bge science@DUSEL

Science Inquiry in Biology, Geosciences and Engineering
at a
Deep Underground Science and Engineering Laboratory

Prepared by the DUSEL Science Community

Executive Summary

This report details an initiative to answer compelling contemporary questions on the dynamic evolution of the shallow Earth crust and of our sustainable activities within it. In particular it examines important discoveries in biology, in geosciences and in engineering (i.e. *bge science@dusel*) that are necessary to advance our understanding. The development of a deep underground science and engineering laboratory (DUSEL) will provide a sub-surface observatory critical to this inquiry. DUSEL would enable many outstanding significant questions in Earth science, geobiology, and subsurface engineering to be addressed.

The proposed laboratory has three important attributes – the laboratory will be deep, voluminous (~20 km^3) and will provide access for more than thirty years. It will provide experimental facilities to a depth of ~7400 feet (2250m) and will provide drilling platforms to probe the upper temperature limits of subsurface life at three kilometers below this. The elevated stresses at depth provide an ideal environment to observe stress-relieved failure of the host rock and examine the coupling between stress and mass and thermal transport. The long-term occupancy schedule is ideal for examining water/rock interactions, reactions of aqueous/gaseous species and microbial alteration of these species and the surrounding host rock mineralogy at in situ temperature and pressure. Observational scales will range from single boreholes (~1m) to borehole arrays (~10-100m) to the scale of DUSEL (~1-5 km) in order to probe the influence of scale effects on the coupled mechanical and transport properties of fractured rocks. The proposed long occupancy enables transients from micro-seconds to decades to be observed and understood. DUSEL will allow both natural and engineered subsurface processes to be documented with unprecedented detail.

The preliminary design report for DUSEL is approaching completion, as is the design of the experiments that may be incorporated within it. This has involved developing and articulating the science case for such investigations together with defining the scope, experimental details and synergies between various experiments. The preliminary design report will be incorporated into an NSF-MREFC[1] proposal anticipated to go before NSF's National Science Board in early- to mid-2011.

This document summarizes the motivation of the science efforts in geobiology, geoscience and engineering currently funded by NSF as an indication of potential scope of inquiry at DUSEL. These activities include investigations of:

- *Geologic Carbon Storage:* To examine the factors controlling the integrity of natural reservoirs utilized for CO_2 sequestration by performing experiments on 500-m-tall artificial reservoirs containing water-CO_2 mixtures. The proposed facility will measure mixed-fluid transport processes and CO_2 phase changes in the presence of artificial thermal, pressure and stress gradients, will test new geophysical tools for quantifying in situ mixed fluid compositions, will examine the impact of microbial activity on CO_2 storage and will provide a test bed for measuring transport properties in other mixed gas-fluid-hydrate systems.
- *The Deformation of Large Underground Rock Masses:* To examine the roles of fractures on the mechanical and transport properties of rocks at a variety of length-scales and in particular the coupling between hydro-mechanical processes.
- *Transformations related to Coupled Thermal-Hydrological-Mechanical-Chemical-Biological Evolution of Rock Masses:* To examine the evolution of the mechanical, transport and reactive properties of rock masses at a variety of spatial and temporal scales and a range of imposed and natural temperature gradients. The proposed facility will simulate subsurface hydrothermal systems to improve understanding of important process-feedbacks and support the development

[1] Major Research Equipment Facilities and Construction

of the next generation of computer models of such coupled processes.

- *The Ecohydrology of Deep Fractured Rocks:* To examine the complex interactions between state of stress of the crust, fluid flow through fractures, energy generation and transmission and microbial activity, distribution and evolution. The proposed distributed facility will provide the basis for development of a multi-scale model of the crustal biosphere that can be applied to the continental and, with some modifications, to the marine crust and will probe the upper temperature limit of microbial life in the crust.
- *The Mechanics of Cavern Design:* To explore spatial and temporal characteristics of rock masses which affect the uncertainty and risk in the construction of large underground excavations at depth. The proposed facility will be designed around the large caverns and other underground openings at DUSEL to provide novel models that integrate rock mass characterization, scale effects, performance and risk for the design of underground geostructures.
- *The Study of Fracture Processes:* To examine mechanisms of rupture and the evolution of faults in brittle fractured rock, the thermal and geochemical processes associated with rock rupture and how the latter processes impact microbial activity. The proposed facilities will be designed to nucleate new faults in intact rock at scales of 1-10m, and they will create dynamic slip along a large existing fault recently discovered along the western side of DUSEL.
- *Subsurface Imaging and Sensing:* To develop methods for the improved 4D imaging of the subsurface. Associated with each of the experiments will be a multi-disciplinary program of geophysical imaging of large, well-characterized rock volumes as they are being perturbed during the course of the proposed experimental investigations.

Together, this suite of experiments takes advantage of the observational window provided by DUSEL to peer into the complex processes and their interactions that shape the dynamic Earth. This improved understanding will enable us to better harness the subsurface for sustainable uses.

Summary Details of 2010 PDR Rollout [agenda] – Online resources in blue.
BGE Science@DUSEL
BGE Grand Challenges
Presentation videos

Recent High-Level Community Introductions to DUSEL
2006 Deep Science Report
2004 NSF-Earthlab Report
2003 NSF-ARMA Report

Recent Community Workshops [summary]
2010 DURA Annual Meeting and PDR Rollout
2009 Science – Workshop and Development of the MREFC
2008 DUSEL Workshop – Towards an Integrated Suite of Experiments

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1. Introduction

The need for underground research laboratories (URLs) to illuminate our contemporary understanding in biology, geoscience and engineering dates back to the 1970s when the Stripa Project addressed the scientific basis for the safe underground disposal of radioactive waste. The many URLs that developed worldwide were in support of deep geological disposal[2] as a preferred long-term option. These many URLs conducted research targeted at this central question – the safe isolation of long-lived and hazardous transuranic waste. Over the intervening decades, these laboratories have made a major contribution to our understanding of engineered and natural processes in the shallow crust.

The current DUSEL initiative began in 2000 when the Homestake Gold Mine announced plans for closure. This has led to a series of studies and publications that describe in general terms how an underground science and engineering laboratory established for the physics community would also benefit Earth sciences and other disciplines. A nascent community of biologists, geoscientists and engineers with common interest in experimentation in the subsurface has evolved. This community has defined the contribution that a dedicated, deep, long-term laboratory may make to contemporary understanding of the dynamics of the shallow crust. These potential contributions are discussed here.

Attributes of DUSEL that have been identified as being particularly attractive for research in biology, geosciences and engineering include:

- Existing drifts in the facility that will potentially provide access to a large underground volume, both horizontally and to great depths. The depth and working volume are both much greater than in existing URLs in other countries. The depth is because the physics experiments require greater shielding for the next generation of high sensitivity detectors for dark matter and double β decay experiments.

    - Access to great depth facilitates experiments that both probe the limits of life at elevated temperatures and explore the role of elevated in situ stresses on the aseismic and seismic fracturing of rock.

    - Access to the large volume of rock facilitates experiments that probe the heterogeneous and multi-scale properties that influence complex interactions of deformation, reaction, transformation and transport in brittle rock.

- The physics experiments being designed for DUSEL all require decades of observational time. This long-term access enables experiments that may explore transformations in reaction and transport properties that occur within the subsurface over months to years to decades. Essentially DUSEL will provide the earth science community a 4-D observatory of crustal processes.

- The Long Baseline Neutrino Experiment will require the construction of 60m tall × 60m diameter chambers at 4850’ depth to house the water Cherenkov detectors. The construction of such large cavities at such great depth represents a unique opportunity for the rock mechanics community to study what factors affect rock strength at large spatial scales and over decadal time scales.

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[2] NAS 1957. *The Disposal of Radioactive Wastes on Land, A Report of the Committee on Waste Disposal*. Publication 519, Division of Earth Sciences, National Academy of Sciences.

- The ~20^{o}C/km thermal gradient means that for the deepest levels of DUSEL at 2.3 km depth the formation temperatures are ~55^{o}C, which roughly corresponds to the lower temperature range for thermophilic microorganisms. The upper temperature limit of known life, ~120^{o}C, and the maximum reported temperature of *in situ* subsurface microbial activity, ~80-85^{o}C, are readily accessible through subsurface drilling. DUSEL, therefore, provides an unprecedented opportunity for the microbiology community to probe the bottom of the biosphere and to define the factors which ultimately limit the depth of colonization by life.

- The Facility for Assay and Acquisition of low Radiation Materials, FAARM, low background counting facility being planned for the 4850' level of DUSEL will provide large volume, high sensitivity, α, β and γ detectors that would significantly enhance the ability to measure cosmogenic isotopes, e.g. ^{39}Ar, ^{85}Kr, ^{137}Cs and ^{210}Pb, that are important to the hydrological and environmental geochemistry communities. These same detectors would also prove essential for detection of ultra-low level metabolites formed from radio-labeled substrates by microbial activity in the proposed BGE experiments.

- The mixture of Precambrian metamorphic and Tertiary igneous rock units traversed by DUSEL here means that the BGE experiments can be performed within rock units of varying strength, fracture density and mineralogy. Different to many URLs, DUSEL accesses cratonic crust typical of the roots of many continents and provides a unique window into this geologic setting.

- The proposed experimental activities are informed by a wealth of scientific data and interpretations of hydrology, geology and geochemistry stemming from the rich 125 year history of the former Homestake mine. Fortuitously, the mixed sequence of dewatering, inundation and current dewatering provide an active environmental loading to the entire laboratory that is useful in probing the interactions of deformation, transport and reaction at scales from meters to kilometers.

The subsurface-science community has been developing plans for such a facility over the last decade. Since summer 2009, projects selected in response to an NSF solicitation (the S4 solicitation) have been developing plans for experiments that may comprise the integrated suite of experiments to be incorporated into any potential DUSEL. These activities involve developing and articulating the science case for such investigations together with defining the scope, experimental details and synergies between various experiments. These studies are currently (November 2010) at full tempo and the preliminary results will be incorporated into an NSF-MREFC[3] proposal anticipated to go before NSF's National Science Board in early- to mid-2011.

This document summarizes the science motivation of the seven science efforts in biology, geoscience and engineering currently funded by NSF as an indication of potential scope of inquiry at DUSEL.

[3] Major Research Equipment Facilities and Construction

2. The Scope of Science Inquiry at DUSEL

The range of science inquiry possible at DUSEL has been explored in a variety of recent reports. These community reports include EarthLab[4] and Deep Science,[5] among others.[6] The suggested general fields of inquiry that might be undertaken in a multi-disciplinary underground laboratory include:

2.1 Carbon Sequestration

Understanding the fate and transport of gaseous and liquid CO_2 sequestered in deep reservoirs is an important contemporary issue with many unresolved scientific questions. Important questions relate to mechanisms of transport and transformations of CO_2 both as an immiscible supercritical fluid and as a dissolved phase, and their interactions with the host reservoir. These interactions are significant and appear important in systems pushed far from chemical and mechanical equilibrium with the injection of a corrosive phase under relatively high over-pressures. Under these conditions the transformations of strength and transport properties may be extreme and averse to containing the injectate over decades to centuries. DUSEL offers the potential to examine these important transformations at intermediate scales – larger than laboratory scale where the material may not be representative of large-scale conditions and towards field scale where current demonstration projects are not well constrained due to imperfect access and observation at the injections zone.

2.2 Fluid Flow and State of Stress

The ability to determine the state of stress and stress history for a large mass of rock such as that represented in DUSEL and relating it to fluid flow to great depth will enable for the first time to test the hypothesis that critically stressed fractures are highly conductive. It is anticipated that new methods for the determination of *in situ* stresses and their relationships to the strain history of the rock will be developed through underground investigations, allowing for additional insights on how faults slip and large subsurface excavations deform.

