Technical Report: Geo-Science and Geo-Engineering Research at DUSEL

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Prepared by

D. Elsworth, Pennsylvania State University
and
C. Fairhurst, University of Minnesota.

Based on material supplied by

Coordinators, Working Groups 7,8,9:

L. Costin, Sandia National Laboratories
F. Heuzé, Lawrence Livermore National Laboratory
B. J. McPherson, University of Utah
J-C. Roegiers, University of Oklahoma
E. Sonnenthal, Lawrence Berkeley National Laboratory.
R. P. Young, University of Toronto

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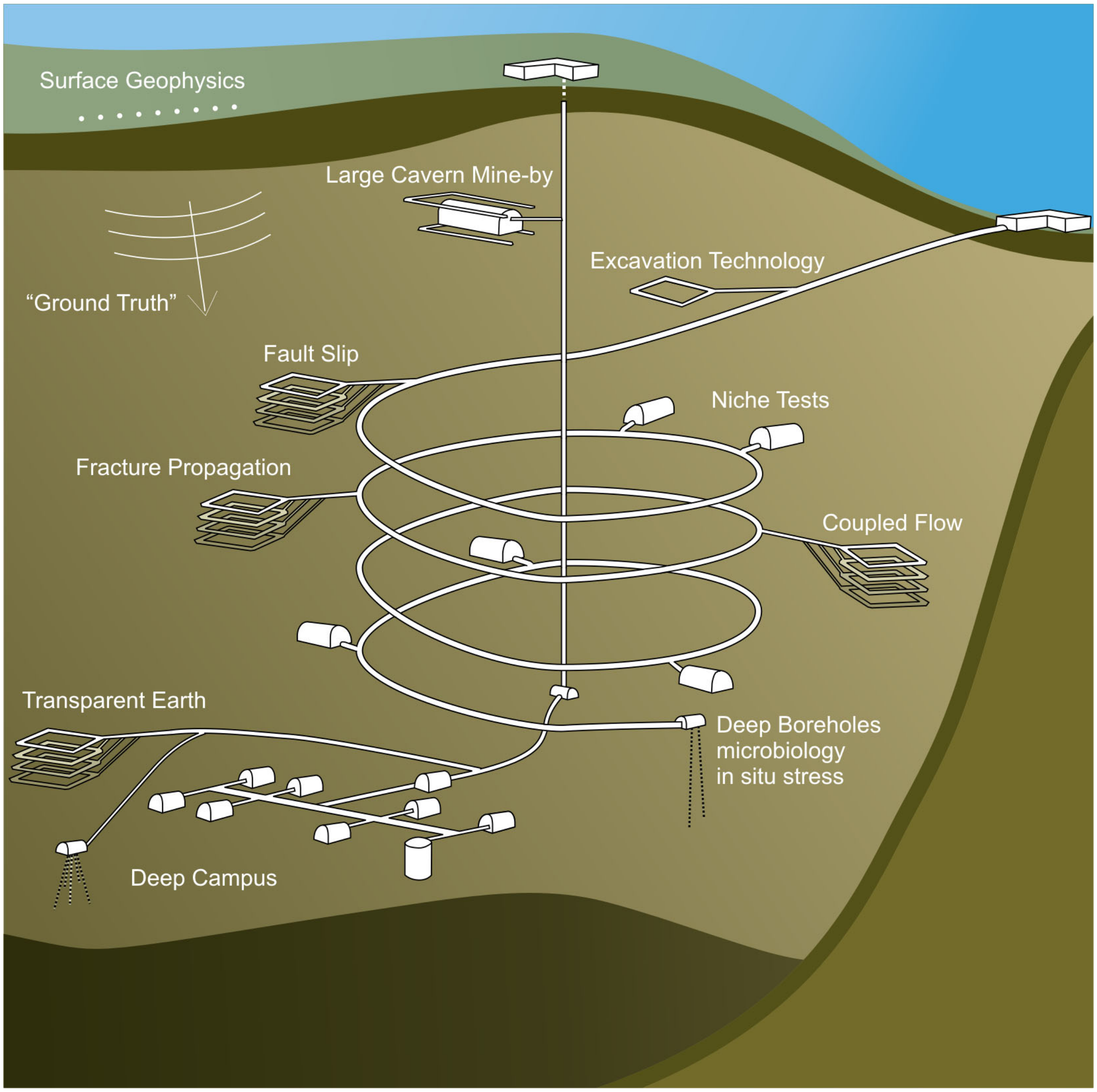

Illustration of Possible Experiments in DUSEL.

Most of the caverns excavated in DUSEL, both at intermediate and deep levels, will be designed to accommodate physics experiments. Excavation of these caverns provides excellent research opportunities for geoscience and geoengineering and geomicrobiology. Development of roadways to the underground facilities provides access to large volumes of rock and further opportunities for research e.g. in 'niches' excavated from the main access drifts This diagram, which is illustrative only, shows examples of the types of geo-experiments that are possible in DUSEL. These are discussed in detail in this report. Actual layout of the underground and design of the experiments will depend on the geology of the site selected for DUSEL. Note: Although a specific location is indicated for experiments on 'Transparent Earth', most of the experiments also will involve measurement and observation techniques that could lead to improved imaging and visualization of processes within the rock, i.e., contributing to the goal of Transparent Earth.

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1.0 BACKGROUND

Development of an underground facility at depth in rock in the United States for research in neutrino physics and cosmology has been an important goal of U.S. physicists for many years. In January 2005, the National Science Foundation accepted a proposal to conduct a site-independent study to examine the potential benefits of such a facility to the main scientific disciplines interested in deep subsurface research. Primary focus was placed on physics, geomicrobiology, the geosciences and geo-engineering.

Fourteen Working Groups (WGs) were established to cover the principal areas of scientific and technical enquiry to be addressed in the underground laboratory, *viz*.

Physics
WG1. Low Energy Neutrinos
WG2. Neutrinoless Double-Beta Decay
WG3. Long Baseline Neutrino Experiments
WG4. Nucleon Decay/Atmospheric Neutrinos
WG5. Dark Matter
WG6. Nuclear Astrophysics and Underground Accelerators

Geoscience and GeoEngineering
WG7. Coupled Processes
WG8. Rock Mechanics/Seismology
WG9. Applications

GeoMicrobiology
WG10.Geomicrobiology
WG11.Microbial Biology and Evolution

Facilities
WG12. Low-Background Counting Facilities and Prototyping
WG13. Infrastructure Requirements and Management

Education and Outreach
WG14

Two Coordinators were appointed to lead each Working Group

A series of Workshops was held over the period August 2004 –July 2005 (See www.dusel.org for details.), supplemented by two visits to government agencies and offices in Washington, D.C. Information and insights gained from these meetings were reviewed by the WGs and refined into a series of Technical Reports.

This report, **Geo-Science and Geo-Engineering Research at DUSEL,** describes the observations and findings of the **Geosciences and GeoEngineering *Working*** Groups.

Coordinators

Coupled Processes (WG 7)	B. J. McPherson, University of Utah E. Sonnenthal, Lawrence Berkeley National Laboratory
Rock Mech. /Seismology (WG 8)	L. Costin, Sandia National Laboratories R. P. Young, University of Toronto
Applications (WG 9)	F. Heuzé, Lawrence Livermore National Laboratory J-C. Roegiers, University of Oklahoma.

The Working Groups were able to draw upon earlier studies and reports, such as the NeSS report (Elsworth, 2002) and the EarthLab Report (McPherson *et al.*, 2005).

2.0 SUMMARY

As in particle physics, underground facilities are needed to address fundamental research questions in the geosciences. Much of the geoscience and geoengineering research also has direct relevance in addressing important societal concerns. Thus,

- Improved identification and sustainable extraction of resources, including minerals, groundwater and geothermal energy are ever- growing imperatives to meet the aspirations of a rapidly increasing world population.
- Disposal of industrial wastes, both radioactive and hazardous chemical, in underground formations is viewed increasingly as the preferred option for removing these hazards permanently from the biosphere. Sequestration of CO_2, produced by the burning of fossil fuels and considered to be responsible for the threat of global warming, at depth in suitable rock formations is being investigated vigorously. Assurance that such wastes indeed will be isolated for the requisite periods requires a better understanding of the hydrological, chemical, thermal, and mechanical processes that develop in the rock when the waste is emplaced at depth. Each of these processes will affect the others to some extent—they are 'coupled'.
- Coupled processes are involved centrally in much of geoscience. Water flowing through fractures in rock at high temperature, for example, reacts chemically with the rock, dissolving and transporting components that are precipitated where the rock is cooler, strengthening the shear resistance of the fractures, changing the flow pathways, etc. Coupled processes are the basis for formation of many mineral deposits; how do these processes and the likelihood of mineral formation, and extraction, change with depth? Operating over geological time, coupled processes affect the rock mass response to tectonic forces. Computer modeling capabilities now allow simulation of coupled processes, provided the governing physics and chemistry are represented adequately in the models. Assessing the validity of the predictions of the simulations is the essential step needed to advance understanding. An experimental program in coupled processes

will be a key component of geosciences research in a Deep Underground Science and Engineering Laboratory (hereafter referred to as DUSEL).

- Urbanization is a growing trend in many regions of the world, both in developed and developing countries. Surface congestion is forcing many cities to consider seriously how to make more effective use of space, both on and beneath the surface. Underground rapid transit systems, introduced in London almost 150 years ago, are now a feature of many major cities. They are usually far more resistant to disruption during earthquakes than are surface systems. Underground space has many other attributes. The ability of a rock cover, of some meters or tens of meters, to provide robust isolation from the surface and from the open atmosphere is being recognized. Is it necessary or desirable to accommodate all industrial plants on the surface? In Stockholm, Sweden, all sewage treatment plants are located underground. How can the risk of unanticipated surface collapse from abandoned underground mines, a growing problem, be reduced? The high cost of constructing urban systems underground is currently a deterrent to greater use of this resource. DUSEL provides an opportunity for development of improved and lower-cost construction procedures in rock

In summary, there are many important and growing societal needs, solutions for which depend on a sound understanding of the nature of the underground environment at all depths down to several kilometers. DUSEL provides an exceptional opportunity to develop this understanding through research.

As illustrated in the Sidebar 'Restless Earth', 'rock' is a general term for a wide variety of heterogeneous materials that have evolved through a long and complex history to their present state. The rock still is subject to tectonic and gravity forces that control its response to any disturbance, external (i.e., by man) or internal (e.g., seismicity). Understanding this environment is the challenge of geoscience research; working safely and economically within it is the challenge of geoengineering.

Transparent Earth, Scale Effects, and Coupled Processes emerged from the Workshops and associated Working Group discussions as important general themes of geoscience research in a DUSEL facility.

- 'Transparent Earth' is intended to describe the overall goal of reducing the opacity of rock. Considerable advances are being made, especially in the application of geophysics on the large scales, from kilometric to global, but the inability to observe real-time changes in structural features, fluid flow in fracture networks, and other stress-induced changes in the rock mass during metric-scale experiments remains a major obstacle. Advances in this domain will affect every aspect of experimental research at DUSEL.
- Scale Effects — The behavior of the rock mass is governed, at all scales, by the interaction between 'relatively intact' rock and discontinuities or 'interfaces,' generally within a heterogeneous rock medium. Much of the scale dependence, with respect to both size and time, appears to be determined by progressive changes in the intact rock

linking the non-continuous system of fractures. DUSEL will allow study of this interaction and response to experimental perturbations of the rock mass over a range of size and time scales under *in situ* conditions.

- Coupled Processes — These were discussed earlier. The opportunity to conduct experiments and observe behavior *in situ* is again a major advantage of DUSEL.

Underground engineering can be improved considerably by DUSEL.

- Some engineering advances will flow directly from the basic science studies. The ability to 'see' just 10 meters or so into the rock immediately ahead of a Tunnel Boring Machine, for example, would be a major accomplishment in avoiding rock 'outbursts' and collapses, inrushes of water, mud, etc. that can be catastrophic, both with respect to loss of life and productivity. Knowledge of scale effects in rock fracture could lead to improved design of hydraulic fracturing treatments in petroleum reservoirs.

There are also engineering opportunities during the DUSEL construction period. Thus,

- Some of the excavations proposed for physics experiments go beyond the 'state of the art.' No excavations of the size and depth proposed have ever been constructed. The requirement for stability over decades is unprecedented. Empirical rules widely used for excavation design to date will not suffice; more rational, numerical-modeling based, design procedures now are becoming available. Design and observation of cavern stability will provide valuable benchmarking opportunities for improved design procedures.
- Many of the specialized facilities in DUSEL will require excavation by explosives. This provides excellent opportunities to investigate improvements in current blasting technology and application of explosives to 'rock conditioning' — i.e., controlled weakening of a rock mass (e.g., to assist block caving and other mass mining techniques). Some of the larger caverns could use supplementary smaller tunnels driven parallel to the axis, and in advance of the main cavern. These tunnels would serve to anchor cables used to ensure stability of the cavern and to monitor rock movements over time. The tunnels could be used to test the dynamic performance of various support designs when subject to blast loading from the advancing cavern. Support design in rockburst–prone mines and application to 'homeland security' issues are obvious applications. Microseismic arrays deployed in boreholes from the tunnels could assess the validity of numerical model predictions of rock mass deformation around the advancing cavern.
- The need to develop additional excavations during the life of DUSEL could provide opportunities for research and development of innovative, more cost-effective mechanized rock excavation techniques.

2.1 Relation of DUSEL to Other Underground Research Laboratories (URLs)

DUSEL represents a special and timely opportunity. It will be the first deep underground facility dedicated to long–term (several decades), 'open' research in the geosciences and geoengineering. There are several Underground Research Laboratories (URLs) in the world, almost all specifically targeted to development of nuclear waste repositories. This involves some of the same issues identified for study in a DUSEL. Study of coupled processes, for example, has been a focus of research in URLs, and important advances have been made. (URL colleagues are involved prominently in DUSEL discussions.)

The site for each URL is chosen carefully to be in geological settings that are considered to be particularly well suited for waste isolation (salt, clay, granite and, in the U.S., volcanic tuff). The long period of isolation required (many thousands of years) dictates study of how to extrapolate short–term research results to the assessment of repository isolation performance over such long periods. Most of the experiments are focused on this overall goal. (See Äspö laboratory diagram in the Underground Research Laboratories sidebar.) One could envisage comparable parallel efforts devoted to a number of the other societal problems discussed earlier in this report. DUSEL can serve to focus attention and stimulate discussion on underground geoscience in general, both nationally and internationally. This could help develop consensus on the most critical problems to be addressed in DUSEL.

Many of the proposed DUSEL experiments are complementary to URL studies; others concern topics not considered in URLs. DUSEL research is open to any topic judged to be worthy of study following the standard evaluation procedures of the National Science Foundation.

DUSEL has an important educational component. The closure of many U.S. programs in mining engineering over the past two to three decades has resulted in a serious shortage of scientists and engineers, both in industry and in academia, with 'underground 'expertise. As noted earlier, this shortage is now critical as societal demands on the underground increase dramatically. DUSEL can provide the focus around which to construct a new interdisciplinary approach to underground science and engineering in the U.S, and new academic programs.

The Restless Earth

Although planet Earth is almost six-and-a-half thousand km in radius, the solid rock crust on which we stand is a mere 40~50 km in average thickness (Figure A) — no more than a thin external 'skin'. Yet this thin layer contains all of the oceans and continental landmasses, and the processes operative within it determine much of the environment in which life on the planet has evolved over its 4.6 billion years existence.

Heat flowing in convective cells from the molten core through the mantle (Figure B) provides the energy that serves effectively to transport the 'lithosphere' (i.e. the crust and solid mantle; see Figure A), as if on giant conveyor belts. The tectonic plates into which the earth's surface is divided move apart from the mid-oceanic ridges, colliding at the boundaries with other plates such that one plate is driven under another in 'subduction trenches' (Figure B). Where the plates collide obliquely, they also may grind past each other (Figure C).

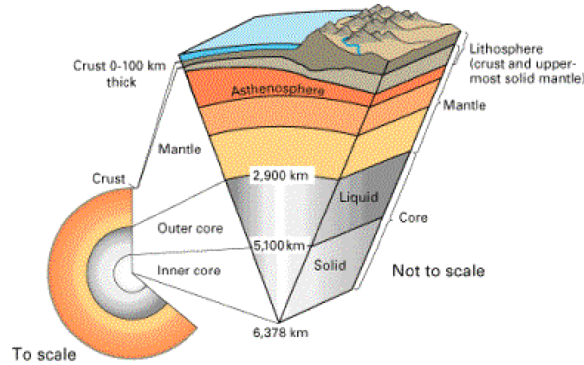


***Figure A** Cross-section through planet Earth.*

Although the most dramatic manifestations of these tectonic processes (i.e., earthquakes, volcanic eruptions, mountain building, etc.) occur at and close to the plate collision boundaries (Figure C), the tectonic forces are exerted throughout the entire plates. Occasionally, earthquakes may occur on ancient faults well removed from the plate boundaries. The interior of the plates also deforms and fractures, creating a heterogeneous network of fractured and deformed rock. Hot mineralized fluids rising through the rock can precipitate locally within the fractures to form mineral deposits.

