Deep Underground Observatory for In Situ Stress, Fluids, and Life

Scope of Working Group: Physical and biological processes occurring naturally or in response to construction, specifically coupling between stress state and deformation; flow and transport and origin of fluids; and microbial identity, diversity and activity.

Overarching Scientific Questions:

- How do state variables (stress, strain, temperature, and pore pressure) and constitutive properties (permeability, porosity, modulus, etc.) vary with scale (space, depth, time) in a large 4D heterogeneous system: core – borehole - drift - whole mine - regional?
- How are fluid flow and stress coupled in a low-permeability, crystalline environment dominated by preferential flow paths? How does this interaction influence the distribution of fluids, solutes, gases, colloids, and biological resources (e.g. energy and nutritive substrates) in the deep continental subsurface?
- What is the mutual interaction between geomechanics/geohydrology and microbiology (microbial abundance, diversity, distribution, and activity)? Can relationships elucidated within the mechanically- and hydroligically-altered subsurface habitat of the Homestake DUSEL be extrapoloated to the pristine subsurface biosphere?
- In the absence of extensive intrusive investigations (drifts, mines, etc), can we characterize hydrogeologic and geomechanical processes in the subsurface? To what depth can we effectively characterize such processes, and what is the confidence in our interpretations?

Why Do We Need DUSEL?

DUSEL represents the first deep-underground field laboratory in the world in which Geo-Hydrologic, Mechanical, and Biological assumptions, theories and bench-top laboratory experiments will be tested in concert under true in situ conditions.

EarthLab and *Deep Science* state that access to the large rock volume in DUSEL permits testing of the critical-stress hypothesis that the Earth's crust is generally near failure. Over its 125-year mining history, many alterations of the original stress state have taken place. How does rock mass respond to human activity? How do stress, strain and pore-water pressure vary in scale from core to 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? What is the interactive relationship between stress/strain/porosity/hydraulic conductivity and microbial distribution and activity? DUSEL is the deepest environment in which these questions can be addressed unencumbered by competing activities. DUSEL is the deepest and most expansive environment in which these questions can be addressed unencumbered by competing human activities.

DUSEL at Homestake is characterized by a series of highly metamorphosed, heavily altered rocks of varying age with low matrix porosity. Fluids move through isolated fractures that are currently poorly characterized. Additionally, large-scale structural features (such as brittle and ductile fault zones) are likely to be important features in the large scale movement of fluids into the subsurface. DUSEL is the deepest environment in which these important fundamental research questions can be addressed unencumbered by competing activities.

Approach:

Our approach is to develop an integrated, interdisciplinary set of *in situ* observations grounded in the fields of geology, geomechanics, hydrology, and microbiology using a variety of methods and techniques. These approaches will nominally include:

- multiscale deformation and temperature (fiber optics, tilt, remote sensing, e.g., InSAR,)
- biostimulation and bioaugmentation in pristine fractures
- multiscale single and multi-well flow and transport testing,
- Three dimensional fluid flow and fluid chemical sampling (i.e. natural tracer analysis)
- Stress measurements by hydraulic fracturing,
- Microgravity for pore-water distribution changes and excavation,
- Long-term monitoring,
  Dewatering
  Active and Passive Earth Processes
- Synthesis by numerical modeling
- A multistage microbial study including a sun of the mine characterization of exisiting boreholes early in the project and subsequent long-term monitoring of experimental boreholes in conjuction with other activities.

Through monitoring of active and passive earth processes we seek to address a number of important hypotheses about how fluids and life interact with solid earth processes.

Expected Results:

- Develop predictive capability for 4D rock-mass response to loading
- Understand interconnectedness among
  - fluid flow
  - stress state
  - identity, diversity, and activity of microbial life
- Improved understanding of microseismicity, geophysics, and large-cavern construction
- Develop a better understanding microbial commuity development and over geologic time scales and over multiple scales utilizing run of the mine access from surface to great depth.
- Develop an understanding of factors limiting microbial growth within the subsurface by coordinating geochemical and dissolved gas analysis with microbial community structure assessments in areas of varied stress and in vicinity of artificially propogated fractures.