2.3 Thermal, Hydraulic, Mechanical, Chemical, and Biological Coupling

Complex interactions of thermal, hydraulic, mechanical, chemical, and biological effects (THMCB) control the flow of fluids, energy and nutrients in the fractured subsurface. These processes are stress, temperature, and scale dependent. However they remain poorly understood, particularly in complex fractured rock, and at large scales. Some of the more important lines of investigation to be addressed in this type of laboratory include determination of the thermal and chemical conditions under which fluid-conducting fractures open or seal with net dissolution, and whether rates are accelerated or retarded in the presence of microbial colonization. DUSEL will also provide constraints on the validity of predictions of transport rates and breakthrough behavior with changes in test scale.

[4] McPherson, B.J., Elsworth, D., Fairhurst, C., Kessler, S., Onstott, T..C., Roggenthen, W., and Wang, H. EarthLab Steering Committee. EarthLab: A Subterranean Laboratory and Observatory to Study Microbial Life, Fluid Flow, and Rock Deformation, Geosciences Professional Services, Inc., June 2003, 64 pp. [pdf]

[5] http://www.deepscience.org/

[6] Elsworth, D. and Fairhurst, C. Engineering Research Opportunities in the Subsurface: Geo-Hydrology and Geo-Mechanics. Summary Report to NSF on the proposed National Underground Science and Engineering Laboratory (NUSEL). May, 2003. [pdf]

2.4 Deep Ecohydrology

Access to the deep subsurface environment and the acquisition of biologically uncompromised samples are important to develop an understanding of the *in situ* relationships between subsurface microbial ecosystems and the geochemical and hydro-geological processes that control their growth, function, and mobility. Important scientific questions that could be answered in DUSEL encompass issues of subsurface microbial ecology and bio-geochemical processes. The limits, evolution, migration and adaptation of life in the subsurface can be addressed in the DUSEL laboratory in ways that currently are not easily accomplished elsewhere. The response of microbial communities to variations in nutrient and energy sources as well as their interaction with the hydrologic system can be facilitated by the presence of this laboratory. One of the more ambitious possibilities would be to investigate the character of life as a function of depth, through drilling even deeper than the extent of the present workings. These lines of investigation represent an opportunity to investigate the interactions and relationships between the biological systems and the hydrology with regard to both past and present systems.

2.5 Design and Construction of Underground Structures

The current DUSEL design provides for the construction of several large excavations at depths that vary from 1.5 km (4850 ft) below the surface to 2.25 km (7400 ft) below the surface. This ensures that a wide range of stresses will be encountered during the construction of excavations with spans of 55 m or more. Design and construction of these excavations constitutes a important opportunity to advance the state of knowledge regarding underground construction and design, which is predicted to be of even greater societal interest in the future. Therefore, it will be important to ensure that the process of constructing DUSEL is coordinated with the research interests. Such coordination will advance the scientific and engineering body of knowledge but also has the possibility of improving the construction process itself.

2.6 Fracture Processes

Fracturing of rock is an important process associated with rocks. It affects the mechanical strength of rock and influences fluid movement through the rock. Fracture processes are also important in the generation and propagation of earthquakes and influence the recovery of resources such as hydrocarbons. Fracturing is manifested over a range of scales from the microscopic to large, pervasive regional fracture systems. To date our most sophisticated characterizations of fracture networks in the subsurface typically involve extrapolating information gained from surface exposures, borehole observations, and inferences drawn from geophysical data. Subsurface access to a well-exposed, extensive, 3-D rock mass will make tremendous contributions to our understanding of fractures in rock. The development of dedicated laboratories investigating how fractures are initiated in four dimensions should shed light on the mechanisms and geometries of fracture initiation and propagation.

2.7 Deep Observatory Geophysical Imaging

Geophysical systems in the underground laboratory have the potential to improve our understanding of the response of rock to several stimuli, including seismic and electromagnetic signals. These include improvements that would result from the installation of three-dimensional arrays as well as those expected as adjuncts in the monitoring of the processes occurring in the dedicated laboratories. A single geophysical station samples the ground motion in time, but an array of stations can sample ground motion in both time and space. This means that it is possible to determine both the time that a signal arrives and the direction in which it is traveling. The array can be aimed, much like a telescope, to look in a particular direction. Furthermore, the availability of data from an array makes possible a wide variety of signal processing and signal enhancement methods that are not options with data from a single station. Depending upon the spatial coherence of signal and noise, these array-processing methods can greatly increase the signal-to-noise ratio of seismic data. The presence of both a vertical array, which is never possible with a surface installation, and a horizontal array, further expands the variety of processing methods that can be used.

2.8 Origin of Mineral Deposits

The Homestake Gold Mine was a prolific producer of precious metals for over 120 years. The means by which metals are concentrated sufficiently to become ore deposits is of great importance and has been the focus of both science and practical exploration throughout history. Many mineral deposits were formed by circulating hydrothermal solutions that change the composition of the rocks through which they migrate, either at or near the time of formation of the host rock or later through the development of fracture systems. Although we are now confident that we understand many of the ore-forming processes, important questions remain. These include developing a clearer picture of the source of hydrothermal solutions that form deposits, the influence of meteoric water as opposed to magmatic or metamorphic waters, and the importance of the contribution of metals from the country rock as compared to original magmas. The three-dimensional access at DUSEL coupled with the vast array of information that will be derived from the other biological and geological investigations offers the prospect of significant contributions in this area.

3. Proposed BGE Experiments at DUSEL – bge science@DUSEL

The Earth-science collaborations in hydrology, geochemistry, geophysics, rock mechanics, ecology/geomicrobiology, and coupled processes have evolved since 2000. There are now seven groups that are developing S-4 proposals seeking to establish research facilities within the DUSEL footprint, to investigate geologic processes and life, and how they interact in the deep subsurface environment. In this section we provide a brief overview of the science that will be addressed by each of these collaborations and the types of requirements that will be expected from DUSEL.

3.1 Facility for the Study of Geologic Carbon Sequestration

3.1.1. Scientific motivation

Geologic carbon sequestration (GCS) is part of the Carbon dioxide Capture and Storage (CCS) process in which CO_2 is injected into deep geologic formations. This strategy is currently being evaluated to help mitigate climate change caused by fossil fuel-based energy sources that currently emit approximately 30 Gt CO_2 per year. This approach to long-term climate-change mitigation will be successful only if the injected CO_2 remains in the intended storage regions. Because of the lower density of CO_2 at all conditions in deep subsurface reservoirs, there is a tendency for injected CO_2 to leak upward out of intended storage reservoirs. Leaked CO_2 could pose environmental hazards, impact subsurface resources, or discharge into the atmosphere negating the climate-change mitigation objective and causing potential loss of carbon storage credit. Advancement of GCS requires a sound understanding of the processes controlling CO_2 storage, trapping, and migration in the subsurface environment.

Vertical flow of CO_2 under subsurface conditions is a poorly understood process because it is inherently difficult to study at realistic length scales. At the sub-millimeter scale, capillary processes govern two-phase flow in porous media, while at the kilometer scale gradients in temperature and pressure drive changes in CO_2 buoyancy. The present understanding of vertical CO_2 flow derives from theoretical simulations, which have a large range of plausible scenarios. To date, small-scale CO_2 injection demonstrations have been conducted in the field under near-optimal conditions. There has been no experience with potential leaks within the sealing caprock, which would permit supercritical CO_2 to migrate upwards and change to gaseous CO_2, with a resulting shift in density and buoyancy.

3.1.2. Overview of proposed research facility

The proposal is to build a deep underground experimental facility to study the vertical flow of CO_2 over length scales that include the supercritical to gaseous transition and through porous media that mimic deep sedimentary formations. The facility is being designed to include three pressure vessels each with a length of 500 m and a diameter of 1 m. The vessels will be supported within a 3m x 3m vertical shaft. The vessels will have an inner column that will be used for monitoring sensors (similar to a monitoring well), and the annular space between this column and the outer vessel walls will be filled with brine and sand or other relevant geological material that mimics the strata encountered in sedimentary basins prior to CO_2 injection. Thermal and pressure gradients along the length of the columns will mimic real subsurface conditions.

At DUSEL, the new vertical shaft will be located ~150 m from the Ross Shaft and will extend from the land surface down to the 1700‘L (Figure 3.1.1). Key to the experimental design is the ability to make measurements and sample fluids along the length of the flow columns. Thus, it is essential that we have access to the vessels at intermediate points between the top and bottom. The location of the shaft was selected with this in mind. Intermediate access will be possible from the 300‘L, 800‘L, 1250‘L, 1400‘L, and 1550‘L. At these levels, new excavations will connect existing drifts with the new shaft. In addition, access to the columns will be possible from an Alimak vertical transporter, which will climb and descend along a track attached to the wall of the shaft.

The columns will be highly instrumented to allow unprecedented monitoring of the governing thermal, physical, and chemical processes. Each vessel will have an inner fluid-filled tube with a diameter of 25 cm serving as a proxy well to accommodate a variety of existing well-logging technologies. For example, a combinable nuclear magnetic resonance tool will be used to discriminate between water and CO_2-filled pores; similar measurements will be conducted using a reservoir saturation tool. Sonic (1-20 kHz) and ultrasonic (100s of kHz) tools will also be used to image fluids, using differences in acoustic impedance to distinguish liquid from gas phases. These measurements will be used to construct a vertical saturation profile, and to determine how it changes over time as the CO_2 plume moves upwards. Distributed temperature and pressure sensors will also be deployed outside of the inner tube to provide continuous in situ data. The various data and interpretations from the suite of technologies deployed during the experiments will collectively be used to develop a better understanding of CO_2 migration and trapping processes over realistic vertical length scales, and to calibrate models that predict the vertical flow of CO_2 and brine in porous media, and to compare the spatial resolution and sensitivity of different monitoring tools.

A final design could be completed by mid-2012. Assuming funding availability for construction, the work on the surface building and site could begin then, and be completed in six months. The next step would be the excavations, which would take six months to complete. This could start after the refurbishment of the Ross Shaft. After the excavations, the remaining procurement, fabrication and assembly of the CO_2 experimental facility would take two years.

3.1.3. Proposed experimental investigations

The proposed facility will test critical hypotheses needed to understand CO_2 vertical flow in the deep subsurface. As part of the suite of experiments, the plan is to simulate a leak in which CO_2 changes from a supercritical fluid to a subcritical gas as it flows up the column. The acceleration in CO_2 flow due to increasing buoyancy will be measured, and the extent to which this acceleration is mitigated by Joule-Thomson cooling determined. Buoyant rise of CO_2 could also be mitigated if it substantially dissolves in brine or gets left behind as small gas bubbles that are trapped by capillary forces. In other experiments involving rock matrices and well cements, CO_2-water-rock interactions will be examined, and it will be determine whether CO_2 will enlarge flow pathways (mineral dissolution) or cause self-sealing (mineral precipitation). Finally, the effects of anaerobic, thermophilic bacteria on CO_2 conversion to methane and carbonate will also be investigated.

3.1.4. Uniqueness of proposed facility

The Laboratory for Underground Carbon Investigations (LUCI) will be the only deep underground laboratory for controlled study of geologic carbon sequestration in the world. The findings from this unique experimental facility will advance carbon management technology worldwide and help reduce global greenhouse gas emissions.

