OBSERVATORY FOR SUBSURFACE HYDROGEOLOGIC RESEARCH AT NUSL

EXECUTIVE SUMMARY

PART 1-RESEARCH THRUSTS AND EDUCATIONAL OPPORTUNITIES

RESEARCH THRUSTS

A. Brief Outlines of Key Hydrologic Questions Identified Thus Far

Will coupled-process-induced changes in rock characteristics affect transport and confinement capacities? (J. Wang and others)
Measurements of permeability changes, deformation, relative humidity, pressure, chemical composition, temperature, and other state variables around and between drifts over decades can greatly enhance the understanding of coupled processes. The evaluation of subsurface coupled processes under long-term stress change, moisture removal, chemical/mineral redistribution, and thermal transfer can lead to more effective design and reliable assessment of long-term stability of underground structures, with the knowledge gained for other storage and containment facilities.

Are fractures closed or remain open to maintain deep circulation? (J. Wang and others)
Simultaneous or co-located quantification in different scales of permeability distribution, fracture connectivity, seepage flux, chemistry distribution, *in situ* stress and deformation, and other state variables will lead to great advancement in the understanding of fractured rock behavior. If the mechanism of deep circulation and the effectiveness of its isolation from shallow system are quantified, the understanding can lead to effective management of deep resource extraction or contaminant containment in reservoirs.

Do recharge flows to great depths for sustainability evaluation of groundwater supply? (J. Wang and others)
Direct measurements of the interactions between subsurface processes and atmospheric variations can determine the damping mechanisms, propagation of episodic infiltration events, and redistribution of percolation fluxes throughout the rocks. The assessment of sustainability at fractured hard-rock sites is especially relevant for many communities located on bedrocks with scarce water resources. A de-watering zone is an example of a **critical zone** (vadose zone or unsaturated zone). Understanding the critical zone around the underground facility will be beneficial for evaluation of many other fractured sites.

Will an in situ NUSL afford a unique opportunity to characterize and understand paleohydrology? (Steve Ingebritsen, USGS)
The hydrologic system evolved through time, and thus are we able to detect a signature(s) of those different hydrologic regimes? Examples:

- Topography and climate have changed through time, and thus infiltration

must have changed. Can we detect changes in regional diagenetic trends?
- In the Black Hills specifically, three episodes of stresses have occurred, including
    - intrusion
    - uplift and doming
    - mining efforts
- How have these episodes affected fracture development and associated hydrodynamics? Is it true that observed mineralization may not be coincident with the intrusion episode? If not, what is the source/cause of this mineralization?

Can deep fracture systems be mapped, their origin determined, and can fracture flow processes be better characterized from in situ? (Jack Sharp, UT Austin)
Example issues:
    - flow
    - earth tides and aperture/roughness (effects detectable in situ?)
    - evolution of fracture surfaces (skin), and mechanisms of detectable changes
    - fracture genesis
    - evolution of porosity and permeability as rocks deform through time
    - lessons learned from Stripa, WIPP, Mirror Lake - how do these affect our science plans for NUSL?

NUSL offers a unique opportunity to study scale effects (Nick Woodward, DOE)
Scaling effects may be more easily quantified by studying in situ, especially permeability, including point measurements of permeability up to in situ pump tests with controlled boundary conditions. Scientific efforts at NUSL should perhaps focus on those attributes or opportunities that NUSL offers that will permit us to pose old questions in new ways or in new contexts. In other words, what studies can we do here, in situ, using 3-d tomography and other like approaches, that we cannot do anywhere else?

Detailed studies of storage properties, leaching and contaminant transport may be accomplished more effectively from in situ (Leslie Smith, UBC)

Storage: one possible experiment would be to change the pumping regime (used to dewater the mine) deliberately and examine the response with a dense network of pressure transducers (saturated extents outside of mine) and tensiometers within. The purpose would be to characterize storage and wetting fronts.