Initial Suite of Experiments:

We propose a series of experiments that are focused on understanding the relationship between physical solid earth processes (such as deformation and stress state) and the movement of fluids and life acting at a variety of spatial and temporal scales. The key to the success of these experiments will be the focus on the transformative knowledge developed to related and un-related geologic environments.

Scale Effects Experiment (SEE)

We propose to make observations of active and passive earth processes as functions of spatial and temporal scale within the observatory. Then we need to establish how stress, strain and pore-water 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 of crystalline rocks affect the stability of tunnels, shafts, wellbores, and large, room-sized excavations? The experimental program falls under the headings of "Stress and Deformation" and "Fluid Flow."

> Stress and Deformation
> Objective: The problem is to understand how point measurements relate to larger volumes and understand how the stress field controls deformation as functions of spatial scale and depth.
> Hypothesis: The scaling of strength and deformation is largely controlled by the fracture geometry, rock lithology, and anisotropy.
> Tasks: The research program will investigate the validity of stress measurements by hydraulic fracturing and to establish a fiber-optic based strain and temperature sensor network such that both distributed and localized changes are measured on scales from centimeters to kilometers. The fiber-optic network will be complemented by a long baseline tiltmeter array.
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> Fluid Flow, Chemical, and Colloid Transport
> *Objective:* The problem is to understand what controls fluid, solute, colloid, and microbial movement in fractured rock environments as functions of spatial scale and depth.
> *Hypothesis:* The scaling of permeability and transport properties is largely controlled by the distribution and connectivity of permeable fractures.
> *Tasks:* We propose to test the above hypothesis by collecting (or obtaining) scale appropriate data at the core, borehole (single fracture, multiple fractures), drift, and observatory scale. Given that the distribution of permeable fractures is likely to change with depth we might expect the scaling relationships at least on the km scale to be somewhat depth dependent. Although large fractures and fault zones dominate shallow (< 1km) crustal flow, we would like to evaluate the relative importance of small fractures contributing to multi-domain flow and whether small fractures can be ignored when modeling these domains**.**

Coupled Fluid-flow and Stress Experiment (Dark Flow) Experiment
The underlying scientific hypothesis to be tested is that stress and fluid flow interact because fractures that transport fluid are those near their shear strength. DUSEL allows the key relationships between *in-situ* stress, fluid flow, and microbial life to be tested from small (cm) to large (km) scales. We propose to make measurements of important state variables (such as stress and strain, fluid pressure, etc.) to investigate this relationship. Key questions include: *How are porosity and permeability maintained with depth? What types of fracture networks conduct fluids? What are the properties of these networks and how can they be characterized? Do patterns of microbial diversity reflect hydrologic connectivity (e.g. can microorganisms be used as a new type of particulate tracer)?*

Objective: Characterize and develop conceptual models for the prediction of the stress state, flow system, and microbial life at DUSEL and the relationships between them.
Hypothesis: Fractures and faults, which are critically stressed, have significant permeability to allow the transfer of mass and energy that influence aqueous and dissolved gas chemistry and thus the identity, diversity, distribution, and activity of deep subsurface microbial life. Low permeability or low hydraulic gradient zones might lead to stagnation.
Tasks:
We will develop a detailed experimental program that will instrument and measure fluid and chemical inputs (natural tracers) in the observatory in relation to measured stress state. Borehole

stresses, deformation, and fluid pressure will be monitored to create tomographic inversions of permeability distributions in regions surrounding the borehole.
A network of pressure tranducers in isolated boreholes will be deployed throughout the observatory to determine permeability and storage. Boreholes monitored for other purposes will be sampled at interval along with the installation of equipment and community responses determined in response to measured geophysical effects.
The possibility of determining rock fracture orientations using fluid pressure responses to earth tides and subsurface fluid pressure to monitor above- and below-ground components of the hydrologic budget will be examined. A bioassay/biostimulation experiment will be conducted to study microbial response in pristine fractures to dewatering and other rock-mass loading. Genetic transformation processes will be base-lined prior to biostimulation experiments to determine whether changing environmental conditions (as a result of dewatering) force microbial adaptation via genome diversification, evolution and horizontal gene transfer. Microbial abundance, physiological status (e.g. energy charge per cell and live vs. dead assessments) and activity measurements will be conducted along with these experiments to develop an understanding of community dynamics in response to geological, geochemical and geophysical factors.