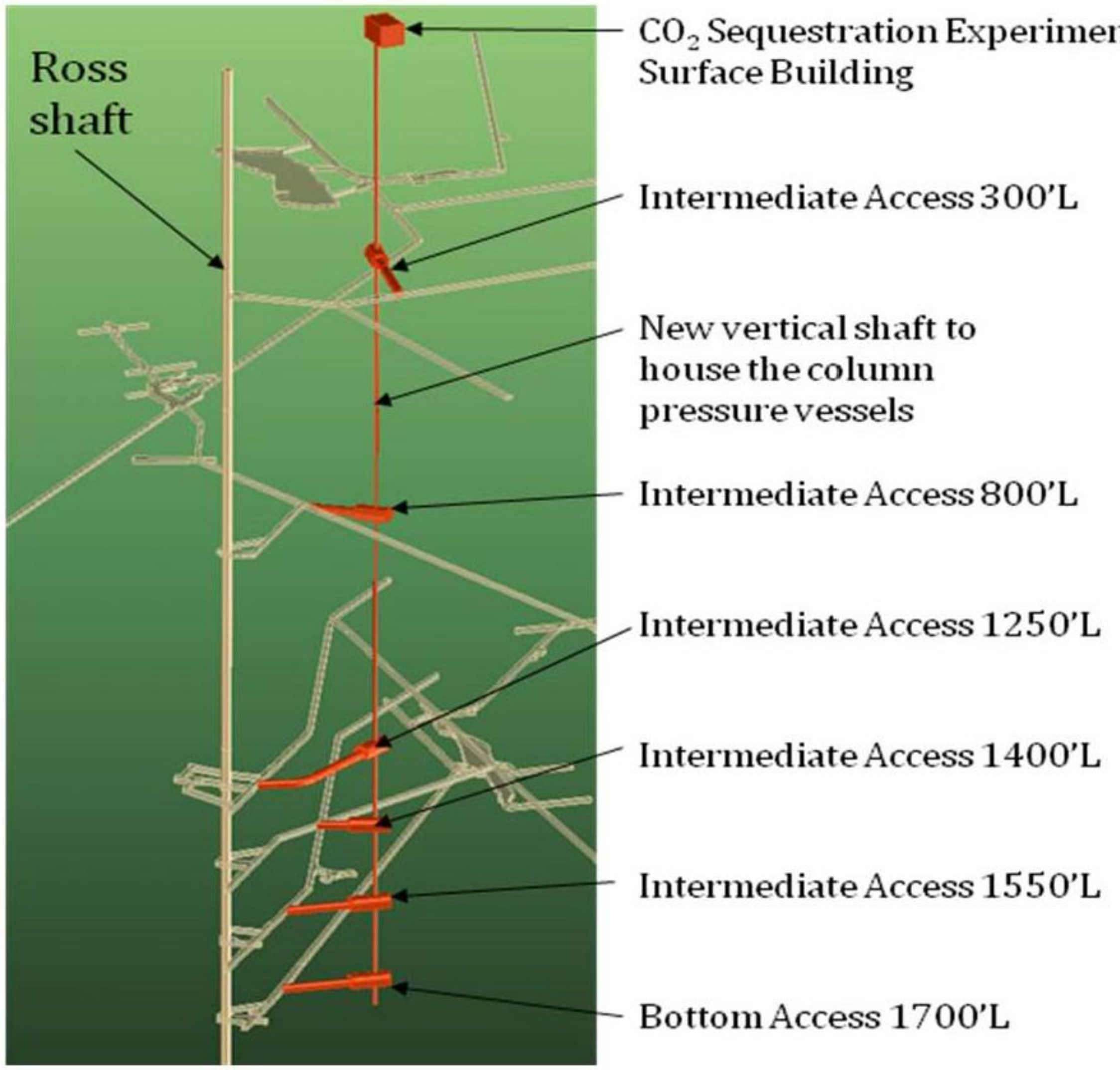

Figure 3.1.1. Proposed layout of the CO_2 Sequestration Facility at DUSEL

3.2. Facility for Monitoring Deformation of Large Underground Rock Masses

3.2.1. Scientific Motivation

Societal infrastructure on the surface or underground is affected by multi-scale deformations from the sudden dislocation of an earthquake to earth tides to the slow accumulation of strain from mine dewatering. The subsurface rock mass is a complex material that is both heterogeneous and anisotropic. The overarching problem is to predict how the rock mass responds to different forces. The large-array, deformation and temperature monitoring experiment is designed to address several key questions about rock-mass behavior.

- How does strain and pore pressure vary in scale from borehole to tunnel to regional geology?
- How are stress state and strength related to geologic heterogeneity, fracture geometry, the presence of fluids, and rock anisotropy?
- How do the fracture network, stress state, and constitutive properties affect the stability of tunnels, shafts, wellbores, and large, room-sized excavations?

The objectives of a facility-scale deformation monitoring array are to advance (1) the understanding of rock deformation over multiple scales of length and time; (2) test technology for characterizing rock deformation; and (3) test technology of underground structural health monitoring (SHM).

3.2.2. Overview of Proposed Research Facility

A central component of the effort is to develop and use fiber-optic sensors, which have been used in commercial applications over the last 15 years. The reason for using fiber-optic methods for measuring deformation lies in cost and efficiency advantages for deployments over kilometers in length, long-term stability, flexibility of incorporating many types of sensors on a single data acquisition cable, and a future promise for the methods becoming even better, cheaper, and faster. The fiber-optic network will be supplemented with long baseline tiltmeters and borehole extensometers to improve the three-dimensional picture.

Fiber Bragg Grating (FBG) and Distributed Strain and Temperature (DST) sensors and water-level tiltmeters will be installed at multiple levels between the 2000-ft and 7400-ft levels, including cavities and drifts adjacent to planned physics laboratories. At each level, fiber-optic sensors will provide measurements from the sub-meter scale to spans exceeding one kilometer. The tiltmeter arrays will provide deformation measurements sensitive to solid-earth tides, over length scales between 30 and 1000 meters. Temperature-sensing fibers will be placed in winzes down to 8000-ft depth, in shorter-length boreholes, and along drift walls to monitor water inflows and air movement.

This effort will result in the world‘s largest and deepest underground network of fiber-optic strain and temperature sensors and tiltmeters. It will contribute to several other scientific collaborations, including large-cavity design, ecohydrology, induced fractures laboratory, coupled processes laboratory, transparent earth, and carbon sequestration.

3.2.3. Proposed experimental investigations

The measurement of rock-mass properties over many spatial and temporal scales requires sensors and instruments that are embedded and stable. The deformation monitoring array will utilize sensors overlapping in their spatial coverage and will consist of different fiber-optic sensors, long-baseline tiltmeters, and borehole tiltmeters. Different embedding technologies will be utilized, including pliable rock strain strips and instrumented rock bolts and cable bolts. A particular difficulty is to develop embedding technologies for distributed fiber-optic deformation sensing. The sensing array will take advantage of deformations induced by natural forces such as earth tides and distant earthquakes as well as by the dewatering of the mine and by new construction within the laboratory. In addition, active experiments on the scale of several meters will be performed using different types of jacks and fluid injection.

3.2.4. Uniqueness of proposed facility

Induced (dewatering, drift and cavity construction) and natural (self weight, earth tides, seismicity) loading observed in the 8000-ft deep Homestake Mine in Lead, SD present a unique opportunity to address questions regarding the mechanical and hydrologic response of rock masses at spatial scales ranging from centimeters to hundreds of meters and temporal scales ranging from milliseconds to decades. Large-scale deployment of fiber-optic sensors appears to be an ideal technology for multi-spatial and multi-temporal measurements of rock-mass response to loading.

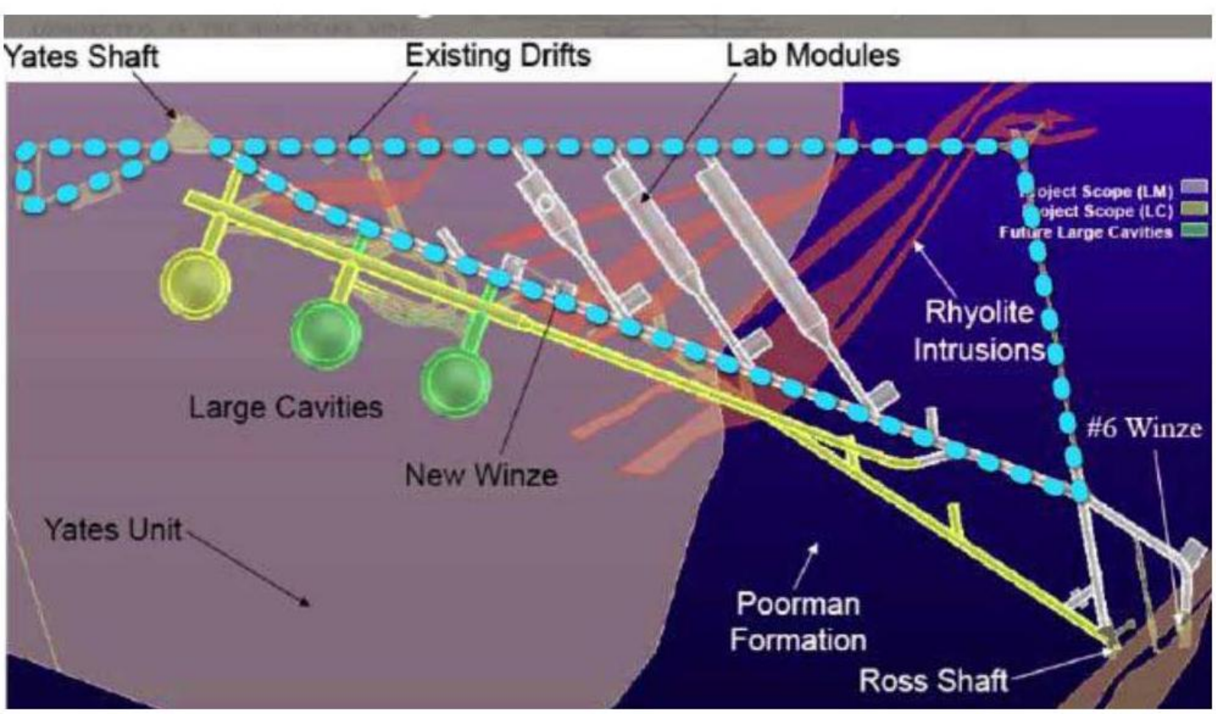

Figure 3.2.1. Blue dots show layout of Distributed Strain and Temperature (DST) fiber-optic sensor wrapping pillars surrounding physics lab modules.

