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PNNL-30847

Creation of Laboratory-scale Testbed for Autonomous Monitoring and Control of Subsurface Systems

January 2021

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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operated by
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for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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Abstract

This report describes the results of an LDRD project aiming to develop a laboratory-scale testbed for autonomous subsurface monitoring and control systems. Modifications were made to an existing polyaxial loading frame to incorporate electrical resistivity tomography (ERT) and acoustic emission (AE) monitoring systems. This allows engineered subsurface processes to be studied under realistic temperatures and stresses in a scaled-down laboratory environment with similar monitoring systems as are deployed in field-scale systems. The paper outlines some challenges that were faced in implementing the ERT system at the laboratory scale and the solutions that were devised. Results are shown from two demonstration tests—one focusing on the ERT system, and one focusing on the AE system.

Acronyms and Abbreviations

ERT	Electrical Resistivity Tomography
AE	Acoustic Emission
EGS	Enhanced Geothermal Systems
SME	Subject Matter Expert
MEQ	Micro-earthquake

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1.0 Introduction

Many natural and engineered subsurface processes are crucial to DOE mission areas. Because direct access to the deep subsurface is possible primarily through boreholes, which are expensive and time consuming to drill and only afford access to small portions of the subsurface, a thorough understanding of these processes is often elusive. Remote geophysical monitoring systems can offer better spatial coverage, but they generally offer only indirect observations of the subsurface processes. As a few examples, geophysical systems can detect changes in the sound speed, electrical conductivity, and mass density in 2D and 3D sections of the subsurface over time. However, the properties that are generally of direct interest are the porosity, permeability, fluid composition, temperature, pressure, and stress. The observable properties and the properties of direct interest are generally only loosely correlated--often correlated in complex and poorly understood ways. These relationships between observable geophysical properties and properties of direct interest are called petrophysical relationship. Many empirical and physics-based petrophysical relationships exist, but our ability to reliably choose and apply appropriate petrophysical relationships remains limited because of the high degree of variability in geologic formations. Improvement of our ability to apply petrophysical relationships is generally hampered by the lack of direct observations of sufficient quantity and quality with which to develop and validate petrophysical relationships.

Laboratory tests on either core samples or surrogate rock samples with similar properties offer the ability to directly measure the quantities of direct interest. Standard laboratory tests exist to measure hydraulic, mechanical, chemical, and thermal processes in such samples. However, such laboratory tests have several important limitations. First, the small length scales involved mean that many important subsurface processes simply cannot be directly simulated in the laboratory. For example, fluid flow in many geologic formations is strongly influenced by natural fractures that form percolating networks. However, the spacing between natural fracture is often several orders of magnitude greater than the scale of laboratory tests, making these effects impossible to directly recreate in the laboratory. The second important limitation of laboratory tests is that limited spatial extent of such interrogations. We may be able to gain a very good understanding of the properties of several core samples, but heterogeneity in geologic formations means that this information tells us very little about the properties of the material only a short distance away.

The project discussed in this report seeks to improve our ability to study subsurface processes by constructing a laboratory test bed that allows both direct measurement of the quantities of interest and the same types of indirect measurements that are attainable at field scale. This capability will allow the development of improved petrophysical relationships, development and validation of new geophysical monitoring techniques, and validation of emerging real-time joint inversion monitoring and control systems.

2.0 Description of Apparatus

The new monitoring capability was designed to be incorporated into a recently commissioned polyaxial loading frame, shown in Figure 1. Polyaxial loading frames are also sometimes called true triaxial loading frames. These relatively uncommon testing frames allow for independent control of the mechanical loading in all three directions. This is in contrast to the much more common testing apparatus, called a triaxial loading frame, where a radially uniform pressure is applied to a cylindrical sample in combination of an independently controlled loading along the axis of the cylindrical sample. The ability to independently control all three principal stresses is crucial for studying the propagation of hydraulic fractures, since the differences between the principal stresses is the primary factor that controls the geometry of a hydraulic fracture. In reality all three principal stresses in the subsurface are almost always unique, making a polyaxial load frame essential to properly simulate actual subsurface conditions.

This recently developed loading frame is also significantly larger than the few other polyaxial loading apparatuses that exist in the national laboratory complex. Because hydraulic fractures generally grow rapidly and unstably to a length equal to several times the wellbore diameter, samples that are only a few centimeters in size do not allow study of the stable fracture growth phase that dominates field-scale hydraulic fracturing treatments. The recently commissioned frame is designed to accommodate a 6-inch cubic sample. With carefully designed tests a period of stable fracture growth is achievable in this frame.

