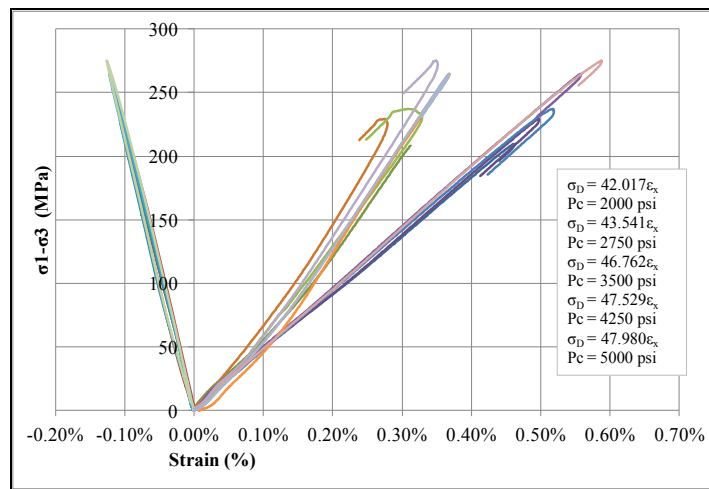


Figure 10: Stress strain response at four stages of multistage triaxial test for Sample no 4, 10365ft depth. Volumetric deflection point increases with increase in confining pressure signifying higher strength; Young's modulus also increases slightly at higher confining pressures. As compared to the shallower samples, this shows more strength.

The failure envelope for both the samples was calculated assuming that the best fit tangent line of non- failure Mohr circles has the same slope as the failure envelope, as shown in fig. above using technique defined by Pagoulatos (2004).

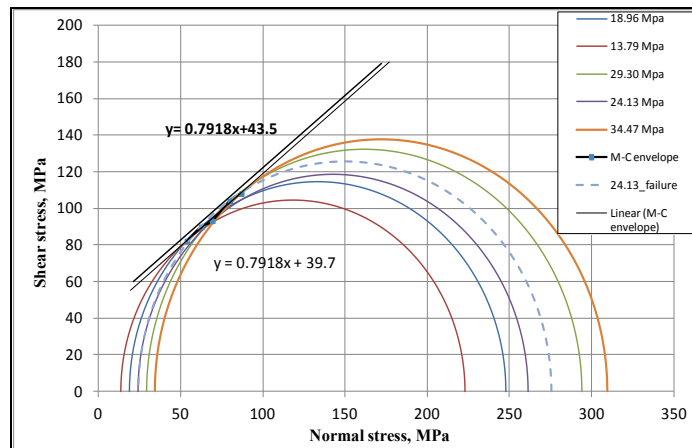


Figure 11: Mohr-Coulomb plot for INEL sample no 4, depth 10365 ft.