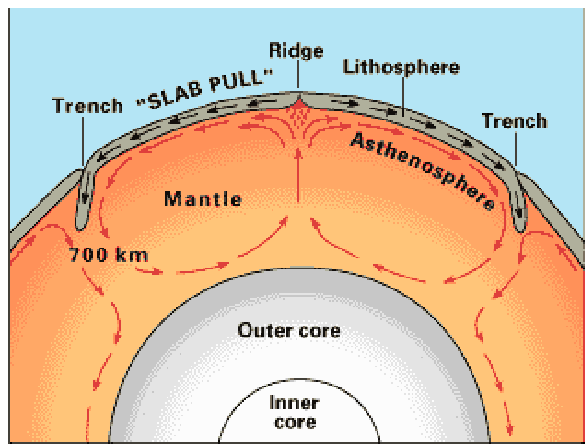


***Figure B** Conceptual drawing of assumed convection cells in the mantle. Below a depth of about 700 km, the descending slab begins to soften and flow, losing its form.*

At the surface, rock exposed at high elevations can be eroded and carried as sediments in water flows. Vegetation, decayed and buried by these sediments over many millions of years, can consolidate to produce hydrocarbon deposits. Ocean salt water evaporated as global climates change produces a variety of 'evaporite' mineral deposits. Sedimentary rock formations become an integral part of the crust, deforming and fracturing in response to the tectonic forces of the plates.

Active over many hundreds of millions of years, these and a variety of other processes have combined to produce the surface, and subsurface, environment in which man and other living creatures find themselves today.

The Earth today, the result of this evolution, consists of an enormous variety of rock types and compositions, with a wide range of ages, structure and mechanical properties. Intrinsically strong and often porous-permeable rock masses are often transected and weakened by networks of faults and fractures.

These discontinuities or interfaces may allow the mass to slip under the action of tectonic and gravitational forces and may serve also as pathways for flow of mineralized fluids. The slip may occur suddenly and be of sufficient extent that it becomes an earthquake. Other rock types may 'flow' in more ductile and viscous fashion, healing incipient fractures and deforming gradually without violent fracture. Imperceptible though these changes may be, tectonic forces and associated processes are important, ever-present realities for the geoscientist and the geoengineer.

Figures provided courtesy of U.S. Geological Survey, "This Dynamic Earth" — http://pubs.usgs.gov/gip/dynamic/dynamic.html

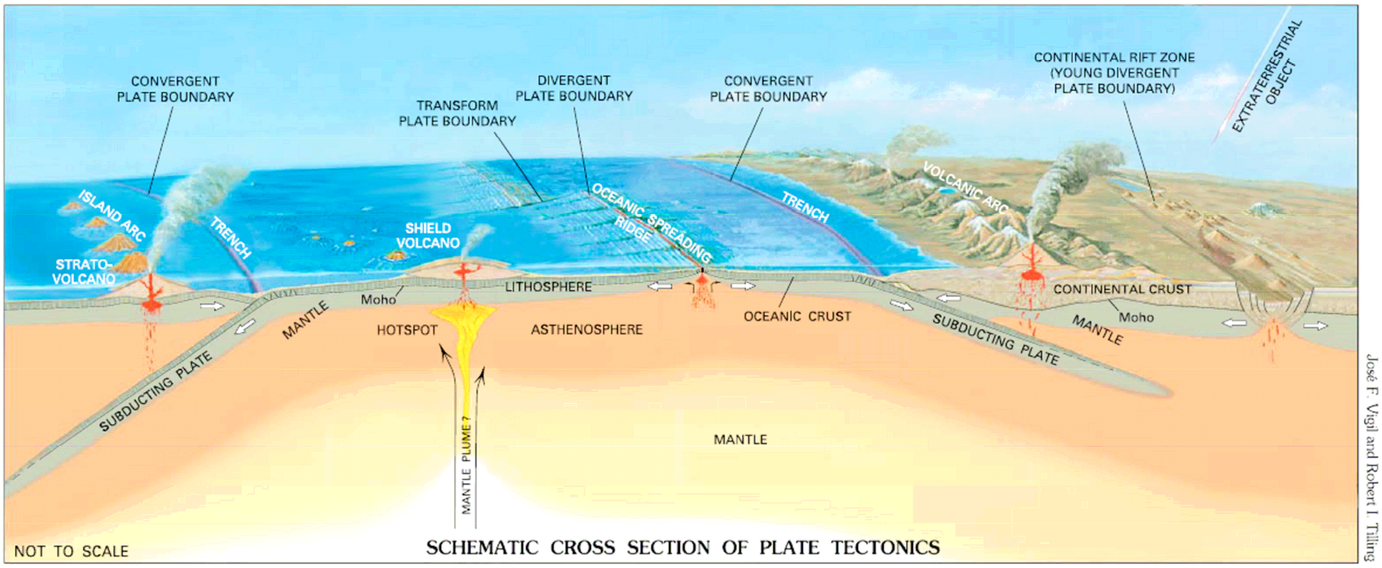


***Figure C** Schematic illustration of tectonic processes in the crust*

So far, man has succeeded in drilling one hole to a depth of 12 km (Kola, Russia), with a few petroleum boreholes reaching 10 km, and the deepest gold mines in South Africa reaching almost to 4 km. The average depth of mining excavations worldwide is approximately 500 m. This is the extent to which current technology has allowed rock at depth to be brought to the surface and mineral resources of the earth to be extracted.

Information on the make-up of the crust and the processes operating within it at greater depths is based largely on inferences from geophysical observations. Clearly, there is much yet to be learned about the planet on which we live — particularly, the processes operating in the rock within the few kilometers immediately below our feet.

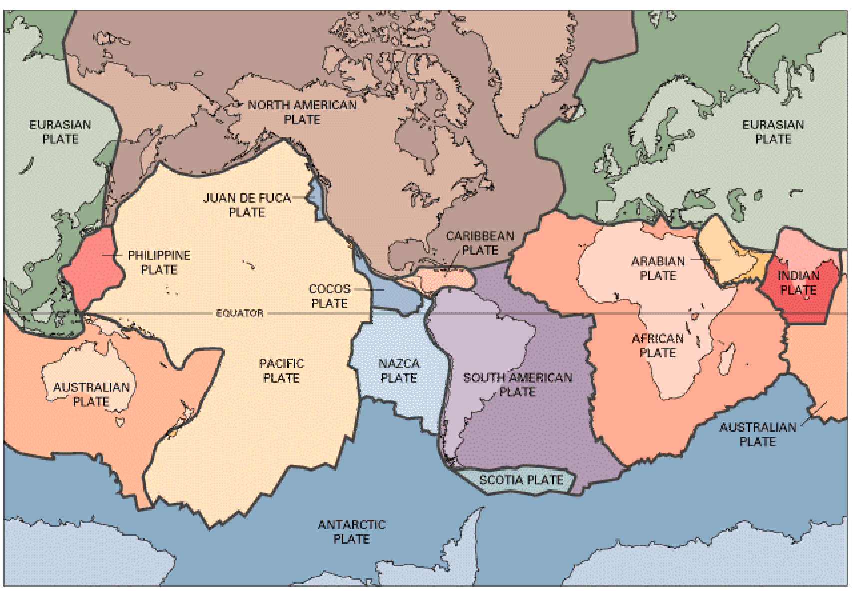


***Figure D** The major tectonic plates into which the earth's surface is divided*

Figures provided courtesy of U.S. Geological Survey, "This Dynamic Earth" — http://pubs.usgs.gov/gip/dynamic/dynamic.html

2.2 Earth — A Planet under Stress

Man has depended on rock and the Earth's subsurface for many of his essential life-support needs since the dawn of civilization. For much of this time, during the pre-industrial era, the demands for shelter, water, minerals and materials of construction were relatively moderate and did not pose a serious drain on the world's resources. The Industrial Revolution, started in Great Britain in the mid-18th Century but still to arrive in some parts of the world, has produced remarkable changes that continue to the present day. Rapid growth of world population (Figure 1), rising expectations, and associated trends such as urbanization are placing unprecedented demands on society and the planet on which we all live.

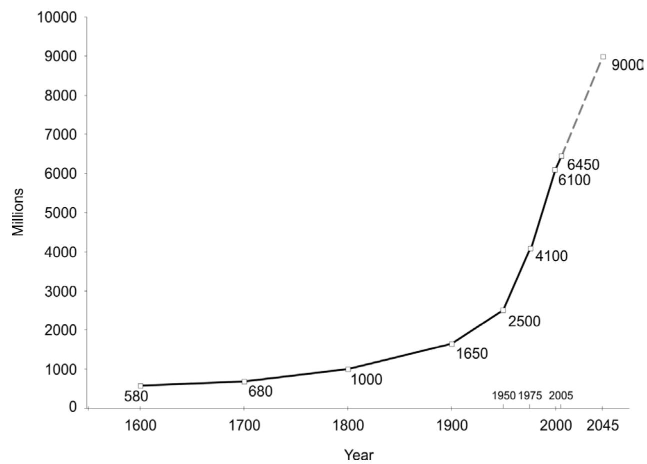


Figure 1 World Population 1600 - present

Some of these — global warming, the possibility that finite oil and gas supplies are approaching exhaustion, looming world shortages of potable water — are debated daily.

Others, such as the critical role of the subsurface to everyday life, attract very little attention, except when contaminated groundwater poisons public drinking supplies, devastating earthquakes cause major loss of life and damage to communities, and attempts to dispose of contaminated fluids by injection into deep wells trigger earth tremors (Fortuna, 1996).

All of these serve notice that *there is more to the subsurface than the dark than meets the eye.* We cannot continue to live in ignorance of how the underground system functions, how it is reacting to man's interaction with it, and how we can live in harmony with it — what is sustainable? Answers to these critical questions require that we be able to carry out research on the rock mass as it exists in place, discontinuities, inhomogeneities, fluids and applied forces included!

3.0 SOCIETAL NEEDS

Important societal benefits will accrue from improved techniques and technologies to recover minerals and energy, to provide safe disposal and containment of wastes, to afford the effective restoration of contaminated sites, and to contribute to safe use of the subsurface for civil infrastructure.

3.1 Resource Recovery

The ready supply of fuels, energy, and minerals powers modern society. The availability of a secure, extensive, and distributed supply of potable water is a societal imperative.

Petroleum products supply modern society with inexpensive and convenient transportation fuels, and an endless array of plastics and petroleum products. Natural gas is an abundant fuel that generates the least CO_2 when burned compared to petroleum or coal, and provides one likely fuel-stock to power the widely touted hydrogen economy (NEPDG, 2006). Effective recovery of these fuels require their initial discovery, typically through surface geophysics and drilling, and their subsequent removal from reservoirs typically 2 to 5 km deep, via an array of vertical or horizontal branching boreholes. Endemic uncertainties relate to the hydraulic connections that may be developed by routine completion methods. Such methods include hydraulic fracturing of the wells, where the roles of structural features such as faults and fractures at a variety of length-scales control the depletion of the reserve. Ambiguity remains between features usefully observed from geophysical imaging, and what these features mean in developing the reservoir. A depleted reservoir may retain 80% of the original-oil-in-place, and improved methods and understanding of the motion of fluids may increase this yield, with subsequent improvement in the reserve base and in energy security. The provision of an underground laboratory may address these issues, albeit in a non-reservoir rock, through an improved understanding of the crucial role of fractures and faults on the displacement of fluids, on the integrity of wells, and in controlled appraisal of geophysical methods in defining hydraulic performance.

Mined minerals are a fundamental need of modern society, encompassing copper recovered for use in power electronics, to gold and other precious metals whose use pervades electronic components and devices. As high-grade deposits are depleted, the lower-grade and deeper deposits only may be recovered if mining methods are economically viable. *In situ* mining provides a potential solution where the desired mineral is recovered directly by a solvent that targets that mineral in particular. The solvent is injected *in situ*, into the ore, through boreholes drilled either from the surface or from the deep mine. *In situ* mining methods offer the environmental advantage of reducing the amount of waste rock produced per ton of recovered mineral, thereby reducing production costs. However, it also poses significant challenges in the development of controlled fracturing in the remote ores, in adequately characterizing the transport characteristics of these pathways, and in predicting the recovery of minerals from the application of tailored solvents. More directly than in the case of petroleum recovery, an underground laboratory provides a unique opportunity to explore these recovery techniques under closely controlled conditions. This evaluation may include the effective exhumation of the test cell to corroborate estimates of transport behavior from time-lapse geophysics, and predictions of reactive transport.

The recovery of geothermal energy from hydrothermal and non-hydrothermal reservoirs offers the potential to drastically reduce the emissions of greenhouse gases associated with the recovery and utilization of fossil fuels. Non-hydrothermal engineered Geothermal System (EGS) reservoirs have the advantage that they are present ubiquitously beneath major population centers in the United States, and the world, with an estimated reserve base one hundred times larger* than that for fossil fuels. The further development of EGS geothermal reservoirs suffers from the disadvantage that access to the large resource is limited, both for want of an inexpensive methods of drilling, and by our understanding of processes for development and production of the reservoir. A deep underground laboratory offers the opportunity of testing and observing the effectiveness of drilling methods, at depth, and in developing geophysical and tracer methods to follow the evolution of the reservoir with time, with unusual access to the reservoir level.

The availability of a dependable, secure, and uninterrupted supply of potable water is a societal imperative — and to date within the U.S., has proved an inalienable right. As population-pressure reduces the excess of availability over demand, any and all potential sources of potable water will play an increasingly important role. Groundwater will become an increasingly important resource that offers significant advantages over surface supply in its potential for protection against surface-borne pathogens, maliciously introduced agents of bioterrorism, and of routine evaporative losses to the atmosphere. Non-traditional aquifers, including those that are fracture-dominated, may become increasingly important. In the Northwest, for example, deep fractured basaltic aquifers may become important if the recharging annual supply from the snowpack is reduced, as projections of global warming indicate. Groundwater resources may become an important secondary source of supply.

3.2 Waste Disposal and Sequestration

Modern society produces a vast array of wastes ranging from the massive and benign unregulated discharge of CO_2 from the burning of fossil fuels, to the scrupulously controlled inventory of long-lived fission products from nuclear power generation. For many of these products, deep geologic isolation is a potentially effective method of disposal, although many questions remain of its effectiveness.

Deep injection offers a convenient, environmentally safe, and economical method for the disposal of liquid and solid wastes in deep saline reservoirs, or in depleted petroleum reservoirs. An injection well is completed to depth, and the waste is pumped either as a liquid, a slurry, or as a grout that will solidify in place. Disposal is relatively inexpensive, and ostensibly secure — formations that once trapped hydrocarbons over geologic time may also provide adequate long-term containment of the injected fluids. Despite the relative surety of this logic, few means exist to track the migration of these fluids and to ensure their immobilization. Similarly, deep sequestration of CO_2 is one potential method to stem the release of anthropogenic greenhouse gases to the atmosphere. Again, saline aquifers may be used, or the CO_2 may be utilized as a stimulant to improve the recovery from otherwise depleted petroleum reservoirs. Current estimates of $100/ton-disposed must be reduced to $10/ton if geologic

* Reserve base based on a drawdown in crustal temperature by 120 °C from a crustal depth of 3 km to 6 km. A 1 °C drop in temperature over the same interval yields 200, 000 Quads (Quadrillion BTU), comparable to the total fossil fuel reserve of 360,000 Quads (Armstead and Tester, 1987) .

sequestration is to be economically viable. Significant unknowns remain in characterizing reservoir capacities, in certifying the integrity of caprocks, and in ensuring containment over many decades. The development of an underground laboratory offers the potential to observe, in a controlled environment, the factors that influence the development of injection processes, albeit in an unlikely candidate rock, and confirm the efficacy of containment

Deep geologic isolation is the preferred method for the interment of spent nuclear fuel for all 30 developed nations that face this issue (Witherspoon and Bodvarsson, 1996). Despite more than $6B spent on site investigation and process characterization studies at the proposed repository for civilian and defense high-level nuclear waste at Yucca Mountain, significant uncertainty remains in the role of hydrologic processes controlled by the effects of the heated canisters. Importantly, the hot repository will alter the current hydrological regime, which, in turn, may modify the transport characteristics of the fractured rocks surrounding the repository. Migration pathways may seal or gape, with the coupling of subtle and of strong chemical, biological, and mechanical feedbacks alike only marginally understood.

The necessity to conduct *in situ* studies underground to assess the feasibility of geological isolation has been recognized for almost fifty years (NRC, 1957). *In situ* tests on the response of salt pillars and excavations to electrical heating (to simulate heat-generating waste placed in the excavations) were conducted in Lyons, Kansas, in the mid 1960s (Boegly *et al.*, 1966). An international program was launched at the Stripa Mine in Sweden in the 1970s and continued until 1992 (Stripa Project, 1993). Several international programs now are underway in various countries (Witherspoon and Bodvarsson 2006), and several Underground Research Laboratories (URLs) currently are conducting *in situ* research (see sidebar on Underground Research Laboratories).

The development of an underground laboratory offers the potential to observe such interactions at a variety of length- and time-scales of relevance, where, importantly, subsequent exhumation will not compromise the integrity of the containment structure.

3.3 Underground Construction

Increasing urbanization and the desire to maintain environmental quality in the face of increased demands for surface space are focusing more attention on the possibility of using the underground space *beneath* cities. The traditional underground road, rail, fresh water supply and sewage systems are being augmented by a variety of uses. In Stockholm, sewage treatment plants are underground; in Chicago, the Tunnel and Reservoir Plan (TARP), now under construction, is intended to capture combined storm and sewer water overflows during high flow periods and to store this contaminated water in an underground reservoir until it can be processed by a sewage treatment plant. This avoids the discharge of sewage into local waterways and, in some cases, into basements.

The ability of a solid rock cover, be it some meters, tens or hundreds of meters thick, to provide a robust isolation of an activity from the surface and the open atmosphere, is a valuable attribute that offers numerous opportunities for the geologic isolation of high-level nuclear waste, for the basing of underground reactor facilities, and for hardened structures.

