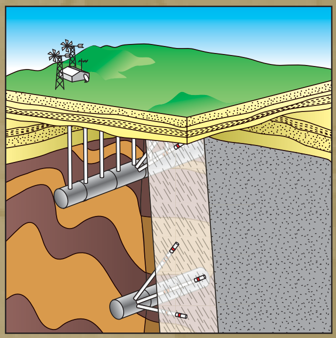
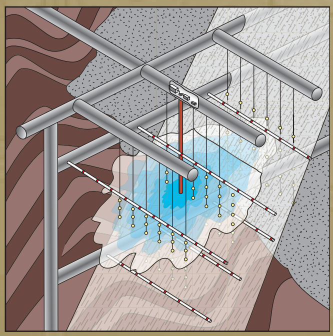
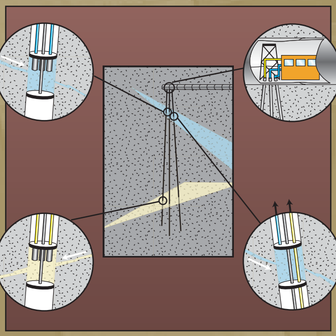
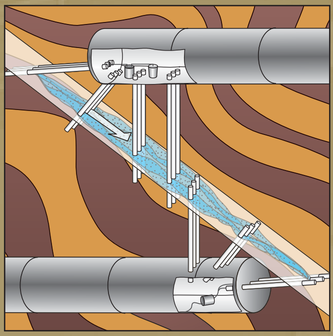
EarthLab

A Subterranean Laboratory and Observatory to Study Microbial Life, Fluid Flow, and Rock Deformation









A Report to the National Science Foundation

This report was prepared for the National Science Foundation by the EarthLab Steering Committee on behalf of the NeSS 2002 workshop participants and other contributors. Support for the workshop and report was provided by the National Science Foundation.

EARTHLAB

A Subterranean Laboratory and Observatory
to Study Microbial Life, Fluid Flow, and Rock Deformation

A Report to the National Science Foundation

June 2003

EarthLab Steering Committee

Brian McPherson*, New Mexico Institute of Mining and Technology

Derek Elsworth, Pennsylvania State University

Charles Fairhurst, University of Minnesota

Stephen Kesler, University of Michigan

Tullis Onstott, Princeton University

William Roggenthen, South Dakota School of Mining and Technology

Herb Wang, University of Wisconsin

*Steering Committee Chair

Contents

Project Summary 1

EarthLab: An Exciting Opportunity to Study Interactive Geologic and Life Processes 2

Scientific Themes 7

- Microbial Life at Depth 8
- Hydrologic Cycle 13
- Rock Deformation and Fluid Flow 17
- Rock-Water Chemistry 20
- Deep Seismic Observatory 24
- Geophysical Imaging 26

Integrated EarthLab Activities 28

- Characterizing the EarthLab Site 29
- Ultradeep Life and Biogeochemistry Observatory 31
- Deep Flow and Paleoclimate Laboratory and Observatory 35
- Induced Fracture and Deformation Processes Laboratory 40
- Deep Coupled Processes Laboratory 45

Scientific and Engineering Innovation 48

Education and Outreach 52

Management and Partnerships 54

Further Reading 57

Appendix 1: Contributors 58

Example Sites

- Homestake Mine, Lead, South Dakota 11
- Soudan Mine, Soudan, Minnesota 15
- Waste Isolation Pilot Plant, New Mexico 23

Project Summary

EarthLab is an initiative to build a laboratory in the deep subsurface to study the biological, geomechanical, hydrological, and geochemical processes that modify Earth from its surface to the limit of habitable depths. The EarthLab facility will consist of multiple specialty laboratories for specific subterranean experiments as well as multiple observatories for monitoring active processes and collecting critical data. These laboratories and observatories will expand our knowledge of Earth's subsurface by permitting direct studies from within. We currently have only limited direct observations within the deep subsurface of microbes that precipitate and dissolve minerals and generate gas, migrating fluids that weaken earthquake-generating faults and change rock compositions, and stress and strain that cause rock to deform slowly and break suddenly. Furthermore, biogeochemical processes, groundwater flow, rock-water interaction, and rock deformation are all coupled in complex ways. A more comprehensive understanding of this coupling is critical to interdisciplinary research ranging from earthquake engineering to bioremediation to exploration for new groundwater resources. The large number and wide variety of scientists that will focus on these problems will help EarthLab achieve its goals.

To carry out the needed experiments, and to observe changes over the long term, EarthLab requires a large-scale underground excavation where drilling, coring, and tunneling can access a variety of structural, hydrological, biological, and geochemical environments. EarthLab's underground operations should encompass a crustal volume of tens of cubic kilometers and should extend to several kilometers depth to permit studies of how these complex phenomena scale with distance, depth, and time. Such a facility will be a unique resource for multidisciplinary and multi-institutional investigations for the international geological and biological science and engineering communities.

In addition to pursuing its primary research agenda, EarthLab will also seek to develop partnerships with the bioremediation, biotechnology, and pharmaceutical industries to develop practical applications of its subsurface biosphere research. Other potential industry applications include developing new geophysical and geochemical tools for characterizing the subsurface and new geological mapping, rock drilling, and other engineering technologies for subsurface exploration and construction. By partnering with NASA, these new technologies could also be adapted to explore for subsurface life within our solar system.

An important part of EarthLab's plan, which crosses all basic scientific and engineering disciplines, is to support a very active program to educate and train future generations of scientists and teachers from pre-college to postgraduate, focusing on underrepresented groups.

The EarthLab concept and goals are a result of many discussions between the physics and Earth science communities, including those held at a joint conference, "Neutrinos and Subterranean Science 2002," or NeSS 2002, held in Washington, D.C. in September, 2002. The physics community has long expressed the need for a deep subsurface laboratory to house new experiments in nuclear, particle, and astrophysics, and new detector technologies that require a deep subterranean site. EarthLab's activities will be closely linked and integrated with those of the physics community and with other regional academic centers to take full advantage of shared technological infrastructure, research expertise, and education and outreach capabilities.

An Exciting Opportunity to Study Interactive Geologic and Life Processes

Most Earth processes are coupled in complex ways. For example, tectonic forces cause rocks to bend and fracture, in turn altering the permeability and porosity of rock, and therefore the directions and rates of fluid movement. Changes in fluid pressures cause changes in the elastic response of rocks to deforming forces, which control movement along faults and, ultimately, the frequency and magnitude of earthquakes. Fluids also distribute environmentally and economically important elements and compounds in the crust, many of which are dissolved in and precipitated from geothermally heated water.

By providing three-dimensional access to large volumes of rock in the shallow subsurface and at depths up to several kilometers, EarthLab will permit a variety of outstanding biological, hydrological, geochemical, geomechanical, and geophysical questions to be addressed, many of which cross disciplinary boundaries (see The EarthLab Underground Observatory box on pages 4-5).

Microbial Life at Depth

One of the great frontiers in the life sciences in the coming decades is the study of life in extreme environments, including the deep subsurface. Fluid flow, energy transfer, and nutrient fluxes control the distribution of life at depth. We know surprisingly little about these processes especially under conditions of high pressure, temperature, and environmental stress in complex geological environments. A better understanding of the feedbacks among key processes is critical to understanding how microbial life survives and proliferates at depth. Microbial activity generates gas and mineral precipitates, and dissolves minerals; these processes, in turn, affect rock permeability, fluid flow, and rock strength. Detecting these by-products of life and distinguishing them from abiological processes is the key to developing life-detection technologies for exobiology. These connections can be explored in EarthLab for the first time, where the growth, activity, and transport of microorganisms can be observed *in situ*.

Hydrologic Cycle

Groundwater is a key source of clean drinking water for most of the planet. The need to tap more and deeper aquifers is increasing as surface water supplies cannot keep up with the growing world population's thirst. To take full advantage of groundwater supplies, we need to know more about how it moves through the subsurface. We need to be able to predict the consequences of aquifer reduction or depletion at the local and regional scale, and how fast some aquifers recharge—if at all. We need to gain a better understanding of how fluid pathways protect water supplies from waste contamination, and how surface water infiltrates the subsurface to plan the locations of roads and communities. In the past, drillholes have been the primary means of obtaining information on subsurface fluid flow. The significantly larger surface area of tunnels, combined with EarthLab's three-dimensional lay out and detailed

"Additional *in situ* research facilities should be developed in fractured rocks in a variety of geological environments."

NRC, 1996

maps made of the subsurface geology, will permit the needed controlled experiments to be designed and conducted.

Rock Deformation and Fluid Flow

The transport of fluids and mobile compounds through fractured rock is fundamental to processes ranging from recovering resources such as water, oil, and gas, to protecting the environment, or understanding the formation of ore deposits. Rock deformation and fracture are controlled by the stress field and fluid pressure field. Many aspects of rock deformation are influenced directly, or even controlled, by fluid flow. Compaction of rock porosity drives fluid flow and fractures and faults may be conduits or flow barriers. The mathematical theory describing coupling between fluid flow and rock deformation is established and accepted, but direct observations are mostly limited to tests performed in surface laboratory machines. EarthLab offers the opportunity to observe and investigate coupled fluid flow and rock deformation *in situ*, within the rocks while fluids flow through them.

Rock-Water Chemistry

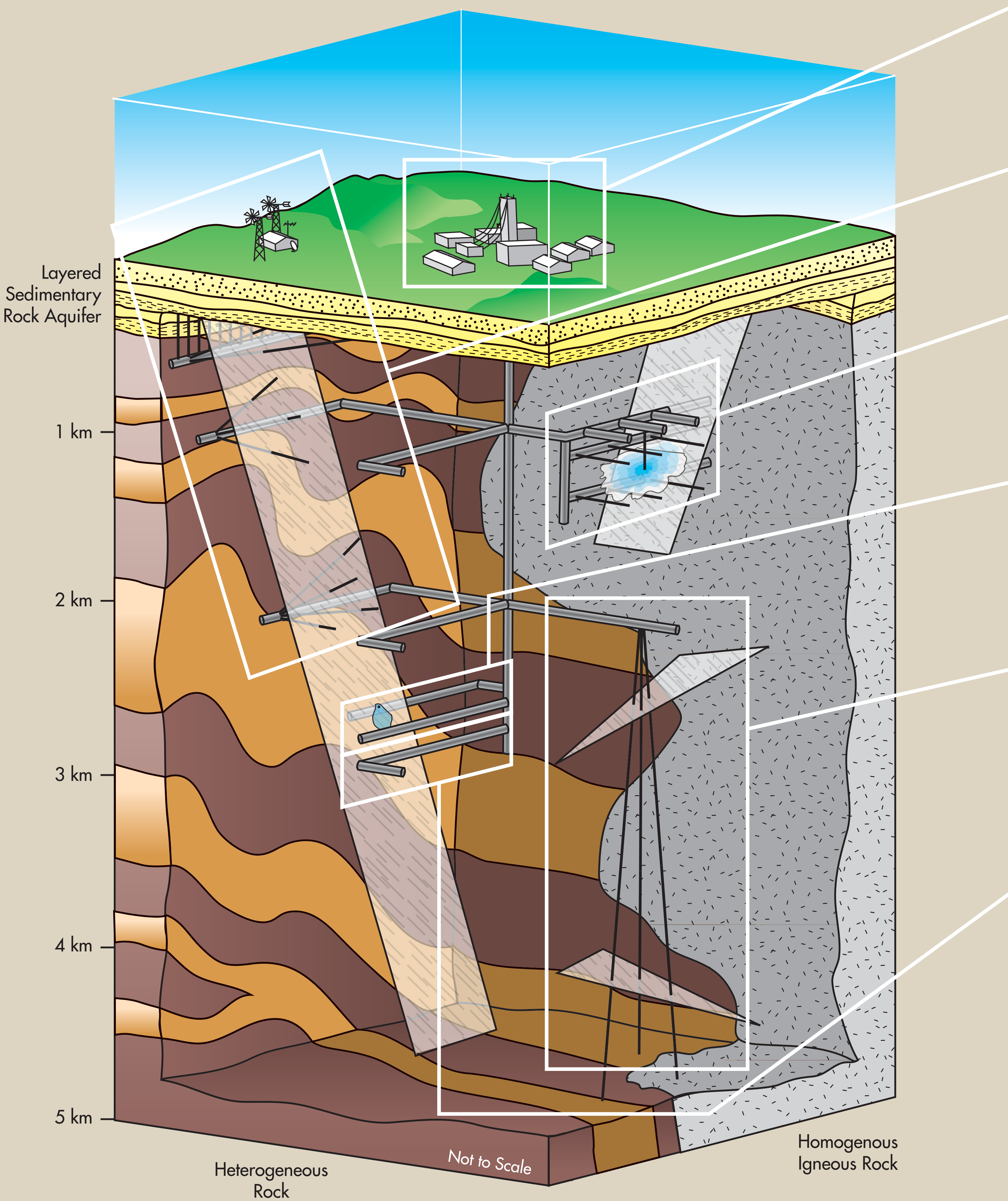
Chemical reactions between rocks and water cause enormous changes in the composition of both and are of great importance to society. These reactions control the quality of drinking water, the rate of weathering that forms soil and acid mine drainage, the processes that form mineral deposits, and the development of stable rocks for foundations and other construction. Rates and types of these chemical reactions depend directly on changes in temperature, pressure, and water composition, all of which vary greatly in the subsurface environment. Although studies on outcropping rocks have provided many important insights into these processes, studies in EarthLab are needed to provide better information on small-scale variations related to changes in mineralogy, permeability, and other characteristics of the rocks that host the water. EarthLab offers the opportunity for improving our ability to predict how rock and fluid chemistry evolves through direct experiments.

Deep Seismic Observatory

Most seismic observatories are at or near Earth's surface where cultural noise, wind and barometric changes, surface topography, and a high degree of rock heterogeneity increase difficulties in data interpretation. A unique, 3-D seismic observatory at depths of over 2 km in EarthLab will overcome most of these problems, providing the potential for recording seismic signals with a fidelity never before achieved. The recorded seismic data will contribute to studies of deep Earth structure as well as local geologic structure, and will provide improved precision for a variety of studies such as location of seismic events and determination of seismic source properties. EarthLab data will also complement those of EarthScope's SAFOD and USArray components.

The EarthLab Underground Observatory:

Studying Microbial Life, Fluid Flow, and Rock Deformation



Surface laboratories for core, water, gas, and microbial analyses, experiments, and archives. Geophysical and hydrologic data from subsurface sensor arrays and geologic mapping are gathered here and recorded on computers for three-dimensional (3-D) display and modeling analyses. The surface complex also includes health and environmental safety laboratories as well as lecture rooms and teaching labs for education and outreach with interactive experimental displays and tour guide facilities.

The Deep Flow and Paleoclimate Laboratory and Observatory will search for continental paleoclimate records and document deep transport processes by instrumenting a sub-vertical fracture zone that extends from the surface to the maximum depth of the laboratory. The experiment will provide important new information on the movement of groundwater in the crust and its relationship to Earth's changing climate.

The Induced Fracture and Deformation Processes Laboratory will conduct extensive studies of three-dimensional rock deformation in heterogeneous rock formations. A borehole array within a vast a rock volume will be instrumented to monitor environmental changes associated with mining out a large cavity, propagating a fracture using high-pressure fluid, and heating a small rock volume. The resulting data are critical to scaling-up models used to predict long-term stability of subsurface excavations.

The Deep Coupled Processes Laboratory will determine the relation among thermal, mechanical, hydrological, chemical, and biological processes in the subsurface environment by performing injection and transport experiments at several different depths along highly instrumented and well-characterized fracture zones. These experiments will aid in subsurface waste disposal, including sequestration of CO_2 or high-level radioactive waste, and alleviation of acid mine drainage.

The Ultradeep Life and Biogeochemistry Observatory will search for the limits of life using three closely spaced boreholes that attain depths up to 5 km and bottom-hole temperatures of 110-120°C, the maximum known temperature for life.

The Deep Seismic Observatory will investigate the fundamental physics relating fracture formation to seismic wave propagation and will monitor local and global seismic events, and mining-induced seismicity, using a fully three-dimensional array consisting of at least 60 broadband seismometers in tunnels and boreholes.

Key Numbers for EarthLab

- Anticipated total tunnel length: ~ 10 km
- Greatest tunnel depth: 2.0 to 2.5 km
- Number of instrumented boreholes: ~ 140
- Total length of rock core collected: ~ 15,000 m
- Operations personnel (including visiting scientists): ~ 50
- Size of surface facility (education, laboratories, and archives): ~ 50,000 sq. ft.

Geophysical Imaging

A common way to develop a subsurface cross-sectional image of a region is to conduct a seismic survey. While the cross sections are actually a measure of the travel time of seismic waves bouncing off layers within Earth, we assign geology to these layers based on general knowledge of regional geology or specific information from local boreholes. EarthLab will permit a significantly superior analysis of geophysical images such as seismic cross sections because of the directly available, detailed knowledge of rock types, fractures, and fluids throughout a large, deep, three-dimensional volume of rock. This "ground-truth" analysis of geophysical images could be applied to studies of the deep geology of other regions.

Priority Attributes of EarthLab

1. Long-term access to large (~20+ km^3) volume of subsurface in which geological features are well characterized in three dimensions, including appropriately placed sensing equipment.
2. Ability to access this environment through selective/choice placement of drill holes, underground workings, laboratories, or observatories. Accessed host rock should reach temperatures of 120°C and water-filled fracture systems.
3. Ability to modify geochemical characteristics of this environment by introduction of materials into holes or workings. At least one fracture zone should be accessed by multiple holes that are instrumented with an array of samplers for transport studies.
4. If an existing mine is chosen as the EarthLab site, complete access to entire archive of existing data and samples.

Selection Criteria for EarthLab Site

Diverse chemical and physical environments, including:

- Variety of hydrologic environments, such as highly permeable, near-surface soils and alluvium vs. deeper, low-permeability crystalline rocks.
- Variety in groundwater compositions, such as high vs. low salinity, pH, and dissolved gas concentrations.
- Variety of structural environments, especially density and orientation of faults and fractures.
- Variety of geochemical environments, especially in concentration of reduced minerals (e.g., sulfides) vs. oxidized minerals (e.g., hematite).

Scientific Themes

EarthLab will be the only facility in the world offering long-term access to a deep, well-characterized, three-dimensional, large-scale subsurface environment for multidisciplinary, multi-institutional experiments. EarthLab's accessible infrastructure will extend to depths of 2.0 to 2.5 kilometers and laterally for several kilometers, and will operate borehole arrays reaching depths of 4-5 kilometers. Because EarthLab's enormous volume will encompass a wide variety of geological, hydrological, and structural environments, EarthLab will be able to perform a wide range of experiments and record observations with economic efficiency and minimal duplication. On-site access to cutting-edge technologies for real-time detailed biological, geophysical, mechanical, and geochemical interrogations will establish EarthLab as the world leader in subsurface science and engineering research. As part of its leadership role, EarthLab will facilitate and integrate subsurface research and development at underground laboratories in other countries, including Canada (Sudbury and Underground Research Laboratory), Sweden (Aspo), Italy (Gran Sasso), and South Africa (various mines).

EarthLab will be the only facility in the world offering long-term access to a deep, well-characterized, three-dimensional, large-scale subsurface environment for multidisciplinary, multi-institutional experiments.

Microbial Life at Depth

A major obstacle to understanding the subsurface biosphere has been our limited ability to access the deep terrestrial environment, to acquire uncompromised samples, and to observe *in situ* the relationships between subsurface microbial ecosystems and the geochemical and hydrogeological processes that control their growth, function, and mobility. Recently, samples collected by the Ocean Drilling Program have permitted scientists to make enormous strides in understanding the microbiology of marine sediments. Studies of biogeochemical and microbial transport in well-characterized, continental aquifers, however, have been limited to brief experiments in two-dimensional well arrays in shallow, geographically dispersed locations, most of which are contaminated by toxic organic or metallic complexes. This has hampered the development of accurate, large-scale models for these complex, interrelated transport phenomena, which are critical to protecting drinking water resources, to subsurface sequestration of CO_2, and to storage of radioactive waste. A recent report on geobiology (Nealson and Ghiorse, 2001) emphasized the need for establishing field laboratories for geomicrobiological research that are available for long-term studies, a need that EarthLab will fulfill.

EarthLab will focus on three major microbial research thrusts: (1) subsurface microbial ecology, which examines how the crustal environment influences subsurface microbial communities, (2) subsurface biogeochemical processes, which seeks to understand how subsurface microbial communities alter the crustal environment, and (3) subsurface abiological processes, which examines the geochemical processes that occur within and beyond the subsurface biosphere. One of EarthLab's first achievements will be a complete vertical profile of the subsurface biosphere from the base of the rhizosphere (soil zone), through the deeper mesophilic, thermophilic, and hyperthermophilic zones and into the hydrothermal zone (Figure 1). EarthLab will also initiate a new technological discipline, subsurface biological resource exploration and development. This research and training program will combine science and engineering approaches to explore biotechnological applications of novel subsurface microorganisms and their enzymes and how to identify those subsurface environments with the greatest potential for extremozymes (see Scientific and Engineering Innovation, p. 48).