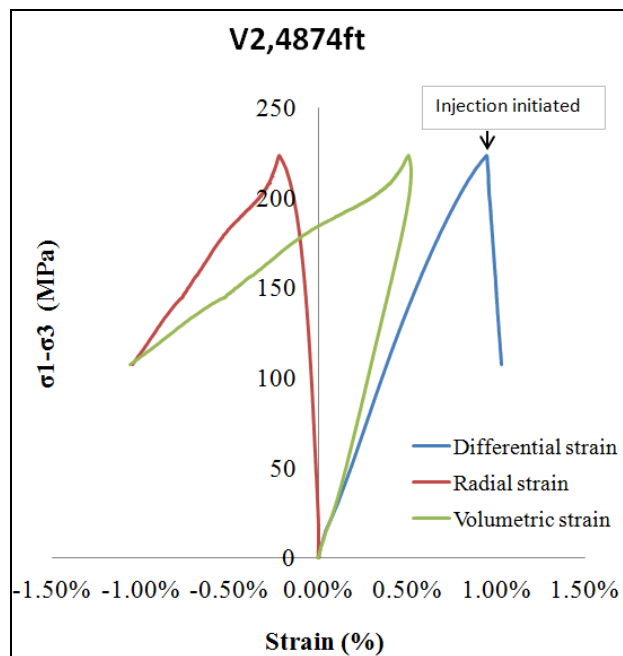


Figure 12: Triaxial – injection plot for sample V2, 4874ft depth

	Sample			
	V1, 4874ft	V2, 4874ft	H, 4874ft	Sample-4, 10365ft
Static Young's modulus (GPa)**	27.5	27.0	34.8	46.8
Static Poisson's Ratio**	0.17	0.15	0.16	0.16
Unconfined Compressive Strength (MPa)*	132.2	-	-	179.2
Cohesion (MPa)*	29.5	-	-	43.5
Friction angle*	42.8°	-	-	38.2°
Peak strength (MPa)**	229.8	223.5	260.1	251.4
Dynamic Young's modulus	36.4	32.6	59.4	55.1
Dynamic Poisson ratio	0.15	0.13	0.14	-

* - Measured using Mohr Circle data

** - Measured at 3500 psi confining pressure

Table 4: Summary of static and dynamic measurements performed on samples from the INEL-1 well

Following inferences can be made from the measurements recorded above:

1. There is some anisotropy between horizontal and vertical plugs from the 4874ft core. Horizontal plug shows higher strength and higher young's modulus in both static and dynamic measurements.
2. Dynamic and static Poisson's ratios are almost same (within 10%). However static and dynamic young's moduli are different (14-41% difference, average 25%) but show similar trend in all four plugs with higher values in dynamic measurements.
3. Deeper core samples (lithologies) are stronger than the shallower core and have higher elastic modulus. This correlates very well with their porosities (lower porosity in deeper core) and velocities (higher velocity in deeper core).
4. Young's modulus increases very slightly as confining pressures are increased in the multistage triaxial tests– this indicates that these rocks are well compacted already.



Figure 13: Pictures of samples after testing; copper jacket hasn't been removed to prevent sample disintegration. Red lines show clear fractures seen on surface. Location of these fractures in 3-D has been studied in next section using acoustic emissions.

4.2 Brazilian Test (Indirect Tensile Strength Test)

Indirect tension tests often referred to as Brazilian tests were performed on plugs from both the core depths. The indirect tensile strength of the specimens were calculated as follows:

$$\sigma_t = \frac{2P}{\pi Dt}$$

Where, σ_t is the Brazilian tensile strength (MPa); P is the load at failure (N); D is the diameter of the specimen (mm); t is the thickness of the specimen (mm) (ISRM 1978). A picture of the test assembly and a test result for the sample from 10,365ft depth are shown below.

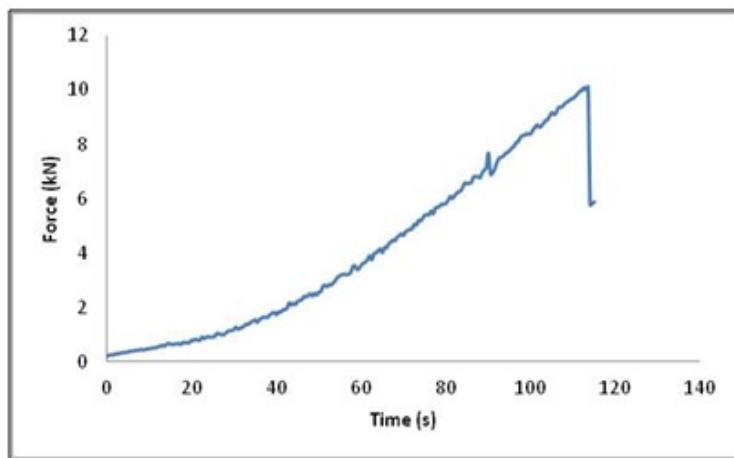


Figure 14: Axial force vs time plot for sample B1 (left) and picture showing the crack at centre of sample after Brazilian test.

Table 5 shows a summary of the tensile strength values for the five samples that were tested. It can be seen that the three plugs from 10,365 ft show significant variation in strength, this happened due to presence of healed fractures in all three samples. S2 had fewer fractures and hence shows higher strength. Samples were loaded to get highest possible value of strength (perpendicular to fractures).