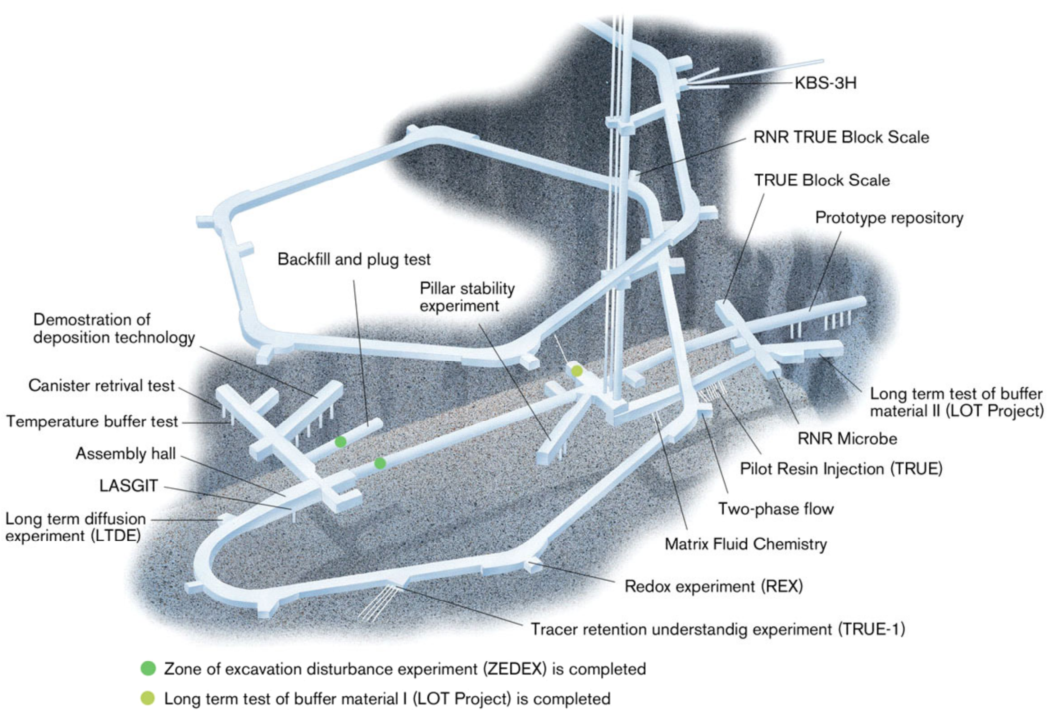
__Underground Research Laboratories__

Underground research laboratories (URLs) have been in operation in various countries since the 1970s. All are concerned with nuclear waste isolation, and all are relatively shallow (100 m ~ 500 m). These include Yucca Mountain (300 m) in the U.S., which is unique in that it is the only URL in unsaturated rock above the water table and in very permeable volcanic tuff. All others are in saturated rock of intrinsically low permeability. Granite at Äspö includes a network of transmissive joints. The Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico operated as a URL from the early 1980s until 1999, when it became the world's first deep repository for nuclear waste. Located at 650-m depth in bedded salt, WIPP is used to store intermediate-level (essentially non-heat- generating) waste. Research in URLs has contributed much to the current state of the art in such topics as coupled hydro-thermo-chemical flow processes, regional groundwater flow systems, rock mechanics, micro-seismic network design, and instrumentation .

The Äspö Hard Rock Laboratory, illustrated below, opened in 1995. It reaches a depth of approximately 500 m below surface in granite. Access to the experiments is provided by a spiral decline from the surface, suitable for vehicular access, and two vertical shafts, each equipped with a hoist. As can be seen from the experiments described on the illustration, many relate specifically to waste isolation, and include topics such as effective backfilling and sealing of drifts and demonstration of waste emplacement technologies.

Although constructed to conduct underground experiments to aid in the design of a permanent repository for high-level nuclear waste in granite in Sweden, no radioactive waste will be stored in Äspö. This is true also of the Mont Terri (clay) Switzerland, and Mol (clay), Belgium, sites. It is intended to use Yucca Mountain for high- level nuclear waste if the site is found to be suitable.

The Deep Underground Science and Engineering Laboratory (DUSEL) will be as much as 2 ~ 2.5k m deep, and will include major excavations for Physics studies in addition to experiments in Geomicrobiolgy, Geosciences and Geoengineering. The experiments will cover a broader, more open range of topics than in the nuclear waste URLs. DUSEL may also include deep boreholes drilled from the underground to depths significantly greater than 2 km (e.g., for microbiological investigations and to investigate how *in situ* stresses vary with depth at the DUSEL site.



The Äspö Hard Rock Laboratory

Atmospheric contamination is a particularly severe hazard because of the rapidity with which it can spread and the great difficulty of controlling the movement of air in the open atmosphere. A number of industrial operations pose significant hazard when located on the surface. In 1984, for example, an explosion at the Union Carbide chemical plant at Bhopal, India, released toxic gases into the air, resulting in almost 4,000 deaths and leaving 11,000 with disabilities. In April 1986, the Chernobyl (Ukraine) nuclear explosion projected a plume of dangerous concentrations of radionuclides into the atmosphere where winds carried it rapidly well beyond the boundaries of Russia and around the world. Nobel Laureate Andrei Sakharov recommended that nuclear plants be located underground. Several designs had, in fact, been proposed prior to Chernobyl (Bernell and Lindbo, 1965; Myers *et al.*, 2006; Watson *et al.*, 1972). The generator plant, 100 m ~ 150 m underground, would be linked to the surface by a number of tunnels containing filters to trap any radionuclides released in the event of an explosion. Several underground nuclear power plants were constructed and operated in Siberia.

The decision to conduct all nuclear weapons testing underground in response to worldwide protests against atmospheric testing of nuclear explosives also indicates recognition of the isolation capability of rock.* The same attribute of rock cover has also been used widely to protect people and sensitive military installations against aerial attack. How to deal with such *hardened facilities* is a continuing military challenge.

Underground structures are intrinsically more robust than surface structures to earthquake events. Ground deformations produced by seismic waves are intensified at the surface, compared to the interior of the rock. Also, structures within a closed surface such as an excavation can be supported by the rock so as to undergo less differential movement than a freestanding surface structure. The Magnitude 6.8 Northridge earthquake (20 miles NW of Los Angeles) in January 1984 disrupted surface transportation systems; the Metro Red Line subway, then under construction, sustained no damage. This is consistent with experience in other earthquake-prone cities such as Mexico City and Tokyo. Transit systems can serve an invaluable emergency role after earthquakes when surface transportation systems are disrupted.

The sudden collapse of apparently stable underground workings is a continuing threat to mine safety. The rock pillars that support the workings, often for several years, may collapse without warning. Clearly, the pillar has weakened over time. Improved design and monitoring have reduced the problem in active mines, but unanticipated collapse to the surface of abandoned mines, often many years after closure, and in populated areas, is a serious and growing problem in various regions of the world. Time-dependent weakening of the rock is, again, a factor in the collapse. Sudden collapse of rock slopes on the surface is another example. The availability of the proposed laboratory for several decades will allow long-term experiments to investigate the

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* Most of the radionuclides generated during an explosion were trapped by the shell of solidified rock melt produced around the underground explosion cavity. Although now banned as part of the Comprehensive Test Ban Treaty, scientific knowledge gained during underground testing led to a number of proposals, such as the Ploughshare program, for peaceful uses of this enormous energy source in major engineering projects.

fundamental mechanisms of the weakening process. Armed with the understanding gained from this research, it should be possible to better identify and detect potentially dangerous situations and prevent collapse. Insights gained into the basic mechanisms of time-dependent weakening could lead to a more general understanding of how such mechanisms may scale over longer time periods.

These are but some of the important societal benefits that may accrue from a proposed underground laboratory. The important scientific and technological advances that must precede this realization are included in the following section.

4.0 GRAND CHALLENGES IN THE SUBSURFACE

4.1 Research Needs

To date, much of our understanding of the complex coupled behavior in the subsurface is derived from the results of laboratory experiments conducted on cores obtained from deep boreholes. This imposes major limitations on our understanding of how the systems behave in reality. Removal of a core from the *in situ* environment introduces unknown changes in behavior: fractures may form and irreversibly alter the mechanical and fluid transport properties, and pore fluids may be contaminated and lost. More importantly, the small core cannot representatively sample the *in situ* fractures, which are typically much larger than the dimension of the core, but which control the behavior of the rock mass. Consequently, for much of the geosciences and for rock engineering, the 'real laboratory' is underground — where the rock can be examined in its natural environment.[*]

Scale Effects — Clearly, the scale of the structural components, time and the rates of change that influence subsurface behavior can vary enormously depending on the problem of interest, and it will never be possible to study these directly over the full range of scales. However, the behavior of the rock mass is governed, at all scales, by the interaction between 'intact' rock and discontinuities or 'interfaces,' generally within a heterogeneous rock medium. All of these elements are to be found in DUSEL, where underground shafts and galleries will provide direct access from the surface to a depth of two or more kilometers and over several hundreds of meters laterally, for a period of several decades. DUSEL offers an opportunity, without precedent anywhere in the world, to make major advances both in underground science and rock engineering. Knowledge gained at DUSEL will lead to more informed short-term investigations in other underground sites around the world. As mentioned earlier, most of these sites are focused on mineral production. Operating mines can help in assessing the more general applicability of DUSEL findings, but they cannot provide the dedicated facility for the long–term research that is needed. Considerable information on rock mass behavior has also been obtained

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[*] It is not possible to make an excavation in a rock mass (be it a borehole or large cavity) without disturbing the rock. However, the extent of the disturbed region is proportional to the size of the excavation, and it is possible, by careful design, to define (and instrument) a block of rock outside the disturbed region that can be considered 'undisturbed' - and that can be used for the *in situ* tests.

from studies on nuclear waste isolation and repository design. (See Sidebar on Underground Research Laboratories in this report.)

As in other scientific and engineering disciplines, developments in computer modeling of the complex coupled interactions and variety of scales discussed above have made, and continue to make, remarkable progress. Analytical and numerical models are available that attempt to define how rock mass features and processes interact and to predict how this behavior scales with size and in time, but verification and advance in understanding require physical data on the behavior of actual systems. For the geosciences and rock engineering, the primary purpose of DUSEL is to conduct the experiments that will begin to overcome this barrier.

Furthermore, the significant opportunity to obtain experimental information during the construction phase of DUSEL will not be overlooked. For example, the opportunity to characterize, design and then monitor structures during construction, combined with the potential to use inelastic and elastic wave transmission in rock during blasting to characterize ahead of the face, are examples of possible applications.

4.2 Some Key Questions for DUSEL

As in much enquiry, many of the consequences of the research cannot be seen in advance. The two examples of major stimuli to fundamental scientific and technological advance cited earlier in this discussion, *viz.* earth-orbiting satellites and plate tectonics, were introduced little more than four decades ago. Who could have anticipated the resulting developments? A similar reservation is appropriate here, but we may take some comfort in the fact that we tend to underestimate the potential for innovation from research.

With this proviso, we suggest that DUSEL may be able to provide insights and possible answers to questions such as the following.

- What can we do with currently available or emerging technologies to ‘see into the rock’?
- How do the thermal, hydrological, mechanical, chemical and biological processes interact in fractured rock systems? And how do these processes effect the safe immobilization of wastes and the sustainable recovery of water, hydrocarbons, and geothermal energy?
- Why can’t we predict earthquake locations and timing more reliably?
- What can we learn from global plate tectonics to better define where mineral deposits are likely to be found, and how to better extract them?
- What are the safe limits to large and deep excavations?
- How can underground space be used most effectively in the service of society, especially in urban environments?

Some important engineering applications of the subsurface that are of particular societal significance are shown in Table 1.

Table 1 Engineering Uses of the Subsurface

Resource Recovery	Petroleum and Natural Gas Recovery from Conventional/Unconventional Reservoirs
	In Situ Mining
	Hydrothermal and Engineered Geothermal Systems
	Potable Water Supply
	Mining Hydrology
Waste Containment/Disposal	Deep Waste Injection
	Nuclear Waste Disposal
	CO_2 Sequestration
	Cryogenic Storage/Petroleum/Gas
Site Restoration	Acid-Rock Drainage
	Aquifer Remediation
Underground Construction	Civil Infrastructure
	Underground Space
	Secure Structures

5.0 NEW OPPORTUNITIES AFFORDED BY DUSEL

The drive to improve the recovery and utilization of necessary resources, and to complete this while providing appropriate stewardship to the environment, requires that we address the crucial technological needs identified previously. A ubiquitous issue that affects all activities of construction, of utilization, and of resource recovery in and on rock is that behavior changes, sometimes drastically, with the scale of the structure or applied disturbance. Rock mass strengths and fluid transmission characteristics change both with the size of the affected sample and with the anticipated design lifetime of the embedded structure. This scale effect is a fundamental motivation in our attempt to understand rock behavior at multiple lengths and time scales, and provides a compelling incentive for the establishment of an underground science laboratory.

Transparent Earth — Increasing the ‘transparency’ of rock masses, so that the processes controlling its behavior can be observed more directly and in greater detail, is a goal that, if successful, would be of major benefit to essentially every experiment contemplated in the geosciences and engineering program at DUSEL. ‘Transparent Earth’ can be divided conveniently into two parts; Physical Transparency and Conceptual Transparency; each is an important component in enabling an improved utilization of the subsurface.

Physical Transparency — Seeing into the Earth — Significant advances are being made in geophysical imaging techniques, but the opaque nature of rock remains a serious barrier to observation and investigation of its behavior. DUSEL offers major opportunities to address this barrier, one that arises in virtually all of the geoscience and engineering experiments that are planned. In many cases, the volume of rock to be made 'transparent' is of the order of 10 ~ 20 m in linear extent, sometimes less.

Medical advances have been aided greatly by remarkable technological advances that allow the interior of the human body to be seen, abnormalities to be detected, and the consequences of treatment observed. The challenge is to develop similar procedures for rock. The ability to 'see into the rock', particularly just a few meters ahead of an advancing tunnel face, for example, could yield enormous benefits to the safety and economy of underground excavation. On a larger scale, such imaging advances could yield major benefits for populations who are becoming increasingly dependent on the 'health of the subsurface'.

Increasingly, injection of toxic and hazardous waste materials at depth is seen as a way to 'eliminate' these materials from the biosphere. However, sometimes these procedures may lead to unanticipated results, with the wastes being sequestered inadequately.

Conceptual Transparency — Understanding the Dynamic Earth — Understanding the transmission of reactive hot fluids in fractured rock masses is an important contemporary challenge that speaks to our ability to effectively recover energy resources and to safely sequester corrosive wastes. The same is true for the case of unstable dynamic slip along a rough joint surface, and other problems important to understanding rock mass behavior. Experiments conducted at DUSEL offer the first potential to observe these important behaviors in progress under the appropriate ambient conditions of scale, stress, and temperature in the earth's crust that are present in reality. Related modeling studies can shed considerable 'light' on the behavior of the actual system, and allow the response on related systems to be predicted with increased reliability.

Improved Utilization of the Subsurface—— Engineering the Earth — Seeing into the rock (for example, to locate fractures or other defects) is useful only if we understand what to do with those new data. In "seeing" a fracture ahead of a tunneling face, it is important to determine if that makes advance less hazardous or more hazardous. This assessment requires that the presence of such a feature (physical transparency) be married with an analysis of the effect of that feature (conceptual transparency). This improved understanding, and the modeling of this response is the essential method of predicting behavior of related structures in rock. This is akin to the conversion of data into information, with this new information necessary for the improved design for structures in the subsurface.

Only if we are able to reduce the opacity of the Earth, and to more fully view and understand the Earth's dynamic processes, will we better be able to harness the benefits of the subsurface.

5.1 Seeing into the Earth — Geophysical Imaging

Most of the techniques to develop the desired transparency in rock rely on some aspect of geophysics. Geophysical techniques have been a central part of subsurface investigation for many years. As illustrated by Figure 2, it is now possible to image the subsurface in layered sedimentary structures in remarkable detail. Achieving similar detail in more complex geologies remains a challenge. Appendix Table A-1 summarizes the main techniques in use currently.

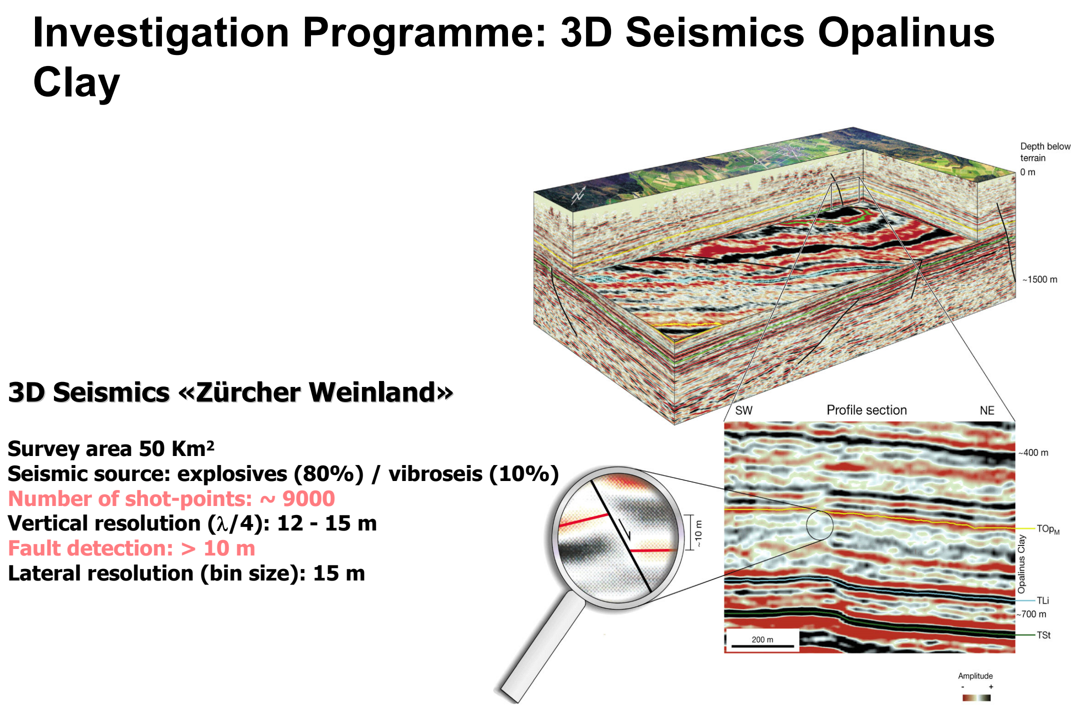

Figure 2 Detailed Geological Structure of Stratigraphic Layers to a Depth of ~ 1500 m As Revealed by 3D Seismic Geophysics (Courtesy of NAGRA, Switzerland)

DUSEL would provide the large-scale 3D access to the earth to develop and 'ground- truth' new geophysical techniques to look into rock and visualize and measure details of rock fractures. The laboratory would integrate large-scale physical observation of the rock with direct measurements of *in situ* fracture properties (physical, chemical and biological — for example mechanical, electrical, electromagnetic and seismic) and high-resolution reflection and transmission imaging methods. Access to voluminous rock masses at depth, at elevated mechanical stresses, fluid pressures, and temperatures are critical to understanding how to scale coupled processes for fractured rock from laboratory-scale to the field-scale of importance in engineering and in nature.