Leaching: another possible experiment: dewater a portion that is currently saturated (beyond the extent of the mine, after creating a new stope), fill with mine waste backfill of known hydrologic properties and known tracers. Control the re-flooding or resaturation to provide a controlled hydrodynamic regime. Such an experiment would require sampling ports at discrete intervals to measure in situ TDS, conductivity variability/evolution via periodic sampling. This type of experiment would permit detailed characterization of transport and storage similar to previous tailings studies (e.g., Borden site), but with high resolution calibration data. A critical question associated with this experiment: is time-scale sufficient?

Paleohydrology: to add to issues raised by Steve Ingebritsen – will NUSL permit us to quantify hydraulic conductivity vs. depth? Can we reconcile the measured trends with the detailed geologic and diagenetic histories?

B. Detailed Summaries of Major Research Focus Areas

B.1 Spatial and Temporal Variation of Recharge and Its Relationship to Other Components of the Hydrologic Cycle (McPherson)

<u>(1) Statement and Significance of the Problem</u>

While quantifying surface infiltration is straightforward through direct measurements, evaluating and characterizing the hydrologic communication or relationship between surface infiltration and subsurface groundwater recharge is extremely difficult.

At the surface, many factors effect the spatial distribution of infiltration, as well as the ratio of infiltration to surface runoff. Some of these factors include surface elevation, surface geology (rock/soil types, local terrain variability, local and regional structural geology), vegetation, and climate. All of these aspects may be measured directly. Once water infiltrates the subsurface, however, its fate is only generally understood. Flow and transport through the unsaturated zone plays a critical role; it is dictated by both surface infiltration, the state of the unsaturated zone, and the state of the saturated zone below. Physical properties of the different zones are important, as well as climate and climatic history. Our understanding of this interrelationship is limited mostly to theoretical constructs.

What is needed is a fundamental characterization of the relationships among surface infiltration, unsaturated zone flow and transport, and subsurface groundwater flow. Specifically, it is necessary to identify and characterize (1) which subsurface factors influence the ratio of infiltration to runoff, (2) how flow and transport in the unsaturated zone responds to infiltration, (3) how unsaturated zone flow and transport are influenced by the fluctuating state of the saturated zone, and (4) the roles that climate and climatic history play in all of these processes.

These issues are a critical gap in our understanding of the full hydrologic cycle. Filling this gap is critical inasmuch as water resources exploration and exploitation become increasingly important as population grows.

<u>Elements Currently Missing that are Required for a Solution</u>

In general, the missing critical link consists of direct measurements, effectively distributed both spatially and temporally, of subsurface properties and processes that will lead to fundamental characterization of the relationship between surface infiltration and subsurface groundwater recharge and flow. An ideal set of measurements would include a dense, 3-dimensional subsurface distribution of fluid pressures/flow rates, fluid chemistry (e.g., dissolved constituents, isotopic measurements, etc.), and temperature, among other variables. Also needed is an effective 3-dimensional subsurface geological characterization including structure, mineralogy/lithology, facies/depositional environments, thermal conductivity, and permeability, among other properties. One of the most important factors is the permeability or hydraulic conductivity distribution, including scaling, and this is the subject of section B.2 below.

Such measurements are most critical for more regional-scale basins and watersheds, where deeper data and information are sparse. Oil and mineral exploration provide most point measurements of necessary data, but even in basins subject to heavy exploration, the best data are biased in favor of oil/gas-producing formations, and not those formations important for water resources.

