Draft Experimental Plan 5/12/08

Eric Sonnenthal (Lawrence Berkeley National Lab – Working Group Leader)

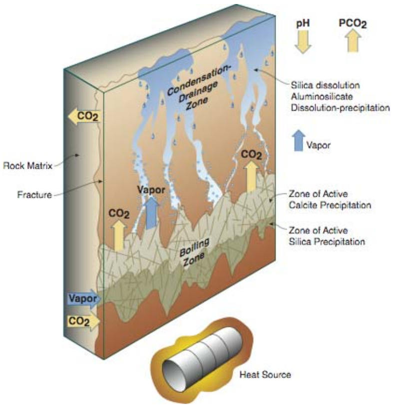
DUSEL Induced Flow, Transport, and Activity Working Group: Coupled Thermal-Hydrological-Chemical-Mechanical-Biological Experiments

OBJECTIVES

The objective of this facility is to quantitatively probe the range of coupled thermal-hydrological-mechanical-chemical-biological (THMCB) processes taking place from the scale of grain surfaces, pores and microbes, to meter-scale fractures, decimeter-scale fluid flow patterns, convection, and rock deformation over a range of temperatures for a potential time period of years to tens of years. To accomplish this goal, the plan is to create a large *in-situ* test site in fractured heterogeneous rock at depth in the Homestake Mine where well-controlled experiments can be performed, interrogated, with supporting laboratory experiments, numerical modeling, and state-of-the-art measurements by *in-situ* probes and sampling.

SCIENTIFIC JUSTIFICATION

Most natural and engineered earth system processes involve strong coupling of thermal, chemical, mechanical, and sometimes biological processes in rocks that are heterogeneous at a wide range of spatial scales. One of the most pervasive processes in the Earth's crust is that of fluids (primarily water, but also CO_2, hydrocarbons, volcanic gases, etc.) flowing through fractured heated rock under stress. Although we can sometimes analyze the rocks and the fluids for their physical and chemical properties, it is very difficult to create quantitative numerical models based on fundamental physics and chemistry that can capture the dynamic changes that have taken place or will take place. The initial conditions and the history are only known roughly at best, and the boundary conditions have likely varied over time as well. Processes, such as multicomponent chemical and thermal diffusion, multiphase flow, advection, and thermal expansion/contraction are taking place simultaneously in rocks that are structurally and chemically complex (a heterogeneous assemblages of mineral grains, pores, and fractures) and visually opaque. For example, in rock where flow is focused through fractures with apertures of only microns to millimeters and there is slow cross-flow and diffusion with fluid in the rock matrix, the large scale flow system can be dominated by mineral-water reactions (or biofilm formation) at the micron-scale leading to sealing, overpressuring, and potentially cycles of rupture. In unsaturated flow created either by boiling, or simply infiltration above the water table, the processes become even more difficult to quantify because the distribution of water is also uncertain and controlled by capillary properties, the transport of water vapor, CO_2, and other gaseous species (see illustration of fracture-matrix interface at right). This makes what could be a basic fluid dynamics problem into something that is much more intractable. The only way to fully understand such processes is to carry out well-bounded experiments at a range of scales that can be interrogated and modeled.



The Homestake Mine presents a unique opportunity to investigate coupled thermal, hydrological, chemical, mechanical, and biological processes in a very different geologic, mineralogic, and hydrologic environment than has been attempted previously. First, the metamorphic mineral assemblages making up rocks are very different mineralogically from the rhyolitic tuffs and granites that were studied in other heater tests, have stronger anisotropy, are are considerably more heterogeneous. In addition, prior thermal tests have generally been focused on thermal-mechanical effects and less on geochemistry and certainly much less on biology. Reaction-rates are highly dependent on reactive surface areas, which in turn are a function of the hierarchy of scale of fluid flow, geologic structure, and mineral fabric. Hence, the well-developed metamorphic fabric of the Homestake iron formation and the adjacent lithologies would provide a unique system in which to monitor fluid flow and reaction-transport processes under a well-controlled thermal environment. The analysis of thermal waters using stable and radiogenic isotopes as well as major ion geochemistry would yield a wealth of information that could be used to validate coupled process models that include thermal, hydrological, chemical, mechanical, and biological processes. For example, because the rocks are approximately 2 billion years old, the $^{87}Sr/^{86}Sr$ ratios of the individual minerals will be very different owing to the different initial Rb/Sr ratios in the minerals. Therefore, shifts in the isotopic ratios of strontium in waters reacting with the minerals could be used to constrain their rates of reaction under hydrothermal conditions. One could also look at the microbial population as a function of temperature and rate of heating, and evaluate the effects of changing conditions (temperature and geochemistry)