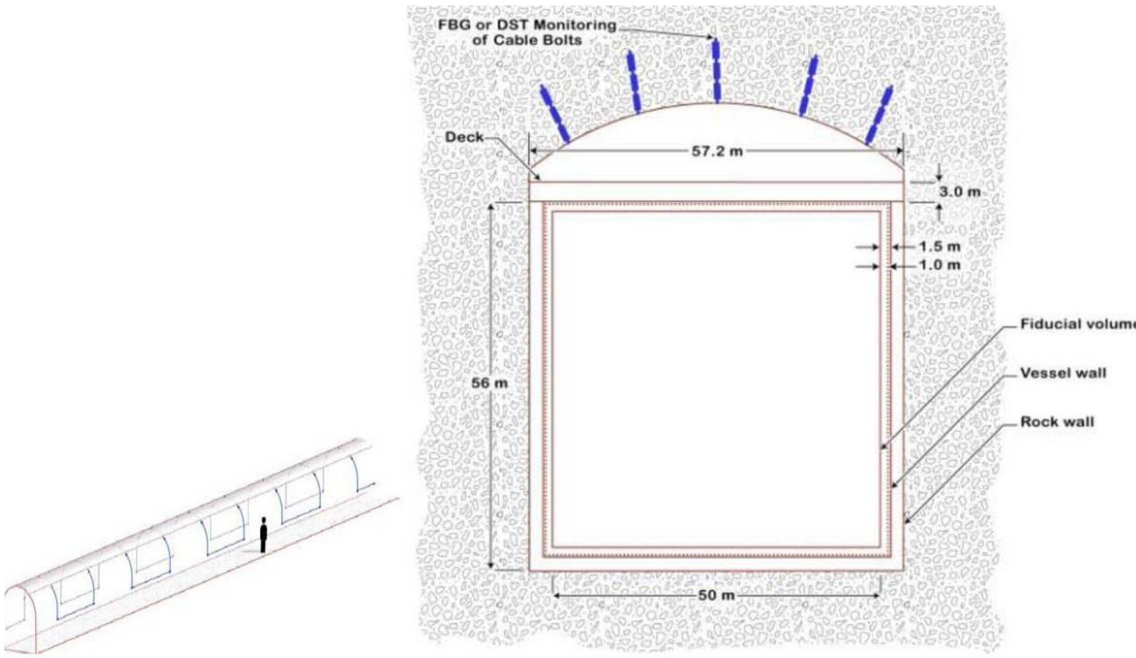

Figure 3.2.2. (Left) Example geometry of DST fiber-optic cable layout within a drift along the dotted lines in Figure 3.2.1. Individual segments of DST will capture deformation at the meter-scale while the entire array will capture deformation at the kilometer-scale. (Right) Extensometers fitted with Fiber-Bragg Grating (FBG) sensing elements to monitor long-term stability.

3.3. Facility for Studying Coupled Thermal-Hydrological-Mechanical-Chemical-Biological Processes (THMCB)

3.3.1. Scientific motivation

Most natural and engineered earth system processes involve strong coupling of thermal, chemical, mechanical, and sometimes biological processes in rocks that are heterogeneous at a wide range of spatial scales. One of the most pervasive processes in the Earth's crust is that of fluids (primarily water, but also CO_2, hydrocarbons, volcanic gases, etc.) flowing through fractured heated rock under stress. Although rocks and fluids can sometimes be analyzed for physical and chemical properties, it is very difficult to create quantitative numerical models based on fundamental physics and chemistry that capture the dynamic changes that have or will take place. Initial conditions and history are only known roughly at best, and the boundary conditions have likely varied over time as well. Processes, such as multi-component chemical and thermal diffusion, multiphase fluid transport, and thermal stressing, are taking place simultaneously in rocks that are structurally and chemically complex—heterogeneous assemblages of mineral grains, pores, and fractures—and visually opaque.

3.3.2. Overview of proposed research facility

The purpose of the DUSEL THMCB experimental facility will be to investigate a range of natural and engineered processes by creating a volume of heated rock and fluid which will be instrumented with sensors (mechanical, thermal, hydraulic) and ports for collecting fluid samples (chemical, biological) as a function of space, time and temperature. It is expected that observation/measurement boreholes will be sited that traverse different regions of the heated rock, which are packed-off to isolate a particular fracture or fracture set, into which fluids, gases, or nutrients can be injected to perturb the local THMCB environment. Monitoring ports may be sited along a fracture to capture fluids that have been injected elsewhere along the same fracture. In addition to geochemical and isotopic (stable and radiogenic) analyses on sampled fluids, gases and solids, state-of-the-art in-situ sampling and monitoring sensors will be employed. The experiments performed at the THMCB facility at DUSEL would be carried out in a phased approach. The working group team, with external input and peer review, will refine the necessary initial data, experiments and modeling that should be performed, prior to starting the in-situ experiments.

3.3.3. Proposed experimental investigations

The transport and interaction of fluids, heat and chemical reactants within a stressed geologic host results in complex feedbacks at a variety of length and time scales. These interactions produce patterns of reaction and mineral redistribution that in turn modify porosity and permeability and are strongly scale dependent. Well-controlled injection/extraction experiments in particular regions of the heated block can be interrogated by in-situ probes and sampling, with supporting laboratory experiments, isotopic and (bio)geochemical measurements, and reactive transport modeling. This experiment proposes to address a variety of questions related to these interactions. These include:

- What are the effective reaction rates between minerals and fluids in fractured rock, and how are they controlled by the evolution of the fracture-fluid interface as a function of reaction progress?
- How does the chemistry of fluids and minerals affect the mechanical behavior of fractures, sealing and permeability evolution under stress?

- At what rates under specific flow and temperature conditions are metals and ionized complexes mobilized through water rock interaction, transported, and concentrated through sorption and/or mineral precipitation (relevant to ore deposition and contaminant transport/immobilization)?
- How do microbiological communities in rocks evolve and migrate in fractured rock undergoing changes in temperature and geochemical environment?
- How does mineralogical and permeability heterogeneity at small scales affect the composition of fluids at a larger scale and how can the effective reaction rates be interpreted from the fluid compositions?

3.3.4. Uniqueness of proposed facility

A large-scale THMCB experimental facility at depth (4850‘ to 7400‘) would allow researchers to quantitatively probe the range of coupled THMCB processes taking place at the pore-scale, in meter-scale fractures, within decimeter-scale fluid flow and convection regimes, for time periods of several to tens of years. As these depths, lithostatic pressures are significantly greater than in any other experiments. The metamorphic mineral assemblages making up the rocks are very different from the rhyolitic tuffs and granites that have been the host rock of other heater tests. The rocks have much greater anisotropy and are considerably more chemically and structurally heterogeneous. The Fe-rich carbonates and mafic silicate minerals have typically higher dissolution rates than quartz and feldspars in granitic rocks and devitrified tuff. Reaction-rates are also highly dependent on reactive surface areas, which in turn are a function of the hierarchical scale of fluid flow, geologic structure and mineral fabric. Hence, the well-developed metamorphic fabric of the Homestake iron formation and the adjacent lithologies would provide a unique system in which to monitor directional fluid flow and reaction-transport processes under a well-controlled thermal environment. The abundance of ore minerals is an added benefit for the study of the transport, precipitation, and sorption of metals under variable temperature conditions and in fractured rock.

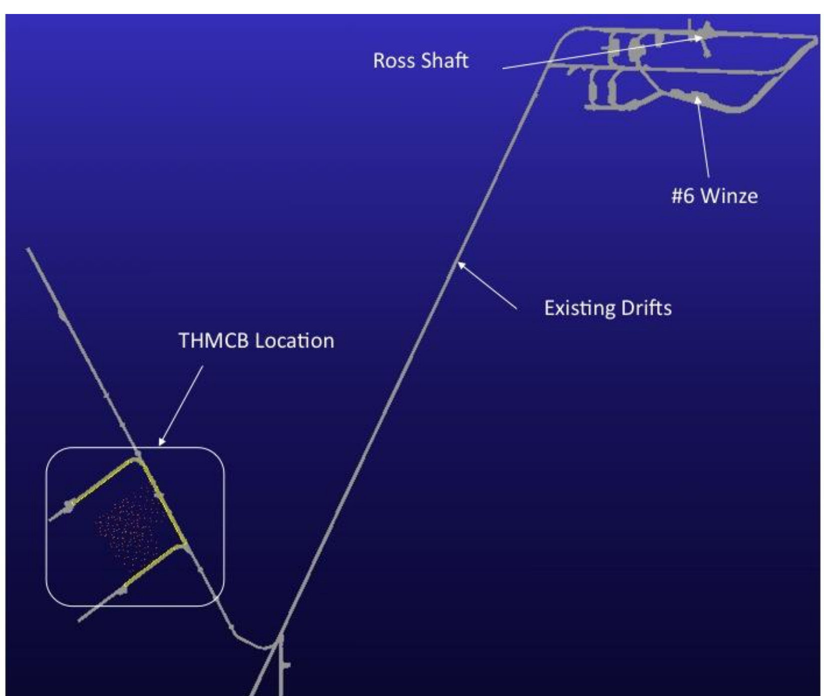

Figure 3.3.1. Layout of THMCB test block relative to the main campus at the 4850L.

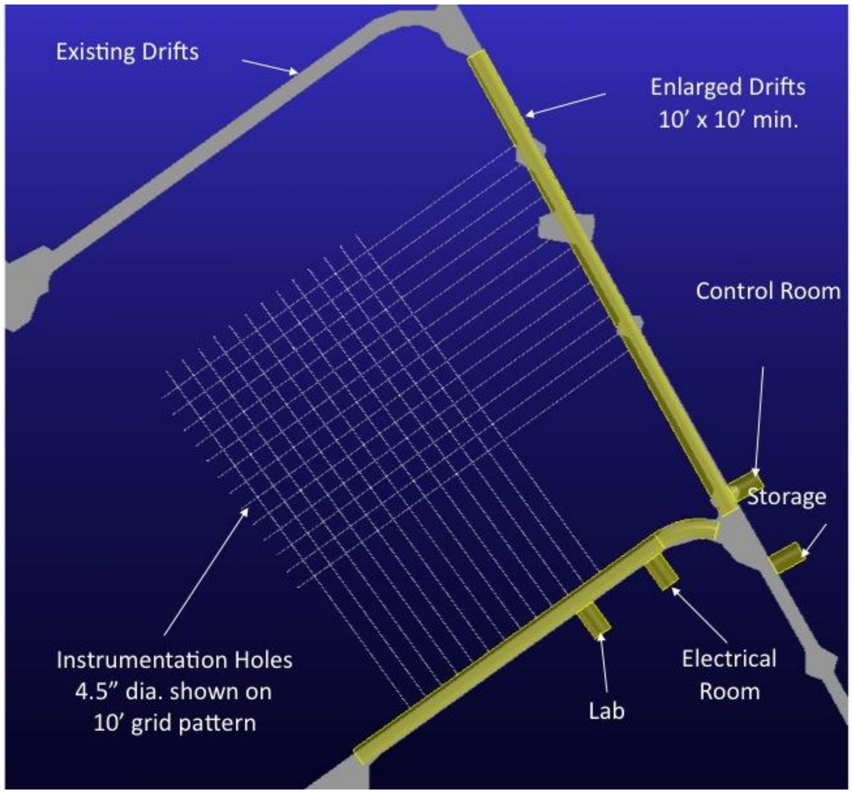

Figure 3.3.2. Plan detail of the THMCB test block showing encircling drift and heater and instrumentation holes.