Development of New Active Source Geophysical Methods — Many new geophysical techniques have been developed, but understanding exactly what features they delineate in the deep earth is hampered by access to well characterized sites that DUSEL will provide. It is currently possible, for example, to determine the stiffness of fractures in small laboratory samples — by monitoring waves that travel along fractures and their interfaces. Fracture stiffness is an important engineering parameter, and these geophysical techniques, once validated, ideally are suited for the remote sensing of large rock volumes. "Difference" imaging, in which geophysical measurements are taken before and after a perturbation that changes the physical properties of the fractures, is another technique for enhancing fracture transparency. Electrical resistivity/conductivity images taken before and after increasing the salinity of the water infractures can be used to "light up" fractures, identifying those parts where changes in conductivity occur. This approach can be used to monitor and "observe" fluid transmission, and from that infer permeability — another parameter of fractured rock that is difficult to measure and predict over large highly stressed rock volumes. It is probable also that, over the lifetime of DUSEL, nano-technology and bio-engineering will have developed to allow experiments in which 'smart fluids' can be introduced into the rock mass to map fractures and their properties. The fluids may contain nano-particles that can be tracked in both space and in time, thereby enabling 4D geomatics of otherwise opaque rock.

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Development of New Passive Geophysical Monitoring Methods — Passive sources in the rock, such as the seismic and electrical/electromagnetic energy released by natural and induced events (e.g., earthquakes or excavation-induced seismicity) can be used to "listen" to rock as it fractures. These techniques lend themselves to the imaging of individual fractures and their properties in essentially the same way that global earthquakes are monitored today. Fractures and their properties can be imaged just as global earthquakes have been used to illuminate all the major tectonic plate boundaries and their properties (see Figure1). DUSEL could result in the same order-of-magnitude increase in fundamental understanding of rock strength and behavior on the engineering scale as the global seismic networks have done for dynamic earth processes. This significant step forward in Earth Science was created in part by the need for global monitoring for nuclear tests — part of the Nuclear Test Ban Treaty. The DUSEL laboratory for fundamental physics research may provide, in turn, a major stimulant to the development of new passive methods to image and quantify rock fractures and thus contribute to addressing what is now a major challenge in rock engineering.

The following section provides some specific examples of the central value of geophysics in illuminating basic questions of geo-science.

5.1.1 Surface and Near-Field Geophysics

Although originally developed for applications requiring high-resolution imaging where instrumentation was deployed from the surface, geophysical techniques have been adapted to find considerable application in the underground. The investigation of fracturing in the subsurface environment will be a major topic of investigation from a number of perspectives, including its effects on hydrology, potential locations of microbial communities, and safety issues. Although drilling ultimately will encounter fractures, it may be guided by near-field geophysical measurements. The challenge, therefore, will be to locate and characterize fracture systems as accurately as possible, including locations, apertures, fluid content and areal extent.

5.1.2 Borehole Geophysics

The safe construction of the deep laboratory and many of the anticipated studies at DUSEL will involve the drilling of boreholes in its host rocks. All proposed DUSEL facilities would present their own set of challenges for accurately interpreting fundamental rock properties. The deployment of sensors in boreholes will provide important information on the state of the surrounding rock. Borehole geophysical studies will yield information about, natural radioactivity, seismic velocities, rock and fluid compositions, contents, and densities.

New developments in borehole geophysics will be expected, particularly with respect to crystalline rocks, due to the interaction of construction, complementary investigations, and cutting-edge geophysical research at DUSEL. Of particular interest will be geophysical signals of rock alteration by chemical and physical impacts, such as fracturing, and in the opportunity to ground "truth" geophysical characterizations with actual observations.

5.1.3 Regional Geophysics

DUSEL will provide a platform for installation of instrumentation useful for more regional and/or global investigations. For example, the USArray component of the EarthScope[1] experiment is a continental-scale seismic observatory for integrated studies of continental lithosphere and deep-Earth structure over a wide range of scales — DUSEL could become a key component. The combination of a low-noise environment with excellent access to a large volume

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[1] EarthScope is an initiative, announced in October 2003 by the National Science Foundation, by which about 1000 GPS stations, some 3000 seismic stations, and various other instruments are to be emplaced to monitor continuously the pattern of tectonically induced surface deformations across the North American Continent. (See http://www.nsf.gov/od/lpa/news/03/pr03120.html

of earth material will constitute an excellent opportunity for the construction of at least two types of geophysical instrumentation.

Seismic Arrays —these arrays comprise an extensive network of geophones extending for thousands of meters in boreholes and within the tunnels of the facility. By virtue of the low-noise environment, and their enveloping distribution in space, these arrays will allow extremely accurate determination of seismic event location, including projections of source mechanisms. In addition, smaller-scale seismic arrays on the order of hundreds of meters may allow additional information regarding rock properties within DUSEL to be determined

Electromagnetic Soundings — The provision of large-scale vertical loop antennae will allow soundings from within the mine to be used to infer the electrical structure of the crust in the vicinity of the facility.

5.1.4 Geophysical Proxy Methods in General

A number of proxy methods are used in the geohydrologic sciences. All of these methods rely on measurements made at or above the surface to infer properties of the subsurface that cannot be measured directly. The opportunity afforded by DUSEL for direct observation and measurement of processes and properties **within** the subsurface allows an unprecedented opportunity to verify proxy or remote methods. For example, the following are used to provide remote "images" of the subsurface:

- remote monitoring of areas closed, if there are pre-existing drifts that are no longer necessary for the operation of the facility seismic testing: to evaluate stratigraphy (rock layering) and potential for oil and gas, as well as monitoring fluid migration in the subsurface;
- remote sensing: satellites now are equipped routinely and used to evaluate the possible presence of water in the subsurface, topography changes, large-scale strain or deformation, etc.; and
- electromagnetic methods: used to evaluate stratigraphy, rock properties, moisture content, etc.

DUSEL offers an opportunity to verify these remote methods by direct observation and measurement.

5.1.5 Geophysics and Safety

Any underground installation must be concerned with safety, which may involve both rock stability and the inflow of fluids. As noted earlier, near-field geophysical methods and borehole geophysics will provide general constraints regarding the physical properties of the rock, and thereby infer stability underground. These methods, therefore, have an important support role in prescribing a safe environment in the evolving DUSEL.

5.2 Understanding the Dynamic Earth

5.2.1 Coupled Processes

As noted earlier, rock *in situ* is subject to a number of processes that act simultaneously and are 'coupled'; a change in one of the processes will produce a related change in the others, as illustrated in Figure 3. For example, a porous rock containing fluid that is stored and/or flowing through the pores will be affected by a change in the ambient temperature. The pore volume will change, forcing fluid to be expelled or imbibed. Depending on the magnitude and rate of temperature change, the fluid pressure in the pores will change; if the temperature changes sufficiently, the fluid may undergo a phase change.

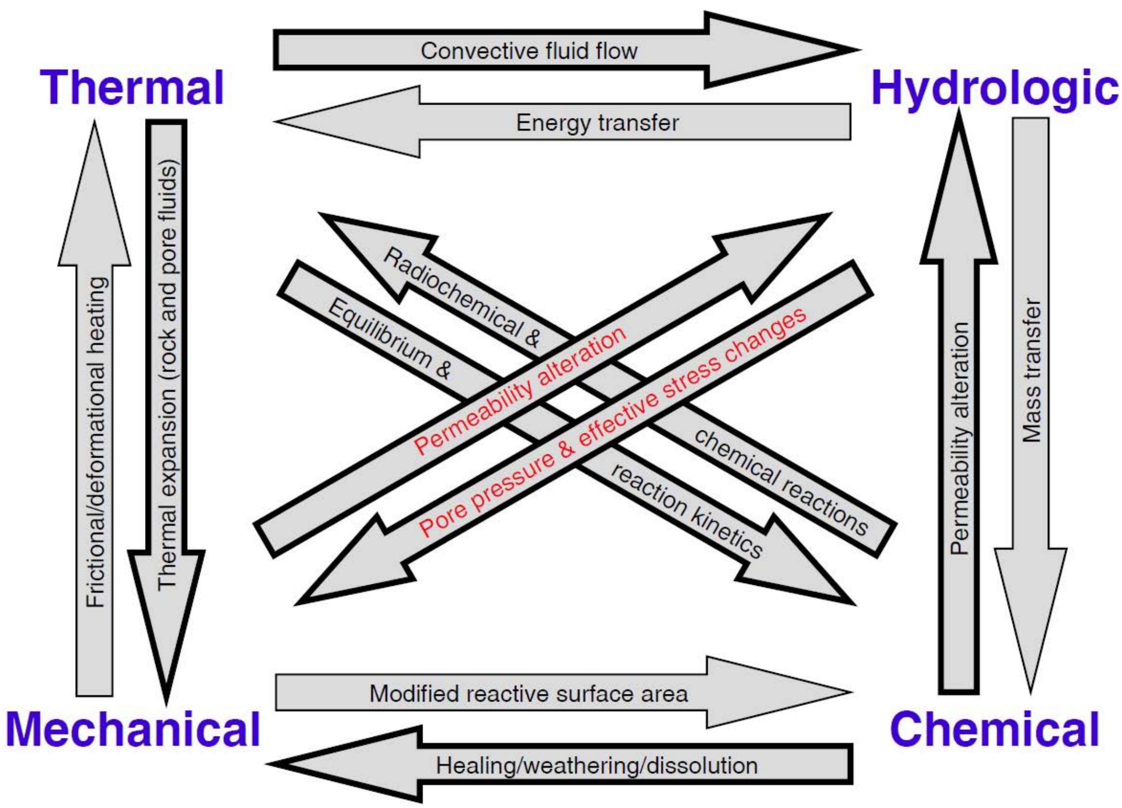

Figure 3 Illustration of the Coupled Interactions between Thermal, Hydrologic, Chemical and Mechanical Processes in Rock Underground (Biological processes, not considered in this figure, now are known to play a role in some coupled reactions.)

Fluid is a key ingredient in most coupled processes. Fluid flow in the deep subsurface is greatly influenced by other processes, such as climate change at the surface and heat flow at depth, chemical reactions, stresses and mechanical deformation, and biological activity. Likewise, all of these processes are influenced by fluid flow — in other words they truly are coupled processes, directly dependent on each other. DUSEL will provide an excellent opportunity to study these coupled processes together, in action, as they proceed within the subsurface.

Figures 4, 5 and 6 show the schematic layout, some results and a view of the experimental set-up for a major THCM coupled flow experiment at Yucca Mountain.

This eight-year-long experiment, carried out in the Yucca Mountain, Nevada, Underground Research Laboratory of the US Department of Energy, is intended to assess the coupled Thermo-Hydro-Mechanical (THM) processes resulting from heating an underground drift to ~ 260 ºC. The maximum rock wall temperature was ~ 220 ºC. The test simulates the coupled effects developed in the rock of an underground repository for high-level nuclear waste, due to heat generated by radioactive decay of the contents of the waste packages placed in the tunnels.

We do not understand the processes governing the transmission of stress and the motion of fluids (*viz.,* fracture geometry, connectivity and transmission characteristics); processes governing their interaction with their environment (*viz*., coupled THMC(B)*; feedbacks involved in developing conduits and in modifying their properties; in effectively characterizing their mechanical and transport characteristics (*viz.* mechanical, hydraulic, tracer, and geophysical techniques), and in effectively projecting system response (*viz*. sensing and monitoring, data fusion and modeling).

Although significant advances have been made in understanding these interactions in the past several decades, stimulated largely by research on geological isolation of nuclear waste, important questions remain. These relate both to the understanding of fundamental process interactions that control the response of the natural system, and how these systems may be harnessed for the recovery of minerals and energy, used for civil infrastructure and the safe disposal and containment of wastes, and with minimized impact on the natural environment.

Fluid-activated coupled processes within a network of interconnected rock fractures are especially complex. Rock stresses are induced, for example, by heating or by changes in tectonic stress, and can change the permeability of fractures or produce slip on the fractures — two important influences. It is not unusual in such networks for small local perturbations to produce effects at substantial distances from the local event. Increases in fluid pressure acting along a fault reduce the shear resistance on the fault and can trigger an earthquake. Water passing through a temperature gradient can dissolve chemicals in one region and interact with the rock in a cooler or warmer region to precipitate chemical compounds there. Biological changes also may occur in response to changes in the rock environment. In sum, while we know much about coupled processes in theory, important questions remain. Observing and confirming these complex interactions is impossible without in situ studies such as what DUSEL will offer.

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* Thermal-Hydraulic-Mechanical-Chemical-Biological coupled processes influence the transport of fluids in fractured rocks. These processes may act against us — for example, limiting the delivery of amendments for bioremediation by pore or fracture clogging — or may act for us, in improving recovery from petroleum reservoirs by hydraulic fracturing, and EOR (Enhanced Oil Recovery) techniques.

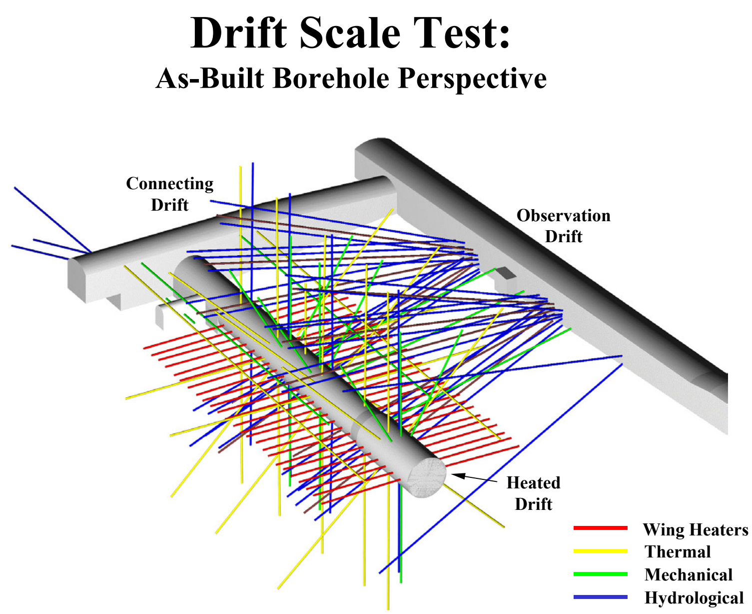

Figure 4 Layout for the Heated Drift Experiment at Yucca Mountain

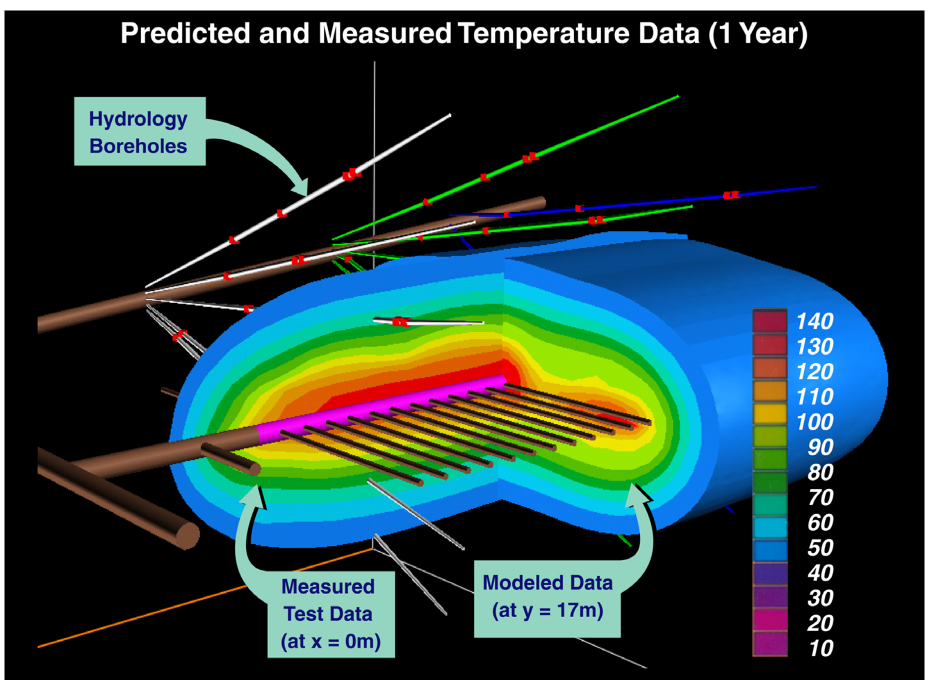

Figure 5 Comparison between Predicted and Measured Temperatures in the Rock after One Year of Heating in the Heated Drift Test

Figure 6 View of the Electric Heaters (center) in the Drift during Set-up for the Heated Drift Experiment

DUSEL will provide a variety of physical settings and conditions in the subsurface for direct observation and measurement of coupled processes. Any experiment designed to understand any one of these phenomena in the rock must at least evaluate the extent to which other phenomena may influence the overall response that is observed. Study of coupled phenomena is fundamental to understanding of the behavior of rock *in situ*. Listed below are examples of important coupled processes that will be studied in DUSEL.