Sample name	Indirect Tensile Strength (MPa)
S1 (10365 ft)	19.2
S2 (10365 ft)	24.8
T1 (10365 ft)	13.8
B1 (4874 ft)	20.0
B2 (4874 ft)	15.2

Table 5: Brazilian test results for the INEL core plugs, the variation in the three values for the 10365 ft can be explained on the basis of presence of natural fractures

5. PERMEABILITY CHANGES DUE TO ROCK FAILURE

Table 6 describes the changes in permeability observed after fracturing. It should be noted that during compressional loading two processes compete – the sample compression reduces permeability due to pore closure, while micro fracturing or shear fracturing increases permeability. Permeability has been observed to decrease with increasing triaxial loading (even after fracture) for high porosity samples like sandstones and to increase for low porosity samples (Ohaka, 2010). The final permeability change is also a function of whether the fracture intersects the ends of the sample or more localized. Horizontal sample permeability was not measured during these tests. It can be seen from below table that most of the samples showed large increases in permeability after fracturing which shows that injection experiments could be successful in creating improved fluid flow in these rocks. The final values of permeability though are still low (μD).

Plug	Initial permeability (μD)	Final permeability (μD)	Ratio of Final to initial permeability
V-1, 4874 ft	18.2	1668.0	92
V-2, 4874 ft	0.068	0.590	9
H, 4874 ft	0.197	10.138	44
Sample 4, 10365	0.086	17.357	201

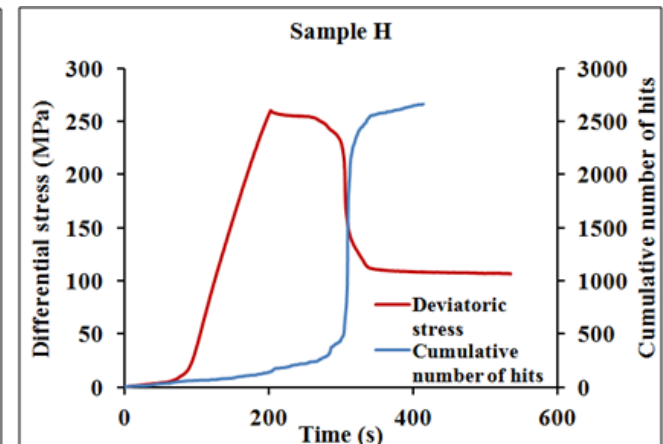
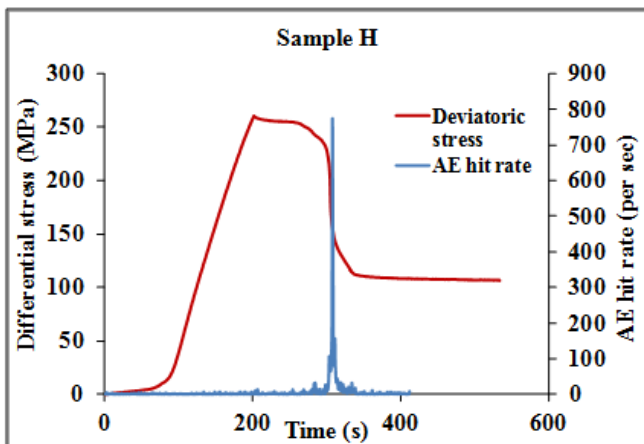
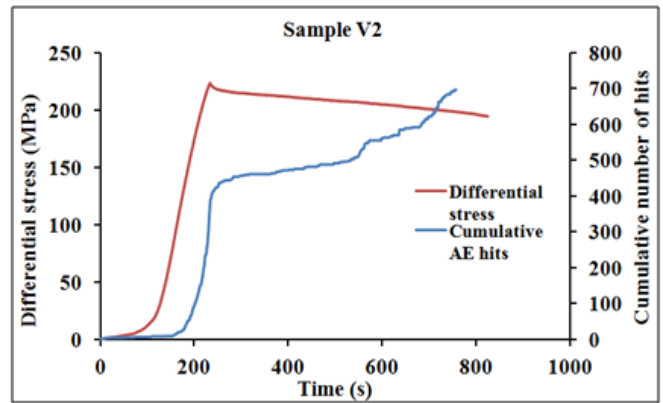
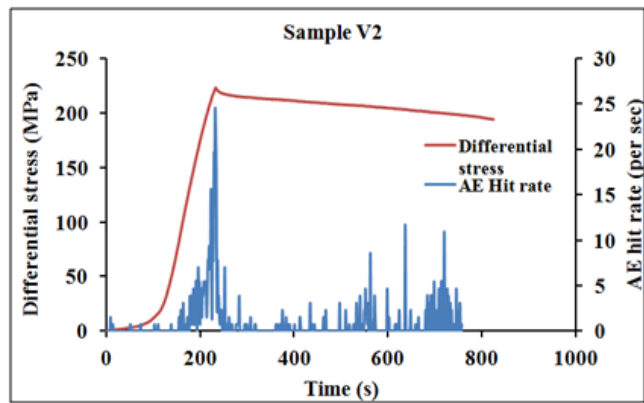
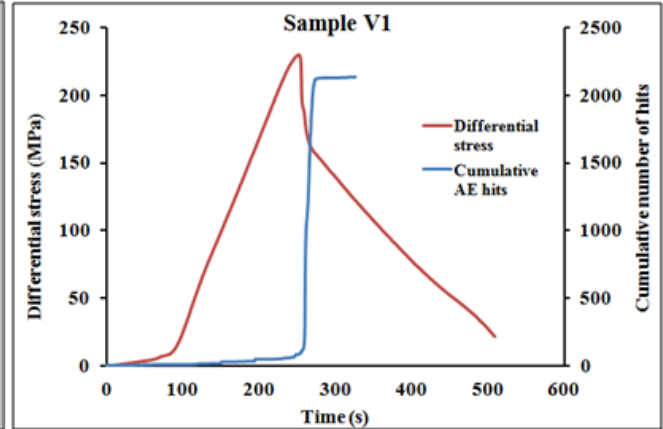
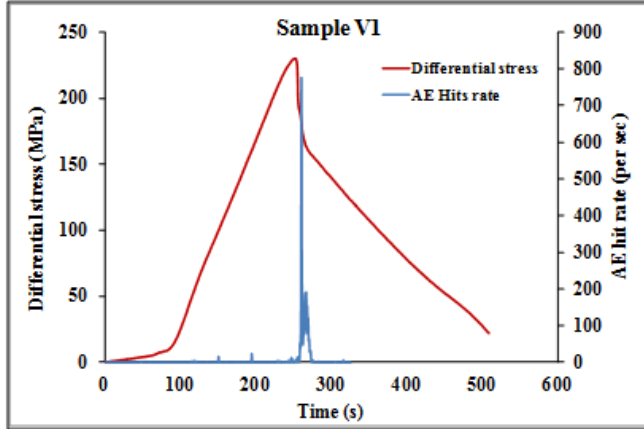
Table 6: Permeability values before and after triaxial testing for the INEL core plugs