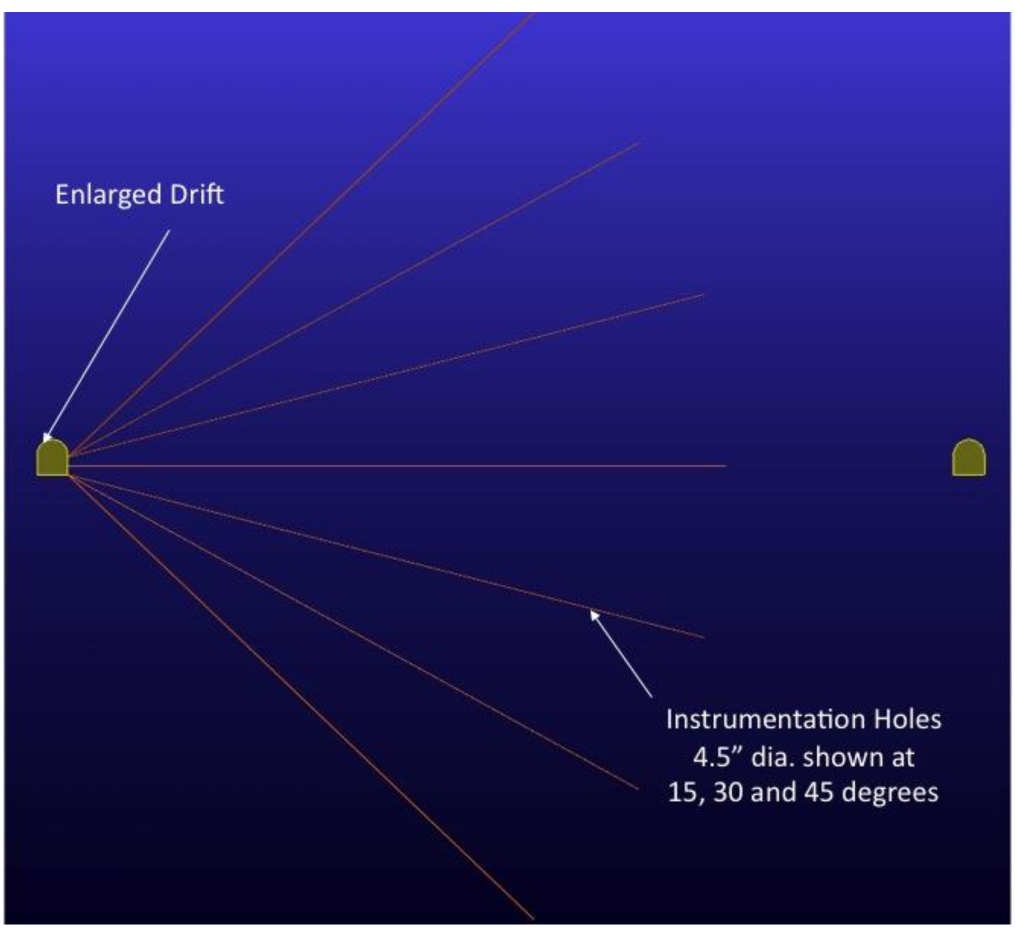

Figure 3.3.3. Side-view detail of the THMCB test block showing heater and instrumentation holes.

3.4. Facility for Ecohydrologic Studies of Deep Fractured Rocks

3.4.1. Scientific motivation

Despite the fact that the deep subsurface harbors a significant fraction of the living carbon on our planet it is the most poorly understood ecosystem. The last frontier of ecosystem discovery on our planet lies within the vast unexplored inner space of the crust. Portals into this unknown province have occasionally been opened at various sites worldwide in recent years, revealing the existence of alternate biospheres, which operate with indifference to the well-worn paradigms of surface and marine ecological thought. The unprecedented assemblage of complementary sciences focused on an intact three dimensional space at DUSEL for a prolonged observational time-scale represents an historic opportunity for the controlled exploration of a novel rock-hosted ecosystem that spans the subsurface biosphere from its top at the base of the photosphere to its bottom at the abiotic fringe.

The deep subsurface has recently been recognized as an ecosystem that can profoundly influence the way the origin and early evolution of life on Earth is viewed, and that can yield novel life forms and enzymes, and approaches to future energy production. The assumption here is that like surface ecosystems, deep subsurface ecosystems involve complex interactions between life and environmental processes, such as the transport and availability of chemicals and energy, and the extent and distribution of settings that provide suitable habitats. But the ecology of the deep subsurface has yet to be defined because it is much more difficult to make observations at depth than it is in the familiar surroundings of Earth‘s surface.

What is known about subsurface life initially came from a few specialized coring campaigns and mine studies which have revealed diverse, active, indigenous communities of microorganisms in deep subsurface terrestrial environments. However, these findings provide only snapshots of what exists at depth. How components of the ecosystem interact with each other and the time frame of these interactions are largely inferred, not directly observed.

3.4.2. Overview of proposed research facility

DUSEL will provide a platform for precise, systematic drilling into the biosphere of a deep continental environment where meteoric water flow is the primary mixing mechanism. With its unique experimental assets, kilometer-scale access in three dimensions and multi-decade observational lifetime, DUSEL will usher in the next generation of exploration into the deep terrestrial biosphere (Figure 3.4.1a) and provide an unprecedented in-situ laboratory for the development of detailed hydrologic and geomechanical conceptual models in a complex fractured host-rock.

The DUSEL facility will enable access to ground water of diverse ages, according to modeling studies (Figure 3.4.1b). On the south side, water flows quickly downward from the surface to 1 km depth in less than a year. Water reaching the lower depths of the north side of the mine emanates from rock pores and may be millions of years old. The potential capture footprint extends outward from current mine workings for kilometers and could provide access to about 100 km^3 volume for hydrologic, geomechanical, and microbial biogeographic studies (purple zone, Figure 3.4.1b).

Large diameter boreholes can be extended an additional 2-3 km from existing infrastructure at the 7400‘ level, where the virgin rock temperature is 55°C, to reach the 121°C isotherm and explore the upper temperature limit of life. Beyond their use for fluid withdrawal, the boreholes will become experimental stations for conducting in situ transcriptomic and proteomic experiments with Mobile Underground Laboratories (MULes), push-pull experiments within the packer-sealed fractures themselves, and cross-borehole experiments (hydraulic, geophysical, and geomechanical) using multi-level packers and induced fluid flow.

The facility will consist of a series of distributed boreholes drilled/cored sequentially from the surface to ~5 km depth. Drill site locations have been selected to allow multiple boreholes that will interrogate large volumes of minimally-impacted fractured rock in generally north and south directions from the former mine. Cavities, designed to require minimal expansion of existing drifts, will accommodate a drill rig and associated supplies plus drilling plant. Scheduled activities at each site will be mobilization, drilling/coring (1-2 months of ~10 people on site, longer at the deepest site), installation of instrumentation, demobilization, and long-term experimentation and monitoring (sporadic visits, months to years). Most sites will include a vertical borehole for in situ stress measurements linking ecohydrology to parallel investigations of stress and fracture processes. Coring will rely upon state-of-the art quality control procedures for geobiological sampling including a steam cleaning station for the drill rods, on site reverse osmosis filtration system for the drilling water, a single pass reverse flow system for the drilling water and multiple tracers for potential drilling contamination.

3.4.3. Proposed experimental investigations

The proposed investigations will be guided by the over-arching question: what controls the distribution and evolution of subsurface life? The hypothesis that is being tested is whether these controls are dominated by processes related to geology, geomechanics, and hydrology. The investigation will consist of field studies supported by numerical simulations. The experimental activities will include extending characterization efforts to great depths using deep drilling deployed from the lowest accessible reaches of the facility. The use of the flooding/dewatering event as a tracer, and the hydrologic and mechanical stressor is a theme that cuts across many of the experimental activities.

3.4.4. Uniqueness of proposed facility

DUSEL offers a unique opportunity for integrated geobiological research because of its enormous span of depth and because of the host formation is comprised of a diverse assemblage of minerals and rock compositions. Although groups in other countries are actively researching the subsurface, none has access to a deep, dedicated science facility. The only comparable effort in the terrestrial subsurface is the Äspö Hard Rock Laboratory beneath the east coast of Sweden, where microbial communities are being studied within fracture fluids. However, the Äspö lab extends to only 460 m depth and is hosted almost entirely by a single rock formation (granite). Working mines, e.g., the deep gold mines in South Africa, offer some access to deep fracture waters, but scientific study at these sites is severely constrained by mining activities and distance-related logistics. Other deep physics facilities, e.g., SNO Lab in Canada offer possibilities for geobiological studies, but they are not as deep. Drilling from a 7400 ft deep platform at DUSEL (deepest available in the U.S.) offers considerable cost savings over drilling from the surface and will significantly improve sample quality by providing clean drilling fluid. For example, drilling in the Taylorsville Triassic Basin to 2.8 km depth for scientific study required an enormous drill rig, cost millions of dollars for a single borehole, and the small-volume samples obtained were contaminated by drilling mud.

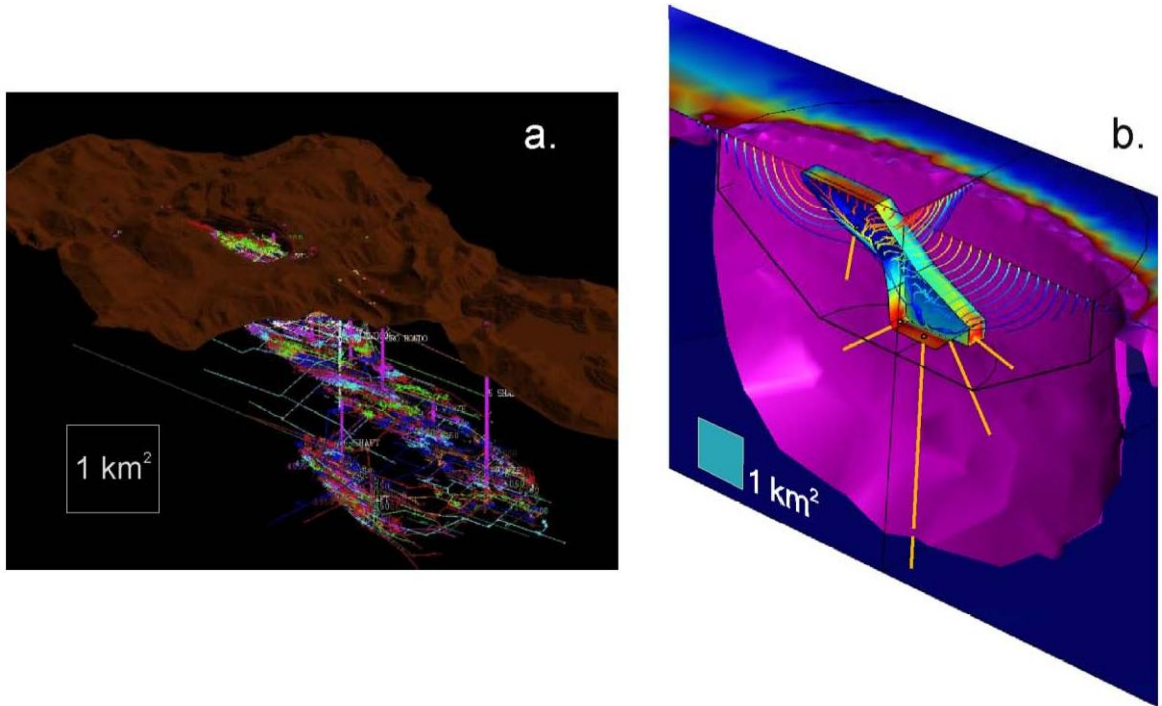

Figure 3.4.1. **a.** Perspective of surface relief and workings of the proposed DUSEL laboratory. **b.** Perspective of mine workings (polygonal areal at center of diagram) and vicinity showing simulated particle flow paths from surface to depth during the excavation period of the mine to present day. Color shading shows the water flux into the workings. The purple area bounds the region where groundwater has been captured by the mine, according to the simulation. Yellow lines identify the locations of potential cored boreholes for future microbiology and hydrology experiments.

3.5. Facility for Studying Cavern Design and Underground Construction

3.5.1. Scientific motivation

The science vision is to determine spatial and temporal characteristics and behavior of rock masses and to estimate the uncertainty and risk associated with large underground excavations. The experiments will benefit the design, construction, and long-term performance control of the cavern and other underground structures and through this will contribute to the safety, cost and completion of the DUSEL facility.

3.5.2. Overview of proposed research facility

Figure 3.5.1 shows some of the specific facilities required. Drift a will be used to conduct the rock characterization and novel construction technique work (experiments 1, 5)[7]. The drift will provide access for installing the monitoring instruments (experiment 2); a total of 100 borings are envisioned, in which inclinometers, extensometers, piezometers, accelerometers and geophones will be installed.