<u>(3) Means of Providing the Missing Elements</u>

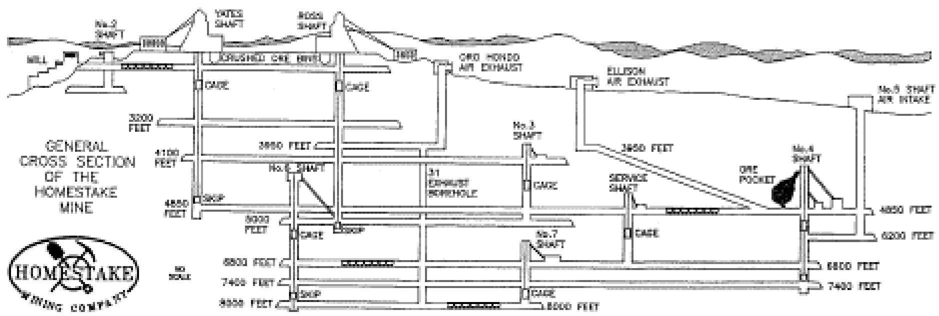

Figure 1. Image source: NUSL Website, http://mocha.phys.washington.edu/NUSL/

The Homestake Mine, located in the Black Hills of South Dakota, is schematically diagrammed in Figure 1. The mine lies within the heart (at depth/in situ) of a typical intracontinental flow system. Such topographically driven flow systems, first outlined in detail by Hubbert (1940) and further analyzed by Toth and others in the 1960s, exist throughout the continents. The Black Hills example cited here is typical of such systems, consisting of highlands driving groundwater flow into adjacent sedimentary basins. All elements of the hydrologic cycle are represented. Most importantly, the mine's shafts stretch from the surface, through the unsaturated zone, and into the deep groundwater flow regime of the flow system.

The mine is extensive, laterally and in depth, with miles of tunnels as indicated by the schematic above. Assuming that scientists will have access to all reaches of the mine's shafts, and that instrumentation may be permanently installed in all areas of the mine, Homestake will provide an invaluable opportunity for acquiring the data outlined in (2) above.

Also necessary in this effort will be surface observatories (or mini-observatories, consisting of precipitation collectors, tensiometers, meteorologic stations, etc.) assembled throughout the recharge areas, to monitor infiltration and climate. A cursory literature review as well as a recently completed study of regional-scale fluid and heat flow in the Powder River Basin (McPherson et al., 2001) suggests that the high topography of the Black Hills are a primary recharge area for adjacent sedimentary basins. Comparing isotopic "fingerprints" between potential recharge areas and fluids flowing into different parts of the mine could help delineate the recharge area distribution and associated different flowpaths.

Much like most other intracontinental regional-scale flow systems, the topography of the Black Hills appears to split recharge in two primary directions: the Powder River Basin to the west (McPherson et al., 2001) and into the Dakota Sandstone and other formations to the east in South Dakota (Bredehoeft et al., 1983). The mine lies in the flowpath of one or both of these systems, and perhaps its presence will help answer fundamental questions about recharge/discharge areas and the general anatomy of these types of regional-scale systems.

<u>(4) Sketch of an Experimental Design for Addressing the Problem</u>

Design of possible research studies include four fundamental components:

Detailed 3-dimensional geological characterization: characterization of all strata that the mine penetrates, from the surface to maximum depth and lateral extent (see schematic above), including assessment of relative rock properties such as lithology, facies or depositional environment description, porosity, permeability, thermal properties, etc. Relevant rock properties for other scientific studies, e.g., mechanical and elastic rock properties for fracture or deformation studies, could also be made in tandem with the hydrogeologic characterization.

Continuous measurements of relevant processes: instrumentation could be installed in all parts of the mine, especially the portions that are adjacent to maximum depth extent and lateral extents of the mine. Most important aspects include fluid flow/moisture content measurements, temperature measurements, and chemical evolution, including isotopic aspects. Detailed precipitation, runoff, recharge and climate information must be measured continuously at the surface.

Comparison or tracking of correlation between subsurface conditions and surface conditions: Continuous histories of data and conditions from the surface through the subsurface will be recorded. Conceptual models will be developed based on correlations between conditions at the surface and responses in the subsurface. Linking of specific recharge areas to different portions or flowpaths may be possible using isotopes or other tracers, given the great lateral extent of the mine. Tracking of recharge:runoff ratios as a function of seasonal climatic variation, and climatic variation over the longer term, will be sought. Anthropogenic changes to the geological/hydrological regime, including the presence of the mine and its effect on the regional hydrologic regime, must be accounted for in these analyses. Additionally, factors and possible changes to the geological environment associated with other scientific studies, including physics and geological research, must also be tracked and evaluated for possible hydrologic effects. At this time, the mine is in place, including necessary infrastructure for access to all parts of the mine. Maintaining this full access after the mine ceases ore-mining operations is critical for the studies proposed inasmuch as maximum spatial coverage is necessary.