Microbial Life — Fluid flow, energy transfer and nutrient fluxes control the development of biota in the deep subsurface. However, these processes are understood poorly under conditions of high pressure, temperature and stress in complex geologic environments. A better understanding of the feedbacks between key processes is critical to understanding how microbial life formed and survives at depth, and whether this form of life preceded or followed others.

Heat Flow — Groundwater stores and carries energy in the form of heat. Heat causes density changes in groundwater, inducing changes in fluid pressure and flow. Characterizing and tracking this coupling permit hydrogeologists to map rock permeability and fluid flow regimes in the subsurface, but with considerable margins of error. DUSEL will permit determining and perhaps reducing the amount of error involved.

***Rock Deformation*:** Many aspects of rock deformation are influenced directly, or even controlled, by fluid flow, whereas 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 limited mostly to tests performed in surface laboratory machines. DUSEL offers the opportunity to observe and investigate coupled fluid flow and rock deformation *in situ*, within the rocks while fluids flow through them.

***Reactive Chemistry* —** Chemical reactions are responsible for most metamorphosis of rocks in the subsurface, changing rock's fabric and its composition, and even to the extent of changing its type! Rates and types of chemical reactions depend directly on changes in temperature, water or brine composition, and pressure; thus, all other processes play a role. Likewise, the chemical state dictates whether microbes flourish. DUSEL offers the opportunity for improving our ability to predict how rock and fluid chemistry evolves, through direct experiments. These experiments must be carried out as a community effort, to optimize their efficacy.

Engineering in the Subsurface — 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 actual experiments may be preceded by predictions using numerical models of coupled processes in fractured rock at a range of spatial scales. Comparison between model predictions to 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.

New Technologies — The acceptable completion of the experimental work will require the development and application of new technologies, including 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.

Oil and Gas Flow and Transport Processes — Endemic uncertainties relate to the hydraulic connections that govern how and where petroleum migrates. Underground flow and transport experiments at DUSEL will address this and other fundamental issues, to evaluate the crucial role of fractures on the displacement of fluids and to appraise state-of-the-art geophysical methods for defining hydraulic performance.

Natural Gas Storage — Current methods for underground gas storage include (partially) depleted oil and gas fields, aquifers and salt caverns. A potential repository for gas may be abandoned mines in relatively impermeable rock formations. Storage of gas in abandoned mines has been attempted, but leakage rates were unacceptable, and the mines shut down after initial tests. To be able to account for gas inventories and to capture leakages and/or anomalies in cavern behavior, theoretical cavern behavior must be modeled as accurately as possible. Extension and/or development of a full physics inventory-control model at DUSEL should be relatively straightforward. Laboratory and large-scale experiments would provide necessary information on the appropriate methods for modeling the inventory of gas in these systems.

Fractured Rock and Fluids — The transport of fluids and mobile compounds through fractured rock is fundamental to processes that range from recovering essential resources, such as oil, gas, or water, to protecting the environment, or to understanding the formation of ore deposits. Despite decades of research, prediction of fluid flow in fractured rocks continues to be highly problematic, primarily due to the length scales involved. In most instances, flow in fractures is the primary flow path to wells and to the water table. Viscous and gravity forces generally dominate the bulk fluid transport and act at a fairly long length scale, while capillary forces act on a short length scale and may either impede or aid flow in the fracture. In 1996, the National Research Council (NRC, 1996) formally specified a number of research areas that need to be addressed, including:

(1) “How can fractures that are significant hydraulic conductors be identified, located and characterized?”

(2) “How do fluid flow and chemical transport occur in fractured systems?”

(3) “How can changes to fracture systems be predicted and controlled?”

These general research areas may be expanded to include many specific issues, including the following.

Fracture Geometry — What are the geometries of isolated fractures, fracture zones, and faults in three-dimensions? How can observed geometries be represented using geostatistical or geometric theories?

Transport Properties — What is the distribution and structure of transport and storage properties (*K*, *S*, *Dispersivity, Diffusion constant* and variations) in settings characterized by different types or geometries of fractures at different depths? How are transport properties related to the geometry of geologic features? What are the best techniques for measuring these properties at different scales?

Scaling — What scaling laws can be used to characterize properties of the observed geologic structures? How can the scaling laws be included in models of transport in fractured rock?

Solute Transport — How well can existing theories predict the migration of solutes in fractured rock? What are the shortcomings and how can they be resolved?

Stress, Pressure, Temperature Coupling — How are transport properties and processes coupled to changes in fluid pressure, applied stress, or temperature? How well can these coupled processes be predicted by theoretical analyses?

Chemical Reactions and Particles — How do chemical reactions and particle migration or deposition affect transport properties and processes? How well can these effects be predicted by theoretical analyses?

Multiple Fluid Phases — How are multiple fluid phases (NAPLs, gases, water, etc.) transported in fractures, and how well can this process be monitored in the field and predicted theoretically?

Natural Transients — What are the paths and velocities of water and mobile compounds through fractured rock under natural conditions at different scales and depths? How do natural hydrologic variations, such as barometric fluctuations, earth tides, seasonal water table variations, or earthquakes affect transport properties and processes? How well can these effects be predicted?

5.2.2 Geochemistry

Important clues into the evolution of natural and human-modified geochemical systems are available from the remnant chemical components in the fluid and the host rock.

Isotopic Geochemistry — Isotopic signatures provide important information in the dating of geological and hydrological events.

Sulfide Weathering — Sulfide weathering in the environment plays a critical role in balancing the global biogeochemical sulfur cycle. An underground laboratory located in sulfide-bearing geological units provides a unique opportunity to study sulfide weathering from pristine (time zero) conditions.

Sulfur Isotopic Studies — The recent discovery by Farquhar *et al.* (2000) of mass-independent fractionation of S isotopes ($\delta^{33}S$, $\delta^{34}S$, $\delta^{36}S$ of both sulfide and sulfate) in rocks older than ~ 2090 Ma led to the postulation that atmospheric conditions changed from anoxic to oxic at approximately this time. Evidently, gas-phase atmospheric reactions control isotopic systematics, and atmospheric photolysis via ultraviolet light in the absence of an ozone shield is responsible for the mass-independent fractionation observed in the old rocks. A very interesting study, perhaps uniquely facilitated by DUSEL, will be to investigate S-bearing units to determine if mass-independent isotopic fractionation is detectable. If S is of syngenetic origin, it is older than ~ 2.0 Ga, and mass-independent fractionation should be present.

Radiogenic Isotopic Studies — The primary source of production to depths of about 3 meters in the lithosphere of low-level radionuclides (such as ^{3}H, ^{14}C, ^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca) and trace stable nuclides, such as Ne and Ar, is spallation from secondary cosmic radiation (mostly neutrons). DUSEL would permit unique experiments to monitor the flux of various secondary cosmic-ray particles from the surface to depths of about ~100 meters. The deepest reaches of DUSEL also would be useful to establish the blank levels that can be achieved in extractions of noble gases and radionuclides from rocks used in cosmogenic surface-exposure dating. In addition, DUSEL would provide a new opportunity to study the production of various nuclides caused by radiogenic processes.

Environmental Geochemistry and Mineralogy — Fluids containing reactive components and colloids provide an important mechanism in circulating minerals within the biosphere.

Importance of Colloidal Element Transport — During the past couple of decades, near-surface research has suggested that colloidal transport of ions in subsurface environments may accelerate the mobility of toxic contaminants. If this transport mechanism is significant, then current models may under-predict contaminant movement in underground repository sites for radioactive and other wastes, as well as contaminant migration in groundwater plumes. In a deep DUSEL environment, tracer and reactive transport experiments may be carried out to resolve the uncertainty. Specifically, particulate materials could be injected into an isolated system, permitting the examination of the sorption properties of the added particulates, determining whether dissolution and alteration of host minerals are accelerated, and whether certain contaminants/metals are selectively adsorbed and transported.

Acid Mine Drainage — An underground laboratory located in geological units comprising sulfide minerals provides a unique opportunity to study sulfide weathering from pristine (time zero) conditions. Initially, pristine sulfide and host mineral samples would be collected — i.e., exact redox conditions would be maintained. This sampling may be coupled with geomicrobiology sampling, which will require that samples be collected without introducing contaminants. Very detailed surface studies of the samples will be performed to establish 'base-line' conditions prior to any weathering (e.g., the task discussed above), then alteration kinetics may be monitored over time scales from the initial few seconds following exposure to oxidizing conditions, to durations of several years. Small samples would be collected over the varied time frame from a focused study area. Furthermore, additional weathering information will be available from mined areas within the Homestake mine that have been exposed for several decades.

5.2.3 Regional and Ore Deposit Geology

DUSEL may be a timely and centralized national facility for advancing underground mine mapping technology and for workforce training in digital methods and information technology. State-of-the-art methods for digital mapping and core logging under extreme conditions are being developed, but they have not been tested or applied widely. This location would facilitate wider testing and use of such equipment. This equipment will be especially useful as open-pit mining reaches an economic limit of stripping ratio and is superceded by underground methods, requiring a workforce of geologists equipped and trained to work safely and productively under extreme physical conditions. 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. Hence, DUSEL would help provide enhanced technical workforce productivity through advancing the quality, efficiency, and uniformity in scientific and technical standards of mine mapping and related activities.

5.2.4 Groundwater Research at DUSEL

The broadest definition of geohydrology is the study of water and the earth, including all phases of water circulation through the hydrologic cycle. Some critical societal issues include:

- drinking water and irrigation water supply;
- hazardous and nuclear-waste disposal;
- remediation of contaminated groundwater;
- ecology and agriculture; and
- climate change.

Geohydrologic processes include subsurface flow and transport of groundwater and of contaminants, nuclear waste management and enhanced hydrocarbon recovery, and geohydrologic characterization of specific waste-disposal sites. Technical methods encompass laboratory and field experiments, geostatistical analysis of heterogeneous geologic media, and numerical modeling of flow and transport, among others. Direct observations and experiments in the subsurface are rare, inasmuch as the earth's surface and drill holes are typically the only venues available for study.

DUSEL offers a new and unprecedented opportunity for direct observations and direct experiments **within** the earth. These include addressing questions related to the protection and safe management of water resources for an expanding population to the effective restoration of contaminated groundwater. Such issues include the following.

> *Groundwater Recharge* — DUSEL is a unique venue to test fundamental assumptions about groundwater recharge and flow under the influence of subaerial topography, leading to a better understanding of water resources for our expanding population. For example, detailed studies of climate and surface conditions coupled with direct observations from within DUSEL of flow and transport in the subsurface may lead to a better understanding of what factors control how much surface water reaches subsurface aquifers.
>
> *Groundwater Storage and Aquifer Sustainability* — Direct observations within DUSEL of groundwater flow and transport in the subsurface may lead to a better understanding of how much groundwater can be stored in a given aquifer, and why. In other words, how sustainable is a given aquifer and why?
>
> *Paleohydrology* — An *in situ* DUSEL will afford a unique opportunity to characterize and understand paleohydrology, which may also lead to a better understanding of present-day evolving water resource systems.
>
> *Deep Fractures* — Can deep fracture systems be mapped, their origin determined, and can fracture flow processes be better characterized from *in situ*?
>
> *Flow in Deep Fractures* — Are fractures at great depths closed or do they remain open to maintain deep circulation? The answer may lead us to increased

understanding of potential deep-water resources and other important geologic processes at depth.

Contaminant Cleanup — Detailed studies of storage properties, leaching and contaminant transport may be accomplished more effectively from *in situ*, including controlled tracer tests and verification studies. In other words, by setting up **mock** contamination sites within DUSEL, using benign tracers, we can make direct studies of factors that control contaminant transport in the subsurface.

Fundamental Scale Effects — DUSEL offers a unique opportunity to study scale effects (rock properties that vary depending on the scale at which they are evaluated).

Well Testing Verification — Well testing provides proxy information about subsurface aquifer properties, guiding how much water is produced within communities and for irrigation. Well-testing verification may be performed within DUSEL by direct measurements and observations within the subsurface.

5.2.5 Mechanics of Rock Mass Deformation

An improved understanding of the mechanics of rock deformation will contribute both to our understanding of the ambient conditions within the earth that participate in the rupture process of earthquake faulting, and in prescribing the stress regime to which all structures constructed in rock, are subjected.

Dynamic Slip on a Stressed Fault — The severe consequences of large earthquakes and the desire to reduce this risk have led, rightly, to major research programs around the world. EarthScope (see footnote, p.1) is a recent initiative in the United States. One of the topics of special interest is the search for a better understanding of how seismic energy releases are initiated and how they progress as slip propagates along the fault plane. Recognizing the impracticability of observing slip initiation and propagation along a major fault, an international team of leading geophysicists is undertaking a study, of how unstable slip develops along a smaller fault at depth in a deep mine in South Africa when the shear stress induced on the fault is increased to a critical level by mining operations. As noted in the preamble to their research proposal (now funded),

> *Despite many years of intense theoretical and observational research, there is no theoretical foundation that relates particle acceleration or velocity in the inelastically deforming zone to stresses (or energy) and material properties. Faults in deep mines provide opportunities for conducting fundamental*

> *observations on the evolution of stress, energy and material properties associated with fault motion.* [DAFSAM*]

DUSEL should be able to complement the South African study by conducting a similar test on a fault or joint within an underground block. Controlled injection of fluid at specific locations along the fault could serve to trigger the slip. Attention would need to be given to ensuring that slip would decelerate and stop within the length of the fault.

Figure 7 shows a simulation of dynamic slip on a rough fault using a two-dimensional, particulate discontinuum code PFC2D (Itasca, 2004) to represent the rock in the vicinity of the fault.

The top diagram shows the section of the (long) fault that is represented by the model. The middle diagram shows the modeled section and the representation of the rock as an assembly of cylindrical particles. The network of black lines connects the center of each particle. The rough surfaces and immediate vicinity of the fault are shown in red.

The lower diagram shows an instant during fault slip when the interface is subjected to shear. Vectors indicate the magnitude and direction of instantaneous motion in the model. Note the large displacements at several locations on the fault where asperities are breaking. Phenomena such as foreshocks, main seismic event, and aftershocks are observed clearly. Underground tests to record seismic motion in the vicinity of a fault that is stimulated to slip can provide valuable date by which the validity of the computer models can be established. Fluid pressure and flow between particles can be simulated in such models, including three-dimensional behavior.

In-Situ Stress Distribution in Heterogeneous Rock — Current estimates of the magnitude and orientation of stresses in rock are based on a very limited number of measurements from a variety of locations and depths around the world. As seen in Figure 8, the results vary widely. The apparent reduction in variation with depth may be a consequence of both the reduced number of observations at depth, and that lateral tectonic stresses at depth must tend to approach the vertical stress as the rock becomes more ductile and fluid at higher temperatures. No information is provided in Figure 8 on the type of rock in which the determination was made and the heterogeneity of the rock mass in the vicinity of the measurement site.

Figure 9 shows estimates, based on a very simple model of rock masses, of the range of strain rates within tectonic plates and the corresponding range of rock mass viscosities. It is seen that both of these variables range over 10 orders of magnitude. Rock mass strength, although confined to a much narrower range, also varies significantly depending on the rock type. DUSEL would allow the local variability of the *in situ* state of stress to be established as a function of rock heterogeneity and the proximity to large features such as faults. This would provide a much

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* Drilling Active Faults in South Africa Mines (Sept 2002). Now underway, this project has been renamed NELSAM; (Natural Earthquake Laboratory in South African Mines)
http://faculty-staff.ou.edu/R/Zeev.Reches-1/nelsam .

more realistic basis for understanding the factors that influence *in situ* stress distribution in rock than currently is understood from data such as provided in Figure 8.

An ability to better "see" into the Earth, and to better understand complex interactive dynamic processes, will enable us to better harness the subsurface for the benefit of humankind. These benefits will include the improved design of underground cavities at depth, both for the extraction of minerals, energy and hydrocarbons, and as civil structures for safe occupancy related to the physics mission of the DUSEL.

5.3 Engineering the Earth

5.3.1 Dynamic Phenomena

The multi–year construction phase of DUSEL will involve considerable excavation and rock blasting. This phase will provide exceptional research opportunities including, for example, the effects of excavation-induced stress redistribution on the rock mass, of high-intensity wave propagation in rock, design of excavation supports to resist high-intensity dynamic loads, such as may occur in earthquakes and mine–induced rock bursts (and in bombing). Although the frequency spectrum for earthquake waves is quite different than for blast waves, the ability to verify model predictions over one range of frequencies would add confidence to results over the earthquake range.

5.3.2 Design of Large Underground Cavities at Depth

The largest free-span cavity constructed in rock today is the 62-meter Olympic Ice Hockey Stadium in Gjøvik in Norway (Figure 10). It is very shallow, excavated into a hillside in competent granite. The crown of the roof is just a few meters below the ground surface. Most mining excavations (except for shafts) are not intended to be permanent, and are designed as economically as possible — consistent with safety.