Subsurface Microbial Ecology

This research area explores the limits, evolution, and adaptation of life in the subsurface; how microbial communities change in response to alterations in their nutrients and energy sources; subsurface chemical, geological, and hydrodynamic properties that contribute to the migration and genetic adaptation of life in the deep subsurface; how microorganisms repair their DNA, cell walls, and membranes under very slow, *in situ* growth rates; and the stability of subsurface microbial enzymes to temperature changes. Delineating and integrating paleohydrology and thermal history with microbial ecology is essential to constraining evolutionary hypotheses, particularly the long-term and large-scale microbial migration in the crust and the impact of geological thermal episodes. These studies will also provide guidance to investigations of subsurface life on other planets and satellites in our solar system. Some of the more significant scientific questions are:

- What is the upper temperature limit of life? This temperature controls the depth boundary between the biological hyperthermophile zone and the abiotic hydrothermal zone in the crust. Is it 120°C, the highest

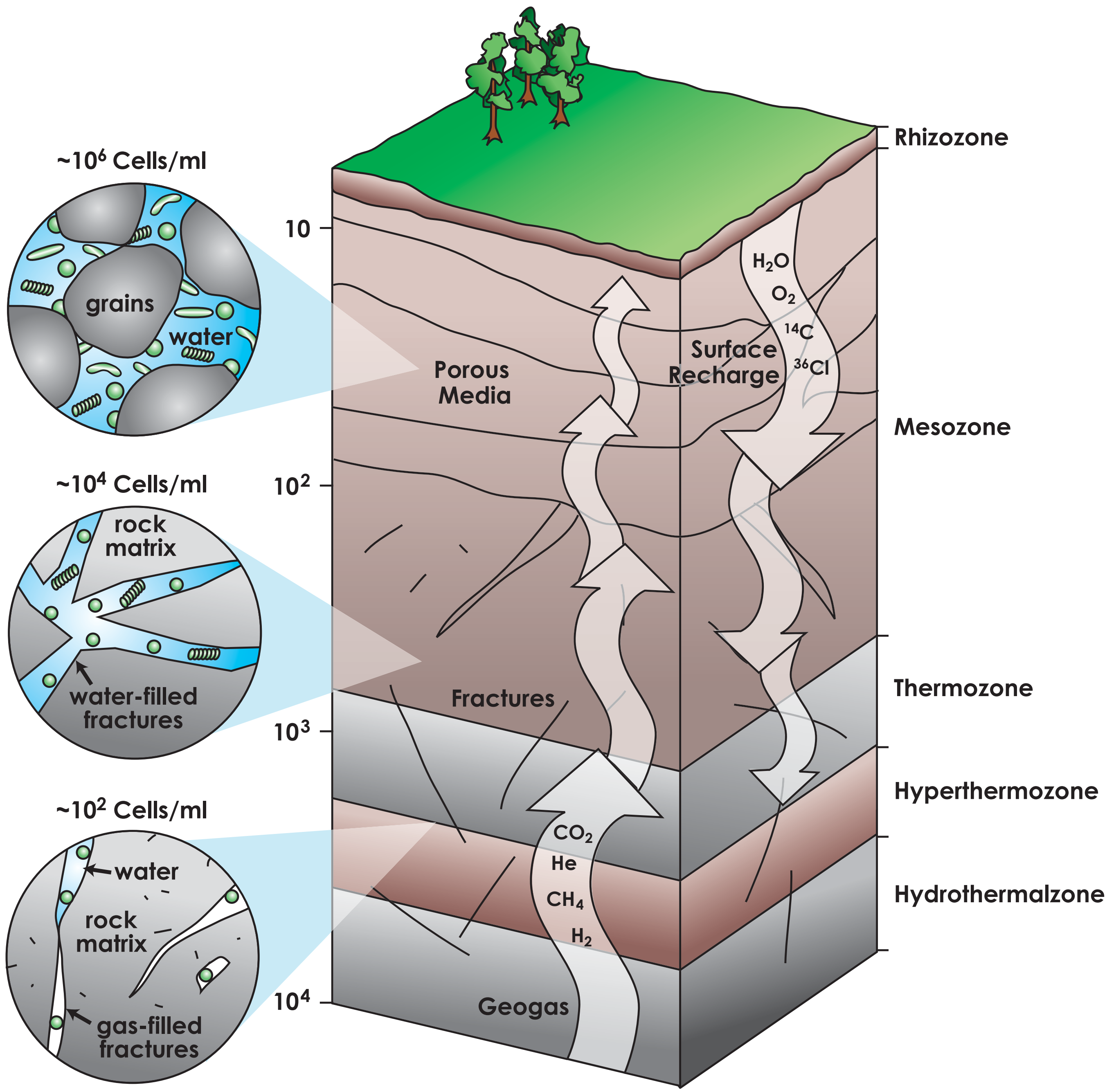


Figure 1. Subsurface biosphere. Microbial diversity and abundance, porosity and permeability decrease with increasing depth. Geogas produced by abiological processes migrates upward diminishing with decreasing depth. Water, O_2, and rhizozone-generated isotopes and nutrients migrate downwards, diminishing with increasing depth. These two fluxes combine with water/gas/mineral interactions to sustain microbial communities. Rhizozone is the same as soil zone or rhizosphere. The subsurface biosphere has been subdivided into Mesozone (10°C < T < 40°C), Thermozone (40°C < T < 80°C), Hyperthermozone (80°C < T < 120°C), and Hydrothermalzone (T > 120°C).

These studies will also provide guidance to investigations of subsurface life on other planets and satellites in our solar system.

survival temperature known for a microorganism in the lab, or can it reach higher levels under favorable circumstances?

- Is large-scale vertical transport of shallow subsurface or soil microorganisms to the deep subsurface occurring with fluid flow? If not, what limits their mobility? In other words, is there a connection between the rhizosphere and the deeper mesophile, thermophile, and hyperthermophile zones, or have these zones been isolated over geological epochs?
- Do deep subsurface microorganisms possess metabolic plasticity that enable them to use several electron acceptors and donors, or do they develop syntrophic microbial relationships where one microorganism facilitates the metabolism of another by using its waste products?
- Is the average life span for microbial cells in these deep environments on the order of thousands of years?
- Do the rates and/or the variability of fluid flux through subsurface fracture networks dictate the quantity, diversity, and activity of microorganisms present? Or, are fracture formation and nutrient flux from the rock matrix into fluid-filled fractures more important factors for sustaining subsurface ecosystems?
- Are the microbial communities colonizing fracture surfaces significantly different in diversity and abundance compared to freely floating (planktonic) communities?

Subsurface Biogeochemical Processes

Over geological time, microorganisms have completely altered Earth's atmosphere, ocean, and land surfaces. With increasing depth and temperature and diminishing pore space, the impact of microbial communities on their environment must decline to the point where high-temperature diagenetic and hydrothermal reaction rates dominate. EarthLab will delineate this transition both in space, using *in situ* experiments, and over geological time, using a combination of geochronology, geochemistry, and petrology.

Subsurface biogeochemical processes emphasize the role of microorganisms in the dissolution, nucleation, and precipitation of mineral phases, the transport and transformation of aqueous chemical and gaseous species, and the alteration of hydrologic properties (i.e., storage capacity and permeability) of aquifers. How microbial colonization of various mineral surfaces affects the water/mineral and dissolved gas/mineral interactions can only be validated by *in situ* observations. Important questions include:

- Will subsurface, chemoautotrophic, and heterotrophic microbial communities contribute to CO_2 sequestration in deep subsurface environments by carbonate precipitation, increasing the pH, or conversion to CH_4 and organic acids?
- In deep subsurface environments where gas and water occur as separate phases, for example, in vadose zones (zones above the water table), natural gas reservoirs, or CO_2 injection sites, will planktonic microbial

Homestake Mine, Lead, South Dakota

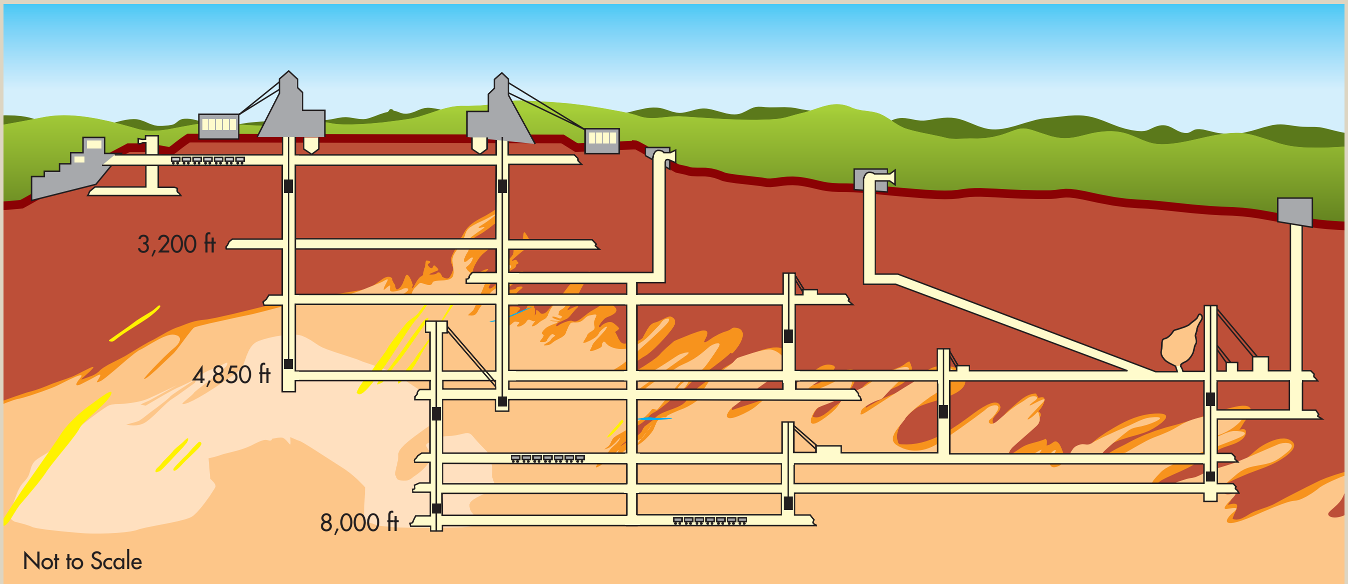
Contributed by Ed Duke, South Dakota School of Mines & Technology

The Homestake mine, located in the Black Hills at Lead, South Dakota, has hosted a neutrino detection facility for 35 years. The mine reaches a depth of 8,000 feet, and its network of 370 miles of underground workings provides direct access to a subterranean volume of rock totaling nearly 8 cubic miles. Prior to closing in December 2001, the Homestake mine had been in continuous operation for 125 years and had produced more than 40 million ounces of gold, ranking it among the largest gold deposits in the world. Because the mine has been pumped and kept dry for over a century, baseline hydrologic and thermal conditions are well known, providing an ideal setting for studying microbial life processes in the deep subsurface.

Among possible sites for EarthLab, Homestake is unique. In addition to the established baseline hydrologic and thermal conditions, the combination of diverse geology—spanning over 2 billion years of Earth's history—and exceptional accessibility in three dimensions creates a fertile environment for collaboration among geoscientists from many subdisciplines.

The earliest geological events recorded in the mine include deposition of unusual chemical sediments—the Homestake iron formation, which contains high concentrations of metals and which may have included primitive forms of microbial life. Deep burial, intense deformation of the rocks, and metamorphism occurred 1.7 billion years ago. These coupled processes culminated in the gigantic fluid flow system that deposited the world-class gold ore bodies. In the more recent past, uplift of the Black Hills began 60 million years ago and was followed by intrusion of alkalic magmas and a second major period of hydrothermal mineral deposition in the mine.

Understanding the age and evolution of isolated microbial ecosystems that may be preserved in this deep environment will require unraveling the complex temperature-depth history of the rocks from the Precambrian to the present. Today, the Black Hills is the recharge area for important regional aquifers, and the vertical extent of the mine provides a rare opportunity to observe interaction between deep and shallow groundwater flow systems as well as the effect of weathering and mineral reactions on the chemistry of groundwater.



communities concentrate at the interface between gas and enhance the flux of dissolved gases into the water?

- Do the microbial communities colonizing fracture surfaces enhance the flux of energy substrates and nutrients from the rock pores and dissolve mineral surfaces to sustain growth?
- How well do theoretical free energy calculations based upon aqueous chemistry predict the type of microbial communities?
- What is the subsurface nitrogen cycle and do microorganisms control it as they do in the oceans?

Subsurface Abiological Geochemical Processes

Because of uplift and erosion, the rock strata housing EarthLab will contain a geological record that documents the transition from the ~300°C hydrothermal zone, where abiological, rock-water interactions dominate, to a lower temperature (<120°C) zone where biologically catalyzed rock-water interactions take place. The hydrothermal zone will be preserved in low-permeability zones or gas-tight rock, whereas the lower-temperature zone will be associated with fractures and permeable rock strata that permit meteoric fluid penetration from the surface. EarthLab will offer an unprecedented opportunity to document the depth and rate of the crustal weathering process that moves rock volumes from the hydrothermal zone to the lower temperature zone. This will be studied by obtaining pristine rock cores at specific distances from mapped fractures. The fluids inside these cores will be dated by noble gas isotopic analyses. If the pore throat diameters of these rock strata are too small to permit colonization by bacteria, then they provide an abiological control or end member to compare to the subsurface biogeochemical processes studied above. Some of the more interesting questions include:

- Are reduced organic species being produced in the crust by interaction of inorganic species with reduced metal oxides and sulfides (i.e., ore deposits)?
- What are the attributes of mineral precipitates formed by hydrothermal processes that distinguish them from those formed at lower temperatures by microbial processes?
- How does the composition of water and gas vary as a function of depth through typical continental crust? In particular, what buffers the oxidation potential and pH?
- Do abiological processes control the C:N:P composition of groundwater or does microbial growth and respiration control it as it does in the oceans?

Hydrologic Cycle

Water is a precious resource and commodity that is becoming more valuable as our population expands. Surface water and groundwater are used in all aspects of our lives, from drinking water to agriculture to industry (Figure 2). Groundwater has become an increasingly important resource because it has some significant advantages over surface water supplies (Figure 3). It protects us from surface-borne pathogens and decreases susceptibility to contamination of water supplies by terrorists or inadvertent means. Wastes that should be isolated from the surface can be stored in subsurface areas that lack potable groundwater. Knowledge of fluid pathways provides assurance that the wastes will not migrate into important aquifers.

To understand the natural hydrologic cycle and to quantify its critical components, we need direct measurements of subsurface properties and processes that control fluid flow. These will lead to better characterization of the relationship between surface infiltration and subsurface groundwater recharge and flow. Such measurements are most critical for 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. Important scientific issues concerning the hydrologic cycle are described below.

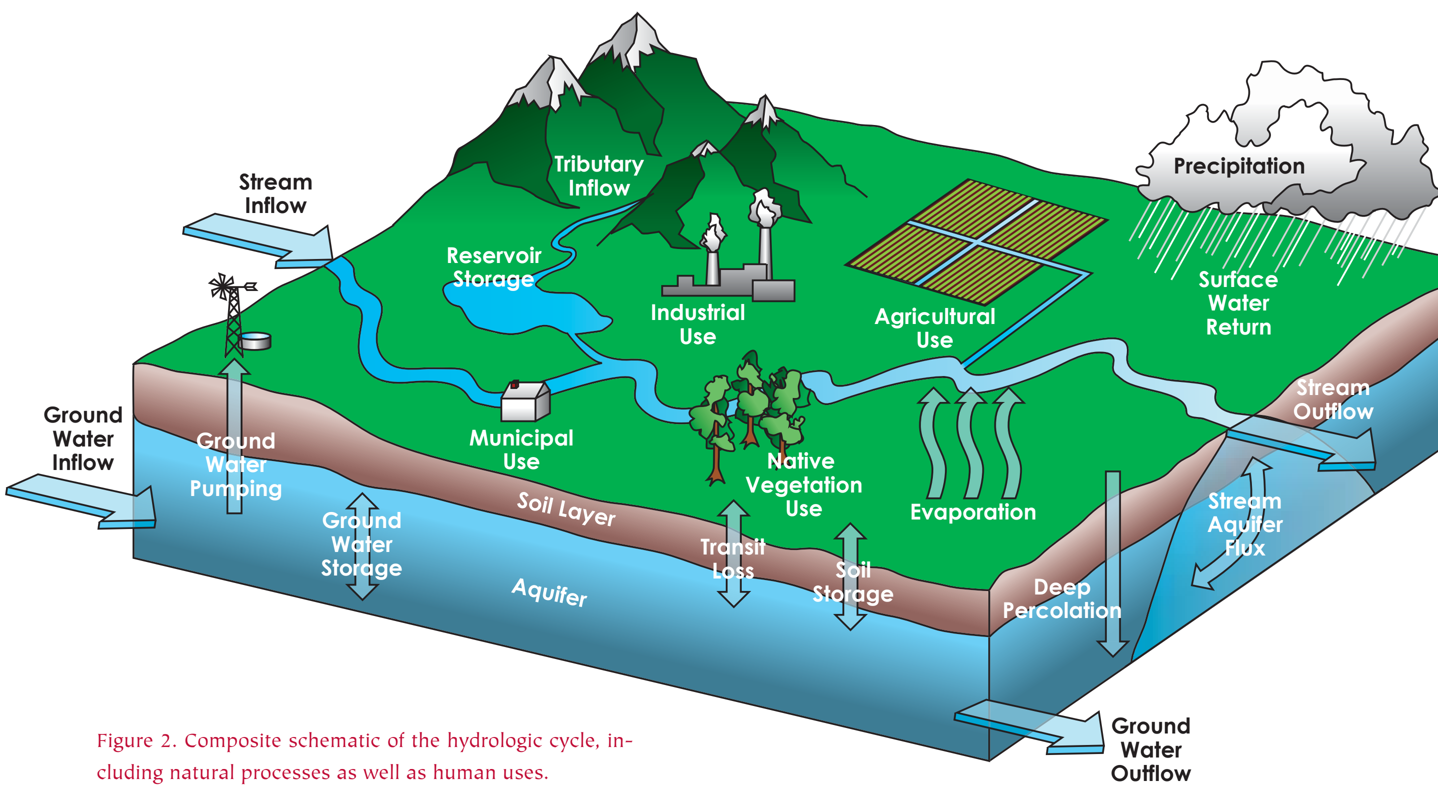


Figure 2. Composite schematic of the hydrologic cycle, including natural processes as well as human uses.

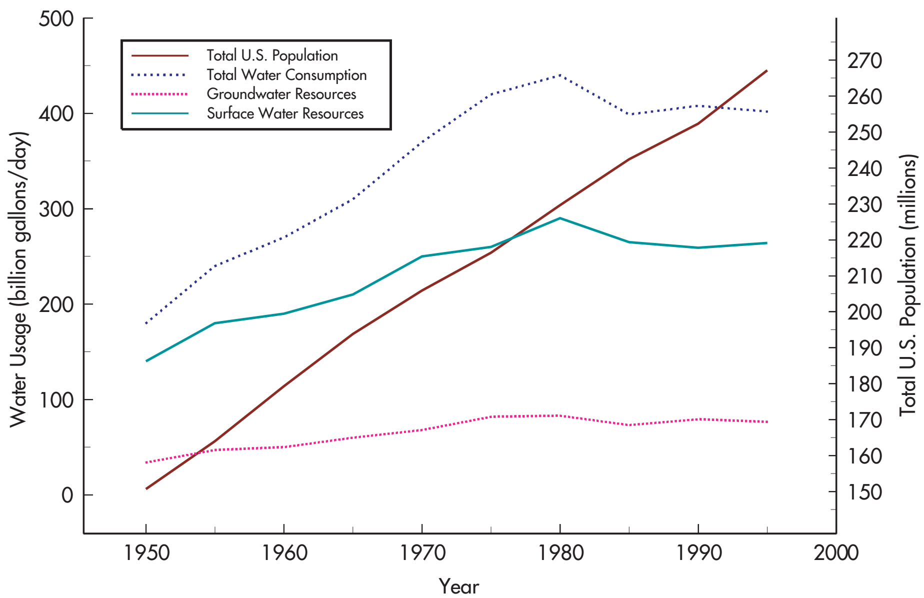


Figure 3. Breakdown of water use by type of use, compared to population growth through time. Water consumption has declined since 1980, but that reduction is primarily from decreased use of surface water resources. Exploitation of groundwater resources has not decreased significantly, suggesting that groundwater exploration must be improved to ensure an adequate water supply, especially in those areas not served by surface waters. Data from "Estimated Use of Water in the United States in 1995," United States Geological Survey Circular 1200 (http://water.usgs.gov/watuse/pdf1995/pdf/circular1200.pdf).

Infiltration of Surface Water to the Subsurface

Recharge of surface water to the water table—the point at which water from the atmosphere joins groundwater—is a crucial link in the water cycle. Many factors affect the spatial distribution of infiltration and the ratio of infiltration to surface runoff, including surface topography, surface geology (rock/soil types, local terrain variability, local and regional structural geology), vegetation, and climate, all of which are routinely modified by humans.