Modeling Studies: Conceptual models of infiltration, unsaturated zone flow and transport, and groundwater recharge and flow response will be developed, based on observations of data and their evolution over the long term. Hypotheses will be developed and tested using new experiments and data in addition to detailed mathematical models of the hydrogeologic evolution. For example, numerical models of fully coupled fluid and heat flow will be appropriate. Additional models including chemical and mechanical processes may also be applicable.

(5) Expected Outputs from the Experiment and their Impacts

Results of these studies will include high quality, high resolution, 3-dimensional data sets detailing infiltration and associated hydrologic response in the intermediate vadose zone and the deeper groundwater flow regime over time, a specific niche in the hydrologic cycle that is poorly understood. Surface and subsurface geologic factors affecting recharge versus runoff could be illuminated. Surface and subsurface geologic factors affecting how recharge varies as a function of climatic variation may also be identified and quantified. The resulting data, analyses, models and interpretations will provide more clarity to a poorly understood part of the hydrologic cycle. The net result will be improved water resources exploration and exploitation, accounting not only for climate and surface conditions, but also subsurface geology and hydrodynamics.

B.2 Permeability: Scale-of-Evaluation (McPherson)

(1) Statement and Significance of the Problem

Permeability of crustal rocks may have different values depending on the scale at which it is evaluated. General quantitative or semi-quantitative relationships between permeability and scale do not exist.

During typical hydrologic analyses such as water resource exploration and management, permeability is typically assessed at one or more scales, usually involving different methods of evaluation. Even if different scale permeability values are available for a given area, it is not always clear which scale is appropriate for evaluating and quantifying water resources, calibrating models, or testing hypotheses in general. General and quantitative relationships between scale and permeability are needed.

(2) Elements Currently Missing that are Required for a Solution

While general and quantitative relationships between permeability and scale-of-evaluation do not exist, a qualitative relationship between permeability and scale of measurement can be established for any specific area, given enough measurements. For example, Figure 2 illustrates a general relationship between permeability and measurement scale for rocks in three different sedimentary basins, including the Uinta Basin in Utah (Willett and Chapman, 1987), the Powder River Basin in Wyoming (McPherson et al., 2001), and the Pierre shale within South Dakota (Bredehoeft et

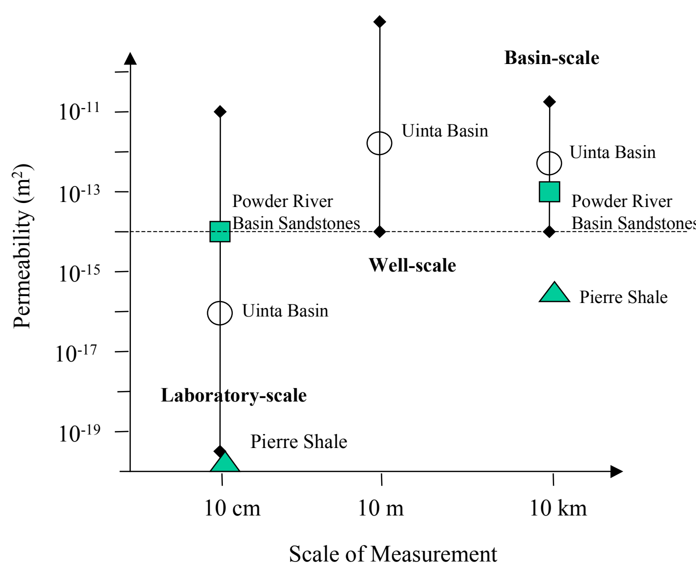

Figure 1. Effect of scale on permeability of rocks in 3 different sedimentary basins in the United States, including the Uinta Basin of Utah (Willett and Chapman, 1987), the Powder River Basin, Wyoming, and the Pierre shale in South Dakota (Bredehoeft et al, 1983; Nuezil, 1994). Dashed line at 10^{-14} m² indicates average crustal permeability inferred by Brace (1980). Error bars associated with Uinta Basin data reflect the full range of permeability evaluated at each scale.

al., 1983; Neuzil, 1994). A similar trend was suggested by Garven (1995) for carbonate rocks in central Europe.