6. ACOUSTIC EMISSION ANALYSIS DURING ROCK FAILURE

The MISTRAS Express-24 channel, Acoustic Emission (AE) system with a frequency range of 1KHz - 1MHz was used with 8 to 12 AE sensors per sample for recording acoustic emissions generated during the triaxial tests. These sensors were attached to the sample using epoxy. A preamplifier of 40 dB was applied to all the sensors. The amplitude cut off on these sensors varied from 45-55 dB; any wave below this amplitude is discarded by the system as noise. Frequency and energy of failure events were also recorded during the tests – these give insights into the nature of failure; typically higher confining pressures result in lower energy released during the failure if the rocks become more ductile. A sample rate of 1 MSPS (million samples per second) was used to record the AE information. 3-D location analysis was also performed using AE information – this technique uses the source amplitude and the differences in time it took the wave to reach the different sensors to arrive at the location of the event. 3-D location is highly dependent upon the rock type – rocks which generate low AE (including Tuff) typically do not give a good 3-D location response as compared to very brittle rocks which generate high amplitude AE waves during the failure process.

AE/MEQ analysis was carried out for all the tests. Figure 15 below shows the time - stress responses in conjunction with AE information for each of the four tests. The figures show the rate and number of hits observed during the respective tests. It can be observed that generally the rocks tested have a good AE response with the strongest AE response observed close to and during failure. Also, low AE activity is observed after failure when slip takes place on the shear surface. Samples V1 generated low AE after failure while samples V2, H, and 4 show good AE response to fracture slippage. Overall the highest number of events were recorded for sample H and followed closely by V1, and 4 and far less for V2. This can be explained as follows:

1. Sample H has the highest strength and is more brittle (sharp drop in stress after failure) than all other samples. This clearly contributed to its high AE rate and total number of events.
2. Sample V1 and sample no 4 both generated similar number of hits, however in terms of rate of AE generation, sample V1 had double the rate at fracture initiation as compared to sample no 4. This is because sample 4 had several healed fractures before testing and deformation localized on those prior to the formation of a new fracture plane. On actual observation after failure, sample 4 had several failure planes – it failed along the healed fractures in addition to newly generated failure planes resulting in a more gradual failure process than V1 which failed in a highly brittle manner.
3. Sample V2 had the lowest AE response, this despite it having almost the same strength and coming from the same exact depth as V1 and almost similar dynamic and elastic modulus. This can be attributed to presence of micro cracks in V1 which contributed to a good initial permeability value (more than 250 times that of V2). As a result the pore pressure within V1 was able to increase more rapidly throughout the sample, causing a more brittle failure as compared to V2 which had a very ductile failure. It can be seen in table 6 that even the final permeability in V2 after failure is lower than the initial permeability in V1.



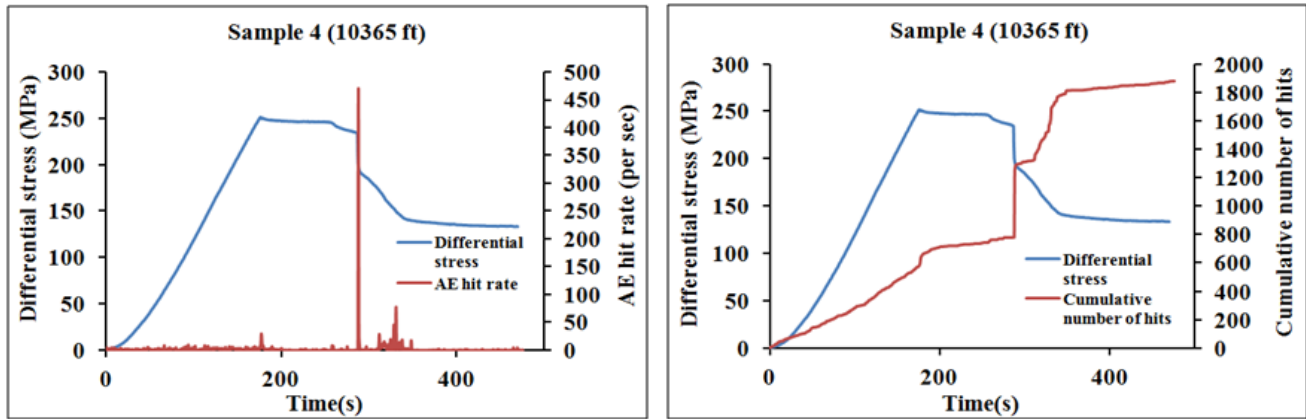
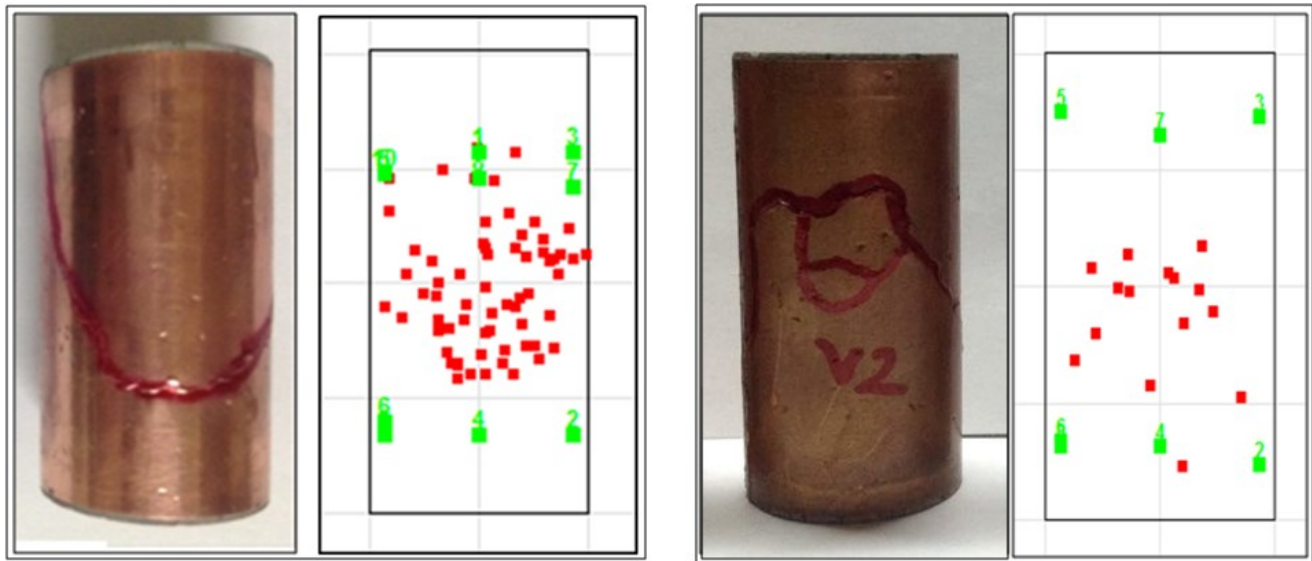