A better understanding of how surface water reaches subsurface aquifers has many important practical applications, such as evaluating the impact of land development on our water supply. Another critical application is improving our ability to predict the movement of water through radioactive waste repositories located in the deep subsurface, an issue under consideration in many parts of the country. Water movement through such systems is enhanced by the presence of fractures, but to date, no system has been available in which a large volume of unsaturated fractured rock could be extensively sampled in both vertical and horizontal dimensions. EarthLab provides the opportunity to evaluate direct indicators of infiltration rates and fault/fracture patterns, as measured from the inside, rather than inferred from the surface.

Key questions are:

- What are the pathways that water takes through soil and rock once it infiltrates the subsurface?
- What are the interrelationships among the physical, chemical, and biological characteristics of the subsurface, and how do they affect infiltration?
- How can the magnitude of recharge and distribution of recharge be predicted using routine measurements?

Soudan Mine, Soudan, Minnesota

Contributed by Marvin L. Marshak, University of Minnesota

The oldest and largest underground laboratory functioning in the United States today is 710 m underground in the Soudan Mine in St. Louis County in northeastern Minnesota. Soudan is a hematite mine, located at the western end of the Vermilion Range, the northernmost of Minnesota's three famous iron ranges. Mining at Soudan started in 1883 and underground mining began at a high level in the 1890s, using stoping techniques imported from Cornwall and workers from a variety of countries, mostly in Eastern Europe.

When U.S. Steel's Oliver Mining Division ceased mining at Soudan in 1962, Minnesota State Parks transformed the mine into a historic tourist attraction. Typically, about 40,000 people visit the underground workings at Soudan each year in a combination of public and school group tours. Science began at Soudan in 1980, when University of Minnesota physicists installed a 30-ton proton decay detector in an existing drift on the 23rd level. In the mid-1980s, the university constructed its first dedicated lab room at Soudan. This lab, 15 m high by 15 m wide by 70 m in length on the 27th level, housed the 1 kiloton Soudan 2 Detector, a tracking calorimeter designed to search for proton decay. Although Soudan 2 never observed any proton decays during 12 years of data collection, it did make important measurements on neutrino oscillations and neutrino mass. The Cryogenic Dark Matter Search (CDMS 2) Detector is currently located in the Soudan 2 Lab.

From 1999 to 2001, the University of Minnesota constructed a second room, 16 m high by 15 m wide by 90 m in length, about 50 m east of the Soudan 2 Lab. The Main Injector Neutrino Oscillation Search (MINOS) Far Detector will be completely installed in this MINOS Lab by summer 2003. Beginning in 2005, the MINOS Far Detector will measure a beam of neutrinos sent to Soudan from Fermilab near Chicago, 730 km away. These measurements will help better determine neutrino masses and the other parameters of neutrino oscillations.

Geologists and other scientists and engineers at Soudan are developing designs for expanding the laboratory downward to provide additional capabilities for underground science and engineering. Basalt, located south and east of the iron formation, is the most likely context for the possible expansion. The expansion plan would take advantage of the existing laboratory and its physical and human resource infrastructure.

The shaft station at the 27th level of the Soudan Mine (from www.hep.umn.edu/minos/images/soudanmine0002.html)

Members of the Soudan Mine Crew (the laboratory staff) entering the shaft cage at the beginning of a shift. The cage descends a half mile to the 27th level to reach the lab in two minutes. (Fermilab Visual Media)

Groundwater Flow

The permeability of crustal rocks—their capacity for transporting fluid—is probably the most fundamental and critical rock property affecting fluid flow in the subsurface. Detailed knowledge of rock permeability is essential for finding and exploiting water resources in the subsurface. It is also useful in tracking and remediating contaminated groundwater, and exploring for oil and gas. A rock formation's permeability may have different values depending on the scale at which it is evaluated (Figure 4), making assessments of fluid flow and aquifer or reservoir capacity highly inaccurate at best. Key questions are:

- What is the relationship between permeability and scale? What scales are appropriate for evaluating and quantifying water resources, calibrating models, or testing hypotheses in general?
- What are the key transport pathways for water, and how can we best measure them?
- How can geochemical tracers be used to accurately predict fluxes of water and solutes through a rock mass?
- Which transport pathways are general to water-saturated environments, and which are unique?

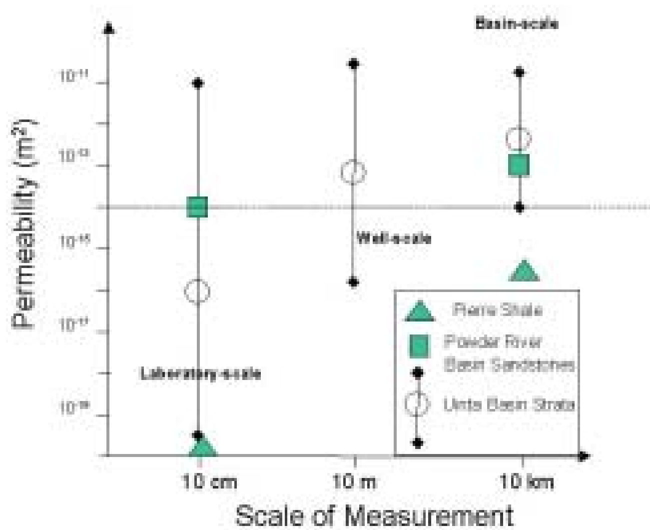


Figure 4. Effect of scale on permeability of rocks in three different sedimentary basins in the United States, including the Uinta Basin, Utah, the Powder River Basin, Wyoming, and the Pierre Shale in South Dakota. Dashed line at 10-14 m^2 indicates inferred average earth crustal permeability. Error bars associated with Uinta Basin data reflect the full range of permeability observed at each scale.

Rock Deformation and Fluid Flow

Rock deformation occurs at many scales, from dislocation cracks to continental faults. Understanding rock deformation and the numerous mechanisms that contribute to it is essential to much science study and engineering activity that share the broad discipline of geomechanics. As the scale of observation is increased, additional mechanisms of deformation come into effect. For this reason, EarthLab provides a unique opportunity to increase our scientific understanding of rock deformation and to improve engineering capability for designing safe, stable structures in rock at depth.

The spatial distribution of fractures and fluid flow, when present within a rock mass, affect its present state of stress and are the product of its geological deformation history. Thermal, chemical, and biological processes also influence fluid flow and the development of fractures. The coupling and feedback among thermal, hydrologic, mechanical (stress), chemical, and biological (THMCB) processes from the lab scale to the scale of large underground excavations to the crustal scale remains one of the outstanding issues in Earth science that cuts across many disciplines. A more accurate model of the interactions among these key processes will not only lead to a better understanding of Earth's history but will also stimulate the development of innovative techniques for resource recovery, waste disposal, site restoration and remediation, and underground construction.

Rock deformation deep in the subsurface is not well characterized, except in a few deep mines, particularly in South Africa. Most present-day deformation is measured at the surface, and these surface measurements are disproportionately made across or adjacent to active faults. Strainmeters, satellite-generated Interferometric Synthetic Aperture Radar (InSAR), and Global Positioning System (GPS) data are used for these surface measurements. Inverse methods of mathematics can be used to estimate the displacements at depth associated with fault motions, and these displacements can in turn be used to evaluate the subsurface stress perturbations associated with faulting. Surface measurements by themselves, however, are completely inadequate for determining the baseline (or ambient) stress distribution at depth, and this baseline distribution must be known to predict how faults will slip and how subsurface excavations will deform. Stress measurements in deep boreholes afford a glimpse of the stresses at depth, but because they are relatively few in number, prone to considerable scatter, and are associated with small rock volumes, they are inadequate to define the stress state for many purposes. Direct, repeatable, *in situ* measurements throughout a large rock volume at depth in a tectonically quiet environment are the only way to define an accurate stress baseline.

EarthLab priorities for geomechanics are to: (1) elucidate the state of stress and stress history of a large rock mass, (2) investigate the nature of three-dimensional fracture systems, and (3) perform active experiments underground to study THMCB coupling.

State of Stress

Fundamental to progress in both geomechanics and tectonics is better knowledge of the spatial and temporal distribution of stresses. Considerable research is needed to provide a more realistic assessment of the state of deformation and stress in rock, on scales ranging from engineering excavations to Earth's tectonic plates. Such studies could assist in verifying the predictions of analytical and numerical models, allowing more confident application of the models to still larger-scale problems. Implicit in this discussion is the need to develop improved experimental procedures for the *in situ* observations.

Techniques are available to determine the state of stress *in situ* and to measure deformation induced by the redistribution of stress, but these are costly procedures and often limited in scope. It is not uncommon to see stress measurements at essentially a point extrapolated far beyond their range of validity. In some cases, isolated point measurements are used to infer stress conditions throughout almost an entire tectonic plate many thousands of square kilometers in extent.

Access to the large rock volume in EarthLab will also permit testing of the hypothesis that Earth's crust is "critically stressed," that is, some portion of the rock is always close to failure by fracture. Repeated shearing of critically stressed fractures can keep flow paths open that minerals precipitated from flowing fluids might otherwise seal. The greatest rock permeability at depth, therefore, is predicted to occur along critically stressed fractures. Characterizing fractures, stress field, and fluid flow within the subsurface will permit a rigorous test (and perhaps an extension) of this critical stress theory.

Key questions EarthLab will address about state of stress in the crust are:

- Is the crust at EarthLab critically stressed as at sites in other stable, intraplate areas?
- How do point measurements relate to regional and global stress values?
- How does stress state vary in scale from borehole to tunnel to regional geology?
- How are stress state and strength related to geologic heterogeneity, the presence of fluids, and rock anisotropy?
- How does stress state affect the stability of tunnels, shafts, wellbores, and large, room-sized excavations?

Fracture Processes

Pervasive fracturing of a rock mass is common and can occur over a broad range of spatial and temporal scales. Fracture persistence, or subsurface areal extent, and fracture connectivity are difficult to predict, making associated engineering efforts prone to significant errors.

Fractures serve as conduits and/or barriers to subsurface fluid flow, so they are important to the flow of groundwater, hydrocarbons, ore-forming fluids, geothermal fluids, and fluids that sustain life deep within Earth. Fracture distributions, and how we think of them, also influence how we design exploration strategies for the subsurface. We still have much to learn about the geometry of fracture systems, the processes that create them, and how they conduct fluids and heat.

To date our most sophisticated characterizations of fracture networks in the subsurface typically involve extrapolating information gained from surface exposures (Figure 5), borehole observations, and inferences drawn from geophysical data. These methods, however, have some limitations, especially when applied separately. Surface exposures commonly are obscured by soil, vegetation, or water, and in many cases fractures formed near the surface are superposed on those that formed at depth. Boreholes sample relatively small volumes of rock, making characterization of large fracture networks problematic. Existing borehole and surface geophysical techniques are unable to detect fractures below certain size thresholds, and they commonly cannot detect details that illuminate how fracture systems develop.

Accurate and detailed information on fracture locations, sizes, orientations, and physical characteristics will be invaluable for testing, improving, and developing new geomechanical models, hydrologic methods, and new non-invasive geophysical methods for subsurface characterization. In general, a trade-off exists between

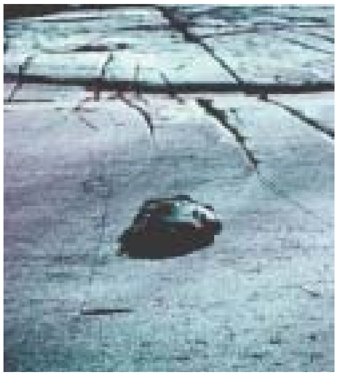


Figure 5. Fracture Network Exposed on Surface Outcrop. Photo courtesy of S. Martel.

geophysical resolution and spatial scale. Innovations developed and tested at EarthLab will provide for more effective and more efficient characterization of subsurface fracture networks in aquifers, in economically viable hydrocarbon reservoirs, and in ore bodies. Note that the geophysical evaluations will be done in conjunction with direct observations rather than separately. This will have a very positive synergistic effect, not just on technique development, but also in fostering interdisciplinary collaboration among geologists, geophysicists, specialists in rock mechanics, and hydrologists.

Subsurface access to a well-exposed, extensive, three-dimensional rock mass will make a tremendous contribution to our understanding of fractures in rock. Key questions that can be addressed are:

- How do fracture networks and faults form and grow?
- At what limiting conditions does the healing of microcracks outstrip their rate of generation, and therefore influence their persistence in time and space?
- How can we improve geophysical imaging of fractures?
- How can we relate geomechanical and hydrogeological properties of faults?
- How do the fractures in a rock volume of about one cubic kilometer relate to regional tectonic patterns?
- How are fracture networks affected by mining and construction activities and vice versa?

THMCB Coupling

Fluid circulation within the crust is not only influenced by the new fractures that may result from changes in stress and temperature, but also by alteration of the permeability of these new fractures by chemical or biological dissolution or precipitation and changes in fluid pressure from chemical or biological activity. The chemical and biological reaction rates are, in turn, controlled by temperature and the transport of energy, and nutrient- and microbe-bearing fluids. THMCB interactions should exhibit strong feedbacks, making their importance at the field scale particularly difficult to extrapolate from small-scale laboratory experiments. Multidisciplinary, large-scale, *in situ* experiments observing THMCB interactions in fractured rock will be one of EarthLab's seminal contributions to the Earth sciences field. These experiments can take advantaged of existing, well-characterized fracture networks to monitor spatial and temporal impacts of thermal, chemical, or biological stimulation on fluid flow and rock stress. By inducing new fracture networks through heating or hydrofracturing, the importance of fracture formation on *in situ* chemical or biological activity can be delineated.

Key questions related to coupled THMCB processes that may be addressed in EarthLab include:

- Under what thermal, chemical, and mechanical (stress) conditions do deep, fluid-conducting fractures remain open or seal by dissolution or precipitation of minerals? Are these conditions influenced by microbial activity?
- How does coupling among fluid pressure, rock stress, temperature, and fracture aperture affect the dynamics of flow and transport in rock?

ROCK-WATER CHEMISTRY

Rock-water interaction involves the many dissolution and precipitation reactions that control the mobility of elements and compounds at and below Earth's surface. Earth varies greatly in composition, in part because groundwater dissolves minerals and rocks and transports their constituents to new locations. This combination of dissolution and precipitation reactions, which is known as rock-water interaction, controls the mobility of elements and compounds and the quality of both water and rock in the crust. Rock-water interaction affects our environment in many ways, determining, for example, the abundance of arsenic in well water (Figure 6), the amount of clay in soil and rock, and the amount of acid drainage from abandoned mines.

EarthLab will allow study of active rock-water interaction at a multitude of scales in both space and time. Most active geochemical processes can be studied in nature only at the surface and after they have evolved for extended periods. The opportunity to observe them in an underground setting, at earlier stages in their evolution and over shorter time scales, will provide better understanding of the processes and will permit extrapolation of results from the laboratory to larger, natural scales. This, in turn, will enhance our ability to use laboratory results to benefit society with, for instance, methods to limit acid mine drainage or dispersal of radioactive waste from disposal sites.

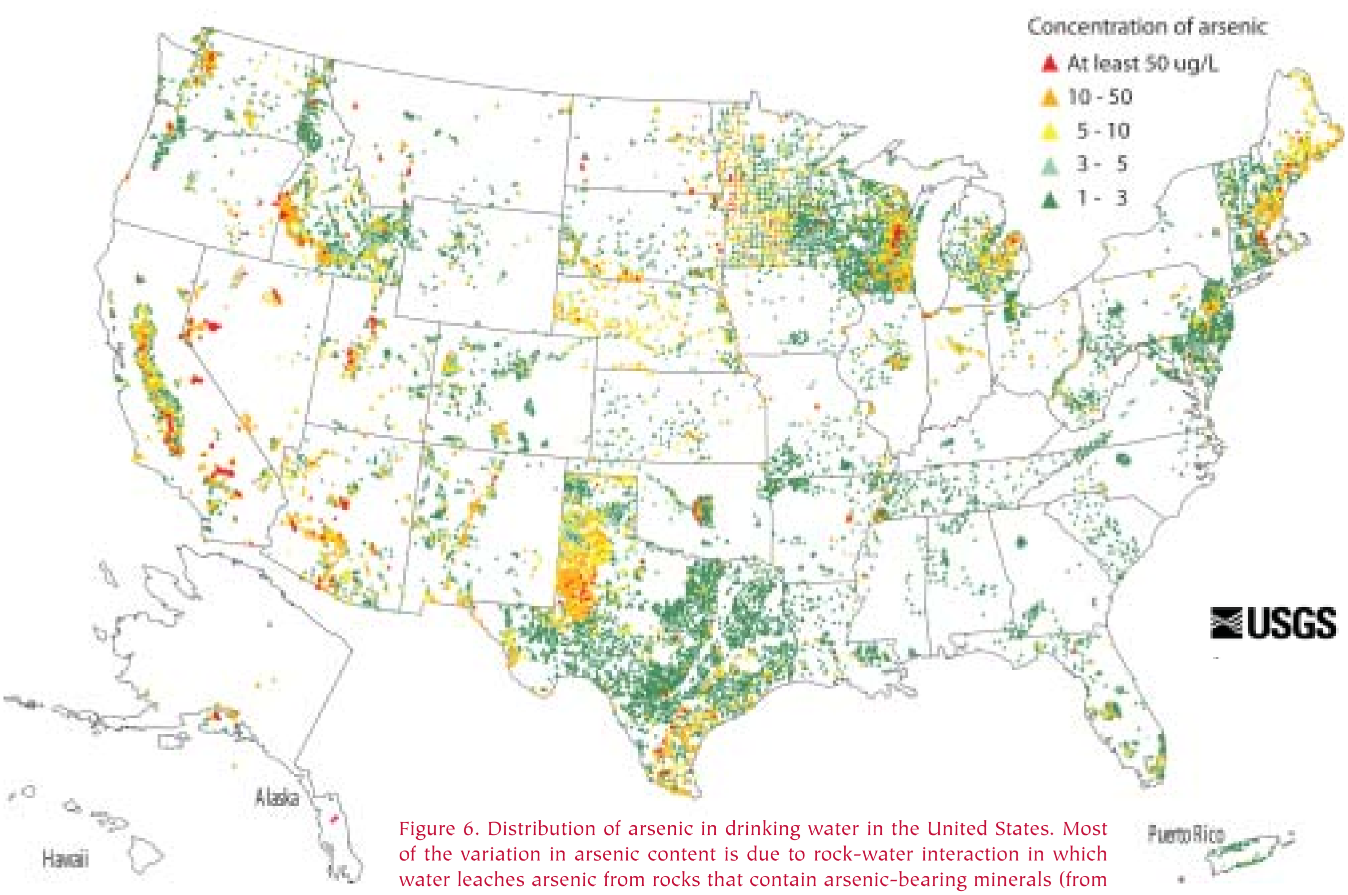


Figure 6. Distribution of arsenic in drinking water in the United States. Most of the variation in arsenic content is due to rock-water interaction in which water leaches arsenic from rocks that contain arsenic-bearing minerals (from U.S. Geological Survey).

Acid Mine Drainage

One of the most important focuses of research on active rock-water interaction in an underground science laboratory is acid mine drainage (AMD). AMD results from active rock-water interactions around working and abandoned sulfide-bearing mines and mine wastes (Figure 7), and it is a multi-billion dollar environmental problem. Over 200,000 active and abandoned mining sites in the United States alone release large amounts of acidic, metal-bearing water into the environment, creating trails of contaminated soil and sediment that extend up to hundreds of kilometers away from their source, usually along rivers and streams. Most AMD-generating sites were created before society recognized this as a large-scale problem. Although AMD has been studied extensively in surface environments, much less information is available on early-stage subsurface processes that generate most of the acid. EarthLab will focus on the processes that initiate oxidative weathering and the minerals that form when this process is interrupted.

Chemical reactions that take place between water and sulfide minerals, the main cause of AMD, are among the most complex and dynamic of all geochemical processes. When these reactions take place in the presence of oxygen, they can generate AMD solutions with pH values as low as -3.6, which are the most acid natural waters observed so far at Earth's surface. Where AMD effluent mixes with air and oxygenated surface water, it precipitates iron oxides, oxyhydroxides, and/or hydroxysulfates that contain very high concentrations of toxic heavy metals. At the surface, these minerals can be dispersed as sediment into surrounding streams, rivers and groundwaters. In underground mines where waters are pumped away, however, they precipitate on walls of fractures and remain there until they are dissolved again as the mine floods. Dissolution of many of these minerals produces large amounts of acid, making them a major source of AMD. Research at EarthLab is expected to provide new information on the forms taken by these minerals, the changes they undergo as oxidative reactions continue, the degree to which they react with rocks along the walls of their host fractures, and the role of subsurface microbiota in facilitating these reactions.

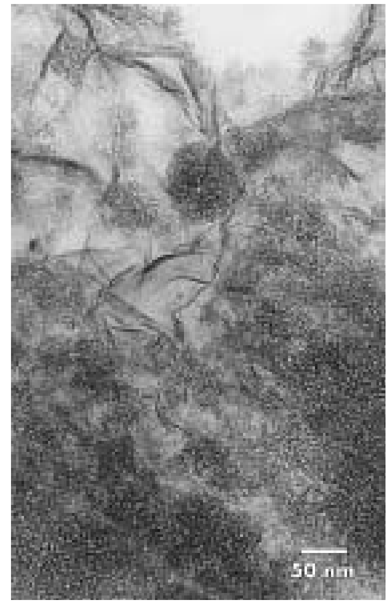


Figure 7. Transmitted electron microscopy (TEM) image of ferrihydrite (the stippled portion of the image, mostly in the lower half) and hydrohetaerolite (the fibrous phase mostly in the upper half). The ferrihydrite (an iron oxyhydroxide) consists of nanometer-sized, semi-crystalline particles; the hydrohetaerolite, a Zn, Mn oxide hydrate, is a "one-dimensional" phase, with fibers as narrow as 1 nm. These phases are from an acid mine drainage site in Montana, and are important in the transport of toxic metals into the environment. Image courtesy Michael Hochella, Virginia Polytechnic Institute.