What do not exist and are needed are high-resolution measurements of permeability, densely distributed spatially in 3 dimensions and at different scales, to develop general and quantitative relationships between permeability and scale. Also needed is an effective 3-dimensional subsurface geological characterization including structure, mineralogy/lithology, facies/depositional environments, and porosity, among other properties, to quantify what factors control the scale-effects. Ideally, such a network of measurements would be made for a typical intracontinental flow system or watershed.

(3) <u>Means of Providing the Missing Elements</u>

The Homestake Mine is located in the Black Hills of South Dakota and lies within the heart (at depth/in situ) of a typical intracontinental flow system. Such topographically driven flow systems, first outlined in detail by Hubbert (1940) and further analyzed by Toth and others in the 1960s, exist throughout the continents. The Black Hills example cited here is typical of such systems, consisting of highlands driving groundwater flow into adjacent sedimentary basins. All elements of the hydrologic cycle are represented. Most importantly, the mine's shafts stretch from the surface, through the vadose zone, and into the deep groundwater flow regime of the flow system. The mine is extensive, laterally and in depth, with miles of tunnels. Given the current status of the mine, it is assumed that scientists will have access to all reaches of the mine's shafts. Also assuming that instrumentation may be permanently installed in all areas of the mine, especially the lateral extents (periphery) and deepest extents, Homestake will provide an invaluable opportunity for acquiring the data outlined in (2) above.

(4) <u>Sketch of an Experimental Design for Addressing the Problem</u>

Permeability has already been evaluated for specific scales and parts of this typical intracontinental flow system, including both basins adjacent to the Black Hills, as illustrated by Figure 2. These permeability data are sparse in number and density, and limited to the basin- and lab-scales. Homestake provides the opportunity for acquiring a dense network of measurements, at a large range of possible scales. More importantly, it provides the opportunity for making these measurements at depth and in situ, without the need of removing rock (e.g., core) for measurements. Thousands of core-scale measurements may be accomplished using mini-permeameters, such as approaches taken by Tidwell and Wilson (1999a, 1999b). Incrementally larger-scale measurements could be undertaken stepwise by designing and completing conventional flow and/or tracer tests between different parts of the mine, including between shafts, and including pump tests induced in surface wells and monitored within different parts of the mine at depth. The opportunity for evaluating permeability at all possible scales is unprecedented.

Another very important possibility is that if these types of studies are performed in tandem with recharge studies through time, discussed in section B.1 above, similar studies regarding scaling effects on hydraulic diffusivity and storage could be designed and undertaken.

(5) Expected Outputs from the Experiment and their Impacts
Results of these studies will include high quality, high resolution, 3-dimensional data sets of permeability, at all possible scales of evaluation. Surface and subsurface geologic factors affecting or dictating permeability variation must be identified. General and quantitative relationships between permeability and scale need to be developed, including characterization of geologic factors controlling these relationships. The resulting data, analyses, models and interpretations will provide more clarity to a fundamental problem in hydrologic science. The net result will be improved water resources exploration and exploitation.