The other key features of the recently developed polyaxial frame is the ability to heat the entire frame and sample to 200 C. To our knowledge this is the only polyaxial designed to withstand these temperatures—making a unique asset for enhanced geothermal system (EGS) studies.

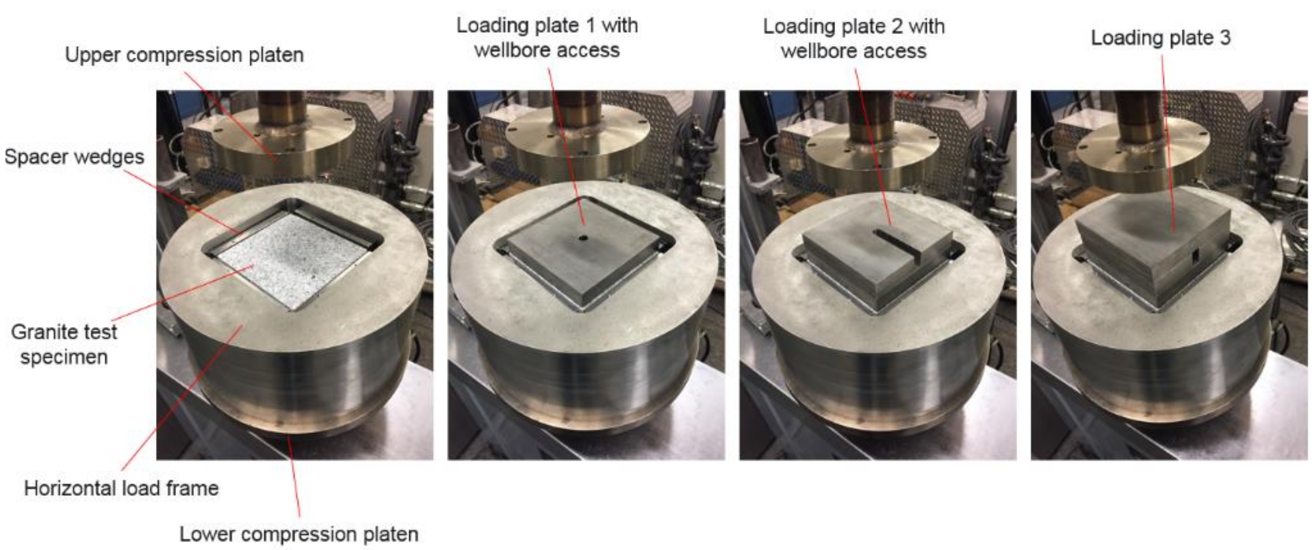

Figure 1. Photos of the polyaxial frame during assembly with a granite test specimen for a geothermal project

2.1 Monitoring system design

Figure 2 shows a cut-away view of the polyaxial loading frame assembly with a sample installed. On each of the four lateral faces of the sample there is a flexible steel hydraulic bladder called a flatjack, and two stainless steel wedges. The flatjack is illustrated in this figure simply as a thin rectangular block. The wedges serve to allow easy installation of the sample while also creating a tight fit of the assembly. Without this tight fit the flatjacks would rupture at a very low pressure. With the tight fit they can withstand a pressure of several thousand pounds per square inch. The loading in the vertical direction is applied using a uniaxial stress frame to a stack of thick steel plates to ensure uniform loading to the sample.

The design challenge for applying ERT monitoring in this apparatus is that the electrodes must be in firm contact with the rock sample but must be electrically isolated from one another. The rock sample also must be electrically isolated. The design solution was to design new spacer wedges from a high strength polymer to replace the stainless-steel wedges. The new polymer wedges were also designed with pockets to contain ERT electrodes and AE sensors along with channels for the instrumentation wires to pass out of the frame while maintaining the mechanical loading. A similar set of polymer plates were installed on the top and bottom of the sample. In total, the designed plates allow for up to 56 ERT electrodes around the surface of the sample. The top and bottom plates were designed to accommodate three large and sensitive AE sensors on both the top and bottom. The ERT electrodes were designed to be of an identical size to a smaller commercially available AE sensor, so that any of the pockets in the side plates can be instrumented with the miniature AE sensors.