Underground Waste Storage

Rock-water interaction is also important to problems of underground waste disposal. Underground facilities are widely regarded as the most secure sites for disposal of nuclear and other highly contaminated wastes because they can be isolated from the surface environment. Nuclear wastes will be placed in containers in most underground disposal sites, and the rock will serve as a secondary barrier. Most other types of wastes are not placed in containers, however, with the rock serving as the primary barrier to waste migration.

There is a strong interest in learning how rock-water interaction will impede the movement of waste. Adsorption is the most important process that allows rocks to serve as barriers. During adsorption, waste elements and compounds that are dissolved in migrating water become chemically attached to the surface of minerals in the rock, thus becoming immobile. The capacity of rocks and minerals to adsorb elements and compounds in the natural environment is a function of their composition as well as the composition of waste-bearing solutions. In many rocks, waste-bearing fluids flow through fractures and the age and mechanism of formation of the fractures can affect the adsorptive capacity of the rock. Temperature is also important because radioactive wastes and even some chemical wastes are hot enough to cause changes in the rocks and minerals, thus affecting their adsorbing capacity. EarthLab will provide a setting for several new types of experiments related to waste disposal, including those in which fractures are induced by fluid pressure, allowing wastes to contact newly formed rock surfaces, and others dealing with flow and adsorption in relatively impermeable rocks different from those that have been tested in most other settings.

Origin of Mineral Deposits

Increased understanding of the geological, chemical, and biological processes that form mineral deposits is critical to improved exploration for new mineral resources. Many mineral deposits are formed by circulating hot waters, or hydrothermal solutions, that change the composition of the rocks through which they migrate. Evidence of this rock-water interaction is found in the rock in the form of fluid inclusions and new minerals. Fluid inclusions are small amounts of the hydrothermal solutions that were trapped in new minerals precipitated, and provide information on the composition of ancient fluids (Figure 8). New minerals that form during rock-water interaction provide useful guidelines toward the location of mineral deposits.

Figure 8. Highly saline fluid inclusions containing crystals of salt (white) and hematite (red) and a vapor bubble (black sphere) in quartz from a porphyry copper deposit. Largest inclusion is 50 micrometers in width. Image courtesy S.E. Kesler, University of Michigan.

EarthLab will permit much more detailed research on ore formation than is possible in most currently available settings. Most hydrothermal deposits are surrounded by altered rock containing new minerals as well as anomalous concentrations of ore elements that greatly enlarge the exploration target. Studies of these features where they are exposed at the surface are complicated by weathering and other surface processes, making underground exposures particularly useful. The specific type of experiments related to ore-forming processes that might be carried out in EarthLab will depend on the exact setting of the lab. If the lab is situated in an inactive mine, it will provide an *in situ* laboratory for testing of ore-forming theories and delineation of far-field effects that enhance exploration efficiency.

Waste Isolation Pilot Plant, New Mexico

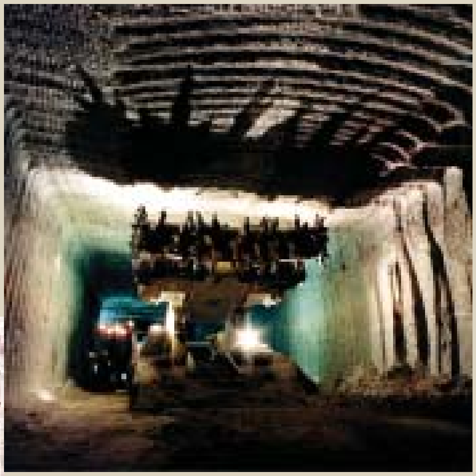
Contributed by Roger Nelson, U.S. Department of Energy

The Waste Isolation Pilot Plant, or WIPP, is the world's first underground repository licensed to safely and permanently dispose of transuranic radioactive waste left from the Department of Energy's (DOE) research and production of nuclear weapons. Located in the remote Chihuahuan Desert of Southeastern New Mexico, the DOE's WIPP project facilities include disposal rooms mined 667 m underground in a 900-m thick evaporite salt formation that has been stable for more than 225 million years. Over a 35-year life operating period, the DOE expects to permanently dispose of about 37,000 shipments of defense-related radioactive waste at WIPP.

In late 2000, WIPP began offering its operations infrastructure and space in the underground to researchers requiring a deep underground setting with dry conditions and very low levels of naturally occurring radioactive materials. The deep geologic repository at WIPP provides an ideal environment for experiments in many scientific disciplines, including particle astrophysics, waste repository science, mining technology, low radiation dose physics, fissile materials accountability and transparency, and deep geophysics.

As an operating facility, WIPP allows experimenters to avoid high start-up and overhead expenditures. Infrastructure and mine operation support are highly "leveraged" by the waste disposal mission. To the extent that the prime mission of waste disposal at WIPP is not compromised, the facilities and equipment can be used to lower the cost of creating customized cavities and conducting research at WIPP. Current estimates to create custom cavities indicate about $20/m^3, with less for larger-volume cavities. This includes bulkheads for ventilation control, lighting, and power distribution. Actual costs depend to a large extent on total volume and configuration complexity.

In the northern reaches of the WIPP underground, DOE recently made about 0.5 km of clean drifts available for experimental equipment. This area has its own ventilation split and is out of the routine mine traffic patterns. The nominal opening dimensions of the experiment gallery are 8 m x 6 m. Compressed air, power and mine phones are also available. See www.wipp.ws/science for more information.



This drum miner (above) removes up to 875 tons per shift. Openings 4 m x 8 m can be advanced at a rate of about 15 m per shift.

A miner's lamp held against the salt (right) shows the diffuse glow of backscattered light from within the evaporite formation.

■ Deep Seismic Observatory ■

Earth's surface is an inhospitable place to operate a seismographic station. Cultural noise, wind, barometric changes, absorption of high-frequency energy by the relatively soft and highly fractured surface rocks, scattering from topography, and scattering from the high degree of heterogeneity in physical properties that exists near the surface greatly increases the difficulties of data interpretation. Despite these pitfalls, most seismographic stations have been installed either at the surface or in shallow vaults a few meters below the surface due to logistical necessities. In recent years, more instruments have been placed in shallow boreholes, typically at depths of 100 to 200 m, often greatly improving signal quality. Some seismometers in boreholes have been successful, including the Cajon Pass borehole and Parkfield borehole, but large-scale vertical and horizontal arrays in the subsurface are nonexistent. With seismometers at a depth of over 2 km below the surface, EarthLab will be a unique seismological observatory, providing enormous potential for recording seismic signals with a fidelity that has not often been achieved.

The types of problems that can be addressed by EarthLab's deep seismic observatory depend on its location, but a site near the center of the continent in a stable geological setting would offer several advantages. A position far from the most important sources of natural noise, such as oceans, and far from the most important sources of cultural noise, such as large metropolitan areas, would be preferable. Furthermore, older continental shields are capable of propagating seismic waves with much less attenuation than younger, more tectonically active regions such as the western United States. These factors, together with the siting of seismometers at depths that avoid the highly attenuating materials near Earth's surface, suggest that it may be possible to observe seismic waves emerging from Earth's mantle that have more high-frequency content than is observed at most surface seismographic stations. This additional high-frequency content will translate into improved precision for a wide variety of seismological studies, such as detection of weak signals, location of seismic events, determination of source processes, deciphering triplications in travel time curves, and measuring polarization anomalies of S waves.

A seismic array is a set of seismographic sensors with common recording characteristics deployed with a geometry chosen for a specific goal. EarthLab ideally will have a large complex of vertical and horizontal drifts, permitting installation of an underground 3-D seismic array. Arrays of seismic sensors have numerous advantages over a single sensor, such as noise reduction and allowing the determination of both the time that a signal arrives and the direction that it is traveling. This capability is extremely useful in the common situation where signals from several different directions are arriving at the same time. A 3-D array would be able to separate the upward propagating wave from the downward propagating reflected wave. The array can be steered, 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, enhancement, and wavefield imaging 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 the seismic data. The presence of a 3-D lattice of instruments, which is not an option when seismographs are installed at the surface, further expands the variety of processing methods that can be used. Indeed, EarthLab would be the first seismic observatory with a large 3-D array, offering unprecedented capability for imaging the seismic wave field. Such a seismological observatory could be composed, at a minimum, of two main components: a single very broadband (VBB, or large frequency array) three-component sensor and a broadband (BB) 3-D array of three-component sensors. If EarthLab is located in a seismically active area, then adding accelerometers at some or all of the stations could enhance the ability of the facility to record high-frequency ground motion. The preferred minimum arrangement consists of a horizontal array with about 20-40 stations, a vertical array of 20-40 stations, and an aperture of about 30-60 square kilometers. Dynamic spatial and temporal filtering will provide an unprecedented ability to separate different wavefield components. This offers the possibility, for example, of better discrimination of small events buried within the waveforms of larger events. This underground array has the potential to be one of the most sensitive and most versatile seismological observatories in the world.

Monitoring of seismic events is not restricted to earthquakes occurring at great distances from the science laboratory. Depending upon the instrumentation selected, the observatory also may provide an important monitoring and location function in recording seismic signals from small events within EarthLab itself, such as rock bursts or collapses. Seismicity can be induced by mining activities, either as a result of stresses due to blasting and closure of the underground openings as they deform under high rock pressures, or from movement along existing shear zones. The latter process more closely resembles the slip associated with tectonic earthquakes. The geoscience experiments and preparations for the physics experiments will entail the underground construction of drifts and large galleries at depths which produce high rock pressures. Depending upon subsurface rock type, this will present an excellent opportunity to examine the processes associated with seismicity induced by the mining operations and will result in a greater understanding of how earthquakes are initiated in Earth. Studying seismic activity at this scale and even "inducing" small microseisms raise the level of experimentation from the laboratory to the field. The prospect of being able to design and install measurement systems designed specifically to monitor these events under conditions that are larger than laboratory scales will provide an unprecedented level of control as well as the prospect of being able to initiate and perhaps even predict the location and timing of the events.

Other applications may also become important during the course of operation of the 3-D seismic array. The goals of EarthScope's SAFOD (San Andreas Fault Observatory at Depth) project are similar to the goals of EarthLab's Deep Seismic Array, but SAFOD is limited to being a vertical array. Additionally, although the goals of EarthLab's Observatory and EarthScope's USArray are quite different, the data from both will be complementary. The single VBB station in the Deep Seismic Observatory will contribute data to the Permanent Backbone component of USArray. The Deep Seismic Observatory will provide high-quality seismic information to correlate with that derived from the Transportable Array component of USArray when these stations move through the Observatory area. USArray, in turn, should yield valuable information about the local velocity structure in the vicinity of the Observatory. This equipment will also provide a measure of the background levels of ground motion, which may be important in the operation of sensitive scientific instruments and experiments throughout the underground complex.

■ Geophysical Imaging ■

The ability to image fractures and to characterize their length, width, and apertures cuts across many different fields of research and societal concerns. Knowledge of fractures and fracture networks is important to studies of groundwater flow, recovery of gas and oil, rock mechanics, hazardous waste containment, carbon sequestration, and as a habitat for subsurface biota. Fractures and fracture networks are critical elements in chemical transport, ore formation, heat flow, faults, and earthquakes. EarthLab will offer a variety of opportunities to develop a better understanding of fracture networks at the field-scale level.

Commonly used geophysical imaging techniques for high-resolution applications include electromagnetics, seismics, microgravity, resistivity, induced polarization, and ground penetrating radar (GPR). Fractures present both mechanical and a electrical conductivity anomalies, especially if they are filled with fluid. As the rock volume of interest becomes larger, other methods involving the determination of electrical resistivity through direct electrical methods or electromagnetic induction methods can probe deeper into the rock to detect and delineate fracture systems.

In the case of EarthLab, the fractures will control the mechanical as well as the hydrologic response of the entire system. It is critical to not only know the initial state of the fractures (geometry, density, spacing, filling, length, and connectivity) but to know how perturbing the system changes the interaction of the fractures with the rock matrix. Recent developments in fracture imaging from the oil and gas as well as the geothermal industries can be used to characterize the fracture system. For example, effects of the fracturing on the transmission and

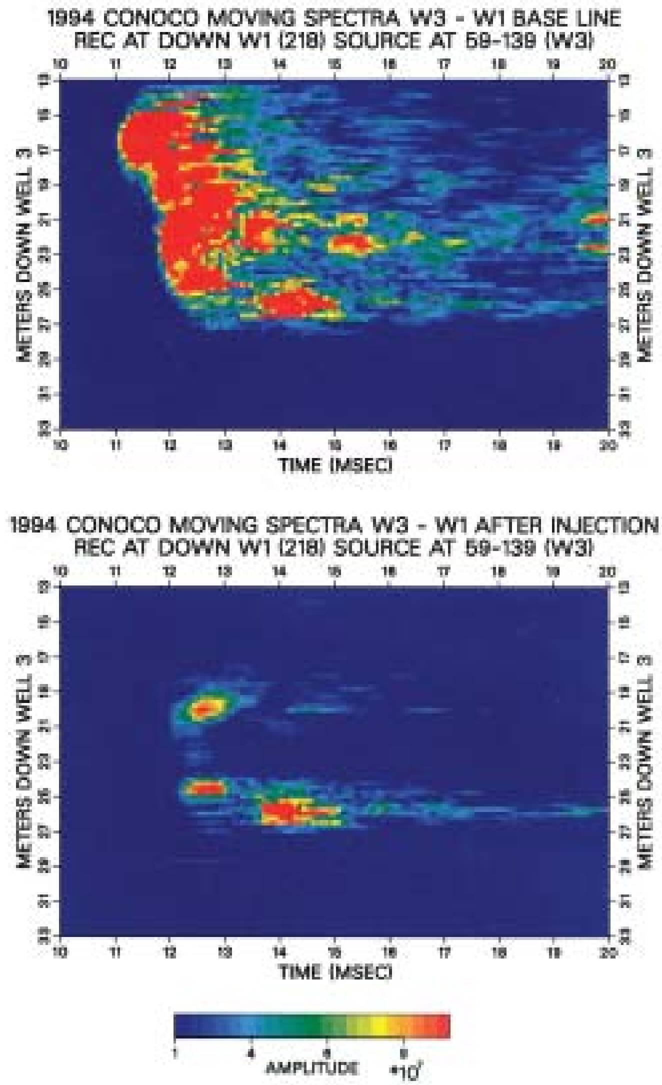


Figure 9. Cross-well seismic data across the fracture before (top) and after gas has been injected into the fracture. The red indicates the location of high-energy seismic data, and the blue indicates the low-energy data. By comparing before and after, one can use transmission data with the reflected data to accurately locate the fracture. From Majer, E., 2002, Soc. Explor. Geophys. meeting abstracts, Salt Lake City, UT.

reflection of seismic energy can be used effectively to map out the extent and, in some cases, the aperture of the fracturing. Figure 9 shows the effect of a small fracture (Figure 10) on the seismic wave as the properties of the fracture filling are changed. In this case, to make the fracture more visible, air was introduced into the fracture (water replaced partially with gas) to decrease the stiffness of the fracture. (This is similar to the medical practice of making the blood paths more visible by introducing x-ray sensitive tracers into the patient.) The gas slows down and attenuates the seismic signal and causes a large change in the seismic signals where the gas has penetrated. Here, the attenuation was used to locate a very small feature, on the order of a few millimeters, that had a very large effect on the hydrologic regime. This fracture controlled the entire hydrologic regime over a 50 m volume.

To gain a more complete understanding of what the geophysical data are telling us, we need be able to correlate with great accuracy the geophysical results with the geology, including fracture geometry, and the corresponding hydrologic and microbial properties. EarthLab is one of the few places where we will be able to ground truth the geophysical data with actual fracture mapping at a variety of scales. A particularly important aspect is the opportunity to scale the results of the different data types. Scaling is one of the most important issues facing the geoscience community today. For example, in the case of microbial ecology, at what scale must we characterize the chemical and physical environment to understand the microbial behavior? At EarthLab it will be possible to make very detailed measurements using drilling results and borehole measurements, as well as make broad volumetric measurements with geophysical and hydrologic techniques. These measurements will help to elucidate scaling issues in geophysics and contribute to understanding scaling laws of nature.

A few key questions to which EarthLab will contribute include:

- How do various types of geophysical data correlate with actual mapped geology over the entire EarthLab volume?
- What scale must be measured to understand the dominant processes and properties controlling important phenomena?
- How do fluid, physical, or chemical properties affect the detectability of fractures by geophysical tomography?
- How many borehole samplers are required to characterize the physical and chemical properties and temporal behavior of a fluid-filled fracture when combined with geophysical tomographic observations?

Figure 10. A core sample through the fracture located with the seismic data. The actual fracture is indicated by the arrow, the other breaks were done by drilling.

Integrated EarthLab Activities

EarthLab will provide a valuable resource for multidisciplinary and multi-institutional investigations. EarthLab's primary goal is to provide an experimental and intellectual foundation for investigating the origin and bounds of life; develop a fully coupled model of hydrological, deformational, thermal, biological, and chemical processes in fractured rock; and develop practical applications for the mining, bioremediation, biotechnology, and pharmaceutical industries. EarthLab will be the only facility in the world where long-term, *in situ* geomicrobiology and biogeochemistry experiments explore the evolution, adaptation, and limits of microbial life in the deep subsurface. EarthLab's research goals will be achieved by closely integrating hydrogeological, rock mechanical, geomicrobiological, geochemical, geological, and geophysical activities and will rely upon geological, geochemical, and geophysical characterization of the underground environment. EarthLab can provide a field platform for developing the technologies required to search for subterranean life on other planets in our solar system, especially Mars.

EarthLab will provide a controlled, though still natural, environment that can be sampled at a multitude of scales in both time and space. A wide range of experiments will be conducted during the life of EarthLab and the details of the experiments will vary depending on their objectives. Experiments will be conducted using state-of-the-art instrumentation for assessing and monitoring subsurface processes. All of the experiments will make use of web-based data acquisition instruments to permit scientists from across the world to monitor experimental results in real time. Data from the experiments will also be archived and made available to the scientific community and the general public. The data will be useful for validating theories and calibrating theoretical models that are developed independently from, but perhaps motivated by, the experiments.

During the first two to three years, scientific efforts at EarthLab will focus upon characterizing microbial, geochemical, geological, and hydrological diversity, selecting sites for subsurface experimental stations, and establishing a surface laboratory and instructional facility. The surface facility will archive samples, centralize data collection and dissemination, and coordinate multidisciplinary research efforts with an educational and outreach program (see E&O section on p. 52).

Five underground research facilities will be constructed for EarthLab, each of which focuses on different facets of subsurface science.

- The Ultradeep Life and Biogeochemistry Observatory will explore the limits of life in 4 to 5-km-deep boreholes.
- The Induced Fracture and Deformation Processes Laboratory will examine the relationships among hydrology, biology, and chemistry to mechanically, hydrologically, and thermally induced fracturing.
- The Deep Flow and Paleoclimate Laboratory and Observatory will refine large-scale, long-term hydrologic models of fluid flow in fractured rock and will examine its coupling with climate change.
- The Deep Coupled Processes Laboratory will delineate the intermediate-scale coupling among hydrology, biology, and chemistry with transport and stimulation experiments in instrumented fracture zones.
- The Deep Seismic Observatory will use a 3-D subsurface seismic array to record local and global earthquakes, and also seismicity induced by mining activities.

Characterizing the EarthLab Site

EarthLab's long-term usefulness to the science and engineering community relies critically upon the installation of versatile, stable, underground experimental stations in geohydrologic environments that enable the many questions raised in the previous sections to be addressed. In order for EarthLab to make optimal and economical use of a site, a well-organized, comprehensive characterization effort must precede design and construction of EarthLab underground facilities.

The location, depth, and orientation of existing rock cores will be cataloged in the three-dimensional data set and a subset of rock cores will be selected for detailed analyses and archiving. The geochemistry, mineralogy, mechanical, and petrophysical properties of representative lithofacies from these select cores will be determined. The aqueous and gaseous geochemistry, isotopic composition, temperature, and microbiology of water emanating from these boreholes will be analyzed.

On-site access to cutting-edge technologies for real-time detailed biological, geophysical, mechanical, and geochemical interrogations, will establish EarthLab as the world leader in subsurface science and engineering research.

Within the first year, existing data on the drilling and excavation history, on the structural geology, particularly the fracture geometry and spacing, on the groundwater geochemistry, and on the petrology and mineralogy of the site will be integrated into a standardized, three-dimensional database with a three-dimensional imaging program. Engineering data from pre-construction and construction activity associated with the neutrino facility will be included as well. A three-dimensional rock mechanical, heat flow, and hydrologic model will be created for EarthLab based upon this spatial data set. These models will identify data types that are completely absent from the site and must be acquired immediately, areas that represent potential experimental sites, areas that are redundant and may be closed off, and areas where further data are required to make this determination.