It is seen that the few large 'permanent' cavities are those designed for physics experiments. The proposal to develop a cavity such as UNO (indicated in pink on the diagram) would be 'stretching the state of the art.' The specific design would depend on the rock type, *in situ* stress state, and the span. Design, excavation, construction and monitoring of the long–term stability of the cavity would provide a wealth of fundamental data that could also serve for design of subsequent cavities. Figure 11 shows a design layout in which auxiliary drifts parallel to the large cavity (long axis oriented parallel to the maximum horizontal stress direction in order to minimize stress concentrations around the periphery of the cavity) are driven to allow placement of reinforcement cables, anchored in the small drifts, to ensure long–term stability of the cavern. The drifts also can serve as locations for instrumentation to monitor deformation of the rock around the cavity over time. The small drifts, excavated in advance of the cavity, also could be used to examine the quasi-static and dynamic behavior of the rock and support systems in the

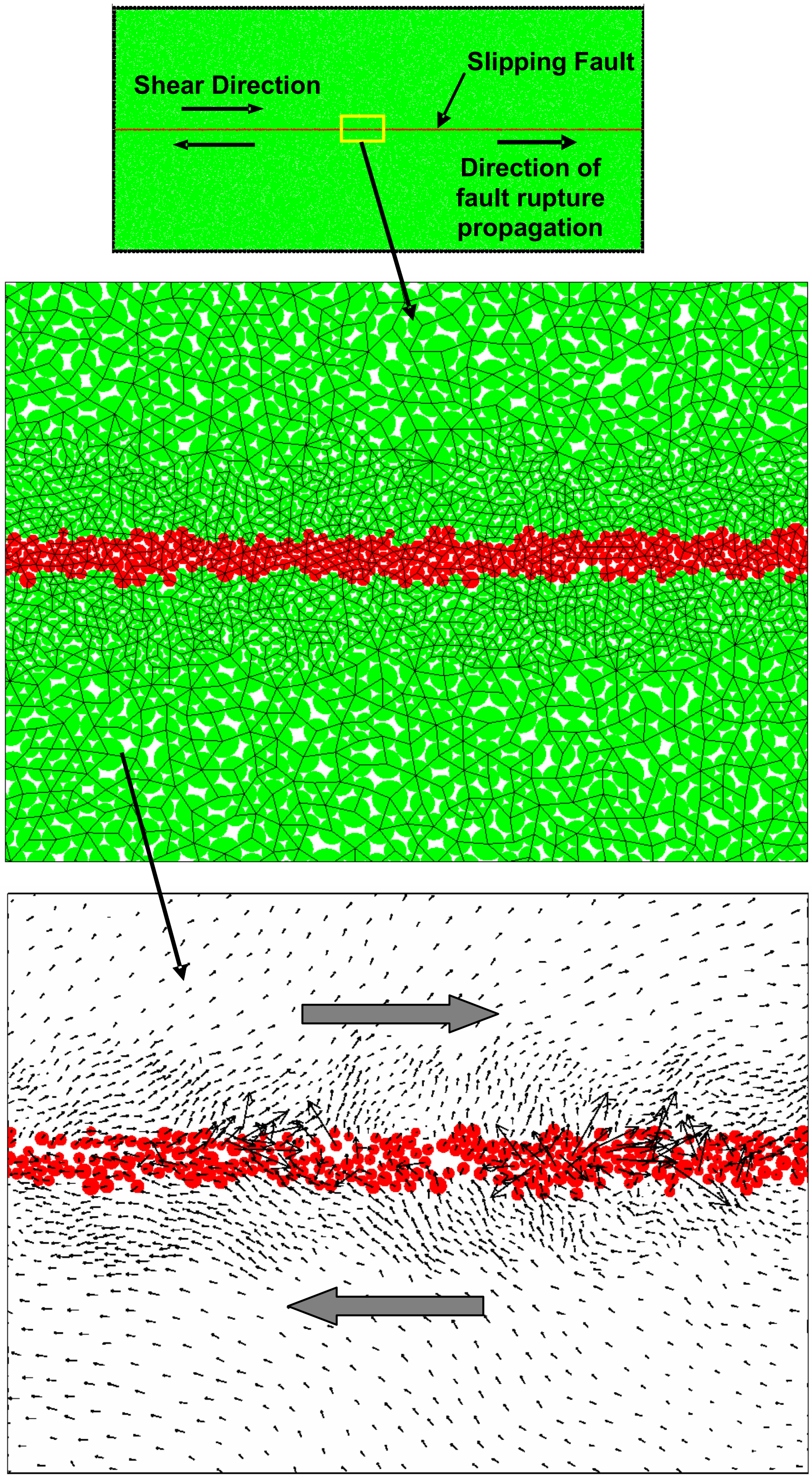


Figure 7 Model of Dynamic Slip of a Rough Fault

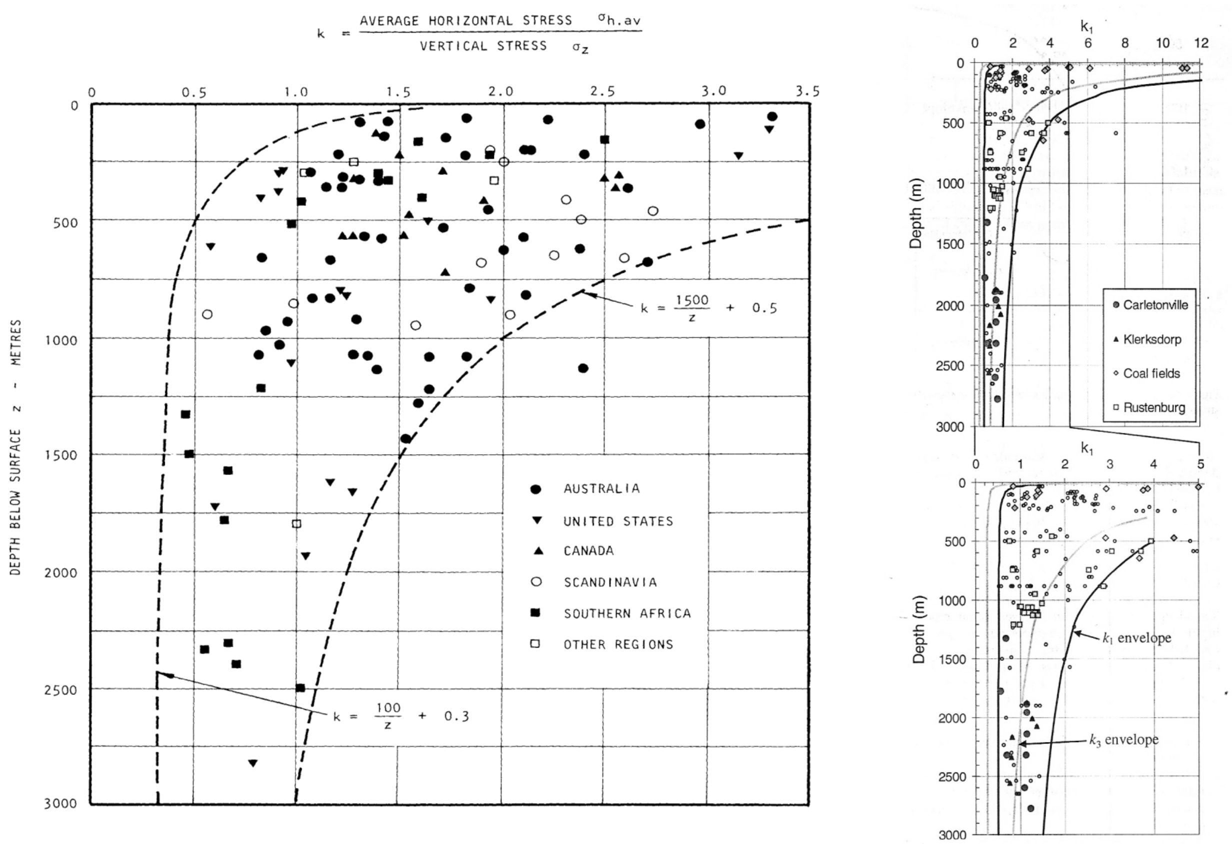
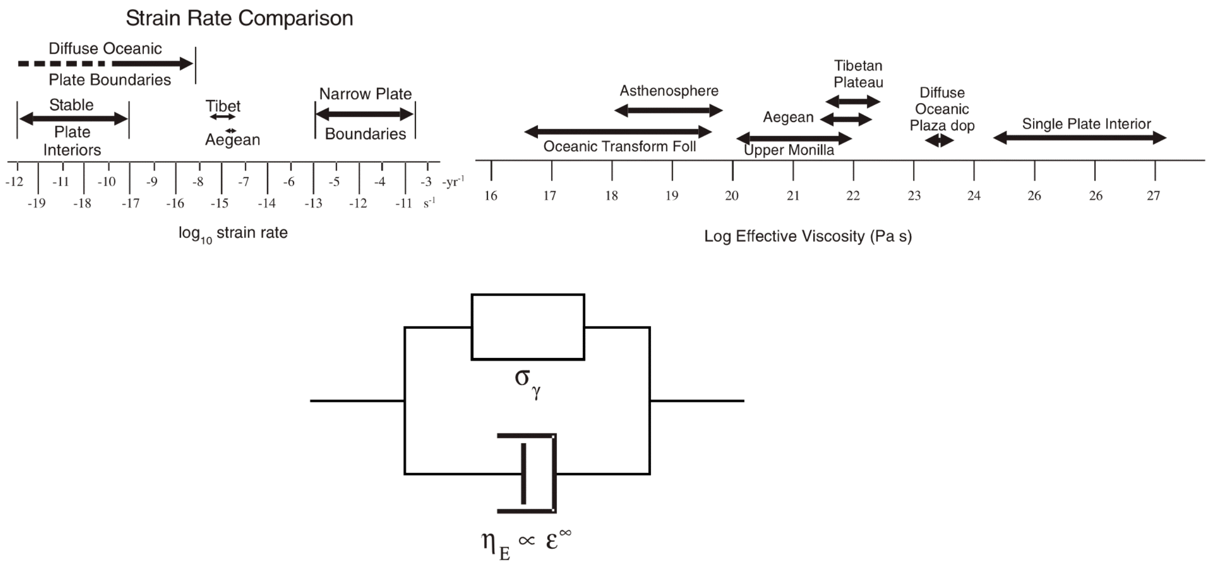


Figure 8 In-situ Stresses Observed at Various Depths around the World (Left: Hoek and Brown, 1982). Right: Wesseloo and Stacey, 2006)



Stresses in Rock Depend on Plate Strain Rate and Rock Constitutive Behavior.
[after Gordon (2000)]

upper lithosphere is brittle/semibrittle; lower lithosphere is viscous

Figure 9 Estimates of Ranges of Strain Rates and Rock Viscosities in the Crust

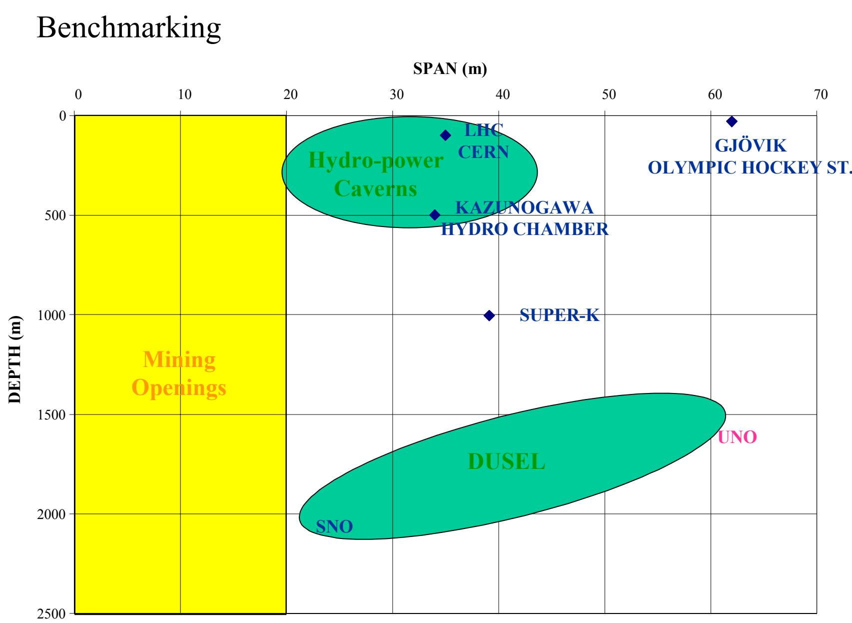


Figure 10 Current Distribution of Large-Span Underground Excavations Worldwide (also showing the possible depth-span range of DUSEL excavations)

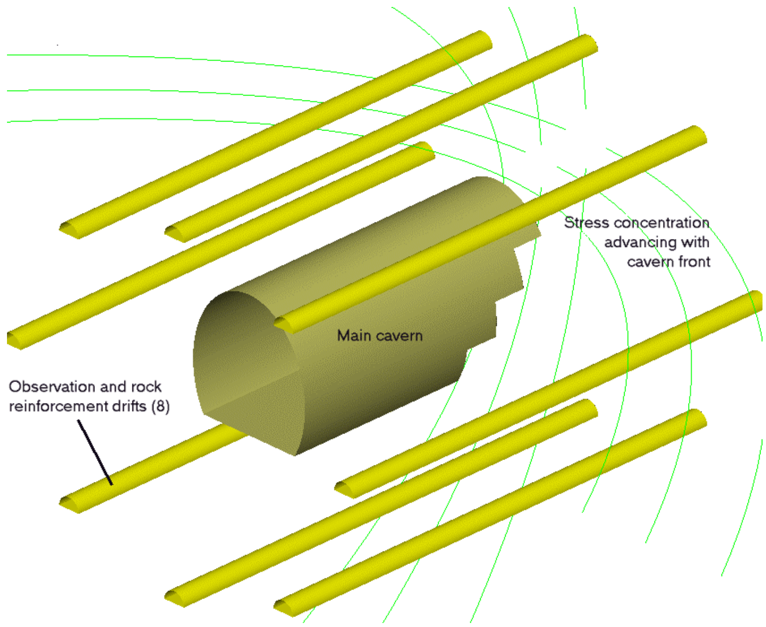


Figure 11 Possible Layout of Large Cavern, Supported by Cable Bolts Anchored in Auxiliary Drifts (Number, spacing and location of the drifts and cables will vary; diagram is schematic only.)

drifts as the large cavity is excavated and advanced toward and beyond test locations in the drifts. The cavern excavation process will redistribute stresses around the cavern. As the cavern advances, so, too, will the region of stress concentration ahead of the cavern front. This change in loading can be used to monitor the response of the ground ahead of the cavern and of supports installed in the reinforcement drifts.

5.3.3 Recovery of Hydrocarbons and Geothermal Energy

Hydrocarbons and hot geothermal fluids are important energy sources for humankind, and lay deep within the earth's upper crust. Saline aquifers and depleted hydrocarbon reservoirs are similarly deep, and provide attractive sinks for the safe long-term disposal of hazardous wastes and gases, as well as for CO_2 produced in energy production. These reservoirs typically are accessed by deep boreholes, fractions of a meter in diameter and thousands of meters in depth, with great challenges related both to their drilling and in engineering an efficient reservoir at remote depths, for example via hydraulic fracturing.

Hydraulic fracturing is a widely used technique to stimulate production in reservoirs. An interval of a well bore in the producing formation is packed-off and pressurized until the pressure is sufficient to induce a fracture (usually vertical) in the horizon. Fluid containing proppant is injected rapidly into the fracture to extend it many hundreds of meters into the formation. The proppant is sand or other particulate material that will keep the fracture open, so that it will serve as a highly conductive pathway for oil or gas to flow back to the well bore when the fluid pressure is released.

Several years ago, the Gas Research Institute conducted a number of extremely well instrumented hydraulic fracturing tests in Texas in an attempt to validate the various design models available in industry. This project resulted in substantial variations, mainly due to the inherent and different assumptions made for each particular model to make it tractable. In general, it was found from production analyses that the fractures created were much shorter than anticipated, resulting in lower rates of reservoir production than anticipated.

Field data increasingly have revealed that singular planar hydraulic fractures are the exception rather than the rule; multiple fractures, one-wing fractures, and non-planar fractures are common, and probably responsible for the discrepancies with the numerical predictions.

More recently, steam injection field experiments (Figure 12) also have confirmed the importance of the pumping rate (or fluid viscosity) upon the failure mechanisms. High pumping rates and/or higher viscosities result in a higher probability of inducing tensile features — i.e., the associated seismic 'cloud' is less elliptic. Access to an underground research facility such as DUSEL would allow these effects to be better quantified and could lead to future optimization of simulation treatments.