Another important consideration for the ERT system is that high pressure fluid must be injected into the sample while still maintaining electrical isolation of the sample. To achieve this Swagelok dielectric fittings were installed on the steel casing at the top of the sample, which effectively electrically isolates the sample from the pump. We worked with electrical and pressure safety subject matter experts (SME’s) to design an enclosure and protocol to safely isolate the ERT voltage source from surrounding personnel and equipment. The ERT system was designed to utilize the exact same surveying equipment that are utilized in the field. For the AE system, a new eight channel monitoring system was purchased to record the small, high frequency acoustic emission events generated in these laboratory tests. The AE monitoring is analogous to passive micro-earthquake (MEQ) monitoring that is commonly employed in hydraulic fracturing operations.

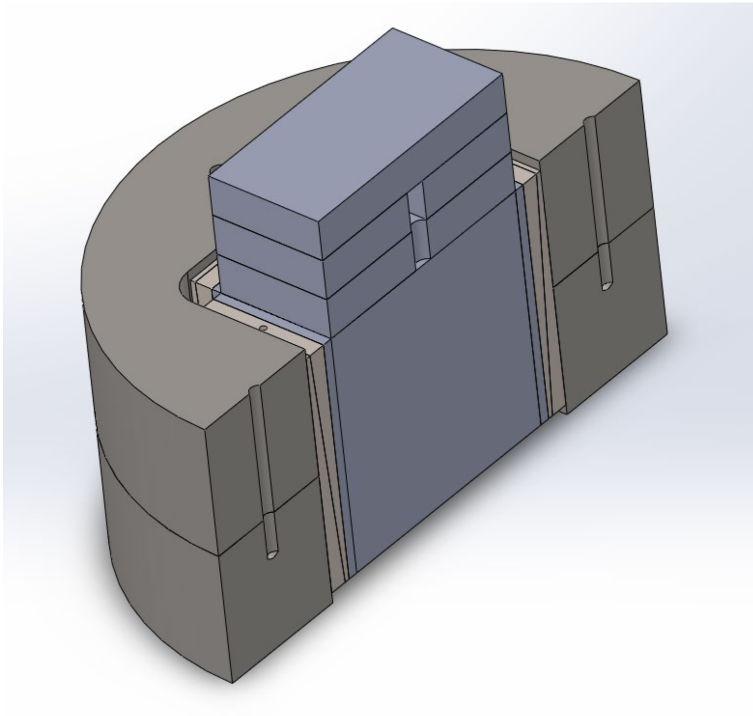

Figure 2. A cut away view of the polyaxial loading frame, showing the cubic sample surrounded by the flatjacks and spacer wedges.

3.0 Test results

The initial plan was to do a hydraulic fracturing test with simultaneous ERT and AE monitoring. These two monitoring methods contain complementary information—the ERT is primarily sensitive to fluid migration while the AE is primarily sensitive to the initiation and extension of fractures. In field studies there seems to be significant evidence that some hydraulic fractures grow aseismically, while some seismic events seem to be induced by hydraulic fracturing but are not themselves located on a hydraulic fracturing plane. Therefore, independent measurements that are sensitive to fluid flow and seismic release events offer the possibility of understanding this process.

Our first ERT test, however, revealed an unforeseen challenge. The contact resistance between the ERT electrodes and the granite sample, which has a very low bulk conductivity, was too high for our instrument to measure at allowable voltages. As a compromise, with the COVID-19 pandemic limiting our ability to tolerate much iteration, we chose to instead conduct a separate ERT test in a rock type with much higher bulk conductivity. A high porosity sandstone (Dunder's Sandstone) that was pre-saturated with a brine solution was chosen instead. This lowered the contact resistance so that meaningful ERT data was collected. The ERT test was then conducted by injecting tap water, which has a lower conductivity than the brine the sample was saturated with and observing the change in resistance over time. Figure 3 is a plot of the bulk conductivity field that was constructed from the resistivity data measured at the beginning of the injection test. The time-lapse ERT data during the injection test have not yet been inverted.