B.3 Well Testing Verification Facility (Murdoch)

(1) Statement and Significance of Problem

Wells are the window through which we view the subsurface. Indeed, early hand-dug wells allowed the intrepid scientist to inspect a subsurface formation directly. Today, a suite of technologies exists for remotely sensing the characteristics, composition, and conditions along the length of even the deepest wells. Insight from these technologies plays a crucial role in recovering subsurface resources, such as water, oil, natural gas and minerals, which are critical to our security and quality of life. However, the resolution of established well testing technologies diminishes sharply with distance, so details of subsurface formations are poorly known only a few meters from the well; the view from the window is highly myopic. Important properties can change abruptly in the subsurface, so decisions made using data from standard technologies are vulnerable to considerable error. It appears to be critical that we increase the resolution of well testing technologies in order to ensure a ready supply of critical resources for the future.

A variety of new well testing technologies are being developed, or appear to be feasible, that will bring details of the subsurface into focus. Geophysical techniques, such as seismic surveys or electrical resistance measurements, can be conducted between adjacent wells and their results interpreted using tomographic methods to provide detailed images of slices through the subsurface. Slim radar transmitters and receivers have been developed that can be inserted into a well to provide images of the enveloping rock. Pressures measured near a pumped well can be interpreted to estimate the structure of the subsurface in increasing detail, and these techniques can be improved further by coupling them with measurements of tracers injected into the formation.

(2) Elements currently missing that are required for a solution
A barrier impedes the progress of innovative well testing techniques: they must be verified and refined under controlled field conditions. It is relatively straightforward to verify techniques in the laboratory, but it can be extremely difficult to obtain the data necessary to verify the performance of high resolution well testing techniques in the field. Verification under field conditions is essential, however, to ensure correct performance and to provide investigators with feedback that can be used to refine and improve the technique. In most locations, however, the data required to verify detailed

assessments in the subsurface are unavailable.

(3) Means of providing the missing elements
The Homestake Mine offers an unprecedented opportunity to develop a facility for verifying the performance of well testing techniques. The mine workings cut through a variety of rock types, geologic structures and conditions, so a broad range of subsurface scenarios are represented. Exploratory borings associated with mining operations will provide important preliminary data for evaluating conditions and identifying potential locations. Ultimately, however, it is the access provided by the underground workings that will be essential because it will facilitate the development of detailed data sets describing geologic settings to be used in the verification process.

(4) Sketch of Experimental Design for Addressing the Problem
The general approach to verifying the performance of well testing techniques will be to first describe in detail several regions in the vicinity of the mine workings. This effort will be initiated by identifying candidate regions using data obtained during mining. Potential sites will be characterized by drilling arrays of borings from mine workings, obtaining core samples from the borings, and conducting geophysical tests, hydraulic well tests, and tracer tests within the closely spaced array. Wells from the ground surface will then be created, or existing borings will be used. Tests will be conducted in those wells and investigators will be required to make initial interpretations without knowledge of the control data. The results of the well tests will be compared to the control data set, and we expect that the well testing techniques will then be refined and evaluated with additional work at the facility.
The proposed facility will include several locations that are characterized by different geologic or hydrologic conditions. Some basic conditions that will be considered when identifying candidate locations within the Homestake mine include: spacing and orientation of fractures, degree of saturation, rock type, composition, fabric, orientation of bedding or local folds.

(5) Expected Outputs and Impacts
This facility will enable major advances across the field of well testing. The opportunity to verify and refine a wide range of well testing technologies will provide capabilities that improve the discovery and production of water, oil, natural gas, minerals, and other essential resources.

Many of the subsurface science investigations conducted as part of the NeSS project will rely on well testing techniques to provide essential data. Advances in well testing techniques, particularly those that are developed at the NeSS, will have direct application to other studies conducted at the facility.

Advances in well testing capabilities are slow to be embraced by industries where they could be utilized, so educational materials will be one of the outputs of the facility. We expect that the site will be used for field-based short courses that provide hands-on teaching of techniques to practicing professionals and students.
We anticipate that this effort will facilitate important advances in its own right, but it

will also contribute to many of the other technical activities at NeSS, and it will enable the promulgation of modern and innovative well testing capabilities through an educational outreach component.