The drift will also provide access to the mine by experiments (experiment 3) and to the large mine pillar facility (experiment 4, Fig. 3.5.2) and allow one to install monitoring instrumentation for experiments 3 and 4.

Mine-by tunnels have a dual function: (1) observation of rock mass response during excavation of two tunnels of different size (a_1 and a_2 in Fig. 3.5.1); (2) rock characterization by sequential mapping of excavation slices. In the Large Mine Pillar facility (Fig. 3.5.2), a large pillar of rock is excavated and its cross section is gradually reduced until it is brought close to failure, while closely monitoring rock response. The disc-shaped regions are left intact and act as "loading platens" while the deformation response of the rock mass is monitored for evolving displacements and micro-seismic behavior as indicators of structural state.

3.5.3. Proposed experimental investigations

The experiments proposed involve large volumes of rock subjected to complex loading and include monitoring over extended periods of time. The experiment will integrate a number of closely related tests associated with the construction and performance of the large water Cherenkov cavern at the 4850 foot level. They are also relevant to other underground structures at DUSEL and elsewhere. The experiments include:

1. Assessment of the rock mass characteristics, specifically fracture patterns and fracture behavior (mechanical, hydraulic) as well as petrographic/mineralogic characteristics.
2. Monitoring of cavern performance during construction and operation through an array of sensors.
3. Construction and monitoring of mine-by tunnels
4. Construction and monitoring of large rock pillars.
5. Development of novel construction techniques for faster and safer excavation.

Integrating all this will be a risk analysis procedure, in which in-situ data will be analyzed using advanced modeling techniques and the risks associated with performance (safety) as well as construction cost and time will be determined.

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[7] Experiments listed in Section 3.5.3.

3.5.4. Uniqueness for Proposed Facility

The large underground caverns at DUSEL need to be fully operational for an extended period of time under demanding conditions regarding deformation and safety. This challenges our current knowledge of rock mass behavior. The proposed experiments will have two major benefits: (1) they will transform the field or rock mechanics and rock engineering; and (2) they are essential in predicting and ensuring safety and satisfactory performance of the large caverns and other excavations at DUSEL.

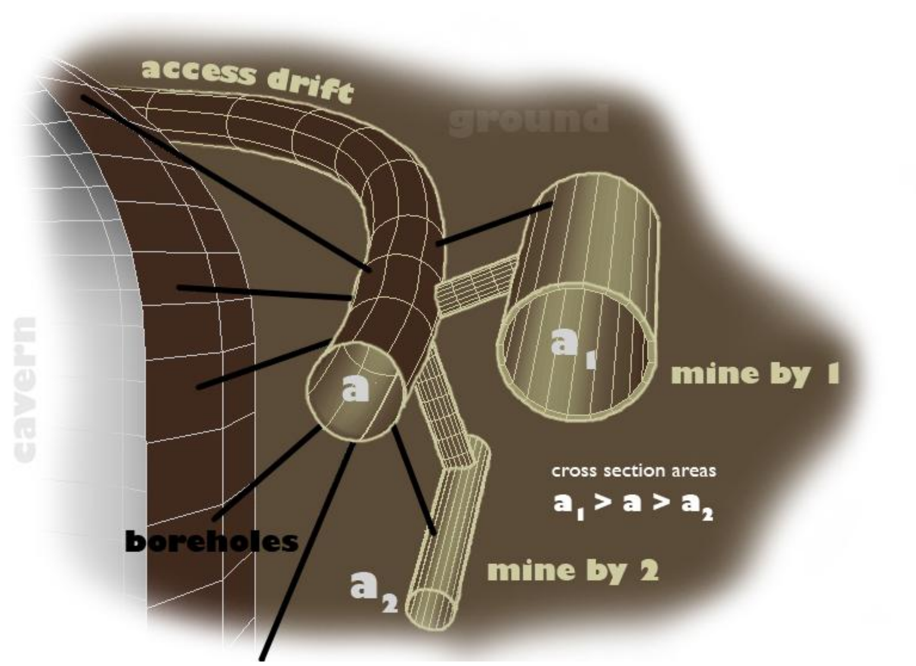


Figure 3.5.1. Concept of infrastructure requested: (a) Access drift; (a_1) and (a_2) Mine-by tunnels

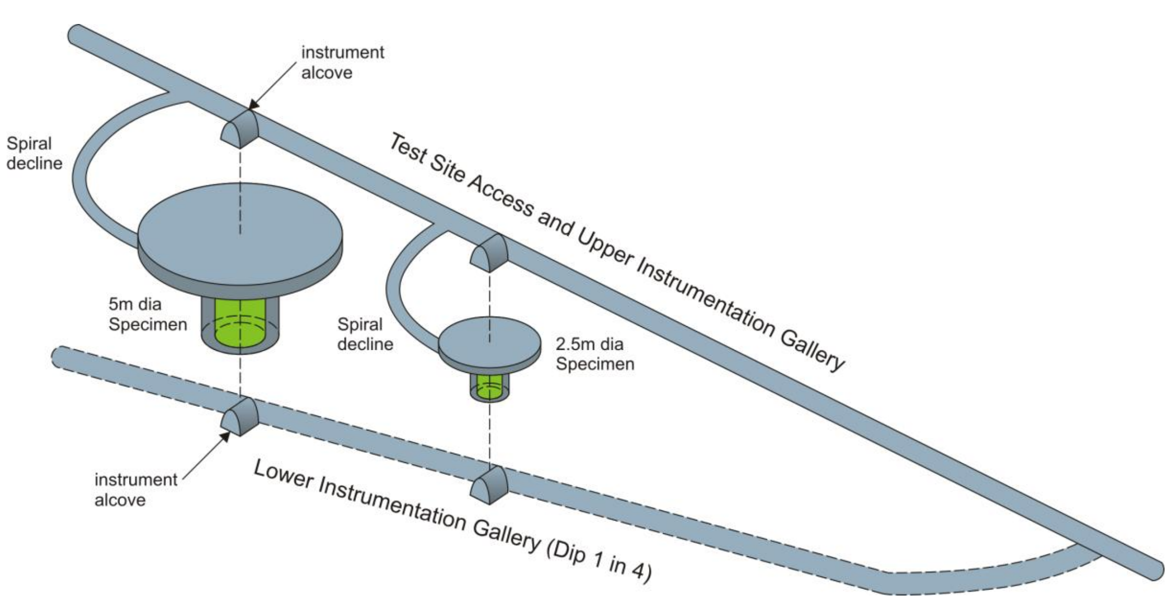


Figure 3.5.2. Large mine pillar facility

3.6. Facility for the Study of Fracture Processes

3.6.1. Scientific motivation

Fractures and fluids influence virtually all mechanical processes in the crust, but many aspects of these processes remain poorly understood, in large part because of a scarcity of controlled field experiments at appropriate scales. Faulting processes are a good example. Faults are typically simulated at the centimeter-to-decimeter-scale using load cells in the laboratory. Laboratory results are then routinely up-scaled by several orders of magnitude to investigate faulting and earthquakes in a wide range of fields.

Advancing the understanding of faulting and fracturing processes is critically important to many fields of earth science and engineering including seismology, resource recovery and environmental remediation, economic and structural geology, and disposal of radioactive wastes and carbon dioxide in the deep subsurface. In particular, the understanding of processes of earthquake triggering will be improved by data from field-scale experiments on controlled fault initiation. Experiments involving fluid-rock reactions coupled with microbial transport in the deep subsurface have implications ranging from the evolution of rock properties, to geochemical cycles, and to how life evolved on Earth.

3.6.2. Overview of proposed research facility

At DUSEL configurations for heating or cooling will be developed to manipulate *in situ* stresses and create faults. A robust implementation approach will circulate chilled fluid through arrays of sub-parallel boreholes drilled along vertical planes. This will reduce the horizontal compression normal to the planes of the boreholes while the vertical stress remains unchanged.

Designs for borehole arrays have been developed for use at DUSEL that would manipulate stresses at scales from less than one meter to approximately 10 m (Figure 3.6.1a). Boreholes for the small arrays would be drilled horizontally and stacked one atop the other, whereas the larger arrays would consist of vertical boreholes drilled downward and aligned in two parallel planes (Figure 3.6.1a). Instrumentation for monitoring the faulting process would be deployed in additional holes flanking the borehole arrays.

The slip patch is expected to span one to several meters before it becomes unstable and propagates dynamically along a fault surface. As a result, an experiment to characterize dynamic fault slip may require dimensions larger than 10 m. To accommodate this scale, a patch nucleation experiment has been design using two thermal panels at different levels along a pre-existing fault (Figure 3.6.1b).

3.6.3. Proposed experimental investigations

The proposed experiments at DUSEL are aimed at providing critical data to constrain the extent to which widespread up-scaling is valid. The goal is to make breakthroughs in fundamental problems regarding rock rupture. This effort will quantify rupture mechanisms in both intact (fresh) and faulted rock including the sizes of the smallest frictional slip event, mechanisms of slip triggering and slip nucleation, mechanisms of strength-gain and fault-healing promoted by reactive fluids and other agents, and the role of velocity weakening in the transition between quasi-static and dynamic fault rupture.

The key to experiments is the creation of carefully controlled faults in crystalline rock. Changes in temperature alter the stress state in rocks, and thermal techniques will be used to locally alter in-situ stresses enough to cause faulting. The general process involves heating to increase compressive stresses, or cooling to reduce them. Because the temperature field can be finely controlled, the stress field can be finely controlled too. Cooling boreholes in aligned arrays (Figure 3.6.1) could be used to manipulate stresses from 1 to 10m or more. Scaling and numerical analyses show that thermal technique can create differential stresses sufficient to induce faulting within a period of several weeks.

The thermal technique will be used to study how new faults form in intact rock, but it can also be applied in the vicinity of existing faults, where it could induce slip on those faults. This is important because most earthquakes are thought to be the result of unstable slip on existing faults. The slip process is likely to be initially localized on a growing patch (or series of patches) that is either weaker than the rest of the fault, or that sustains a locally elevated shear stress. Growth of the slipping patch moderated by the background stress rate may lead to an instability that results in a dynamic shear rupture propagation – this phenomenon is recognized to be related to the triggering of earthquakes. Thermal loads can be supplemented with manipulating fluid pressures to control the location of the growing slip patch and to study its transition to instability.

3.6.4. Uniqueness of proposed facility

The fracture experiments will create carefully controlled faults at scales of 1-100 meters, which are significantly larger than currently possible. The design includes facilities at four levels, which have been selected to optimize the scientific return by providing a range of different experimental conditions. Theoretical modeling based on the common natural fault parameters and ambient stress levels suggests that the transition to instability occurs for the nucleation patch size ~1 m. This represents a fundamental limitation for laboratory experiments, where the induced dynamic patch could be tractable, and necessitates larger scale field tests such as proposed at DUSEL.

Recent (summer 2010) field work has identified a large fault on multiple levels and in borehole core. The 'Homestake fault' is sub-parallel to the local foliation in the Poorman formation and extends at least 1.5 km along strike and dip, with a center ~1.5 km deep along the western side of the mine. It strikes NNW, dips ~70° NE, and is characterized by a ~0.3- m-thick distinct gouge (Fig. 3.6.2a) that contains crushed host rock and black material that appears to be graphite.

The Homestake fault is readily accessible on the 4850L (Fig. 3.6.2b) and 7400L levels and presents a unique opportunity to conduct dynamic slip experiments on a well developed fault under stress states of different magnitudes. It has been intersected by hundreds of core holes and has been sampled in exceptional detail—this is probably one of the most highly sampled faults currently known. The exceptional accessibility and level of sampling of this fault makes DUSEL Homestake uniquely suited to conduct experiments involving dynamic slip on existing faults.