Temperature profiles and strain measurements of select dry boreholes will be measured. The results of detailed geological and fracture maps of tunnel walls will be added to the three-dimensional data base. As these characterization data are acquired, the mechanical, thermal, and hydrologic models will be updated. These models will be used to determine locations of optimum candidate underground laboratory sites based on predicted structural integrity.

The final location of the several EarthLab experimental stations will be determined from more detailed characterization of candidate sites. This phase of characterization may require drilling and coring new boreholes from the tunnels, cross-tunnel and cross-borehole geophysical tomographic imaging, geophysical borehole logging, and *in situ* stress measurements. The cores will be collected with aseptic techniques so that the microbial composition as well as the geochemical and petrophysical properties of the rock formation can be analyzed. For any water emanating from boreholes, the fluid pressures, flow rates, water and gaseous chemistry, and microbial composition will also be determined. Hydraulic, flow meter, and tracer tests will be performed to characterize local hydrologic properties, including fracture connectivity and transport properties. This information when combined with the core analyses and the pre-existing three-dimensional data base and a local-scale mechanical, thermal, and hydrologic model will provide a solid basis for assessing the suitability of the candidate site for the planned long-term experimental station. This detailed characterization process will also provide the geological, hydrologic, structural, and microbial baseline measurements, prior to further excavation and drilling, required for comparison with subsequent experimental results. The detailed characterization data and local-scale model results will be used to refine the larger-scale EarthLab mechanical, hydrologic, and thermal model. Finally, as the results of each stage of characterization are published, the three-dimensional database will be made accessible to the public via a searchable data depository on the Internet.

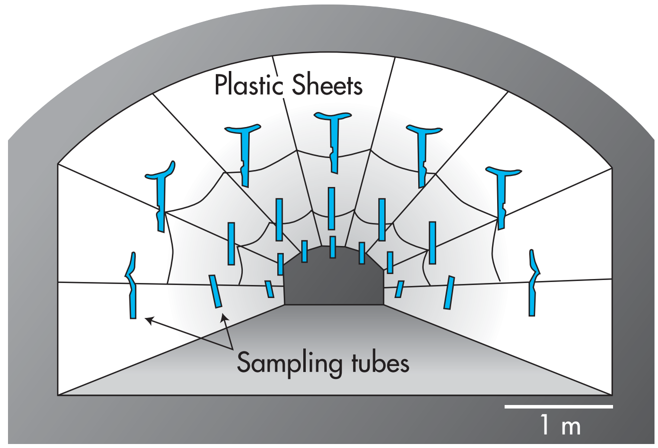


Figure 11. A large-scale flow and tracer experiment was carried out in the Stripa Project mine in Sweden by covering the upper part of the walls with plastic sheeting, and collecting the water seeping from the rock. Over a period of 1.5 years, tracers were injected into three boreholes drilled vertically upward from the main drift. The complexity of the fracture and flow system is indicated by the great variability in results. Of the nine tracers injected, three were not detected during the course of the experiment, and recovery varied from 2.8% to 65.8% for the rest. Figure and caption modified from Abelin et al., 1991, *Water Resources Research*, 27 (12), 3017-3117.

ULTRADEEP LIFE AND BIOGEOCHEMISTRY OBSERVATORY

Goals

The goal of this observatory is to define the upper temperature limit of life in the crust and what factors control it by identifying the mineralogical and geochemical signatures marking the transition between the hyperthermophile and hydrothermal zones, and between biological from abiological processes.

Critical Applications

- *Borehole Life-Detection Technology*: Develop new technologies for detecting and characterizing microbial life using borehole sensors that can be adapted to explore for subsurface life on other planets.
- *Biotechnology:* Highly stable, high-temperature extremozymes have potential for remediation of metal and organic-contaminated sites.

Basic Processes

- *Maximum Temperature for Life*: Determine how thermophiles and hyperthermophiles are able to maintain cell function and integrity at high temperatures with the paucity of energy resources that characterize deep subsurface environments.
- *Signatures of Abiogenic Versus Biogenic Processes*: Delineate abiotic geochemical reactions from biologically activated geochemical reactions that occur at high temperature.

Facility Design and Construction

The design and construction of the Ultradeep Life and Biogeochemistry Observatory will take place in the first two years following EarthLab characterization and site selection and will involve the following:

- Drill three 2-3 km holes from the bottom level of EarthLab to depths that will reach rocks with temperatures of ~120°C, the highest temperature limit for known life forms. The three boreholes will form a triangular array, ~20 m on each side. Geophysical and televiewer logging of the first borehole will be used to identify fracture zones and coring intervals for the second and third boreholes.
- Collect ~30, 2-m-long cores for biological, geochemical, and petrophysical analyses. Tracers will be used during coring to monitor and quantify contamination. Samples from each core will be placed within evacuated canisters on site for pore gas analyses. Other samples will be processed in an anaerobic glove bag for microbial enrichment and activity experiments. Cores will be archived for molecular, isotopic, petrographic, geochemical, petrophysical, and geochronological analyses at -70°C in EarthLab's surface facility.
- Completely characterize the rock strata using geophysical cross-borehole tomography. These data, when combined with petrophysical data from the cores, will provide a three-dimensional image of a crustal slice down to 4.5-5 km.
- Conduct pump tests of fracture zones isolated by packers to determine the hydraulic conductivity of the fractures.
- Isolate fractures in one borehole with packers and pump fluids into an anaerobic microbiology lab located on site for microbial growth experiments and genetic analyses.

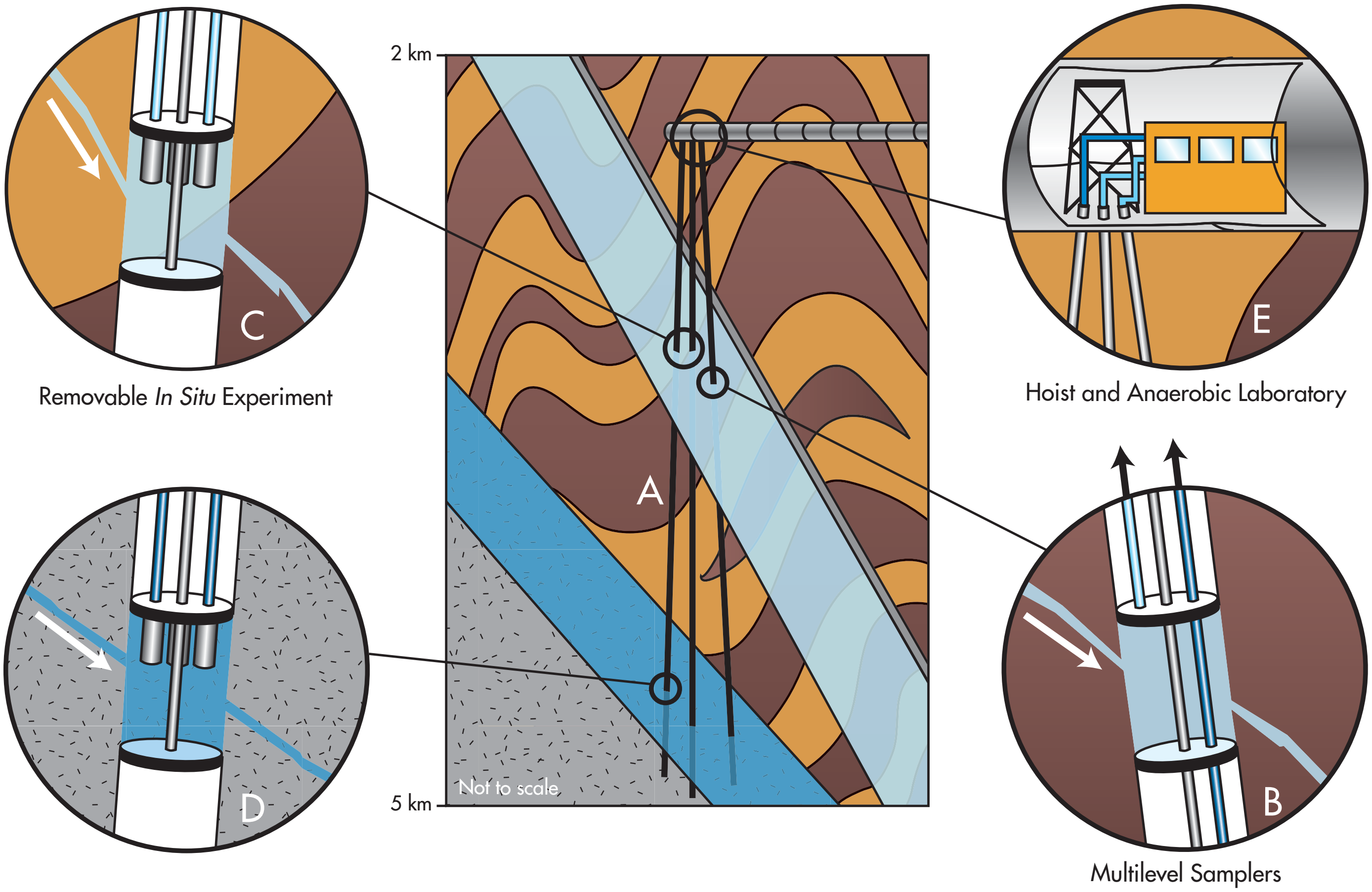


Figure 12. The Ultradeep Life and Biogeochemistry Observatory. A. Three boreholes penetrate 2 kilometers intersecting several fluid filled fractures and attaining a bottom hole temperature of ~ 110-120°C. After holes are drilled, cored and logged, and the inter-borehole rock volume tomographically imaged, fluid-filled fractures are isolated with multilevel samplers (B) or *in situ* experiment samplers (C and D) equipped with compression packers. Fluids from both types of samplers travel through tubing to well head and pass through SS double gate high-pressure valves and into laboratory equipped with anaerobic glove bag (E). Winch enables the samplers and geophysical probes to be inserted and removed from borehole.

- Install retrievable packers to isolate fractures in the other two boreholes for *in situ* experiments at 100-120°C and ambient pressures.
- Fit one borehole with strainmeters to provide stress data to determine if the crust at EarthLab is critically stressed.

Experimental Program

By the end of Year 2, the instrumented boreholes will provide an ideal experimental facility for observing life processes at high temperature and pressure. Some of the potential experiments that could be performed at Ultradeep Life and Biogeochemistry Observatory include:

Abiogenic Versus Biogenic Processes

The results from analyses of the cores and fluid will provide a great deal of information relating the limits of life for the ambient conditions and paleothermal history. They will also provide background information for *in situ* experiments:

- For each fracture fluid, determine its viral, microbial, and eukaryotic composition; its dissolved and colloidal inorganic and organic composition; its isotopic composition; and the stable, cosmogenic, and radiogenic composition of the dissolved organic, inorganic, and gas species.
- Perform fluid-inclusion analyses on fracture-filling minerals to compare the temperature and pressure, organic, inorganic, and isotopic composition of the ancient water and gas with that of present-day fracture fluid.
- Perform fission track and U-He apatite and $^{40}Ar/^{39}Ar$ K feldspar and illite analyses of the cores to provide a record of the temperature versus time history of the rock unit as it cooled from the hydrothermal zone through the hyperthermophile zone, determining the age at which changes in the fluid composition occurred.
- Use ion microprobe, chemical, and stable isotope analyses of fracture-filling minerals to determine the composition of the fluid flowing through the fracture zones as the strata were uplifted and eroded. These analyses can also distinguish thermodynamic equilibrium isotopic fractionation from biologically produced kinetic fractionation as the rock strata cooled from the hydrothermal zone to the hyperthermophile zone.
- Chemical and isotopic analyses of pore water and gases trapped in the low-permeability matrix of the rock core may still record the ancient pristine hydrothermal fluid that has yet to mix with younger water passing through fractures. Noble gas analyses of rock cores can constrain the age of the fluid. These analyses will also identify and quantify the chemical energy fluxes from the rock to the fracture fluid, as this energy is necessary for organisms to live at depth.
- The $\delta^{13}C$ and δD of methane and light hydrocarbons can distinguish a microbial versus thermogenic versus abiogenic origin for these gases.
- Nucleogenic isotopic analyses of the fracture fluids will constrain their age and the ambient radiation flux when combined with detailed geochemical analyses of the rock composition.

Maximum Temperature for Life

A variety of observations and experiments will significantly advance our understanding of subsurface life at extreme temperatures including:

- Comparison of the molecular and genetic data from the cores with that of the fracture fluids will determine the extent to which planktonic and sessile communities are different.
- Comparison of the molecular and genetic data from the multiple fracture fluids of one borehole with the geochemical and isotopic data will determine what geological factors control microbial diversity at high temperature.
- The two boreholes with removable packers can also be used for microbial or chemical transport experiments along specific fracture zones or for push-pull, *in situ* microbial activity experiments.

- Hyperthermophilic isolates can be incubated with solid substrates surrounded by filters in the boreholes and their metabolic products and activity measured in real time. These *in situ* experiments will determine the factors that limit life at those high temperatures. Static, *in situ* experiments will employ radio-labeled or isotopically enriched compounds. Upon retrieval, biofilms will be analyzed by fluorescent *in situ* hybridization combined with either micro-autoradiography or secondary ion mass spectrometry. In the case of hydrocarbon substrates, these experiments can examine the fundamental processes associated with petroleum degradation *in situ*.

Biotechnology

- Experiments performed in the subsurface lab using the fluids from the borehole and radionuclides or toxic metals can test the ability of subsurface hyperthermophiles to tolerate and remediate these compounds. Genes responsible for these abilities can be isolated, sequenced, and cloned for biotechnology applications.

Borehole Life Detection Technology

- Boreholes with removable packers enable the insertion of various devices designed to detect the foot print of low level microbial activity. These devices may detect changes in gas chemistry or electron flow and can be combined with downhole incubation experiments as a means of providing position controls.

▪ Deep Flow and Paleoclimate Laboratory and Observatory ▪

Goals

A primary goal of this is experiment is to characterize water flow and the fate and transport of paleoclimate proxies, dissolved compounds, gases, and microorganisms from recharge in the rhizozone along fracture pathways to great depths. A related goal is to trace groundwater originating as surface recharge and identify factors affecting the distribution of its organic, inorganic, and biotic constituents as it flows through fractured rock and mixes with deep, ancient groundwater.

Critical Applications

- *Global Warming*: Delineate the Pleistocene record of climate preserved in groundwater and associated mineral phases. Comparison to marine paleoclimate records and Global Climate Model predictions could provide invaluable insight to global warming effects on continental regions.
- *Water Resource Management*: Determine factors affecting the availability and sustainability of deep sources of fresh water in fractured rock. Evaluate factors affecting the vulnerability of deep water sources to contamination from surface pollution.
- *Hydrologic Models and Methods*: Evaluate and test the efficacy of state-of-the-art groundwater dating methods, paleoclimate proxies, techniques for characterizing the distribution of storage and transmission properties, and approaches for modeling flow and transport in large-scale fractured systems.

Basic Processes

- *Paleohydrology*: Determine how climate and groundwater recharge are coupled. Natural fluctuations in surface climate ranging over time scales of hundreds to millions of years can affect the ambient pressure, flow and composition of groundwater recharging a subvertical fracture system.
- *Paleoclimate*: Delineate the Pleistocene record of climate preserved in groundwater with cosmogenic and stable isotopes, temperature, dissolved noble gas analyses, and analyses of minerals deposited in fractures.
- *Microbial Ecology*: Evaluate processes affecting the transport of microbes from the shallow rhizozone to great depth, and evaluate the extent of subsurface colonization.
- *Hydrologic Cycle*: Characterize surface recharge and deep flow components of the hydrologic cycle, leading to more efficient potable water resource exploration and use.
- *Hydrologic Properties*: Evaluate the distribution and scaling of properties affecting the storage and transmission of subsurface fluids in fractured rock.

Facility Design and Construction

This project is designed to characterize ambient hydrologic conditions along flow paths and use those characteristics with other geologic measurements to infer how conditions and processes evolved through time. The project will be conducted by instrumenting and monitoring two major sensor arrays, including: (A) a fracture zone that acts as a fluid pathway from shallow depths to the lower reaches of the lab, and (B) an undisturbed region of shallow subsurface affected by recent recharge. Both parts of this facility should be completed and an initial set of data collected by the end of the second year.

Details of the Fracture Zone Array

- Identify a continuous subvertical fracture zone being recharged from the surface using a combination of subsurface mapping, geophysical surveys, and geochemical analyses. Identify or establish a network of tunnels in the vicinity of the fracture zone over a depth range of 1 to 2 km.
- Intersect the fracture zone with multiple boreholes from tunnels at several depths from 100 m down to 2400 m.
- Obtain rock cores through the fracture zone using techniques designed to preserve the cores' chemical, biological, and mechanical integrity to the greatest extent possible.
- Log each borehole using a borehole camera and a suite of geophysical tools, including acoustic televiewer, resistivity, gamma, and neutron techniques.

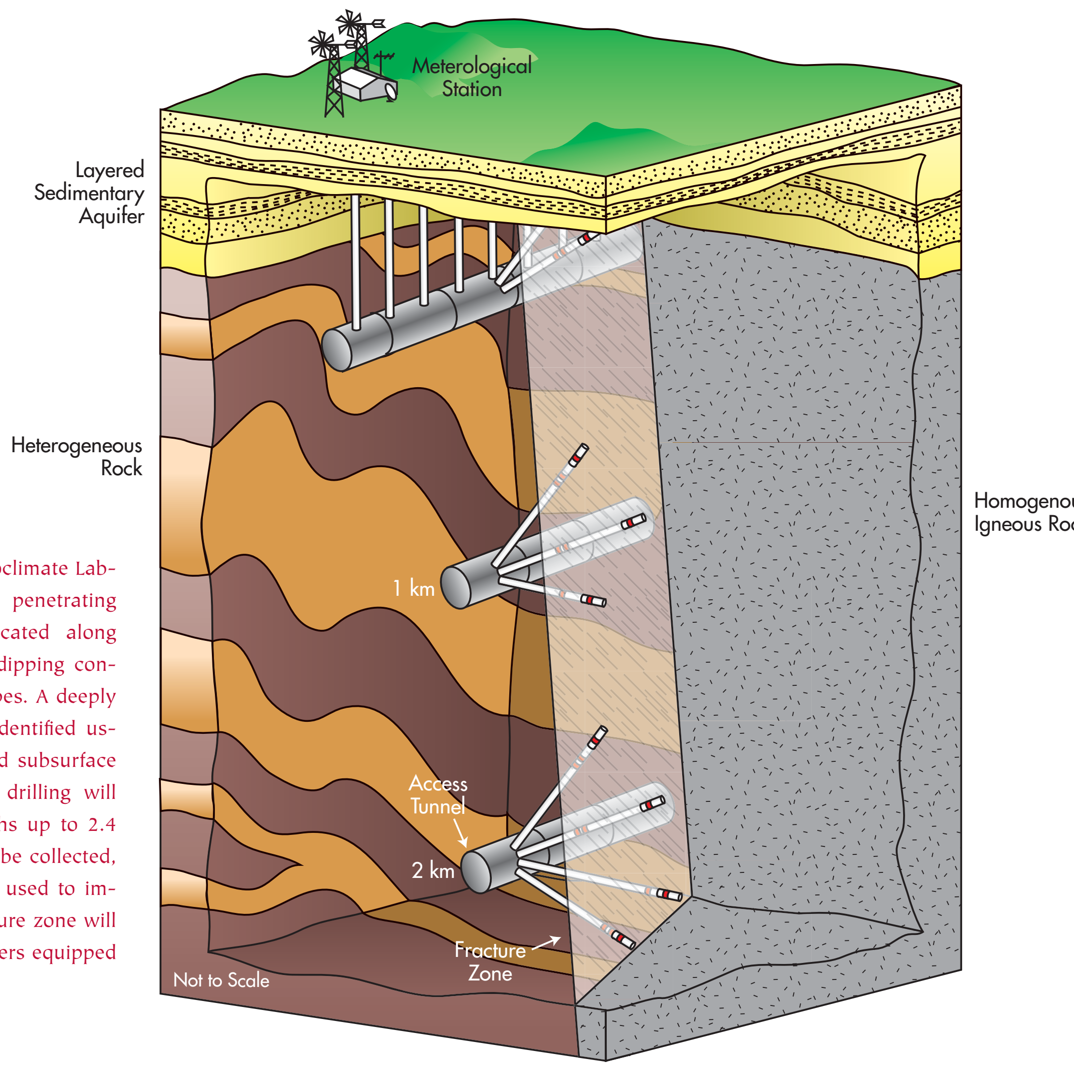


Figure 13. The Deep Flow and Paleoclimate Laboratory and Observatory. Deeply penetrating crustal fractures are typically located along reactivated fault zones or steeply dipping contacts between two different rock types. A deeply penetrating fracture zone will be identified using surface geophysical surveys and subsurface mapping. Surface and subsurface drilling will intersect the fracture zone at depths up to 2.4 km. Cores of the fracture zone will be collected, cross-borehole tomography will be used to image the fracture zone, and the fracture zone will be isolated using compression packers equipped with gas/fluid samplers.