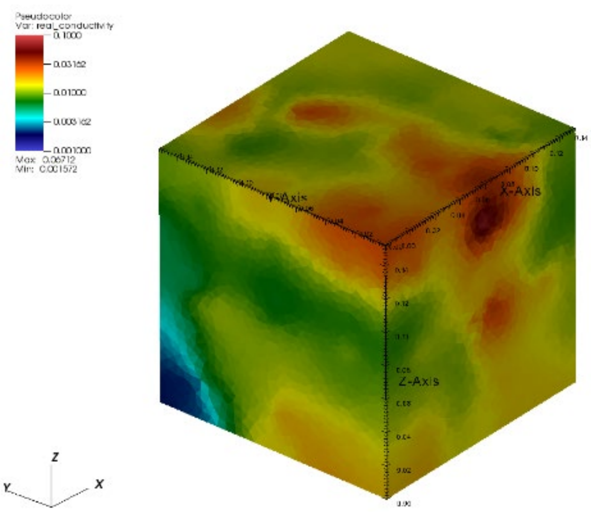

Figure 3. Plot of the bulk conductivity field in the sample obtained by inverting the resistance measurements at the start of the injection test.

At attempt was made to conduct a hydraulic fracture test in the same high-porosity sandstone with simultaneous AE and ERT measurements. However, the permeability of the sandstone was too high to fracture with water injection from the ISCO pump we had available (limited to 25 mL/min). We attempted to perform the fracturing test with glycerin as the injection fluid, since it has a viscosity approximately 1000 times higher than water. However, even with this higher viscosity we were unable to generate sufficient pressure to fracture the sample. With these setbacks and limited access to the laboratory due to COVID-19, we instead chose to conduct an AE test in the granite sample with no ERT monitoring.

The upper plot in Figure 4 is a plot of the wellbore pressure versus time for the fracturing test. The wellbore pressure was first raised in steps to 1000 psi, which was the value of the minimum principal stress. Then the block was fractured with a constant injection rate, which is the period with the rapid increase in pressure followed by a sudden drop of pressure, often called the breakdown pressure. The lower plot in this figure is the cumulative number of AE events recorded. There was a small number of events prior to breakdown, then a large surge in events as the fracture extends to the edge of the block, followed by a much smaller rate of acoustic emissions after breakdown.

Figure 5 is a plot of the location of a subset of the AE events. Not all recorded events are locatable. To be locatable clear P-wave arrivals must be registered on at least three, and preferably all eight channels. Figure 6 shows photos of the four faces of the block where the fracture was visible after the test. As the photos indicate, the fracture is mostly planar and formed perpendicular to the minimum principal stress—which in this case was applied in the vertical direction so that the fracture formed perpendicular to the wellbore as it would with a horizontal well. The cloud of AE events are centered roughly in the center of the block, as expected, but do have a much more broad spatial distribution than would be expected. The eight AE channels used in this test were enough to demonstrate the capability, but still leave some location uncertainty so that the spatial scatter of the events is likely a result of the relatively sparse coverage/small number of AE sensors. The location accuracy would be substantially improved with a larger number of sensors.

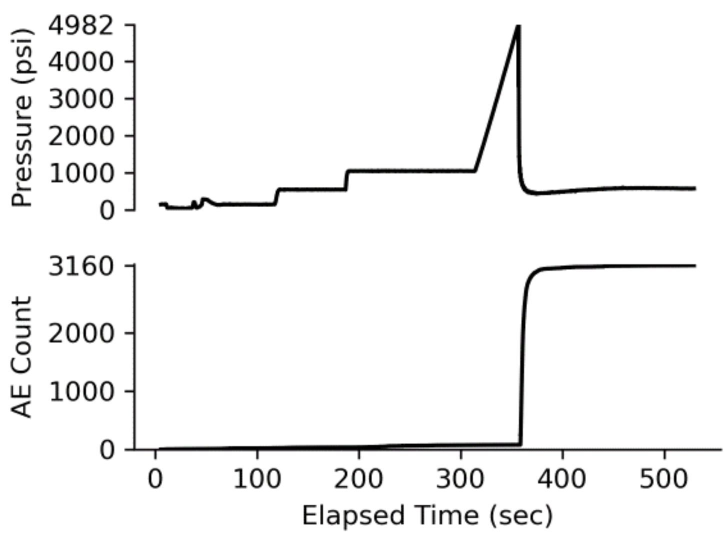

Figure 4. Plot of the injection pressure (top) and number of recorded AE events (bottom