4D Hydromechanical Simulator

A comprehensive, mine-wide numerical model will be built to synthesize observations for site selection of cavern construction, borehole locations, and bioaugmentation/biostimulation experiments. The understanding of the coupling between temperature, stress, deformation, pore pressure, geologic heterogeneity and anisotropy, rock fracture, fluid flow, fluid chemistry, and microbial life will be tested through predictive numerical models. The discontinuum and continuum numerical models needed will be significantly more complex and comprehensive than those available presently. Hence, the SEE research program includes a significant development effort in computational methods, especially upscaling methods to deal with effects of spatial scale, in close concert with the observational results.

Synergies with other ISE proposals:

We have identified a number of synergies with other working groups. Given the laboratory wide nature of our work we seek to leverage data being collected by other groups. In particular, these activities will complement the biological activities of the baseline studies group by assisting in site selection for early borehole studies. Additionally we seek to actively collaborate with the ultra-deep drilling project. Surface geophysics, such as seismic, ground-penetrating radar (GPR), or electromagnetic (EM) could be conducted in shafts or stopes at different depths. These methods would provide information related to rock properties that could potentially be correlated with permeability measurements. Depth of the upper weathered zone of the fractured rock setting could be estimated by land-surface seismic surveys, and results could be compared and calibrated to measurements taken underground. Other methods could include surface-to-subsurface seismic tests or subsurface-to-subsurface seismic tests. Also, if the flow of water into the mine from the open pit could be measured, aquifer properties potentially could be estimated. The entire SEE R&D program is to be connected to a parallel program in geophysical imaging ("What lies between the boreholes?") and microseismicity ("How and why do rock masses fail?").

Baseline Characterization:

The tasks needed to characterize the baseline state of the rock mass that makes up the former Homestake mine are: (a) creation of a user-friendly and web-accessible interface to the Vulcan database, (b) thorough review of the Vulcan database, drill core, and paper records to establish quantitatively, insofar as is feasible, the history of rock mass lithology, fracture geometry network in each lithology, physical, mechanical and hydraulic properties of intact rock, roughness and aperture distributions of fractures, mechanical and hydraulic properties of fractures, excavation, water seepage including hydraulic boundaries and water chemistry, rock mass deformation and stresses, and microseismicity, (c) mapping fractures three dimensionally in as much of the mine as can be accessed safely, using manual as well as state-of-the-art multimedia technology for recording walkthroughs, or possibly remotely-controlled, lighted vehicles, which permits rendering three-dimensional reconstructions, (d) obtaining rock samples to determine physical, mechanical and hydraulic properties of intact rock in a laboratory and hence to develop constitutive models for intact rock, (e) obtaining samples of fractures to determine roughness, aperture, mechanical and hydraulic properties of fractures in a laboratory and hence to develop constitutive models for fractures and (f) establishment of baseline values of stresses, tunnel dimensions, seepage including hydraulic boundaries, pore pressures, and water chemistry over a large volume of the mine, (g) baseline microbial abundance, identity, diversity, and activity in fluids and rock cores, (h) base-line values of genetic transformation processes (genome diversification, evolution and adaptation by horizontal gene transfer) prior to biostimulation experiments.

Development Needs:
Fracture mapping
LIDAR surveying
Existing borehole discovery and characterization
Installation of sampling infrasture on existing boreholes (e.g. outlet valving).
Existing hydrologic information
Fiber for data
Drilling and capability wireline
Water and gas chemistry and bioassay
Microbial community analysis and archiving of samples

Cost and Schedules: The ISE cost estimates are based primarily on personnel costs and secondarily on anticipated equipment costs.