Progressively update the characterization with directional borehole radar, and seismic or resistivity tomography, as the boreholes become available.

- Instrument the boreholes with arrays of sensors and sampling capabilities, including:
  - Pressure transducers,
  - Displacement transducers,
  - Temperature probes,
  - Sealable ports for obtaining fluids for chemical measurements,
  - Accessible ports for placing retrievable biosubstrates.

Details of the Shallow Recharge Array

- Identify a region where the subsurface is undisturbed from the ground surface to depths of approximately 100 m. Use records to identify a region that is free from borings and mine workings if a mine is selected for siting EarthLab, and use shallow geophysical methods to confirm the absence of undocumented anthropogenic features. Identify or create one or more access tunnels at a depth of approximately 100 m.
- Create an array of borings upward and laterally outward from the access tunnels. Obtain samples of rock and fluid during and immediately after drilling. Rock and fluid samples will be collected from the lateral extents of EarthLab to provide three-dimensional mapping of isotopic tracers, basic fluid chemistry, and physical properties. Conduct hydraulic and gas-phase well tests, borehole geophysical logging, and cross-hole and borehole-surface geophysical imaging tests. Combine the resulting data to characterize the three-dimensional subsurface geology, including structure, mineralogy/lithology, facies/depositional environments, thermal conductivity, and permeability, to provide a baseline of subsurface physical factors controlling infiltration and thermal aspects. Fractures will be mapped in detail to identify their effects.
- Instrument boreholes to monitor hydrologic conditions as functions of time using both direct measurements (pressure, temperature, displacement) and indirect geophysical imaging.
- Create a network of stations overlying the instrumented regions to monitor conditions at the ground surface. Each station will be designed to monitor meteorologic conditions (e.g., precipitation, temperature, barometric pressure, humidity, wind speed, solar energy flux, moisture flux) along with parameters in the shallow (few m) subsurface (e.g., temperature, moisture, fluid pressure). These data will establish the distribution of key parameters affecting the movement of moisture at the ground surface as functions of space and time.
- Conduct a set of systematic overflights to obtain remote-sensing data used to estimate the distribution of ET, soil moisture, and other key variables affecting the hydrologic cycle. Combine these data with results from monitoring at the ground surface and in the subsurface to refine methods for estimating recharge using remote sensing.
- Evaluate hydrologic, chemical, and other subsurface measurements with respect to the geologic properties between the surface and the points of measurement. This correlation will permit an assessment of the relative importance of geologic factors that alter these surface "signals" as they propagate through the subsurface.

Experimental Program

Global Warming and Paleoclimate

Analyze the chemical compositions of rocks and water and use the results to infer specific processes, including:

- Measure the atmospheric noble gas concentrations, $\delta^{18}O$ and δD of the groundwater to infer paleotemperature and precipitation.
- Measure concentration of the cosmogenic isotopes, ^{3}H, ^{14}C, ^{36}Cl, and others to infer flow paths and ages of the groundwater.
- Combine the above two data sets to delineate changes in the climate with time.
- Perform U-Th disequilibrium dating on any carbonate fracture-filling minerals that may provide another record of Pleistocene climate changes that can be compared with the one above.
- Perform transition metal and isotopic analyses on carbonate minerals to document any changes in the groundwater redox state during these climate changes.
- Measure high-resolution (temporal and spatial) temperature profiles in the subsurface for use in detailed paleoclimate reconstruction analyses (vertical subsurface temperature profiles record historical variations in surface temperature, with time scales of hundreds of years in the past).

Microbial Ecology

- Characterize the microbial, eukaryotic, and viral communities on fracture surfaces, in rock pores, and in groundwater. Combine these results with data describing the distribution and transport of dissolved and colloidal compounds to infer the sources (e.g., the rhizozone or elsewhere) and colonization pathways of subsurface organisms. Other isotopic, chemical, biological, and colloidal signatures preserved in the groundwater may record chemical and biological processes occurring in the rhizozone that have evolved through time in response to climate fluctuations.
- Monitor migration of soil microorganisms and soil constituents in fractures for seasonal fluctuations. These measurements will be compared to seasonal variations in temperature and recharge, to evaluate possible correlations.
- Monitor migration, diversity, and metabolic activity of microbial communities over extended time periods.
- Take low-level ^{14}C measurements to help discern organic carbon and microbial cells that originated in the soil zone.
- Install temperature probes with each fluid pressure sensor to collect data that could be used to test kilometer-scale coupling between groundwater flow and heat flow.

Water Resource Management

Both sensor arrays will provide a comprehensive four-dimensional dataset of fluid movements in the subsurface. These data will characterize the physical controls on groundwater flow as well as the fate and transport of both chemicals and microbes in the subsurface. These data will also characterize how much deep groundwater flow is from surface recharge and how much is from deep, large-scale through flow, and how fractures affect groundwater, water chemistry, and microbiotic life in the hydrologic cycle. The shallow sensor array results will be compared to these physical data and baseline surface conditions to:

- Determine the factors and processes that control the spatial and temporal redistribution of precipitation. Account for water fluxes such as precipitation, evapotranspiration, lateral flow across the land surface or in the shallow subsurface, and fluxes that ultimately become groundwater recharge. By comparing known surface topography, plant distribution, geology, and precipitation conditions at the surface to the amounts and distribution of recharge reaching subsurface monitoring sensors in the shallowest tunnel (Figure 13), the effects of rock types, topography, and other features can be isolated. Even in the dewatered portion of EarthLab, active infiltration experiments such as this may be used to evaluate with higher resolution the preferential flow effects in the unsaturated subsurface.
- Compare isotopic "fingerprints" between potential recharge areas and fluids flowing into different parts of EarthLab to help delineate the recharge area distribution and associated different flow paths. These "fingerprints" will also permit identification of surface recharge versus deep through-flow in the system if isotopic measurements of precipitation are also collected from distant recharge areas.
- Use the network of pressure and displacement transducers to evaluate the magnitude and distribution of storage properties. The pumping regime used to dewater EarthLab will be deliberately modified and the resulting changes in fluid pressure and displacement across fractures will be monitored using the sensor network. Storage and poro-elastic properties will be characterized using the resulting data. Three-dimensional characterization at this scale has never been possible before.

Hydrologic Models and Methods

- Use measurements of pressure, temperature, and displacement as functions of time to evaluate the effects of Earth tides, barometric variations, seasonal variations in recharge, and other natural transients in the subsurface. Compare these measurements to geochemical and microbial analyses to evaluate correlations and trends. Use data and other results of this program in tandem with data from other EarthLab experiments to maximize the information and avoid redundancy. This suite of measurements will also be used to evaluate transient effects related to operation of the EarthLab facility.
- Perform noble gas, pore gas, and aqueous geochemical analyses of the rock adjacent to fractures to determine the age the fracture and the flux of formation fluid constituents from the rock matrix to the fracture fluid.
- Perform U-He and fission track apatite analyses of cores and compare results to those determined for host formation far removed from this fracture zone. These data will be used to test coupled thermal and fluid advection models.
- Characterize the field data describing the rates and patterns of water flux, and the fate and transport of chemicals and microbes, using state-of-the-art theoretical methods. Refine the methods, or develop new ones, to improve predictive capabilities.
- Take core-scale measurements using mini-permeameters to establish a quantitative relationship between permeability and scale. Take incrementally larger-scale measurements by designing and completing conventional flow and/or tracer tests between different areas of EarthLab, and by conducting pump tests induced in surface wells.

▪ Induced Fracture and Deformation Processes Laboratory ▪

Goals

The goals of these experiments are to evaluate and refine models of fracture initiation and propagation, rock mass deformation, fluid flow, and transport of aqueous and gaseous species in the vicinity of induced fractures, and microbial activity proximal to them, and colonization of fracture surfaces.

Critical Applications

- *Resource Recovery*: Improve the ability to predict the propagation and performance of induced fractures during recovery of petroleum, gas, water, and geothermal energy.
- *CO_2 Sequestration*: Advance capabilities to predict the effects of induced fractures during the sequestration of CO_2 or other waste materials injected into the subsurface.
- *Waste Isolation*: Characterize potential roles of induced fractures on the long-term isolation of nuclear waste and other hazardous materials stored in underground repositories.
- *EarthLab Safety*: Evaluate the effects of induced fractures on the safety of tunneling procedures and the operation of large underground openings planned for EarthLab.

Basic Processes

- *Fracture Propagation*: Evaluate conceptual and theoretical models of fracture propagation processes accompanying injection of fluids into boreholes, excavation of openings in rock, heating of rock, or release of high-energy gas by propellants and explosives. Investigate how fractures induced by different processes interact with natural geologic features, such as lithologic contacts, joints, or faults.
- *Fluid Flow Within Propagating Fractures*: Evaluate the patterns and processes controlling fluid flow within, and in the vicinity of, a propagating fracture. Evaluate and refine current models of particle transport within fractures. Evaluate and refine current models for interpreting records of injection pressure to estimate fracture form or state of stress.
- *Effects on Well Performance*: Characterize the transport of fluid and heat to or from induced fractures intersecting wells to optimize well-stimulation techniques.
- *Pressure Solution*: Evaluate stress-induced dissolution and transport processes where fracture walls collapse during pressure solution.
- *Rock Mass:* Evaluate and refine models for the influence of discontinuities on rock mass deformation.
- *Microbial Life*: Examine how the induced fractures alter the flux of aqueous and gaseous species into fractures and how this altered flux affects microbial activity and growth. Determine the rates of microbial colonization of newly formed fracture surfaces, determine how quickly fresh mineral surfaces age, and evaluate how microbial community structure evolves on new fracture surfaces.

Facility Design and Construction

The state of stress plays a key role in rock deformation and the growth and performance of induced fractures. For a variety of reasons, the ambient stress state changes markedly over the depth of the lab. The facilities developed for this experiment will be located at three levels to take advantage of the different states of stress. Induced fractures are expected to be horizontal at shallow depths in the lab, where horizontal compressive stress exceeds vertical compression. A shallow ex-

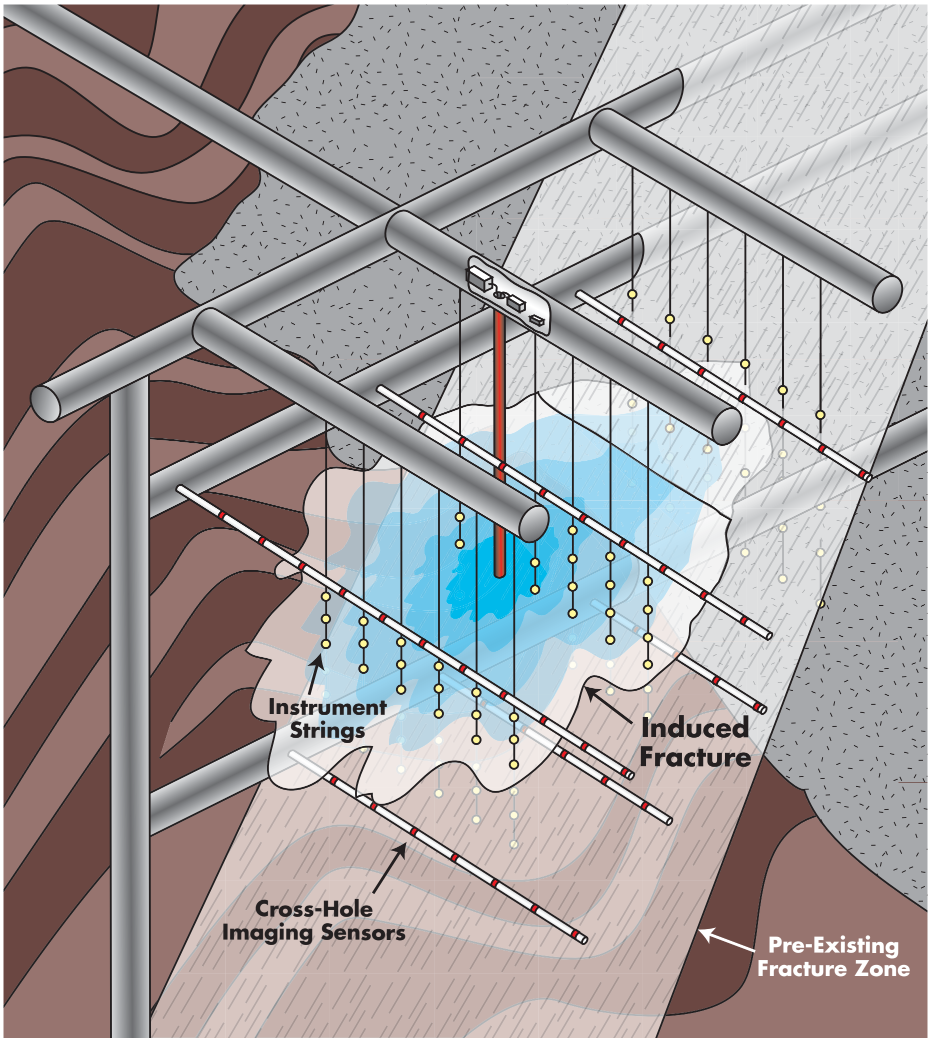


Figure 14. The Induced Fracture and Deformation Processes Laboratory. Facilities developed for this experiment will be located at three levels to take advantage of the different states of stress in EarthLab. Induced fractures are expected to be horizontal at shallow depths. A network of boreholes will contain pressure and displacement transducers, temperature sensors, flow meters, and fluid sampling ports for monitoring fracture propagation. Additional sets of boreholes will be created perpendicular to the first set and used for cross-borehole geophysical imaging. The instruments will be placed in those holes and then sealed with cement. Vertical sensor strings will intersect the induced fracture above and below it, and will be connected by wires and tubing and embedded in cement. An array of seismometers will also be used to monitor microseismicity accompanying fracture growth.

perimental facility will be located in this region. Induced fractures are expected to be vertical in the lower reaches of EarthLab, where the vertical compressive stress exceeds the horizontal stress. A deep experimental facility will be located in this region. Another facility will be located at intermediate depths where horizontal and vertical stresses are equal.

- Identify suitable tunnels at three different levels based on the state of stress, proximity to pre-existing fracture zones for interaction studies, and separation from existing workings. Blocks of rock several hundred meters on a side will be sought to minimize unwanted interference with mine workings.
- Create a preliminary network of boreholes and conduct a suite of geologic, geophysical, and geomechanical tests to characterize the geology, distribution of fractures, mechanical properties, and state of stress. Conduct detailed simulations using state-of-the-art codes to predict the propagation of induced

fractures using the site characterization data. Apply the results of the simulations to the design of the experiments.

- Create a detailed network of boreholes containing instrumentation for monitoring fracture propagation. If necessary, the shallow facility will contain an array of borings drilled vertically downward because they will be intersected by horizontally propagating fractures, whereas the deep facility will contain an array of horizontal borings designed to monitor growth of vertical fractures. The monitoring array at the intermediate level will be a hybrid of the other two. Boreholes will contain pressure and displacement transducers, temperature sensors, flow meters and fluid sampling ports distributed as an optimally located, three-dimensional array.

Additional sets of boreholes will be created perpendicular to the first set and used for cross-borehole geophysical imaging. Spacing between monitoring boreholes will range from less than one meter to more than several tens of meters depending on the details of the experiment. An array of seismometers will also be used to monitor microseismicity accompanying fracture growth.

Experimental Program

Two major facets of these experiments will be explored, one evaluating the propagation of induced fractures and another involving effects of induced fractures on deformation, fluid flow, geochemical flux, and microbial processes.

Imaging fracture growth and the movement of fluid in fractures will be conducted during all of the experiments using seismic and electrical resistance tomography, borehole radar, and other relevant techniques. The refinement of these methods, and the development of new imaging techniques, will be critical to conducting the experiments, and advances in imaging *in situ* processes in fractured rock will be an important ancillary contribution by this experimental program.

Fracture Propagation

Hydraulic Fracturing

- *Objective*: Evaluate and refine existing theoretical models for processes related to hydraulic fracturing, including processes of fluid and proppant transport within hydraulic fractures, interactions between hydraulic fractures and geologic features that affect fracture form, conditions at the tip of a propagating fracture at the field scale, and methods for interpreting pressure records to infer state of stress.
- *Approach*: Create fractures by injecting liquid at controlled rates. Sequentially mix different tracers (e.g., different colored proppants) with injected liquid to track how the fracture is progressively filled during propagation. Monitor transient displacements, pressures, flows, and temperatures in the propagating fracture and in the vicinity, particularly in fracture zones nearby. Use closely spaced monitoring points to characterize transient fluid flows and displacements at the fracture tip. Monitor seismic emissions that accompany fracturing and use geophysical imaging techniques to evaluate fracture growth. Repeat using different borehole designs, casing perforating methods and borehole orientations.

  Drill and collect cores of the fracture to verify the monitoring data and refine monitoring techniques. Excavate critical regions in the vicinity of fracture and describe the location, aperture, and distribution of proppant or liquid tracers. Map relationships between the induced fracture and joints, faults, formation contacts, and other geologic features. Conduct lab tests on cores and controlled *in situ* tests to refine characterization of mechanical properties and stress state in the vicinity of the exposed fracture.

Propellants

- *Objective*: Refine models for coupled, high-velocity fluid flow and dynamic propagation of large-scale fractures.
- *Approach*: Create fractures from boreholes using propellants or explosives. Monitor fracture propagation and then excavate and describe the results using methods outlined above. The monitoring array used for this experiment will be sampled at a higher rate to characterize fractures that propagate at faster velocities than the other experiments. Repeat experiments using different propellant energies and borehole orientations.

Tunneling

- *Objective*: Evaluate and refine models for designing and predicting the long-term stability of large underground openings subjected to static and dynamic loads.
- *Approach*: Create an instrumented region and advance a tunnel through it to monitor fracturing accompanying tunneling. Identify paired areas where geologic conditions are similar adjacent to the tunnel, and in one area create controlled dynamic loads using explosives or mechanical actuators to simulate mining activities or the operation of heavy machinery. Limit the dynamic loads in the control area. Monitor displacements and fracture propagation using instrumentation described above. Ultimately excavate and describe the fractures and geology and compare results from the paired regions. The monitoring array used for this experiment will be more closely spaced to characterize fractures that are more localized than in the other experiments.

Thermal Fracturing

- *Objective*: Refine existing theoretical models for predicting the onset and extent of fracture growth and permeability changes caused by thermal fracturing.
- *Approach*: Create fractures by increasing temperatures using heaters in boreholes. Thermal loadings will consist of temperature changes of tens of °C to many hundreds of °C applied over several days to several years or longer. The monitoring and evaluation phase is similar to that described above.

Effects of Induced Fractures

Well Performance

- *Objective*: Refine models for characterizing and optimizing the performance of induced fractures for well stimulation and waste sequestration.
- *Approach*: Create a well with open interval in a region containing monitoring bores as outlined above. Use the well for one of several scenarios, including the injection or recovery of tracer-bearing water, exchange of heat during circulation, or the injection of CO_2. Monitor fluid migration and associated effects. Then, create a fracture in the well using methods outlined above (liquid injection or propellants), but avoid excavating. Explore the fracture by drilling boreholes and installing the instrumentation described above. Repeat the well utilization tests and monitor fluid properties in the boreholes to evaluate how the hydraulic fracture has affected the trans-

port of fluids to or from the well. Duplicate these tests at different locations and depths to evaluate effects of fracture orientation, interaction with geologic features, and closure stress on well performance.

Microbial Colonization

- *Objective*: Refine conceptual and theoretical models for geochemical fluxes, microbial activity, and microbial colonization associated with fracture formation.
- *Approach*: These experiments can piggy-back on the fracture propagation experiments described above. Inject fluid into a well to create new fracture surfaces. Several injection fluids (e.g., inert gas, ambient groundwater) will be evaluated during preliminary tests to minimize changes in the biogeochemistry during the fracturing process. The fluid will be spiked with marker microorganisms selected from the indigenous population and tagged with a viable stain. The monitoring wells will be used to observe changes in fluid and gas chemistry, particularly redox-sensitive species such as H_2 gas, that can be created during fracturing, and to detect the propagation of the marker microorganisms through the fracture. Using sterile coring methods, samples of the fracture will be acquired at different distances and time intervals after fracture formation to quantify rates of microbial colonization and growth on the fracture surface. Fluid pressures, flow velocities, and temperatures will be monitored to evaluate coupling of geochemical and microbial variations with physical processes. By using multiple fluorescent tags, several microorganisms can be injected simultaneously to evaluate the effect of organism specific properties, such as size, physiology, and adhesion properties, to rates of colonization and growth within newly formed fractures.

Pressure Solution

- *Objective*: Evaluate and refine theories for pressure solution.
- *Approach*: This experiment can be piggy-backed on previous experiments. It represents a longer time frame observational program to be conducted over multiple years following the first fracturing experiment and monitoring of near-term biogeochemical responses. High-resolution displacement and pressure transducers will be installed into the boreholes containing the preexisting fluid sampling ports. Fluid will be circulated between boreholes to estimate fracture transmissivity. Displacement and transmissivity will be monitored as functions of time for evidence of pressure solution. Cores will be obtained after displacements have been observed. The experiment will be repeated at different depths and temperature using different *in situ* rock types, fracture orientations, and stress magnitudes.