B.4 Propagation of Hydraulic Fractures (Dr. Jean-Claude Roegiers and Dr. Richard Hughes, University of Oklahoma, Dr. Gary Callahan, Respec)

Goal: To understand the fundamental mechanism(s) that control fracture propagation in a medium containing randomly distributed discontinuities.

Background: From outcrop observations and the few mineback field experiments, it is well known that in-situ discontinuities affect the propagation of hydraulically induced fractures. In general, the resulting geometry reveals an offset of a certain magnitude which is, presently, impossible to predict. On one end of the scale, this offset can be infinite; in which case the induced fracture is "contained". This would be the ideal situation if one wants to keep stimulation treatments within the producing reservoir, avoiding growth into the upper and lower barren barriers. On the other end of the scale, the offset could be nil; in which case the induced fracture has essentially "ignored" the presence of the preexisting discontinuity. This is ideal if one considers the problems associated with the transport phenomena, especially the placement of the associated proppants. In other words, the petroleum industry would like the fracture to be contained in one direction, while avoiding offsets in the other perpendicular propagation direction. About thirty years ago, a number of preliminary laboratory tests where performed on composite parallellipipeds which revealed that the 'arrest' criterion was very much a function of contrasts between the properties of the materials. Later on, some coalbed methane projects involved mining the hydraulic fracture back and revealed both containment and offset, speculating that the behaviour of the discontinuity played the most important role as well as the pumping rate. Thus far, no theoretical approach has been able to provide sufficient guidelines for field treatments.

Proposal:

(i) Theoretical: Using commercially available finite element and boundary element codes, it is proposed that an existing fracture be simulated with all its attributes: cohesion, angle of friction, normal stiffness and shear stiffness; and to study - both in 2D as well as 3D- the evolution of the stress concentration factor as an induced fracture approaches at a certain angle. There is no doubt that the preexisting discontinuity will 'sense' the approaching fracture and that the original stress distribution along the fracture will start to be affected. If one considers, for example, the shear stress distribution, it will change from uniform to bi-modal. Hence, one of the peaks (only symmetrical for a fracture approaching @ 90 degrees) could conceivably exceed the shear strength of the joint, leading to a secondary fracture initiating in the second medium prior to the initial fracture reaching the discontinuity. Such a mechanism, if verified, could explain the offsets and one should gain some insight on the parameters governing their magnitudes.

(ii) Experimental: A number of servo-controlled laboratory experiments could be conducted on stacks of blocks subjected to triaxial loading conditions. A polyaxial frame of 10,000 psi differential capacity is indeed available; this equipment has seven independent loading systems, allowing the various lithologies to be subjected to different lateral stress conditions. Recent experience with joint castings will also allow varying the roughness of the existing discontinuities. The central block would contain a small pressurized borehole from which a hydraulically induced fracture would be propagated. This experimental phase would be carried out to validate some of the theoretical developments.

Specific Opportunity Afforded by NUSL at Homestake Mine: The National Underground Science and Engineering Laboratory will provide unique opportunities for this particular project in that the crystalline formation already contains a number of fractures which, hopefully, will have been characterized at least as far as their attitude is concerned. It would be easy to drill some short holes from the existing mine workings in a direction which will be dictated by the regional and local in-situ stress tensor. After propagating a hydraulic fracture, any mineback could accurately record the offsets, and by inversing the problem, the characteristics of the intersected discontinuities could be back-calculated. A large underground shear test could then validate the computed data.

Educational Objectives

A detailed educational outreach plan, focusing on hydrogeology, should go here. I suggest we start with K-12 outreach possibilities and a visiting scholar/postdoctoral researcher program.

Implementation

In this section, perhaps we should outline the actual equipment and facilities, both short term and permanent, that will be needed to carry out the science and educational outreach plans described above. Also, the general budget (that Herman Zimmerman detailed we would need) should go in this section.

PART 2-PROPOSED SHORT TERM RESEARCH AND INFRASTRUCTURE ACTIVITIES

A. Proposed Activities

B. Facilities and Footprint

IMMEDIATE RECOMMENDATIONS

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