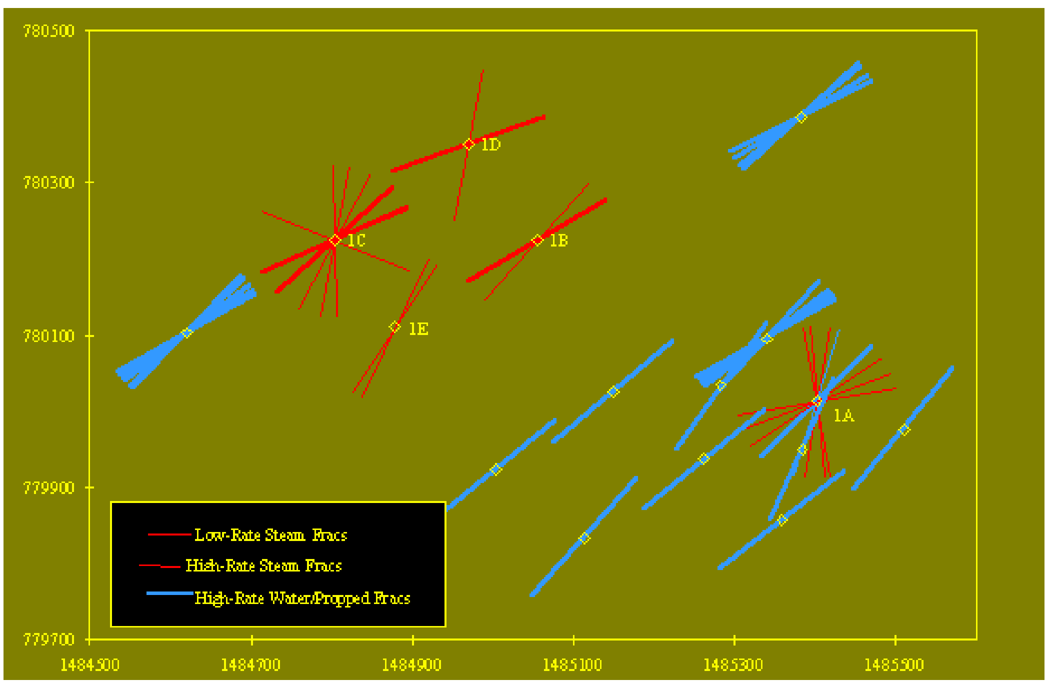


***Figure 12** Hydraulic Fracture Orientations for Different Stimulation Procedures (Courtesy of Pinnacle Technologies)*

Application of sound rock-mechanics principles to engineering problems lately has switched from the traditional mining and civil domains to the oil and gas industry. Inherent challenges to develop hydrocarbon resources in more difficult environments have resulted in needs for more fundamental research to complement current applied research.

In addition, plugging and/or decommissioning wells with 30% to 60 % of the resources left in place has been seriously questioned; new enhanced Oil Recovery (EOR) treatments, such as selective microbial enhancements, have encountered regulatory difficulties. Some of the challenges are provided below.

Detection and Characterization of Heterogeneities — Wave propagation dispersion and attenuation vary as a function of the ratio of wavelength to layer thickness; hence, by studying the dispersive characteristics of P-and S-waves, it should be possible to determine the type of media under investigation. Recently developed mathematical models describing such phenomena (Chesnokov, 2005) now need controlled field experiments to establish their practical validity. Experiments to date have been limited to the laboratory scale. Access to an underground research facility would allow critical upscaling and validation of this potential technical breakthrough. From a practical point of view, it would shed light on the mechanism responsible for prolific gas production in formations such as the Barnett shale (presently the biggest "play" in the continental United States) and delineate other potential resources in shales.

Drilling Optimization — The petroleum and geothermal industries are developing ever deeper and more 'difficult' reservoirs requiring unique and rather expensive drilling rigs. Although drilling automation is being applied slowly in the field (e.g., downhole data transmission, surface automation, etc.), expert human intervention is still necessary and often crucial. Recent developments in decision theories and computer technology make it possible to develop 'intelligent drilling', whereby the bit makes some adjustments in real time, depending on the local encountered conditions. For example, unexpected high-pressure gas pockets, or even radioactive waste in abandoned drums, such as in the Hanford facilities in Washington State, might trigger immediate deployment of downhole safety measures. Because time is often of the essence in those cases, one could envision adding technology to 'see-ahead' of the bit. In addition, by monitoring the vibrations of the bottom-hole assembly, changes in lithology could be detected. All these data should be processed downhole, avoiding the inherent limitations of data transmission rate via the drilling mud. Access to an underground research facility where boreholes could be drilled from existing drifts could help in validating such new concepts.

Naturally Fractured Reservoirs — Although every geological formation contains fractures, reservoirs do not necessarily behave as 'fractured media' (i.e., where deformation of discontinuities overshadows porous media behavior). The inherent compressibility of such fractures introduces an additional difficulty in that the response of the reservoir becomes production rate-dependent. An irreversible consequence resides in the fact that artificial impervious barriers might be created if a 'critical flow rate' is exceeded, affecting both production as well as accessibility to all reserves. Another issue is the influence of pre-existing discontinuities on induced fracture propagation — resulting 'offsets' might limit the penetration of solid propping particles, leading to early screen-outs. In addition, multiphase flow in fractures is poorly understood and plays a rather important role when considering the maximum storage pressure in underground cavities. This primarily is due to the length scales involved by invoking fracture mechanics principles. Access to an underground research laboratory definitely will increase the state-of-the-art in understanding the fundamental and phenomenological mechanisms that control the flow of fluids in fractured rocks as well as their propagation across existing discontinuities.

***Gas Sequestration and Storage* —** Supply and demand of hydrocarbons are relatively volatile topics, mainly due to political changes and/or conflicts in exporting countries. To ensure uninterrupted gas supplies, storage facilities are often a necessity. Depleted reservoirs, tankers, and solution-mined salt cavities have been the traditional approaches. However, the United States also has a number of abandoned underground mines that might provide inexpensive additional storage space. A number of such mined-out facilities already exist in a number of countries for oil storage. For natural gas, sealing of the existing fractures is a major concern. The hydraulic gradient method is not acceptable, as gases can still escape via the 'champagne effect', leading to safety issues. A small cavity could be isolated easily within an existing underground research laboratory to delineate the critical pressure above which leakage can occur (refer, for example, to the accident in Kansas that destroyed a number of houses, even though they were located a few miles from the underground storage space).

6.0 EXAMPLES OF GEOSCIENCE AND GEOENGINEERING EXPERIMENTS AT DUSEL

The following five general examples of experiments that could be conducted in DUSEL are illustrative only. Many others could be suggested, and all will need to be refined depending on the geology of the site chosen for DUSEL. A large series of geophysics experiments on various scales certainly will form part. Microseismic networks will be used to monitor many experiments and, as other imaging techniques evolve as part of the Transparent Earth initiative, these will become part of the measurement and observation tools for experiments. A classical seismic observatory also is contemplated at depth in DUSEL, taking advantage of the low seismic background environment compared to a surface installation.

Some experiments may be completed within one or two years, while others, conducted in several phases, could last for several decades. DUSEL will open a new era in the Geosciences, allowing hypotheses and modeling predictions of how rock and the processes operative within it behave in its natural environment. Determination of how these processes scale with size of the rock structure and with time has been a primary goal of geosciences and geoengineering research for at least 50 years. It would be naïve to expect early success, but recent studies to combine numerical modeling of rock masses with detailed field measurements, (Lin *et al.*, 2006; Damjanac *et al.*, 2006) demonstrate that the tools and approaches are now at a stage where real advances should be possible.

Figure 13 is intended only to illustrate the DUSEL concept. Actual layout of the underground excavations, types of experiments and their location, will depend on details of the geology and access to the site.

6.1 Characterization Experiments — "Unperturbed" Block (Fracture Detection and Mechanical Hydro/Chemical Coupling)

In low-permeability rocks, fractures, and the networks they form, exert a critical influence on strength, deformation, and fluid transmission characteristics. Detecting these features, defining their structure, and evaluating their component and ensemble properties are important needs in predicting their response — for example, to the transmission of fluids as reservoir rocks for hydrocarbons or geothermal working fluids, or repository rocks containing CO_2 or other sequestered components. The close-in access to a large (10 m x10 m x10 m) block of rock, at stresses and temperatures relevant to deep reservoirs, affords the possibility of characterizing response in fine detail. This includes developing and testing geophysical methods to both "see" into the rock, and to better define the physical characteristics of the block, and then to use these evaluations to predict the response to applied changes in the ambient conditions. These "changes" would include the injection and recovery of single and multi-component fluids, including conservative, reactive and particulate tracers, with perturbations applied by heaters to modify stresses and adjust fluid flow paths.

Importantly, DUSEL allows close access at depth to a large block that contains a statistically representative sampling of fractures, anticipated to mimic the response of usually inaccessible reservoirs at-depth. Such a facility would allow multiple contemporary questions to be answered in an environment that approaches the controlled boundary conditions of a laboratory experiment, but accessing materials close to their natural state. These questions include:

- To what resolution can we detect the presence and location of fractures?
- What geophysical signatures best denote their mechanical and transport properties?
- Can these signatures infer initial stress states and connectivity of fractures and fracture networks?
- What improvements in characterization are available from dense networks of sensors, and how dense may this coverage develop, for example using MEMS?
- What improvements in characterization are feasible by linking geophysics with fluid transmission and tracer tests?
- What improvements in characterization are available through methods of data fusion?
- How will mechanical and fluid transmission behavior change with exposure to reactive fluids and at elevated temperatures?
- Are these responses broadly predictable from geophysical characterizations?
- How do natural radiogenic and biological tracers enhance the ability to characterize the transport, reactive, and heat transfer characteristics of rock masses?

6.2 Experiments on Stress Determination, its Variability over Scale of 10 ~100 m and Correlation with Structure.

The *in situ* state of stress underground is rarely well defined. A 'rule of thumb' often used is that the vertical stress, σ_v , is approximately $\sigma_v = 0.027$ H MPa*, where H is the depth below surface in meters, and that the lateral (horizontal) stress, σ_h , is approximately $\sigma_h = [\upsilon / (1-\upsilon)]\ \sigma_v$, where υ is Poisson's ratio for the rock. Thus, if υ is taken as 0.25 ~ 0.33, as is typical for rocks, then $\sigma_h = (0.33 \sim 0.5)\ \sigma_v$. It also is assumed that the two horizontal principal stresses are equal. As can be seen from Figure 8 in this report, the ratio of horizontal/vertical stress can vary considerably from this idealized assumption, and the maximum and minimum horizontal stresses may not be equal — and may not be principal stresses. In folded strata, for example, an anticline of rock that is stiff (high modulus) compared to adjacent rock can act as an underground arch, supporting the overlying less stiff rock, and transferring a higher than average stress through the stiff (folded) layer. Thus, at a certain depth, the vertical stress in such as formation could be considerably higher than the average value while, correspondingly, the stresses in adjacent layers can be below the average value. It is probable that, in general, both the gravitational and the tectonic forces will be non-uniformly distributed in the subsurface. Equally, the response of the various rocks will vary — the more brittle rocks will tend to accumulate stress, and may possibly fracture, whereas more ductile formations may deform and fold. The current state of stress at depth will be the result of forces, both tectonic and gravity, which have been applied to the rock, often for many hundreds of millions of years or more. Tectonic regimes and force directions probably have changed several times in this period

The redistribution of forces induced by activities such as excavation or other man-made changes (e.g., fluid injection) take place at a much more rapid rate. The response of the rock will differ; time-dependent viscous changes will be relatively insignificant in most rocks over such short periods. Thus, the state of stress in rock at depth can be complex, with the pre-existing stress distribution determined by the very long-term constitutive response of the formations and the changes induced by human activities determined by the relatively instantaneous response of the rock.

Some success has been achieved in attempting to predict the observed *in situ* stress state in rock from laboratory 'creep' measurements on specimens of the rocks (Wileveau and Cornet, 2005).

Several comprehensive campaigns of numerical modeling of the geological structure at various underground locations, estimation of the time-dependent properties of the rocks, *in situ* stress determination at several locations in the structure, and comparison of predicted and observed stresses could lead to important advances in understanding of the influence of geological structure on *in situ* stress distribution. Directly applicable in the design of safer mines, such investigations could contribute also to understanding of long-term rock deformation at the larger scale of plate boundaries.

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* This assumes that the vertical stress is equal to the weight of the overlying rock, height H, and that the average density of this rock is 2.7 tonnes/cu m.

6.3 A Perturbed Block (Pillar) Experiment to Study the Failure of Rock

The failure of rock bears importantly on the potential success of a facility such as DUSEL. The construction of large cavities that may span 60 m at a depth of 2000 m pose unprecedented engineering challenges and will require careful site investigation, design, and extensive stability monitoring — issues of stress-control and protection from rockbursting will be important considerations, as will the strength of the rock mass at the scale of the proposed excavation. The hazard of rockbursts is a ubiquitous problem in deep mining, worldwide. For example, the Creighton Mine (Ontario, Canada), which houses the SNO lab and now reaches to ~ 2400 m, sustains a few M>3 events annually, with the largest event recording M = 4 (1984). These events pose a significant safety hazard, but offer scientific challenges in the improved understanding of rupture mechanisms that relate to length scales from nanometers to kilometers, and timescales that span milliseconds to thousands of years. This is the principal focus of this proposed study.

DUSEL offers the potential to complete fundamental engineering and scientific studies of rupture mechanics via the physical (seismic, stress, fluid pressure, deformation) and chemical (reactant fluxes and compositions) monitoring of a test that will isolate and fail a large deep block of rock, *in situ*. Loading of the block would be applied by excavation-induced stresses, and applied thermal and fluid stresses. It also would include the potential to control external and confining loads by actuators and through pressurized membranes. This heavily instrumented test would both complement, and be complemented by, the process understanding of rock failure gained by the monitoring of the observatory site by geophones and other instrumentation, and concentrated around critical caverns.

The observations provided by the failing of a large block of rock, at depth, under controlled stresses and geometry, and triggered by energetic and reactive fluids, would illuminate important contemporary issues in earthquake mechanics and seismicity. The physics of earthquake nucleation and rupture is not yet well described because of the impossibility of near-field access to fault zones. For example, understanding shear zone formation (i.e., how a zone of freshly fractured rock accumulates displacement and eventually forms a friction-controlled fault) would contribute critical knowledge toward understanding earthquake processes. A natural laboratory also would lend itself to other studies that would contribute to the knowledge of earthquake failure mechanics, such as understanding the mechanisms of triggering across short distances and timescales, mechanisms of strength-gain and fault-healing promoted by reactive fluids and other agents, and the respective roles of velocity weakening and energy surplus effects in defining the transition between quiescent rupture and energetic failure.

The observations would contribute to the constraint of rate and state friction constitutive laws that have emerged as powerful tools for investigating the mechanics of earthquakes and faulting. Although these laws are capable of reproducing virtually the entire range of observed seismic and interseismic fault behaviors, ranging from preseismic slip and earthquake nucleation to coseismic rupture and earthquake afterslip, our understanding of key parameters in these laws remains poor. A major limitation in developing process-based models of these parameters is the scaling problem associated with applying laboratory-sized samples. Numerical models are available to apply laboratory-based friction laws to problems such as earthquake triggering and fault interaction. However, the natural-scale laboratory data necessary to carry out such studies do not exist. These data are needed to understand the role of fault roughness and gouge on frictional properties and stability. The proposed underground laboratory will allow detailed studies of frictional strength and stability, including resonant behavior and shear destabilization. The observations will constrain theoretical models based on friction constitutive laws.

Importantly, DUSEL offers the unique opportunity for long-occupancy of a site with a prescribed dense coverage of observations, access to an unusually large block of rock, and the application of high stresses at depth. Consequently, the proposed underground laboratory will provide an important link between the laboratory and natural tectonic events, which has so far only been possible by studying mining-induced seismicity and by borehole recordings.

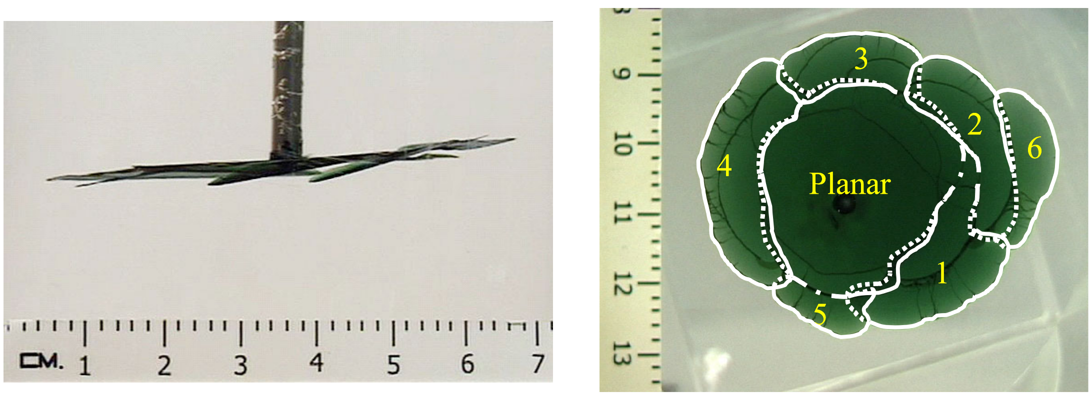
6.4 Mechanics of Fracture Growth and Scale Effects in Rock Fracturing

Fractures are ubiquitous in rock, and understanding fracture propagation in rock is fundamental to processes across the geosciences, and at all scales. Fracture growth is the basic mechanism controlling rock strength, time-dependent failure, earthquakes, dike propagation in volcanic eruption — and much more. Industrially, for example, hydraulic fracturing is a procedure that is used widely in the petroleum industry to stimulate petroleum and gas production (see Section 4.3.3). A section of a well bore in the production horizon is packed off and pressurized with fluid until a fracture is generated in the rock. Continued pumping extends the fracture, often several hundreds of meters into the rock. Granular materials injected with the pumping fluid hold the fracture open when the pumping pressure is released. This creates a high-permeability pathway for flow of fluids from the oil or gas bearing formation to the well. Despite the major economic significance of the technique, the fracturing process is not well understood. Improved understanding could lead to significant improvement in application.

Fracture growth can be viewed as a balance between the energy needed to create new fracture surface and the energy released by the propagation process. Fracture surface is created by breaking bonds within or between mineral grains, and additional work is required to displace opposing fracture walls against the confining stress or to account for viscous dissipation by fluids flowing in the crack. During propagation, these energy sinks are coupled with the release of strain energy stored in the rock, as well as with the energy from other sources, such as heating, chemical reaction, fluid injection,-or seismic waves.