1. Vulcan Data Mining - $300,000.
2. Baseline in 2012 for long-term monitoring of stress, temperature deformation, pore pressure, water chemistry, microbial community analysis and archiving of samples - $4,200,000.
3. Borehole experiments - $1,800,000.
4. Monitoring dewatering, actively coupled processes, and large-cavern excavation - $4,500,000.
5. Laboratory testing of intact rock and fractures for physical, mechanical and hydraulic, and microbial tranport properties--$900,000.
6. Hydromechanical Simulator – $450,000.
7. Annual workshops – $300,000.

TOTAL = $12.9 M
These cost estimates are very preliminary and can be refined considerably by discussion with equipment manufacturers, and with industrial groups.

Schedule:

Facilities:

E&O:

DUSEL is an exceptional opportunity for university, industry, and national laboratory researchers to work in partnership on problems from construction to basic geoscience and geo-engineering by occupying a single *in situ*, large-volume, underground laboratory with three-dimensional access. It provides the opportunity for experiential learning for K-12 through graduate school students within the deep earth environment where they can be in contact with the crushing weight of thousands of feet of overlying rock, the geothermal gradient, and deep underground fluid flow. It is an environment in which the coupled nature of rock response to temperature, stress, microbial life, and chemical reactions is seen as a single process. It is the environment in which the underground can be seen as a societal resource space. Students and the public will gain an appreciation of how knowledge about underground rock mass response is gained by observing researchers pose questions, conduct experiments, make observations, and analyze and interpret the results.

Some specific examples:

- Partnerships between university, industry, and national laboratory researcher
- Experiential learning in deep earth environment for K-12, university, and public
- Embed teachers into research activities (RET) during summers to develop curriculum
- Student activities
    - Investigate on-line dewatering and climatological data Monitoring stream flow, e.g., False Creek, USGS borehole pressures, surface GPS measurements
    - Connect "textbook" physics concepts with experiment, e.g., pendulum equation and gravity
- Create "Hydrologic Science Investigations" (HSI)
- Show and tell of underground tour, LIDAR, etc. – student produced video

Risk Identification and Management:

Interested Principals and Collaborators:

Herb Wang - U. Wisconsin-Madison, Dave Boutt - U. Massachusetts, Martin Saar - U. Minnesota, Pinaduwa Kulatilake - U. Arizona, Larry Stetler – SDSMT, Larry Murdoch – Clemson, Todd Rasmussen - U. Georgia, Jim Volk – FermiLab, Bezalel Haimson - U. Wisconsin-Madison, Alan Turner - Micron Optics, Mary MacLaguhlin - Montana Tech, Steve Blair - LLNL (Retired), Andy Long, Mark Anderson, Allen Shapiro, John Lane – USGS, Steve Gabriel - Spearfish School District, Hailiang Dong - Miami U. (Ohio), Duane Moser, Desert Research Institute, Las Vegas, NV

Possible Subprojects and personnel that support or crosscut several of the ISE experiments (coordinator in bold):

1) Fiber Optic and Tiltmeter Monitoring of 4D Deformations – ***Wang***, MacLaughlin, Volk, Stetler, Murdoch, Fratta, ….
2) Deep Borehole Pore Pressure/Deformation Monitoring, Discrete Fluid sampling, and Scale Measurements – ***Boutt***, Rasmussen, Saar, Stetler, Long, Shapiro, Blair, Carlson, Wang, ….
3) Validity of Stress Measurements by Hydraulic Fracturing – **Haimson**, Cornet, Doe, Hickman …
4) Biological Communities in Relation to Stress and Fluid Flow – ***Dong***, Wang, Boutt, Moser, ….

5) Hydromechanical Simulator – ***Murdoch***, Saar, Wang, Boutt, Stetler, Kulatilake, …
6) E&O – ***Gabriel***, MacLaughlin, Wang, ….