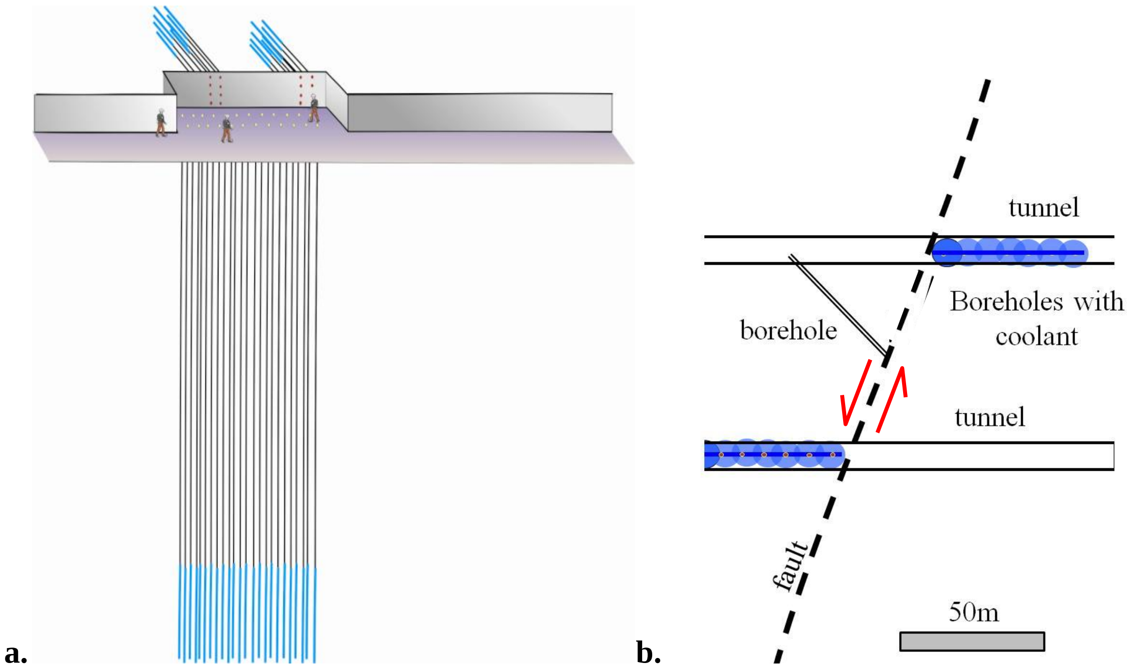


Figure 3.6.1 **a**. Perspective view of Fracture Process Facility where faults of different scales are created in horizontal or vertical arrays of boreholes used to control stresses by cooling (blue). **b.** Conceptual design of a dynamic fault slip experiment. A natural fault is loaded by means of cooling/heating of two thermal panels (arrays of parallel cooling/heating boreholes). Fluid is injected at a given location on the loaded part of the fault to promote slipping.

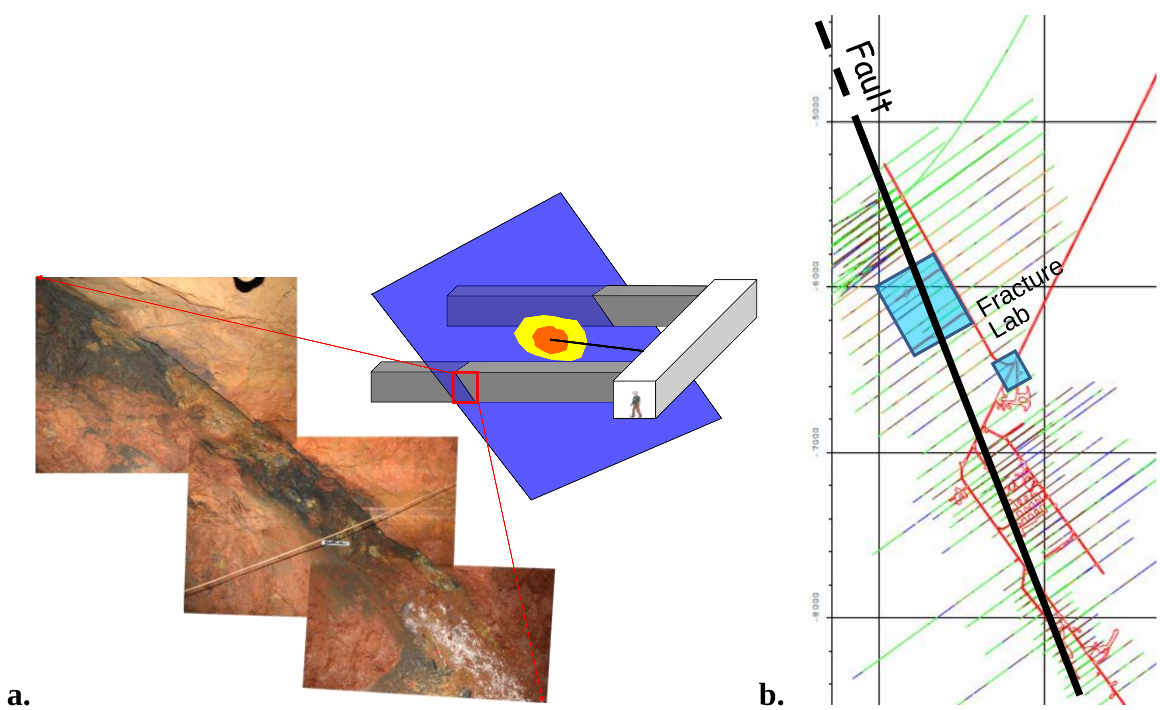


Figure 3.6.2 **a.** Homestake fault gouge and schematics of its intersection with the 4850-ft level. **b.** Proposed location of the Poorman Fracture Lab on 4850L

3.7. Transparent Earth - Subsurface Imaging and Sensing

3.7.1. Scientific motivation

Astronomers and astrophysicists can image deep into space to study the formation of the universe, the creation and death of stars, and the collision between stars, and the dynamics surrounding black holes; yet geologists and engineers have great difficulty imaging and studying processes even tens of meters into the Earth surface. The Transparent Earth - Subsurface Imaging and Sensing group proposes to develop an analog to the Hubble telescope into, not away from, the Earth. Just like physicists using multiple frequencies and physical parameters to study the universe, the Transparent Earth project will develop and refine measurement methodologies and science required to image the Earth at multiple scales. The proposed suite of experiments will combine a number of different physical measurement methodologies to provide complementary information, and strong constraints, for the necessary inversion solutions. This methodology will bring images into sharper focus and will help provide deeper scientific understanding of geological and engineering processes and behavior in the context of a highly stressed geological environment.

3.7.2. Overview of proposed experimental facility

The transparent earth team proposes installing and operating a permanent and portable geophysical observatory to illuminate the volume of DUSEL. The instrument system will be designed, much like a telescope, to look into particular directions and volumes within the mine using different excitation mechanics (e.g., strains, vibrations, electromagnetic field diffusion and propagation, density contrasts). For example, seismic wave monitoring instrumentation will be located in the furthest possible outreaches of the mine to capture the mechanisms related to earthquake generation and formations.

3.7.3. Proposed experimental investigations

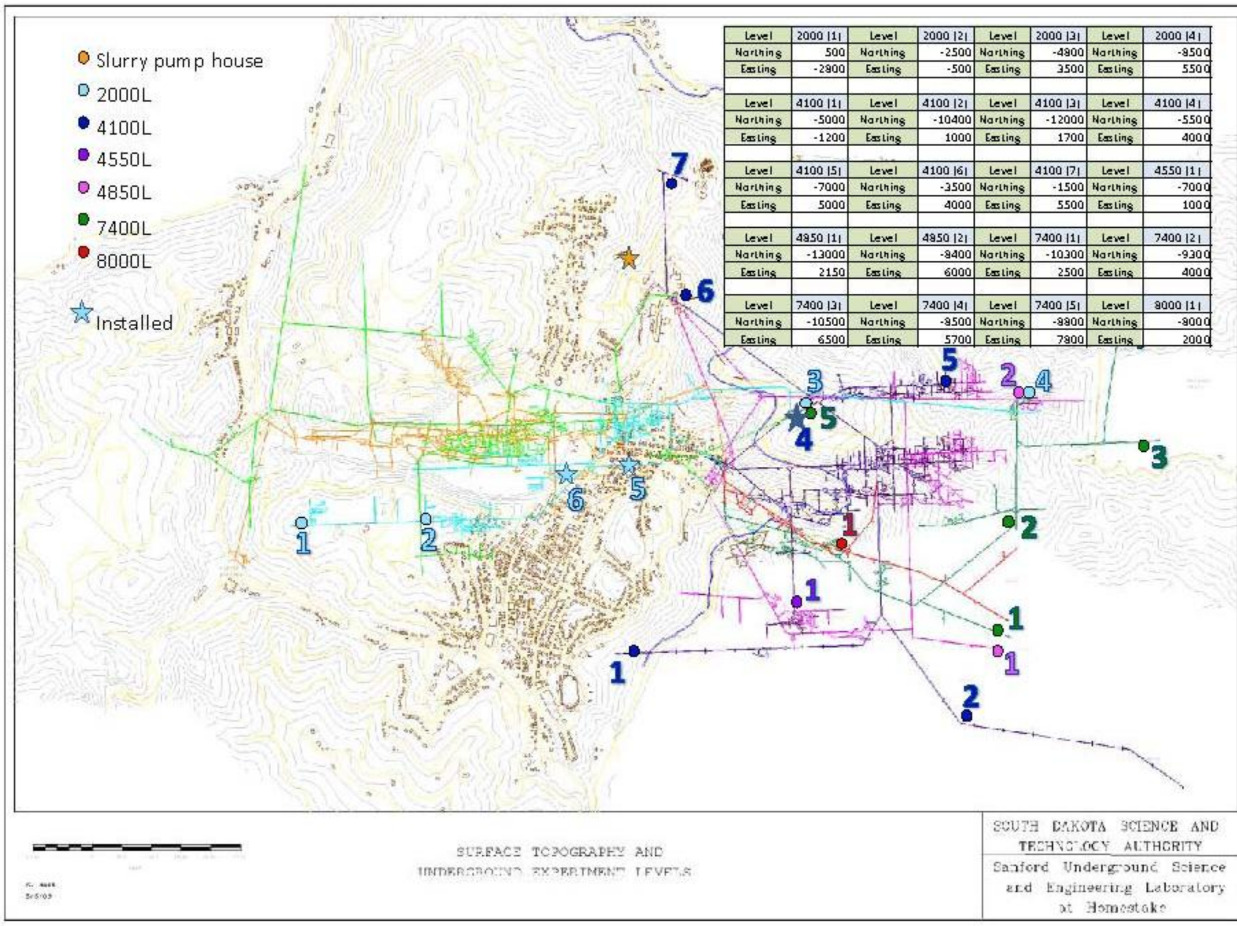
Through this effort imaging methodologies and procedures will be developed to pursue a variety of fundamental science and engineering objectives. Multiple modalities of geophysical instrumentation within and surrounding the mine volume will allow passive- and active-source measurements of various geo-activities, including rock mass re-stressing caused by the lowering of the water table by hundreds of meters, fluid injection and hydraulic fracturing, drilling and excavations during construction of the Laboratory, earth tide and barometric effects, and daily operations. The gathering of so many modes of geophysical measurement modalities will provide a large number of constraints for inversions, leading to new discoveries in the areas already discussed here, and beyond. One possibility is the development of new measures for *in situ* stress, with the possibility of applying these methods to predict rock fracture and pore fluid pressures. Another likely possibility is the development of new linkages between seismic and electromagnetic earth science. Further, the proposed large volume micro-seismic array will provide the tools needed to study the direct connection between the rock damage and the seismic waves generated during the process. This knowledge will be applicable to all geophysics arrays, and provide strong evidence for answering some important questions concerning the energy budget of fracture growth and dynamics, local frictional behavior within a rock mass, seismic scaling laws, and the interpretation of seismic moment tensors.