Figure 15: AE hits rate and cumulative number of hits correlated to axial stress during triaxial testing observed in the four INEL -1 well core plugs. More brittle failure (V1, H and sample no 4) show high number of hits as compared to sample V2 (ductile failure – observe stress plot). Most of the hits are generated during fracturing although some are generated just before and during fracture sliding.

It should be noted that the AE was recorded using 8-12 sensors and these rocks were observed to generate far less AE activity when compared with sandstones (for example Berea sandstone in a similar experiment generated over 10000 hits). AE responses vary from rock to rock and typically.

The following plots show the 2-D and 3-D location analysis of AE events for all the four samples. The figures show the failed sample next to the 2-D location plot and a three dimensional plot showing location of events. It should be noted that the red lines on the sample show the fracture location. Also, location analysis shows the location of micro-fracturing in addition to the large shear fracture locations.



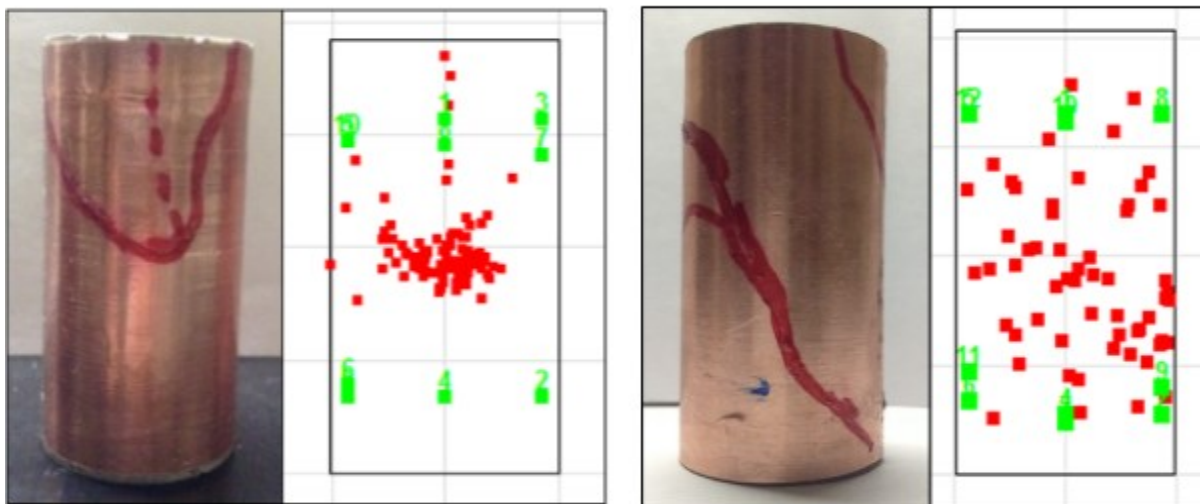


Figure 16: Sample 2D location plots with Sample V1 (top left), sample V2 (top right). Sample H (bottom left) and Sample no 4 (bottom right) showing event locations in 2-D within the sample as compared with the fracture location in the respective samples (marked red). Location algorithm picks up micro cracking as well within the sample.