Rock Deformation

- *Objective*: Evaluate and characterize the influence of discontinuities on rock mass deformation.
- *Approach*: This experiment can be piggy-backed on previous experiments. Characterization of rock mass behavior will be a critical component in understanding and evaluating the results of the other experiments. Displacement measurements and changes in stress will be made in the experimental areas. Collected cores will be used to determine intrinsic rock properties.

■ Deep Coupled Processes Laboratory ■

Goals

The general goal of this laboratory program is to characterize the coupled processes that affect critical environmental engineering applications and to advance our understanding of complex, subsurface Earth processes. This underground laboratory will develop and validate a fully coupled model of subsurface flow processes, including the fate and transport of solutes, gases, and microorganisms in fractured rock environments under a range of ambient temperatures and stresses. The effect of fracture formation on these coupled processes will be examined in the Induced Fracture and Deformation Processes Laboratory.

Critical Applications

- *CO_2 Sequestration*: Determine the effects of coupled mechanical, chemical, and microbial processes on the transport and storage of CO_2 in fractured rocks.
- *Microbes and Contaminants*: Determine the effects of microbial oxidation or reduction on the chemical form and mobility of toxic metal and radionuclide analogs.
- *Resource Recovery*: Determine the effects of coupled processes on the recovery of resources, such as water, precious metals, petroleum, natural gas, and geothermal energy.
- *Environmental Geochemistry*: Measure the *in situ* kinetics of acid mine drainage (AMD) generation, determine the influence of microbial communities on AMD processes, monitor surface alteration of sulfide minerals including formation of secondary phases, and monitor changes in AMD solution composition including release and transport of toxic elements (e.g., As, Se) or precipitation of secondary minerals.

Basic Processes

- *Ambient Processes*: Evaluate how coupled processes occur under natural conditions, how they vary with depth, and how they can be scaled to improve our basic understanding of Earth systems.
- *Chemical Fate and Transport*: Determine how coupled processes affect the dissolution, deposition, and transport of compounds in water.
- *Multiphase Fate and Transport*: Evaluate details of multiphase flow in fractures and how such flows are affected by other processes.
- *Microbial Colonization, Growth, Predation, and Transport*: Determine the fate and transport processes associated with biogeochemical cycling and the microbial ecology of fractures.

Facility Design and Construction

The design and construction of the Deep Coupled Processes Laboratory will require approximately two years to complete and entails the following activities.

- Use site characterization data to identify accessible, sub-horizontal fractures at varying depths (e.g., ~100, ~500, ~1500, and ~2400 m) and temperatures (e.g., from 10 to 50° C).
- Install borehole and heater arrays, that intersect fracture zones and span ~50 m vertical transport distance.
- Acquire cores of the fracture zones for characterization of the sessile microbial communities, fracture geometry, surface mineralogy, petrophysical properties and surface charge.
- Install multi-level samplers in the boreholes that target specific fractures based on core analyses. Attach multi-level samplers to autosamplers for water collection and sensors for monitoring water chemistry.

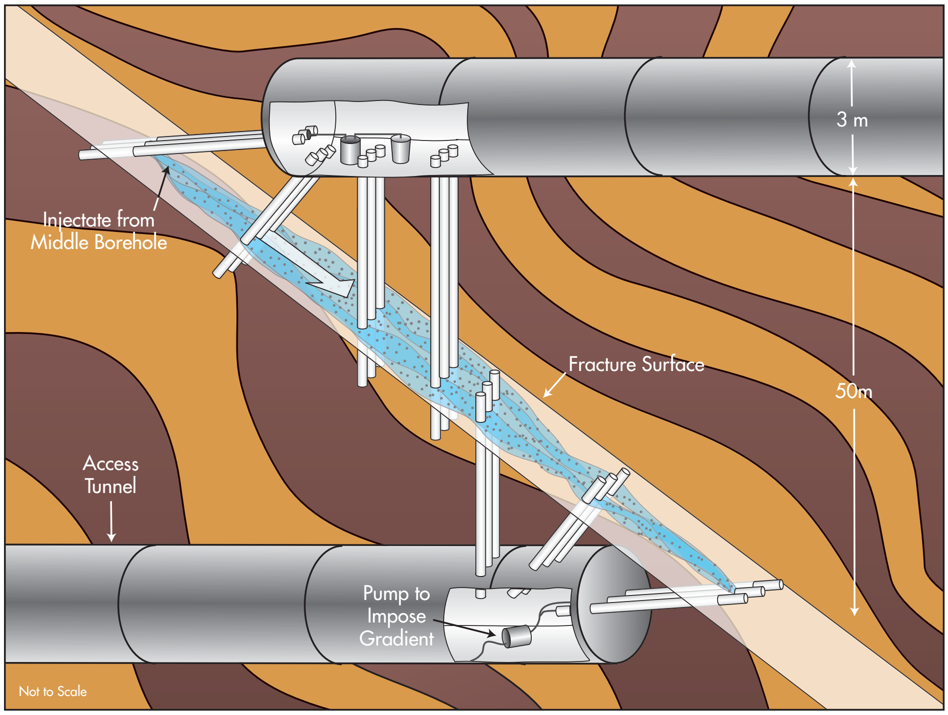


Figure 15. The Deep Coupled Processes Laboratory. Four experimental arrays will be established at different depths and within the same heterogeneous rock formation. Subhorizontal fractures will be intersected by an array of ~20 boreholes. Cross-borehole geophysical tomography and multiple tracer tests will be used to characterize the hydrologic structure of the fracture zone. Based upon this analysis, injection and heating experiments will be modeled to optimize experimental design. Liquid or particulate injections may occur at top of array, whereas gas injection, for example, CO_2, could occur at the bottom of the array to monitor leakage. Hydraulic gradients can be imposed upon the fracture as can varying degrees of water saturation.

Multi-level samplers will be removable so that solid substrates or model microbial communities can be inserted into the fracture environment.

- Inject a variety of geophysical and geochemical detectors, such as micro-electromechanical systems (MEMS), into the borehole arrays in these experiments. Data loggers will collect data in real-time for concurrent analyses of chemical and microbial transport and conversion rates.
- Conduct pump tests, petrophysical analyses, geophysical tomography, and tracer tests to characterize the three-dimensional hydraulic structure of the fracture zones.

Experimental Program

The results from hydraulic testing of the fractures will already provide insight relating these properties to ambient stress, temperature, and petrophysical properties as well as enhance geophysical techniques for characterizing the hydrogeologic properties of fractures. Some experiments that could be performed using these instrumented fractures may last a year and include:

- *CO_2 Sequestration*: Isotopically labeled CO_2 gas will be injected at the base of a fracture array experiments in forced or natural hydraulic gradient modes. The upward migration of the CO_2 will be monitored along with changes in fluid chemistry and microbiology. Cross-borehole tomography will be used to image changes in the water/gas values during the course of experiments. The results of this first experiment will be used to design subsequent experiments that would enhance CO_2 sequestration.

- *Microbes and Contaminants*: Radionuclide or toxic metal analogs will be injected into the fracture along with conservative and reactive tracers. Its rate of migration will be monitored from analyses of water samples. Static and dynamic self-potential measurements will also be used to monitor changes in ionic strength, fracture surface charge, and streaming potential during the course of the experiment Evaluate applications for inverting self-potential measurements to characterize the pattern and magnitudes of fluid flow. The results of this experiment may lead to follow-up experiments in which the geochemical or microbial conditions for different parts of the fractures are altered during the course of the transport experiment. Co-injection of select microorganisms with toxic metal analogs will examine the effect of metal binding to the microorganisms on metal transport rates.
- *Microbial Colonization, Growth, Predation, and Transport*: Alter the aqueous and gas chemistry of the fracture system by injection of isotopically tagged electron donors, acceptors, shuttles, and gas phases. Determine *in situ* transformation rates for these substances from stable isotope analyses and microbial cells using compound-specific isotope approaches (CSIA), ion probe mass spectrometry (SIMS), radioisotopes (^{3}H, ^{14}C, and ^{35}S) and fluorescent *in situ* hybridization of the ^{16}S rRNA (FISH) to relate geochemical reactions to microbial community structure and growth rates. The borehole array is extensive enough to spatially separate different types of amendments and a no amendment control from each other. These include inserting isotopically spiked, artificial mineral substrate coupons into the fracture system, removing them at specific time intervals, and analyzing the microbial colonies by a combination of FISH, microautoradiography, and SIMS.
- *Resource Recovery*: Precious metals are often to inaccessible for economic recovery by standard mining. Experiments that inject sulfide-oxidizing microorganisms into the fracture zone will be used to test *in situ* bio-leaching technologies in the ultradeep environment.

Subsurface biological resource exploration and development

Subsurface biological resources include new microorganisms with novel biological capabilities and microbial products with potential applications in pharmaceuticals (e.g., antimicrobial agents), feedstock chemicals (e.g., chiral synthesis), bioremediation of industrial waste, industrial processing, and nanotechnology. The exploration and development of this resource will provide opportunities for comparative genomics/proteomics and will lead to new insights into the mechanisms of prokaryotic and eukaryotic development and new technologies designed to detect and quantify these processes. Some subsurface environments may offer greater biological potential than others, but unlike oil exploration, subsurface biological exploration currently has no guiding scientific principles. During its construction and through its experiments, EarthLab will lay the groundwork for subsurface biological resource exploration using the following approaches: (1) a high-throughput, micro-gel enrichment procedure for growing hard-to-grow subsurface isolates, (2) *in situ* enrichment and enzymatic assays, (3) analyses of the environment for enzyme-specific genes, and (4) screening of samples for proteins or extremozymes of potential value.

As EarthLab builds relationships between subterranean environments and the enzymes expressed by its microbial inhabitants, borehole geophysical tools normally used for hydrocarbon exploration will be modified to identify those environments with greatest biological resource yield.

CO_2 Sequestration

Modern society's energy needs produce a vast array of wastes, including tremendous amounts of CO_2, NO_x, SO_x, and Hg from coal and/or gas-fired power plants, and long-lived fission products from nuclear power plants. Increasing levels of "greenhouse gases" in the atmosphere, especially CO_2, are often cited as the most likely cause of global warming. At this time, the burning of fossil fuels provides about 85% of the world's energy. In the United States, approximately 90% of greenhouse gas emissions are due to energy production, and most of these come from the burning of fossil fuels. Although the development of more efficient and alternative energy systems may lead to reductions in emissions, the burning of fossil fuels will continue to provide a considerable proportion of the nation's energy well into the next century. One strategy for reducing emissions of greenhouse gases to the atmosphere is to capture CO_2 from power plant flue gases and sequester it below Earth's surface, either on land or in the oceans.

Many questions remain regarding specific methods of sequestration and their relative effectiveness. For example, how will CO_2 interact chemically and mechanically with fluids (brine, oil, etc.) and rock units in deep aquifers or petroleum reservoirs? Under what conditions will CO_2 displace existing fluids? How will CO_2 react with existing rock, and can rock-fluid-CO_2 interactions be assessed at temperatures and time scales (hundreds to thousands of years) of interest? Other issues are common to both hydrocarbon retrieval and CO_2 sequestration and concern uncertainties geological response over long time periods in complicated mechanical, hydrological, and chemical environments. For example, what rock types and material properties (permeability, porosity, connectivity, fluid saturation) make a good sequestration site?

Can these properties be identified remotely by geophysical techniques such as seismic, electromagnetic, or other imaging techniques? Can these techniques identify rapid-flow pathways that could compromise the integrity of sequestration sites? Although the petroleum industry has considerable experience with oil and gas fields, much less is known about the geologic, thermal, and fluid properties of deep aquifers.

EarthLab will be an ideal location for field testing different sequestration strategies, including evaluating rates of CO_2 leakage and conversion to bicarbonate and carbonate, and the impact on subsurface microbial ecosystems and the physical properties of the rock. For example, a specific sequestration site aquifer(s) at depth below, adjacent to, or between tunnels of EarthLab may be identified using high-resolution imaging techniques and other methods, as described in other sections of this report. A high-storage-capacity (high porosity and permeability) site with adjacent sealing units such as shales, typical of such sites chosen near power plants, will be sought. Carefully engineered and controlled CO_2 injection testing may then be performed with pressure and strain sensors installed to evaluate estimated storage integrity of the site(s). Post-test coring may be used to evaluate reactive transport processes, and subsequent computer modeling may be calibrated using these results. Methods for measuring these processes *in situ* must be developed at a facility such as EarthLab, which permits the type of closely spaced, real-time observations that are needed.

Potential for Scientific and Engineering Innovation

EarthLab will generate technological innovations in many areas as a result of deep subsurface scientific and engineering studies, including:

- Genetic materials, novel microorganisms, and biotechnology applications
- Analytical techniques for geomicrobiology and exobiology
- Environmental remediation
- Subsurface imaging
- Drilling and excavation technology
- Natural resource recovery
- Mine safety

Instrumentation for Monitoring and Mapping in Extreme Environments

Geochemical research in an underground laboratory will encourage development of field-deployable, long-term, remote-monitoring instruments using microelectromechanical systems (MEMS). Instruments of this type are badly needed to provide information on geochemical processes at spatial and temporal scales that will permit us to understand active rock-water interaction from both equilibrium and kinetic perspectives. The greatest challenge for instrumentation of this type is to find ways to make measurements on a continuing basis without disturbing the chemical environment.

A second instrumentation frontier for research relates to underground mine mapping. As our exploitation of natural resources continues, we will find it necessary to mine deposits at greater depths, usually by underground methods. Data collection in these environments will require laser-based systems using data capture software, EarthLab can serve as a test bed for new sensor technologies in extreme environments.

which need to be tested in the underground science laboratory (Figure 16). These systems must function under extreme physical conditions over a broad spectrum of geological environments, including above ground, underground, and airborne platforms. Relatively few universities currently provide training in mining geology and the on-site training once routinely provided by corporations for their technical staff is becoming a rarity. Justification for this approach lies in improving and expanding the technical workforce productivity through advancing the quality, efficiency, and uniformity in scientific and technical standards of mine mapping and related activities.

Figure 16. Geologist using a real-time digital mapping system in a mine. By combining stylus input on a PC pen tablet with a LIDAR range finder that locates features out to 300 m, mapped geology is displayed instantly on the computer screen in 3-D coordinates. Pen tablet computers can also support real-time spectrometry to identify minerals remotely. Photo courtesy of George Brimhall, University of California, Berkeley.

Some of the experimental work at EarthLab will focus on the development and application of inexpensive and miniaturized sensors capable of widespread deployment and distribution, and capable of reporting reliably at high sampling rates and for long durations. These signals will provide a wealth of data applicable to bioremediation, exploration and geologic engineering, and other applications. Thus, EarthLab can serve as a test bed for new sensor technologies in extreme environments.

Rock Engineering

Access to extreme depths in rock for long time periods provides an opportunity to improve rock engineering practice, such as the long-term (100 yrs ±) structural support of rock masses. The long-term effectiveness of rock bolts, durable linings, and shotcrete currently are poorly defined. As a result, even though rockbolts and shotcrete are commonly used as initial support for underground excavations in rock, their potential contributions to the long-term strength of reinforced concrete linings are commonly neglected in design. It is important to understand the mechanisms that contribute to loss of support over time, such as corrosion of rock bolts and steel fibers in fiber-reinforced concrete, the loss of keying in a blast-damaged zone, and the potential buildup of fluid overpressures as drainage conduits degrade over time. By testing a variety of support methods (e.g., bolts, anchors, cables, mesh, and shotcrete) in a range of configurations in new tunnels and caverns adjacent to an underground facility, both their short-term and long-term effectiveness can be monitored.

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. All experiments will be preceded by predictions using numerical simulation models of coupled processes in fractured, lithologically heterogeneous rock at a range of spatial scales. Comparison between model predictions and outcomes of experiments will provide insight into our understanding of process-feedbacks of varying complexity, and the scale-dependence of behavior at scales not possible in the laboratory.

Remediation of Contaminated Groundwater

Detailed studies of storage properties, leaching, and contaminant transport may be carried out using geochemical tomographic techniques, including controlled tracer tests and verification studies. By inducing hydraulic and geochemical signals through an engineered rock mass within EarthLab, then measuring these signals at the boundaries of the rock mass (e.g., between tunnels), we can test our ability to predict the flux of water and solutes through the rock mass. Potential signals to record include: (1) hydraulic waves, (2) injected tracers (benign solutes dissolved in water), and (3) environmental tracers (solutes that are present in precipitation due to either natural or anthropogenic processes.) EarthLab will be uniquely suited for such research because the boundaries of the rock mass could be accessed in three dimensions without perturbing the engineered structure of the rock mass.

Well Test Verification Studies

Well testing is a fundamental tool for characterizing the subsurface, but advances in well testing techniques are currently limited by the lack of facilities to verify new methods. EarthLab's controlled environment, combined with a well-characterized geological setting obtained during tunnel and workroom development, provides an ideal location to develop a verification facility.

The approach for creating a well testing verification facility is to identify a relatively undisturbed region and characterize it in detail using a closely spaced array of boreholes drilled from the underground access. Characterization will be done using cores, borehole logs, hydraulic tests, and tracer tests. The borings will be sealed to prevent them from influencing the characteristics of the site. The dataset will be assembled to provide a detailed, comprehensive characterization of the region in three dimensions.

One or more wells will then be drilled into this highly characterized region. Well tests will be conducted in those wells using advanced geophysical and hydraulic methods, and the results will be interpreted using state-of-the-art algorithms. The results of the interpretations will be compared to the 3-D control data set to evaluate the effectiveness of the well testing technique. The comparison will highlight shortcomings in the well testing methods, which will inspire refinement in current techniques and the development of new ones.

The improvements made possible by this facility will have applications in all subsurface investigations, and will be particularly important to the development of petroleum and natural gas reservoirs, the use of aquifers, the safe injection of hazardous wastes into wells, the sequestration of carbon dioxide in deep geologic settings, and other applications critical to society.

Education and Outreach

EarthLab will affect a large segment of the public, ranging from students at every level to the general community. Educational and Outreach (E&O) activities will engage, recruit, and retain the next generation of science and engineering professionals. EarthLab will enlighten and provide materials for our educators, community officials, and legislators and will educate and involve the public in the world of astrophysics, the search for life in the universe, and an underground journey back into geological time. Public tours will reveal the relationships between complex geology and life at various depths and show the deepest physics experiments in action. EarthLab will include the necessary infrastructure to move both large and small groups of people depending on the educational or outreach program (e.g., school field trips or undergraduate summer research opportunities).

EarthLab educational programs will involve K-12 to graduate students to post graduates to senior scientists, and K-12 teachers from international, national, regional, and local institutions in a unique multidisciplinary venue. A variety of outreach programs are being considered:

1. Hold secondary school workshops focusing on local schools, and develop real-time instruction aides that can be disseminated over the Internet for regional schools, including lesson plans for K-12.
2. Hold secondary school teacher training workshops focusing on local schools, which are supplied with educational aides and video tours of excursions.
3. Deploy experiments designed by local and regional high school students that can be monitored in real time through the Internet. Local science and engineering fairs provide an ideal venue for organizing student participation and the mentoring experience by their teachers. Experiments could include:
   a. Microbiological. Insert media-bearing cartridges designed by the students into boreholes along with pH, Eh, and O_2 sensors connected to short-term memory storage at the borehole head, which can be periodically downloaded through the Internet. The media cartridges can be removed for analyses at the high school or for electron microscopic observations. Images would be displayed in real time on the Internet.
   b. Geophysical and rock mechanics. Observe and interpret seismic data generated by excavations and hydrofracturing experiments or tomographic data in cross-borehole CO_2 gas sequestration or biostimulation experiments.
   c. Geological. Map underground with infra-red and laser equipment.
   d. Hydrologic. Collect and measure samples during fracture transport experiment where students could monitor and model the progress of a plume over a period of a semester.
4. Conduct a summer field research institute that trains local, national, and international college students and senior scientists. It will be modeled after the summer program of the Marine Biological Lab at Woods Hole and the recent minority educational workshops and REU held in South Africa (http://geomicro.utk.edu/). The summer institute will also offer an underground mapping component for summer geology field mapping courses.

Figure 17. Above: One of two groups, consisting of United States and South African workshop participants (undergraduate students, technicians, and mentors), are ready to go into the South African gold mine. Courtesy of a U.S. mentor, Mary DeFlaun, GeoSyntec.

Right: As part of the NSF-funded Life in Extreme Environments and Biotechological Applications Workshop, undergraduate students from the United States and South Africa collected fissure water and biofilm samples for laboratory analyses. Courtesy of a U.S. mentor, Mary DeFlaun, GeoSyntec.

5. Host an REU site at EarthLab that targets underrepresented students. Coordinate the EarthLab REU with the NSF-REU site for South Africa so that students will have an opportunity to attend both. The REU site will provide an interdisciplinary summer research experience for undergraduates that includes underground excursions coordinated with conducting research into biogeochemical processes in the subsurface environments.
6. Target minority communities at the secondary school and college level, and internship, undergraduate, graduate, post-masters, and postdoctoral programs.
7. Encourage undergraduate and graduate students funded through NSF's IGERT Program, for example, at Oregon State University and Portland State University (Subsurface Biosphere Interdisciplinary Doctoral Program), to conduct research at EarthLab.
8. Host visiting scientists intent on performing underground experiments, and conferences for societies such as the ISSM (International Society for Subsurface Microbiology) and the ISE (International Society for Extremophiles), and others.