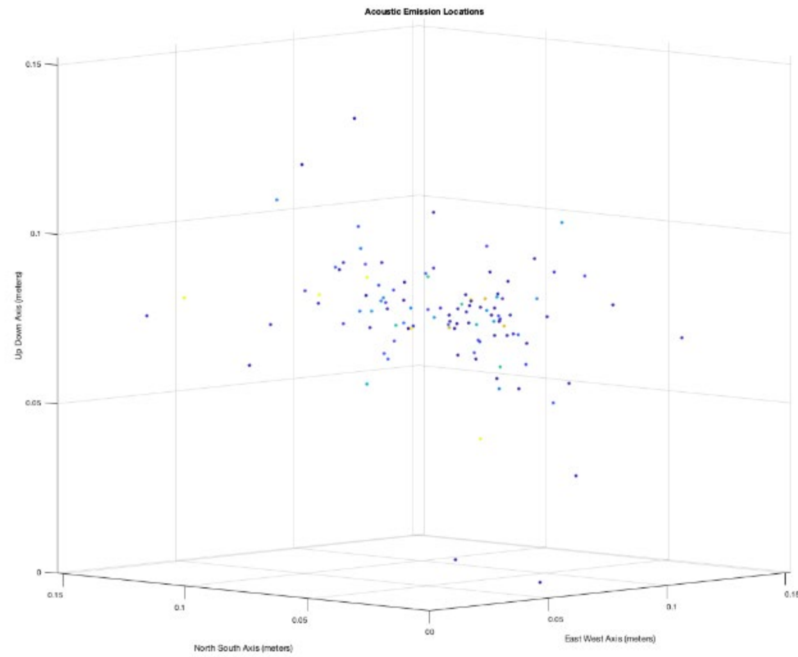

Figure 5. Plot of the located AE events

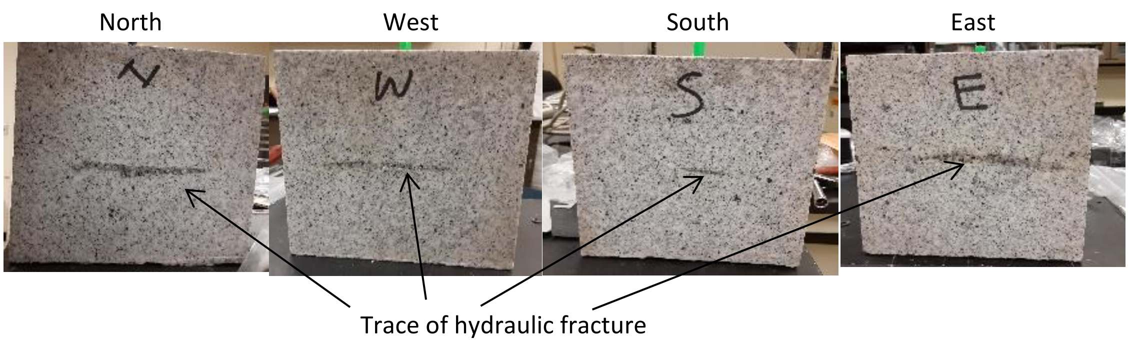

Figure 6. Photos of the faces of the block showing the trace of the mostly planar hydraulic fracture

4.0 Conclusions

The results of this project successfully demonstrated the feasibility of the concept and made clear three areas of improvement in future tests. First, the ERT electrode contact resistance limits the range of rock bulk conductivities that can be tested with the current design. The ability to perform ERT monitoring on lower bulk conductivity samples could be improved by either enlarging the electrodes, embedding them into the rock to increase the contact area, or significantly increasing the applied voltage. Enlarging the electrodes significantly would likely result in fewer electrodes and thus diminished spatial resolution, so some tradeoffs would have to be considered.

The second area of improvement would be increasing the number of AE transducers. The AE monitoring system purchased is expandable by purchasing additional 8-channel cards. The miniature AE sensors used in the side plates are not as sensitive as the larger piezoelectric-based sensors used on the top and bottom faces, but they were able to detect some events. Given the limited sample surface area, it is probably not feasible to use more than the three large sensors on the top and bottom, so increasing the number of AE sensors would need to be done using miniature sensors on the side plates. In this case the AE sensors and the possibly larger ERT electrodes would be competing for space, again leading to some design tradeoffs.

The finally area of future improvement would be to add active-source AE monitoring. In this configuration the AE sensors would also act as transmitters, intermittently sending out acoustic pulses that would be detected by the other sensors. This would be analogous to active-source seismic surveys in the field and could be used to detect changes in seismic velocity and attenuation over time—providing another means of understanding the processes in the sample.

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