Scaling — The energy required to create new fracture surface in laboratory experiments using cm-sized samples is well known, with typical values of 10 J/m^2 for rock (Atkinson and Meredith, 1987). However, this basic value is poorly known at larger scales typical of many natural processes. The few data that are available indicate that fracture surface energy is highly scale-dependent, with fractures in the range of 100 m to 1 km in length, requiring 10^3 to 10^5 J/m^2 [Delaney and Pollard, 1981; Shlyapobersky, 1985; Dyskin and Germanovich, 1993]. The largest fractures on Earth, deep crustal faults and mid-ocean segments, require even more energy, of the order of 10^7 to 10^9 J/m^2, to create new fracture surface [Macdonald *et al.*, 1991]. An explanation for this scale dependency lies in recognizing that the growth of a large-scale fracture is not a separation of two atomic planes in a crystal, but a complicated process of the simultaneous development of numerous smaller scale defects. Furthermore, the energetic budget of fracture growth in rock at any given scale will include the defects at all smaller scales.

Fracture Segmentation — One process that may account for the scale dependence of fracture surface energy is the tendency for the propagation process to produce multiple fracture segments at the fracture front. Slight rotations in principal stresses, or modest changes in material properties, can cause a smooth fracture front to split into segments separated by intact rock bridging opposing sides of the fracture [Pollard *et al.*, 1982]. Continued propagation causes the rock bridges to crack, but more energy is required to do this than to advance a smooth fracture front. Moreover, the segmentation process can produce tenuous connections that inhibit fluid flow, further increasing the energy required for propagation. Fracture segmentation under mixed Mode I+III conditions has been documented in the laboratory at the centimeter scale (Figure 14), but active experiments at larger scales have been infeasible. Fractures consisting of multiple segments are observed in nature at scales up to 100 km.



(a) (b)

Figure 13 Hydraulic Fracture in a Brittle Plastic (PMMA) Specimen under Mixed Mode I + III Loading (Wu et al., 2006)*

Figure 13 presents (a) a side view of mode III segmentation of the propagated fracture, and (b) a plan view of the propagated fracture. Numbers in (b) indicate the sequence of segmentation. A Mode 1 planar radial fracture was generated by applying fluid pressure to the bottom of the central borehole. A slight torque was then applied to the specimen, and the fluid pressure then was increased in order to extend the fracture. It is seen that the single radial fracture now breaks into a series of separate segments. (Addition of the torque changes the principal stress orientation at the tip of the fracture. The segmentation is a response to this stress change — i.e., fractures re-orienting toward the direction of maximum tension).

* Mode 1 is fracture propagation by Tension or Opening of the crack; Mode II is propagation by In–Plane Shear or Sliding; Mode III is propagation by Out-of-Plane Shear, or Tearing (Illustrations of the three modes may be seen at http://www.efunda.com/formulae/solid_mechanics/fracture_mechanics/fm_lefm_modes.cfm).

Roughness — Segmentation and other processes during propagation leave their legacy as roughness on the fracture surface. The cracked bridges between segments appear as ridges on a fracture surface, although asperities of all scales with myriad other geometries are also produced during propagation. These features are important, because miniscule displacements during propagation can cause an asperity on one surface to be mismatched with the opposing fracture surface. Mismatching asperities create voids along the fracture that both store and transmit fluids such as petroleum, water, or natural gas. Fluid flow and transport along fractures is known to be dominated by a few preferred pathways (Tsang and Neretnieks, 1991), and it seems likely that these paths are the product of roughness created during propagation.

Mechanical and Hydraulic Behavior — Roughness also plays a role in the mechanical and hydraulic behavior of fractures. The amplitude of asperities causes friction on fractures that opposes shear displacements. As a result, roughness can be a critical factor, affecting displacements along faults during earthquakes, slip on surfaces beneath landslides, or failure on planes underlying rock falls. Asperities also deform when the fluid pressure in a fracture changes. For example, decreasing the fluid pressure will increase the effective stress, which compresses asperities and causes fractures to close slightly (Murdoch and Germanovich, 2006). This modest change in aperture expels fluid and is the reason why petroleum and water can be recovered from deep reservoirs or aquifers. Fractures at different scales are likely to have different roughness patterns.

Network Connectivity — Interactions between a propagating fracture and its neighboring fractures also have widespread implications. Interactions that cause fractures to intersect will produce connected networks, whereas mechanical interactions that inhibit fracture intersection will produce a network of isolated fractures (Olson, 1993; Renshaw, 1997). The connectivity of a fracture network is an important control on fluid flow and mass transport, as well as the bulk strength and modulus of a rock mass. The development of connected networks of fractures at realistic field scales, particularly networks composed of multiple fracture sets, remains enigmatic.

6.4.1 Proposed Research

A four-part program of *in situ* field experiments is proposed. Each part will build on previous experiments and extend the scope of research questions investigated at the DUSEL to increasingly broader areas of the geosciences.

> ***Part 1 — In situ Stress Characterization*** of the program will involve creating small hydraulic fractures to characterize the *in situ* stress state. These data, site-specific information about hydraulic fracturing techniques obtained during testing, and the evaluation of effective methods for the real-time monitoring of fracturing will be used to design the next experiment.
>
> ***Part 2 — Fracture Propagation Experiments*** will consist of creating larger-scale hydraulic fractures at different depths, monitoring their growth in detail, and excavating and describing the results. The purpose of this experiment is to

learn how fluid flow and mechanics are coupled during crack growth under different conditions.

Part 3 — Fracture Network Experiments involve applying hydraulic fracturing methods to create controlled, *in situ* fracture networks of specific geometries. Networks of fractures with different orientations will be created by modifying *in situ* stresses using heating (Wu *et al.*, 2006) or by pressurizing existing fractures, cutting notches, or related methods. Interactions controlling the formation of networks will be evaluated, and the fracture networks then will be used for experiments involving fluid flow, fracture assessment, transport and remediation.

Part 4 — Pressure-Displacement Coupling Experiments involve evaluating the interaction between pore fluid pressure variations and shear displacements across small fractures and faults. This will involve conducting injection tests and characterizing the hydro-mechanical response, as well as monitoring the natural variations in fluid pressure and displacement across discontinuities over a range of scales.

6.5 Experiments in Very Deep Boreholes.

It is anticipated that the excavations in DUSEL will reach approximately 2 km in depth. Conditions encountered by boreholes in the rock below this depth will be the same whether the holes are drilled directly from the surface or start from excavations at 2km. There are,however, operational advantages, including cost and access, to starting at depth. Geomicrobiological experiments in holes that may attempt to reach several km below the deepest excavations are contemplated. Depending on the site chosen, such very deep holes could provide valuable scientific information on crustal geophysics, thermal structure at depth, formation of ore deposits, and tectonic stresses. The high temperatures [(200-300)°C] and in situ stresses encountered in the holes could lead to borehole instability. These technological challenges provide valuable opportunities for innovation in both drilling and stabilization of the holes, and in research and development of logging and instrumentation techniques capable of operating in such a harsh environment. Such technology is of particular interest to the petroleum industry, which is being driven inexorably to exploit reservoirs of the order of 8~10 km depth. DUSEL represents a very valuable opportunity for geoscience and geoengineering experiments in all aspects of ‘very deep’ borehole research and development.

6.6 Experiments during Construction

Construction of the caverns and associated drifts required for some of the physics experiments will present significant engineering challenges. As illustrated in Figure 10, excavations of the size and depth, and long-term stability, required for DUSEL have never been constructed before. These challenges also present numerous opportunities for R&D, as illustrated by the following three examples. There are, of course, many more.

6.6.1 Scale Effects in Tunnel Stability

The approach taken to the development of large excavations that will be stable over several decades will depend on the geological environment and the rock types present at the DUSEL site. It is likely that both mechanical excavation and 'drill and blast' methods will be used. Large caverns (such as the one illustrated in Figure 12 in this report very probably will involve blasting of the cavern headings. The array of smaller drifts surrounding the cavern, driven (probably by mechanical excavation) in advance of the cavern, would serve as the locations for anchoring of rock cables installed to reinforce the rock and ensure the long-term stability of the cavern. These drifts also would serve to help define the geological character and variability over the cavern volume and, through scan line surveys along the drift walls, supplemented by boreholes in various orientations, the fracture orientations and the fracture continuity or 'persistence'. Samples would be taken to determine the mechanical properties of both fractures and 'intact rock'. Determination of the overall deformational response of the drifts as they are driven could be compared with modeling predictions, using the results of data obtained as described above. Microseismic networks installed in the drifts could monitor the deformational behavior and stability of the large cavern both during construction and for years after.

Comparison of the deformational response of the large cavern with that of the drifts, both predicted by modeling and observed over time, would provide invaluable information on the nature and importance of the scale effects of size and time, particularly with respect to excavation design. The response of the drifts could be observed as the stress concentration front moved over the drifts as the cavern excavation progressed.

6.6.2 Explosives and Blasting Research

Current technology allows precise timing of the detonation of explosives, such that it is possible to predict and use explosive wave overlap and interaction to condition (weaken) rock for more effective collapse in mass mining operations. Experiments could be conducted during excavation to compare wave propagation and interaction with modeling predictions at various locations in the rock mass. The periodic large blasts that would take place during cavern excavation could be used to assess the dynamic response of various support systems installed in the drifts. This research would aid in more reliable and safer excavation support design in rockburst-prone mines and in more effective 'hardening' of underground facilities.

6.6.3 Mechanical Excavation of Tunnels

Considerable potential exists to improve the technology of machine excavation of rock (i.e., by TBM (Tunnel Boring Machine). DUSEL could provide a test bed for evaluating innovative designs of TBMs.

Figure 14 shows an example of a prototype machine, the CMM (Continuous Mining Machine), developed several years ago (by the TBM manufacturer WIRTH in collaboration with a Canadian consortium HDRK) to excavate the rock by cutters attacking the rock laterally across the tunnel face in contrast to the direct attack of the cutters advancing in the direction of face advance used on standard TBMs. The CMM uses 4 cutters only, compared to typically ten or more that number on a TBM).

Each cutter is mounted on a rotating arm. Arm 1 removes a central 'basin-shaped' cut (red in the figure) across the center of the face. Arms 2, 3 and 4, spaced 120° apart on the rotating central arbor, cut outward toward the tunnel periphery. Arms can be retracted to allow for machine maintenance, inspection of the face, etc. as needed. The CMM has a much shorter turning radius than a classical TBM. Cutting forces are directed 'more tangentially' across the face of tunnel than for a standard TBM; hence, the reaction forces to be resisted by the gripper plates (pressed against the tunnel wall) are much lower. The cutting arms are computer controlled, such that non-circular profiles (e.g., flat floor) can be excavated.

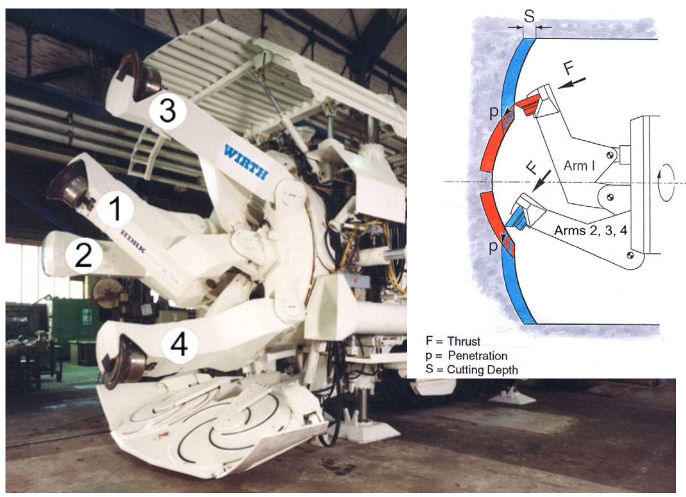


Figure 14 The CMM (Continuous Mining Machine) Prototype

While rock removal from the inner region of the tunnel is accomplished much more efficiently with the CMM, all machines must maintain a constant tunnel profile. This requires excavation of corners whether the cutters advance parallel or normal to the direction of tunnel advance (Figure 15). Cutting the corners around the periphery implies the production of finer and finer cuttings. The energy consumed in creating rock particles increases dramatically with reduction of particle size (Figure 16) — i.e., as the corner is approached (Figure 16). Cutting forces, cutter temperatures, and wear increase correspondingly. Thus, although the CMM (and similarly innovative designs) remove much of the rock much more efficiently, the overall efficiency remains relatively low, because the highly inefficient 'corner cutting' process remains. There is considerable room for innovation and design improvement — e.g., by use of high-pressure water-jet cutting to excavate corners. The cutter-wear problem would be avoided, and the water would reduce dust at one of the main sources. There is evidence also that addition of a low frequency (~ 40Hz) vibration to the cutters can reduce forces significantly. Although mechanical components of TBMs are being improved constantly to be more robust, little has been done to improve the efficiency and effectiveness of the excavation process.

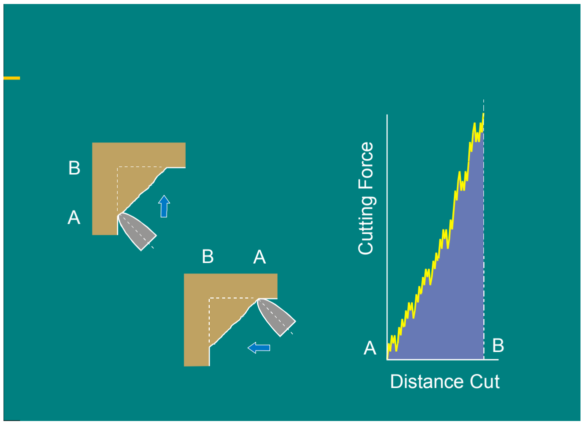


Figure 15

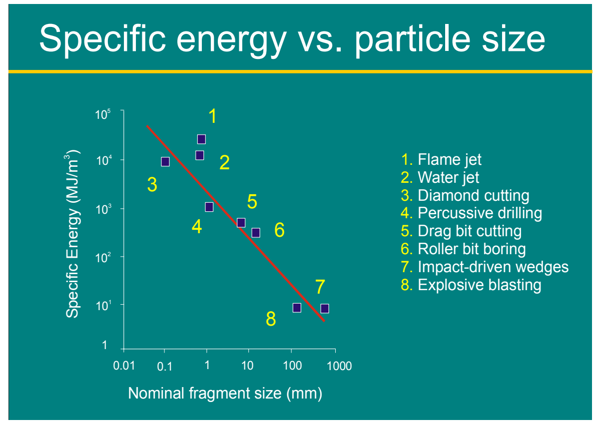


Figure 16

7.0 CONCLUSION

This chapter has attempted to illustrate the many ways in which a Deep Underground Science and Engineering Laboratory (DUSEL) can provide an unprecedented research opportunity for the Geo-sciences and Geo-engineering. The applications mentioned are by no means exhaustive. Many others will emerge once the facility becomes available and research is underway.

For the first time, it will be possible to carry out long-term experiments on the rock in place and under stress, at a scale that allows the all-important role of fractures to be studied. For the first time, it will be possible to mount a concerted research effort to make opaque rock ‘transparent’ through developments in geophysical imaging. And, for the first time, it will be possible to test the validity of the computer models that we use to explain the coupled processes and complex interactions that operate underground. All of these fundamental advances will have major benefits in engineering.

DUSEL could be the stimulus needed to draw the attention of the U.S. academic community to the critical importance of education and research in underground science and engineering. Closure of many mining engineering programs over the past several decades has resulted in a serious void in this essential field of scholarship. The field has now expanded to include several disciplines. DUSEL provides a stimulus for the development of new interdisciplinary programs that recognize this change.

Success of the DUSEL initiative will lead inevitably to other underground research sites in different rock settings, and different rock formations. As the world population increases, so do the demands on the subsurface. Humankind has expanded across the surface of the planet and has learned much through research about the world above. It is time now to learn about the world on which we stand, the world beneath our feet.

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APPENDIX

Table A.1 Current Geophysical Methods

METHOD	PRINCIPLE	TYPICAL MEASUREMENT	PHYSICAL PROPERTY MEASURED	INTERPRETED PARAMETERS
Airborne sensing	Detects reflected electromagnetic radiation	Aerial photography and remove sensing in several spectral bands	Spectral-development reflectance of electromagnetic radiation	Geologic lineations, variations in vegetation, surface disturbances
Electrical and electromagnetic	Detects current flow in sub subsurface materials	Currents, voltages, spatial locations	Electrical resistivity	Depth, earth material resistivity, porosity, inferred fluid chemistry
Ground-penetrating radar	Transmits radio waves in the 10 MHz to 500 MHz band into subsurface and detects returning reflected waves	Distance, wave arrival times, and wave amplitude	Dielectric permitivity, electrical resistivity, magnetic susceptibility	Shallow interface depth and geometry, electromagnetic wave speed, electromagnetic wave attenuation
Magnetics	Detects local variations in Earth's magnetic field caused by magnetic properties of subsurface materials	Proton precession frequency	Magnetic susceptibility	Geometry and magnetic susceptibility of local subsurface features
Microgravity	Detects localized minute variations in the gravitational field of Earth	Displacement of gravitational-force-sensitive mass	Mass density	Depth, geometry, and density of local subsurface features
Seismic methods	Source of seismic waves provides sampling of elastic properties in a localized volume of Earth	Distance, wave arrival time, and wave amplitude, different wave types	Speeds of compressional, shear and surface waves; attenuation of these waves	Interface depth and geometry, elastic moduli, location of faults
Thermal methods*	Measures temperature and changes related to active or passive thermal sources	Temperature and temperature changes at specific locations	Thermal conduction, heat capacity	Density, moisture content, thermal anomalies, thermal sources, rate of geochemical reactions

*Thermal methods added for this report
SOURCE: NRC (2000, 2000 1b)

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