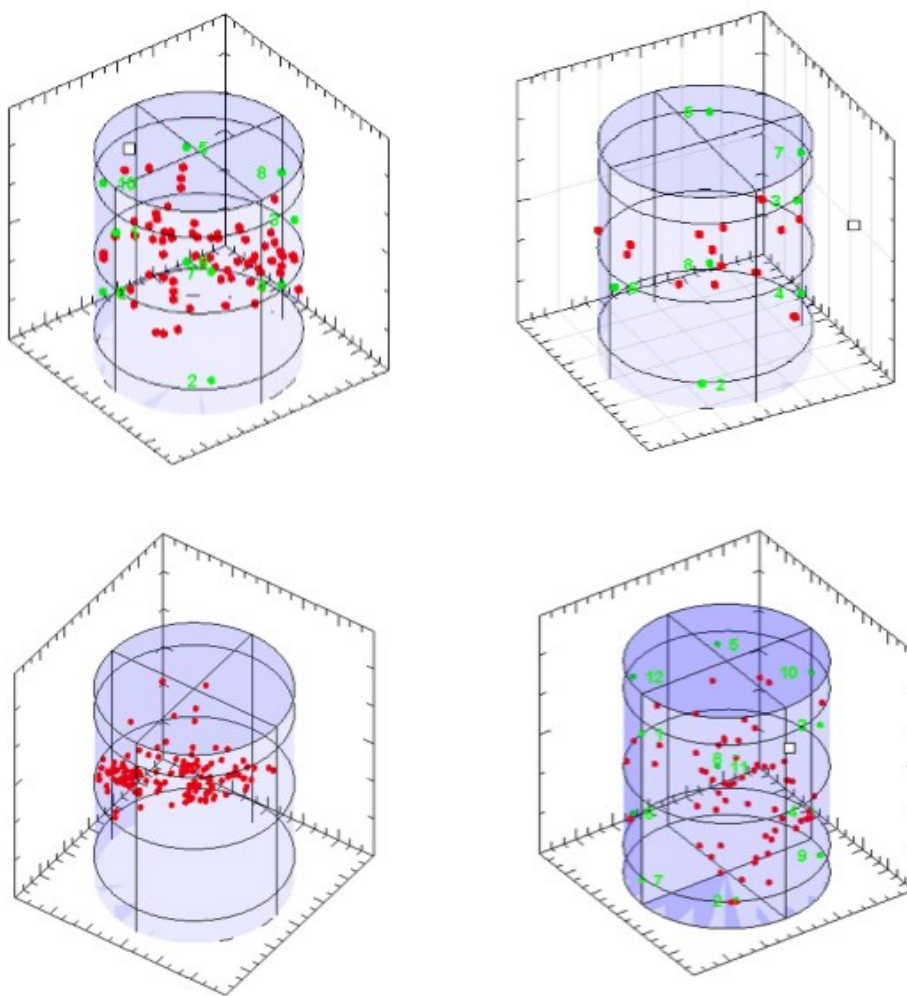


Figure 17: Sample 3-D location plots showing event locations in 3-D within the sample (right)

CONCLUSIONS

Geomechanical properties of drill cores from the INEL-1 well have been characterized in this work. The results provide information regarding the elastic and failure properties along with pore structure, compositional analysis, and porosity and permeability. The mineralogical analysis clearly shows presence of mainly feldspars (42-48%) and silica (24-27%). Clay composition varies from 24-27%. Porosity varies from 14% at the 4,874ft depth to 4% at 10,365 ft depth – this can also help understand the higher strength in the deeper core. The deeper core showed the presence of healed fractures and the sample failed along these fractures. Elastic properties were found to increase with depth and a high MEQ rate was also observed. This can be seen in the much higher values of Young's modulus in the deeper core. Velocity measurements show considerable anisotropy in vertical and horizontal plugs in the 4874ft core – this correlated very well with strength measurements on the core plugs with horizontal plugs showing higher strength and velocities. Since only one plug was available from 10,365 ft depth, it is recommended to obtain more plugs with a different orientation to understand variations in strength, if any. Permeability measurements clearly show a large increase after fracturing – this shows that although fracture closure in absence of proppants will reduce overall conductivity, it will still be much higher than existing permeability. AE activity was observed during the tests, and was observed to increase exponentially during fracture with low activity during slippage.

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