To complement these activities, the Transparent Earth instrumentation system will perform a wide variety of scientific and engineering experiments. The permanent large-scale seismic array, combined with double-difference tomography, will provide an ongoing measure of mine stability required for occupant safety and the well being of the experimental facility. Many of the proposed techniques will be easy to mobilize and operate near new workings, changes in geo-behavior, and by new experimental teams.

The nature of extended free field scattering will be studied. Electromagnetic sensors will be designed to monitor different emission mechanisms and processes at different temporal and volumetric scales. Electrical resistivity, low frequency electromagnetic and induced polarization methods will be used to image hydrogeological processes in the mine. Portable, high-resolution gravity meters will be used to map the mine and to evaluate the formation distributions and processes related to lowering water table and surface water changes.

3.7.4. Uniqueness of proposed facility

This observatory will be unique in that the mine volume is surrounded (sides and bottom) and penetrated by hundreds to thousands of boreholes suitable for instrumentation. The observatory will operate on a local (internal and external to the mine volume), regional, and global scale. The Transparent Earth observatory will integrate with the numerous offices USGS, and the LIGO geo-team to add more modality and scales to everyone‘s geophysics.



Level	2000 (1)	Level	2000 (2)	Level	2000 (3)	Level	2000 (4)
Northing	500	Northing	-2500	Northing	-4800	Northing	-8500
Easting	-2800	Easting	-500	Easting	3500	Easting	5500
Level	4100 (1)	Level	4100 (2)	Level	4100 (3)	Level	4100 (4)
Northing	-5000	Northing	-10400	Northing	-12000	Northing	-5500
Easting	-1200	Easting	1000	Easting	1700	Easting	4000
Level	4100 (5)	Level	4100 (6)	Level	4100 (7)	Level	4550 (1)
Northing	-7000	Northing	-3500	Northing	-1500	Northing	-7000
Easting	5000	Easting	4000	Easting	5500	Easting	1000
Level	4850 (1)	Level	4850 (2)	Level	7400 (1)	Level	7400 (2)
Northing	-13000	Northing	-8400	Northing	-10300	Northing	-9300
Easting	2150	Easting	6000	Easting	2500	Easting	4000
Level	7400 (3)	Level	7400 (4)	Level	7400 (5)	Level	8000 (1)
Northing	-10500	Northing	-8500	Northing	-8800	Northing	-8000
Easting	6500	Easting	5700	Easting	7800	Easting	2000

Figure 3.7.1. Installed and Proposed Seismic and E/EM Stations

4. Coordination and Integration of a Multi-User Facility

As seen in Figure 4.1, many of the proposed experiments share the same location within the facility and can potentially share the same boreholes, same power supplies and communication/data lines. Substantial savings in the drilling and completion of new boreholes for each experiment would be achieved by coordinating the timing of these activities. Data acquired by one experiments through the analyses of cores or the geochemical measurements of fracture water will be valuable to other experiments such as transparent earth and vice versa. Optimal use of infrastructure provided by the facility, such as transport to site, communication lines, water and power, coordinated sharing of data and expertise, prioritization of scheduling for installation of the experimental facilities are the goals over the next couple of years as the MREFC is reviewed.

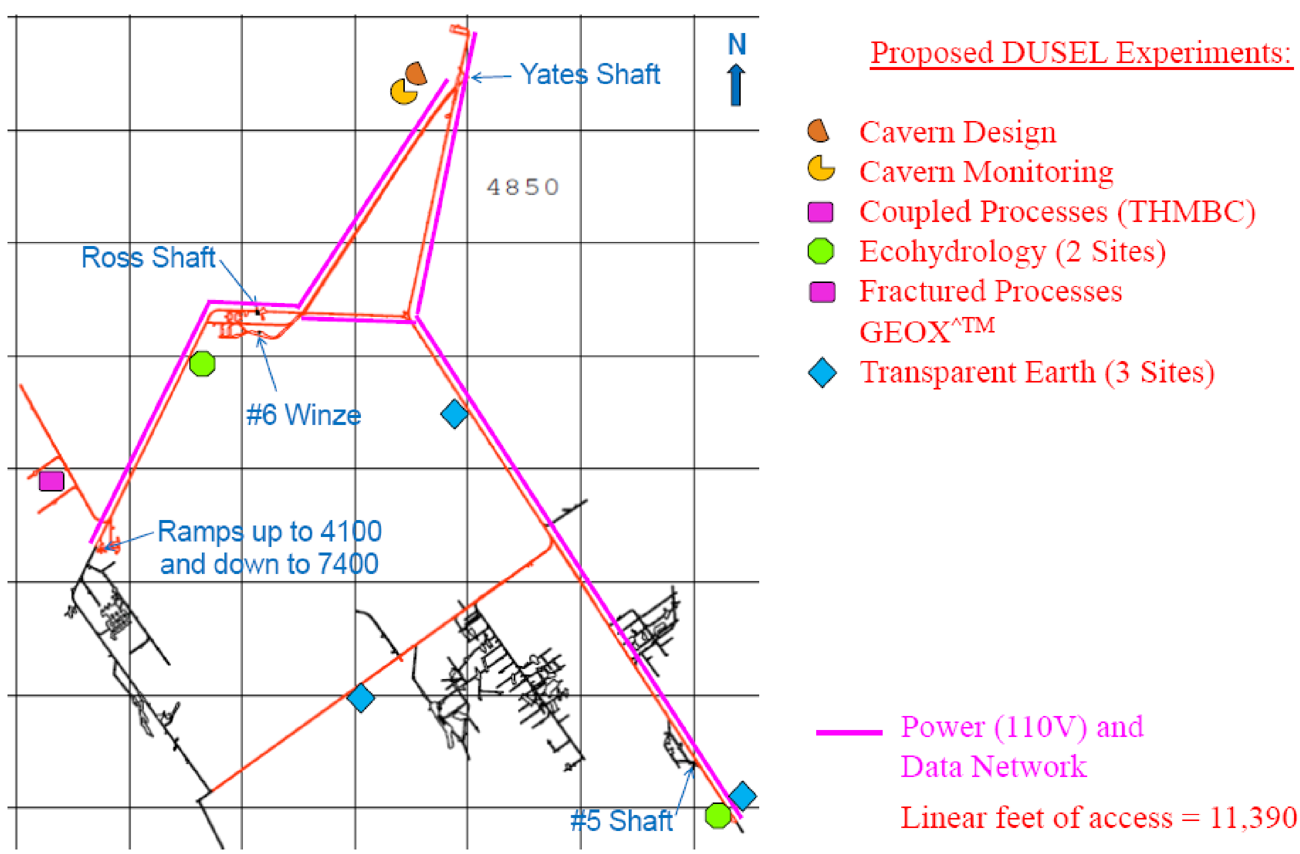


Figure 4.1. Plan view showing the location of various experimental facilities on the 4850 level. Physics experimental laboratory modules and large cavity detectors are located between Ross and Yates Shaft. The square grids are 1000 × 1000 feet.

5. Anticipated Results from DUSEL in the Coming Decade

The following are questions that may be uniquely addressed at a deep underground research laboratory.

The Limits of Life – *What is Dark Life? What are the paradigms that explain the abundance, diversity and activity of subsurface life in the face of meager and depth-diminishing nutrient fluxes? These include:*

- Discovery of the ultimate high temperature limit for life in the crust and what controls it. What is the relationship between temperature and partial pressures of metabolic gases, nutrient fluxes, fluid fluxes and biological maintenance energy demand rates? Does this relationship determine the biomass concentration and spatial distribution or patchiness in the crust?
- Discovery of what controls the "average age" of microorganisms in the deep subsurface. Are subsurface microbial carbon utilization and respiration rates many orders of magnitude slower than surface microbial life? Are average cellular "ages" on the order of thousands of years or more? If glacially slow metabolic rates are the norm, then what physiological properties or microbial community behaviors are selected for optimum survival?
- Discovery of what other factors control biomass concentration, "age" and evolution. Do viruses control the abundance of microorganisms through lysis? Do viruses affect the evolution of subsurface microorganisms through horizontal gene transfer? Do multicellular, extremophilic metazoans or protists control microbial biomass by predation? Does horizontal gene transfer occur between subsurface microbial species in the subsurface? Do evolutionary rates coincide with episodes of nutrient stimulation and rapid growth?
- Discovery of new geophysical sources of energy for deep subsurface microbial communities. Do stress fluctuations, fracture formation and faulting release bioavailable energy? Do rock-inhabiting, microbes utilize "nanowires" or conducting minerals to transfer electrons to or from their environment?

The Dynamic Earth – *What are the crucial processes that control the dynamic evolution of the crust? These include:*

- Discovery of how faults slip. What are mechanisms for nucleation, triggering and reactivation? How does slip on one fault trigger remote failure on another with relatively small dynamic stresses? How does fault strength and permeability evolve? And how does this affect slip reactivation?
- Discovery of how deep rocks and fluids interact and evolve. How does permeability evolve in the deep crust? What factors control the competition between mechanical, hydrological, chemical and thermal agents that increase permeability and those that staunch it? What factors control these competitive rates at growing length scales? What are the important interactions of mechanics, chemistry and microbial populations on this evolution? How do microbial communities migrate in fractured rock in response to chemical and thermal gradients and how does deep crustal fluid flow affect the population distributions?
- Discovery of how rock mass behavior evolves and differs at depth on different space (nanometers to kilometers) and time scales (microseconds to decades). How does rock deformation partition from long baseline behavior (InSAR and GPS) to short- (tiltmetry and seismicity)?

Resource Recovery, Sequestration Science and Sustainability – *What are the crucial processes and features that limit the effective recovery of resources and the safe sequestration of wastes in the deep subsurface? These include:*

- Discovery of complex process interactions that are currently poorly-observed *in vivo* and therefore poorly understood. How do mechanical, transport and reactive properties vary from nanometer to kilometer scales? How do we effectively image these processes in real time using available current and new geophysical tools? What are the most effective methods of harvesting heat from fractured geothermal reservoirs while minimizing induced seismicity? What constraints may be placed on reactive or heat-transfer surface area by physical, chemical, isotopic and other methods.
- Defining critical factors that affect the safe sequestration of CO_2 in deep geological reservoirs. How will fingering driven by capillarity and by reaction control migration in reservoirs and repositories? Will Joule-Thomson cooling inhibit the upward migration of liquid CO_2 relative to reduced buoyancy? How do these processes evolve at different length-scales? What are the roles of microbial biota in these processes? How do trapping mechanisms of CO_2 evolve with time and over varied length- and time-scales? What is the long-term prognosis for secure trapping and effective isolation?

Construction Engineering in the Deep Subsurface – *How do we better characterize the subsurface to enable faster, cheaper, safer and more resilient construction in the subsurface? This includes:*

- Defining the effect of geological heterogeneities on rock mass behavior at depth and the resulting risk from characterization uncertainties. What are the relationships between stress and strain in the shallow crust? How do we image in the subsurface to define the form, the location and the constitutive characteristics of these heterogeneities? What controls stress evolution and how effective is rock stiffness as a proxy for *in situ* stress? What acoustic and electromagnetic signatures allow us to better constrain processes complicit in the fracturing of rock?
- Developing innovative design, construction and risk-analysis approaches for deep underground structures.