Management and Partnerships

A large number of individuals and groups developed and nurtured the EarthLab concept. EarthLab is unique among other similar initiatives because its definition and goals are truly interdisciplinary, and are the result of collaboration among biologists, geologists, physicists, and engineers. All phases of decision-making and implementation at EarthLab, including project planning, data collection, data management, and project review, will be closely coordinated with input from all groups. Research at EarthLab will require multidisciplinary, collaborative proposals, including multi-institutional funding arrangements. An information management infrastructure will be developed to meet EarthLab's data needs, and will take advantage of ongoing efforts in the areas of geoinformatics and Earth data systems, linking and incorporating multidisciplinary data resources that extend far beyond the data resulting from EarthLab research.

Many different management structures are possible for EarthLab. The research community as a whole will work with the NSF and other agencies to develop the most appropriate management mechanism to optimize EarthLab and its proposed programs.

National and International Partnerships

EarthLab is a national deep Earth observatory and laboratory program, with the lead agency role to be carried out by the National Science Foundation, along with federal agencies and other national and private groups. Partnerships are forming among state and federal agencies, as well as other research projects and consortia such as NCAR, EarthScope, IRIS, and CUAHSI. All partners are interested in the fundamental science and engineering objectives that can only be carried out in the deep subsurface.

Physicists and Earth Scientists: A Synergistic and Symbiotic Partnership

The EarthLab concept is not new, but the extremely strong and synergistic partnership between the particle physics community and the Earth science community is recent. To take advantage of economies-of-scale and complementary goals, EarthLab will be constructed in the same underground site as the proposed physics facilities discussed during the NeSS 2002 conference held in Washington, D.C. Following the conference, plans for EarthLab, including development of this report, were made in concert with the physics community. One of the unknown but interesting aspects of the geoscience/physics partnership will be the consequences of daily interactions between physicists and Earth scientists.

A principal area in which Earth science and physics goals overlap is the extent of the underground excavations required. The physics community proposes a large proton decay detector requiring a cavity that is 60 m by 60 m by 180 m. The preferred depth for this facility approaches ~1.5 km (5000 ft), consistent with several EarthLab requirements. The cavity would be filled with a half megaton of water and instrumented with walls of photomultiplier tubes. A variation of this experiment proposed for a deeper level (2.1 km, or 6900 ft) requires 10 upright cylindrical cavities, each 50 m in diameter and 50 m in height, positioned along the circumference of a 250 m radius circle. To our knowledge these would be the largest deep underground excavations yet attempted. Deep excavations are needed for EarthLab's Ultradeep Life and Biogeochemistry Observatory.

The rock mechanics/engineering community involved in developing this report has already played an important role in these physics proposals, using two-dimensional and three-dimensional models to assess the stability of the proposed excavations as a function of depth and rock formation. These excavations for the physics experiments as well as new underground excavations for Earth science efforts will be carefully instrumented after construction permitting rock mechanics modelers to examine and test their results. This validation process will also be extremely valuable to the physics community by providing calibrated baselines for future large excavations, some of which will be done at depths of 2.25 km (7400 ft) or more.

As discussed during NeSS 2002, the physics and applied science communities propose to develop the world's most sophisticated low-level counting facility. It will include high-purity germanium detector arrays, counting systems with high position sensitivity. The facility's staff scientists will continue to develop new counting methods as experimental demands increase. The required surface laboratory will include chemistry facilities for purifying and processing samples from neutron activation, before below-ground counting. Earth science has many of its own counting needs, ranging from tracer analysis to dating. The physics counting facility will be shared by all EarthLab scientists and will also be open to users from the community.

Interest in ascertaining the responses of biological systems to very low levels of radiation has been expressed: is the response characterized by a threshold, or is it linear for small doses? This question creates a possible area of collaboration between EarthLab geomicrobiologists and physicists. The physicists will characterize the cosmic rays from surface to 2.44 km (8000 ft)—flux, spectrum (which hardens substantially with depth), and the secondaries produced from interactions in rock. Conceivably this could allow geomicrobiologists, using the indigenous microbial communities in the subsurface, to investigate whether there is evidence for cosmic ray radiation influences on microbial life and, if so, how it tracks with depth/dose.

Partnerships with Other Underground Laboratories

EarthLab activities and environment will be selected to complement those of other underground laboratories worldwide (Table 1). Underground laboratories, including the Waste Isolation Plant in New Mexico (see p. 23), the URL in Canada, and the Soudan Mine in Minnesota (see p. 15) are candidate sites for EarthLab, as detailed earlier in this report. EarthLab will be distinct from these laboratories in reaching significantly greater depths and in containing a wider range of rock types and hydrologic environments. EarthLab will permit evaluation of the significance of heterogeneity on subsurface processes by comparing its results with those of other laboratories.

Most of these laboratories focus their research on the transport, rock mechanics, and biogeochemical processes associated with the storage of high-level nuclear waste. As a result, facilities such as the Aspo Hard Rock Laboratory in Sweden, the Whiteshell Underground Research Laboratory in Canada, and the proposed Mizunami Underground Research Laboratory in Japan are sited in water-saturated, homogeneous granite with maximum depths of ~ 500 m. The Meuse/Haute Marne underground laboratory in France also focuses on radioactive waste storage processes, but is located in water-saturated shales at ~500 m depth.

Table 1: Worldwide Underground Research Laboratories for the Earth Sciences

Lab	Host Rock and Depth	Location
Aspo Hard Rock Laboratory	Homogeneous granite, 0-450 m	Sweden
Whiteshell Underground Research Laboratory	Homogeneous granite, 240-420 m	Canada
International Facility for Underground Science	Deformed gabbro, 100-1600 m	Initiative just funded to be located at Sudbury Neutrino Observatory, Canada
Meuse/ Haute Marne	Shale, 450-500 m	France
Mizunami Underground Research Laboratory	Homogeneous Granite, depth not determined	Exploratory drilling underway Japan
Grimsel Underground Research Laboratory	Granite, 450 m	Switzerland
Exploratory Studies Facility	One tunnel in welded tuff, 300 m (vadose)	Yucca Mountain, USA
EarthLab	Heterogeneous rock strata, 0-2400 m (vadose+saturated)	USA

Partnering with other operating underground laboratories is critical to maximize EarthLab research results as well as results coming from these other underground labs, and to eliminate any possible redundancy. Close coordination with the new International Facility for Underground Science that has just recently received funding from the Canadian government, and that will be located at their Sudbury Neutrino Observatory (SNO) in Canada, is one example. The photomultiplier arrays in large particle detectors at SNO respond to seismic activity by producing false signals. By obtaining data from EarthLab's seismometers that are accurately time-stamped, they could calibrate instrument response as a function of the strength of the disturbance and to help with rejection of false events. Physicists, in turn, can use timing information obtained from SNO and other labs to characterize and also reject false events.

Currently, the only underground experimental facility is operated by U.S. DOE at Yucca Mountain, Nevada and comprises a tunnel located in dry, welded tuff at 300 m depth. DOE also supports the Subsurface Science Initiative (SSI) at the Idaho National Engineering and Environmental Laboratory (INEEL), which focuses collaborative, interdisciplinary, and multi-institutional research to enhance the scientific and engineering underpinnings of DOE's environmental remediation programs. The SSI is currently constructing a highly controlled, mesoscale surface experimental facility and a vadose zone research program but it has no underground laboratory. Active collaboration between EarthLab and INEEL SSI will potentially provide opportunities for the field results derived from EarthLab experimental facilities to be used in mesoscale experiments at INEEL SSI to test DOE relevant processes and vice versa.

Further Reading

Acid Mine Drainage

- http://geology.er.usgs.gov/eastern/environment/drainage.html
- http://www.dep.state.pa.us/dep/deputate/minres/bamr/amd/science_of_amd.htm
- http://www.epa.gov/region3/acidification/what_is_amd.htm

Deep Life

- Fredrickson, J.K. and Onstott, T.C., 1996, Microbes deep inside the Earth, Scientific American, 275 (4), 68-73.
- Nealson, K. and W.A. Ghiorse, 2001, Geobiology – A report from the American Academy of Microbiology, American Academy of Microbiology, Washington, D.C., 16 pp.

Groundwater Resources and Quality

- http://webserver.cr.usgs.gov/trace/arsenic
- http://www.epa.gov/mercury
- http://water.usgs.gov

Mineral Resources

- http://minerals.usgs.gov
- http://mrdata.usgs.gov

Nuclear Waste Disposal

- http://www.nrc.gov/waste/hlw-disposal.html
- http://www.em.doe.gov/em30/wastdisp.html

Rock Deformation and Fluid Flow

- ANDRA Underground Research Laboratory (http://www.andra.fr/eng/labo/index.htm)
- Atomic Energy of Canada's Underground Research Laboratory (http://www.liv.ac.uk/seismic/research/url/url.html)
- National Research Council, 1996, Rock Fractures and Fluid Flow: Contemporary Understanding and Applications, National Academy Press, Washington, D.C., 551 pp. (http://www.nap.edu/books/0309049962/html/R1.html)
- Pettitt, W.S., C. Baker, R. P. Young, L.-O. Dahlstrom, and G. Ramqvist, 2002, The assessment of damage around critical engineering structures using induced seismicity, *Pure and Applied Geophysics*, 159, 179-195.
- Young, R. Paul, 1993, Seismic methods applied to rock mechanics, *ISRM News Journal*, 1 (2), 4-18.

Appendix 1

Contributors

Rock Mechanics and Engineering		
Herb Wang	University Wisconsin-Madison	wang@geology.wisc.edu
Bill Pariseau	University Utah	wgparis@mines.utah.edu
Richard Schultz	University Nevada Reno	schultz@mines.unr.edu
Steve Martel	University Hawaii	martel@soest.hawaii.edu
Laura Pyrak-Nolte	Purdue University	ljpn@physics.purdue.edu
Mark Zoback	Stanford	zoback@pangea.stanford.edu
Larry Myer	Lawrence Berkeley National Laboratory	lrmyer@lbl.gov
Steve Blair	Lawrence Livermore National Laboratory	blair5@llnl.gov
Teng-fong Wong	State University of New York at Stony Brook	teng-fong.wong@stonybrook.edu
Michelle Cooke-Andresen	University of Massachusetts, Amherst	cooke@geo.umass.edu
Bezalel Haimson	University of Wisconsin-Madison	haimson@engr.wisc.edu
David Holcomb	Sandia National Laboratories	djholco@sandia.gov
Charles Fairhurst	University of Minnesota	fairh001@umn.edu
James E. Monsees	Parsons Brinckerhoff	Monsees@pbworld.com
Ahmed Abou-Sayed	Advantek International Corporation	admin@advantekinternational.com
Bernard Amadei	University of Colorado	amadei@spot.colorado.edu
Gary D. Callahan	Respec Consulting and Services	gary.callahan@respec.com
Richard G. Hughes	University of Oklahoma	rghughes@ou.edu
Peter Smeallie	American Rock Mechanics Association	smeallie@armarocks.org
Doug Tesarik	Centers for Disease Control and Prevention	det4@cdc.gov
Larry Murdoch	Clemson University	lmurdoc@clemson.edu

Hydrogeology Science and Engineering		
John Gale	Memorial University, Newfoundland	jgale@mun.ca
Steve Blair	Lawrence Livermore National Lab	blair5@llnl.gov
Steve Ingebritsen	U.S. Geological Survey	seingebr@usgs.gov
Leslie Smith	University of British Columbia	lsmith@eos.ubc.ca
Kip Solomon	University of Utah	ksolomon@mines.utah.edu
Joe Wang	Lawrence Berkeley National Laboratory	JSwang@lbl.gov
Brian McPherson	New Mexico Institute of Mining and Technology	brian@nmt.edu
Larry Murdoch	Clemson University	LMURDOC@clemson.edu
Grant Garven	Johns Hopkins	garven@jhu.edu
Chris Neuzil	U.S. Geological Survey	ceneuzil@usgs.gov
Dan Driscoll	U.S. Geological Survey	dgdrisco@usgs.gov

Jean Bahr	University of Wisconsin, Madison	jmbahr@geology.wisc.edu
Derek Elsworth	Pennsylvania State University	elsworth@psu.edu
Mathew Mauldon	Virginia Tech	mauldon@vt.edu
Paul LaPoint	Golder Associates	plapointe@golder.com
Eric Sonnethal	Lawrence Berkeley National Lab	ELSonnenthal@lbl.gov
Nicholas Sitar	University of California, Berkeley	nsitar@ce.berkeley.edu
Fred Phillips	New Mexico Institute of Mining and Technology	phillips@nmt.edu
Mitchell Plummer	Idaho National Eng. and Environ. Laboratory	plumma@inel.gov

Geophysics		
David Blackwell	Southern Methodist University	blackwel@passion.isem.smu.edu
Dennis Nielson	DOSECC	dneilson@eng.utah.edu
Ernest Majer	Lawrence Berkeley National Laboratory	elmajer@lbl.gov
J Filson	U.S. Geological Survey	jfilson@usgs.gov
Jeff Daniels	Ohio State	jeff@geology.ohio-state.edu
Lane Johnson	Lawrence Berkeley National Laboratory	lrj@ccs.lbl.gov
W. Roggenthen	South Dakota School of Mines & Technology	wroggen@silver.sdsmt.edu
Wayne Pennington	Michigan Tech	wayne@mtu.edu
Misac Nabighian	Colorado School of Mines	mnabighian@earthlink.net
James C. Pechmann	University of Utah	pechmann@seis.utah.edu
Shane Ingate	IRIS	shane@iris.edu

Geochemistry		
Philippe Collon	Lamont-Doherty Earth Observatory	pcollon@ldeo.columbia.edu
Ed Dewitt	U.S. Geological Survey	edewitt@usgs.gov
Edward Duke	South Dakota School of Mines & Technology	Edward.Duke@sdsmt.edu
Stephen Kesler	University of Michigan	skesler@umich.edu
Moira Ridley	Texas Tech University	mridley@ttacs.ttu.edu
Tom Campbell	South Dakota School of Mines & Technology	Thomas.Campbell@sdsmt.edu
John Valley	University of Wisconsin	valley@geology.wisc.edu
Joaquin Ruiz	University of Arizona	jruiz@geo.arizona.edu
George Brimhall	University of California, Berkeley	brimhall@socrates.berkeley.edu
Michael F. Hochella	Virginia Polytechnic Institute	hochella@vt.edu
Ed Ripley	University of Indiana	ripley@indiana.edu
Barbara Sherwood-Lollar	University of Toronto	bsl@quartz.geology.utoronto.ca

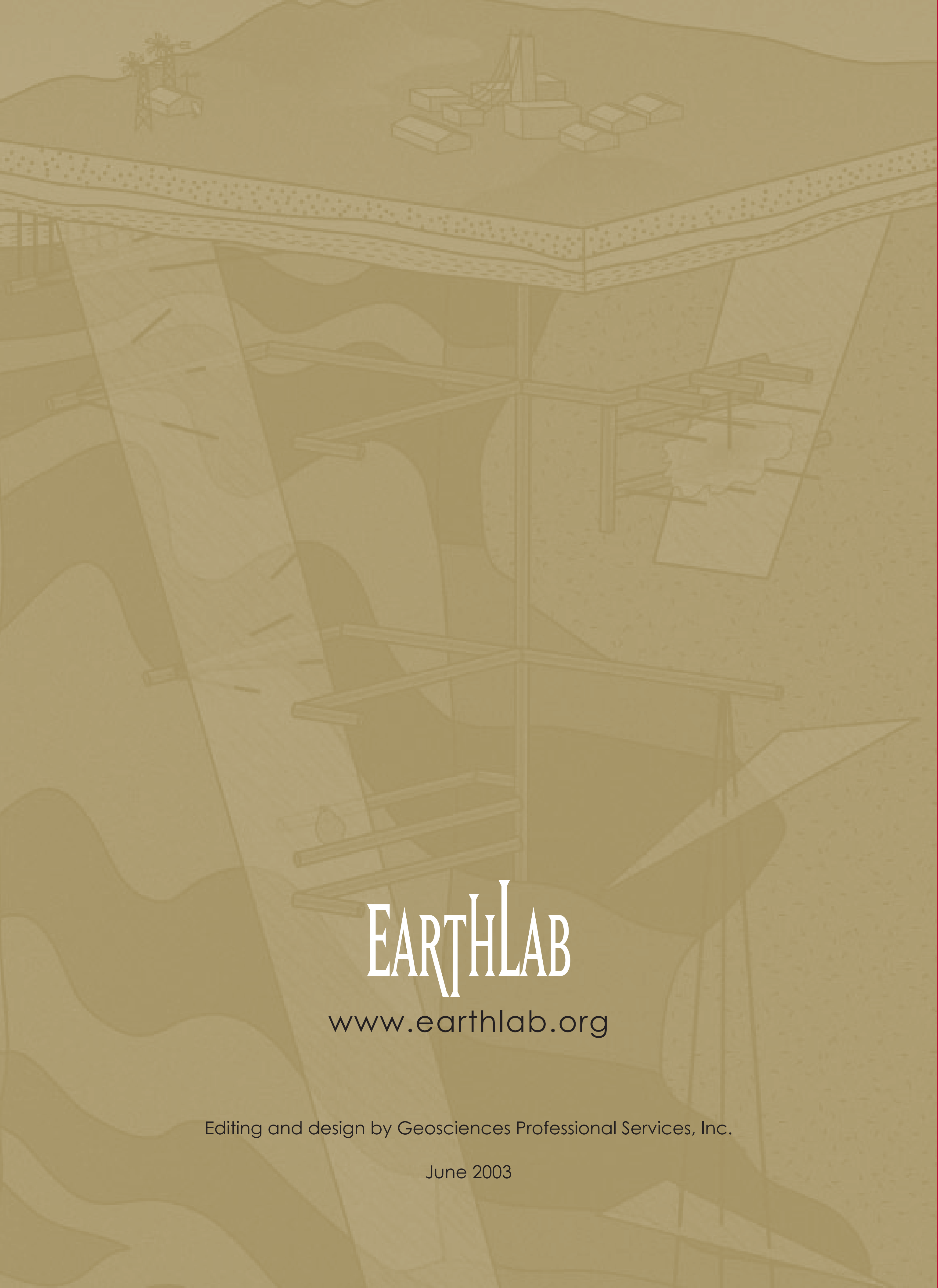
Geomicrobiology		
John Valley	University of Wisconsin	valley@geology.wisc.edu
Tommy Phelps	Oak Ridge National Laboratory	phelpstj@ornl.gov
Sookie Bang	South Dakota School of Mines and Technology	Sookie.Bang@sdsmt.edu
Tullis Onstott	Princeton University	tullis@princeton.edu
Susan Pfiffner	University of Tennessee	pfiffner@utk.edu
Tom Kieft	New Mexico Institute of Mining and Technology	tkieft@nmt.edu

Other Contributors		
Jim Fredrickson	Pacific Northwest National Laboratory	Jim.Fredrickson@pnl.gov
Duane Moser	Pacific Northwest National Laboratory	Duane.Moser@pnl.gov
Ray Wildung	Pacific Northwest National Laboratory	r.wildung@pnl.gov
Terry Hazen	Lawrence Berkeley National Laboratory	TCHazen@lbl.gov
Tom Langworthy	University of South Dakota, Vermillion	tlangwor@usd.edu
Mary DeFlaun	GeoSyntec Consultants	mdeflaun@geosyntec.com
Rick Colwell	Idaho National Eng. and Environ. Laboratory	fxc@inel.gov
David Lambert	National Science Foundation	dlambert@nsf.gov
Herman Zimmerman	National Science Foundation	hzimmerm@nsf.gov
Gene Bierly	American Geophysical Union	ebierly@agu.org
Harvey Leifert	American Geophysical Union	hleifert@agu.org
Randy Showstack	American Geophysical Union	rshowstack@agu.org
Glen Gettemy	New Mexico Institute of Mining and Technology	ggettemy@geophys.nmt.edu

Acronyms

AMD .... Acid mine drainage
CUAHSI .... Consortium of Universities for the Advancement of Hydrologic Science, Inc.
DOE .... U.S. Department of Energy
E&O .... Education and Outreach
IGERT .... NSF's Integrative Graduate Education and Research Training program
InSAR .... Interferometric Synthetic Aperture Radar
IRIS .... The Incorporated Research Institutions for Seismology
NASA .... National Aeronautics and Space Administration
NCAR .... National Center for Atmospheric Research
NRC .... National Research Council
NSF .... National Science Foundation
NUSEL .... National Underground Science and Engineering Laboratory
REU .... NSF's Research Experience for Undergraduates program
SAFOD .... EarthScope's San Andreas Fault Observatory at Depth
THMCB .... Thermal-hydrologic-mechanical-chemical-biological
USArray .... EarthScope's United States Seismic Array
USGS .... United States Geological Survey

Recommended report citation: McPherson, B.J., and the EarthLab Steering Committee, 2003, EarthLab: A Subterranean Laboratory and Observatory to Study Microbial Life, Fluid Flow, and Rock Deformation, Geosciences Professional Services, Inc., 60 pp.



EARTHLAB

www.earthlab.org

Editing and design by Geosciences Professional Services, Inc.

June 2003