In terms of understanding thermally-induced fluid pressurization, hydrothermal convection, mechanical deformation, and mineral alteration, heating of these rocks under saturated conditions would allow for investigation of strongly coupled processes that are an important phenomenon in many geological environments, but which have never been studied under well-controlled conditions over long time periods and large spatial scales. Experiments at the scale of 10’s of meters or larger, could be sited between existing adits and monitored from adjacent adits. Because of the low thermal conductivity of rocks, the effects of heating would at first be localized to a relatively small region around the heated boreholes. Thus many coupled processes and their effects could be examined, such as fracture generation and propagation, microseismicity, microbial and colloid transport and plugging, at locations under ambient conditions well before the effects of heating (months to years), during the heating period, and eventually as the system cooled. The experiment would be a site to test novel geophysical techniques as well as in-situ thermal, chemical and biological sensors in extreme environments over long time periods.

The quantitative understanding of these processes is necessary not only from the scientific perspective, but also to society in several important areas – hazard prediction and mitigation (e.g., earthquake dynamics, volcanic-hydrothermal interactions, landslides), resource recovery (geothermal injection, hydrocarbon stimulation), and subsurface waste storage/sequestration (nuclear waste and carbon sequestration). Multi-decade long experiments will allow the evaluation of fractured formations for enhancement of production and for sealing and prevention of leakage. Our ability to quantify these processes to the extent needed for assessment of the safety and efficacy of such systems necessarily requires well-controlled experiments and numerical models that capture the salient physical and chemical processes.

APPROACH

Initiate and organize coupled process collaboration for experiments potentially at the 4850 level (Sanford Laboratory) and the Homestake DUSEL with a phased approach. The working group team, with external input and peer review, will refine the necessary initial data, experiments, and modeling that should be performed, prior to starting the *in-situ* experiments. In addition to peer review by funding agencies, it is expected that graduate student and postdoctoral work would be incorporated in the planned experiments, modeling and supporting laboratory studies. The experimental rock mass shold be a facility that is open to researchers throughout the larger community to propose experiments funded by NSF, DOE, or other agencies. A series of experiments should initially be performed in the ambient rock mass to characterize the permeability structure, reactivity, microbial distributions, stress state, etc. The potential phases of the experiment(s) could be as follows:

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1) Selection of candidate rock mass and tunnel complexes to perform experiments. (2008-2009)

2) Preliminary design of experiments, which would be refined through the following steps of characterization and pre-test modeling.

3) Rock mass characterization - sample collection, mineralogical/geochemical/isotopic analyses, analysis of mechanical and hydrological properties, samples for biological characterization, fluid fluxes and chemistry, fracture distributions, microseismicity, etc. First boreholes for ambient geophysical measurements (e.g., ERT, GPR) hydrological testing (pressure and tracer tests) and core sample collection.

4) Laboratory experiments on fundamental kinetic dissolution rates of minerals from candidate rock mass. Mechanical and thermal conductivity/heat capacity measurements on minerals and rock samples. Assessment of thermodynamic data for minerals and laboratory measurements if required. Analysis of biological samples. Lab experiments on biological samples for analog in-situ conditions under varying temperatures and fluid compositions, with mineral substrates. Experiments on fracture closure/pressure solution under conditions expected in test block. THMCB predictive models for ambient system and potential experiments.

5) Installation of first phase of heater experiment – Single borehole heater with array of measurement/collection boreholes. Parallel in-plane boreholes first used for observations/measurements will later be used to install heaters as the test is expanded to a larger planar array. Systematic monitoring and sample collection from far-field unheated rock up to heater borehole. Selected monitoring/collection of specific features, such as high fluid flow pathways and surrounding rock. Non-heated experiments in selected locations in test block, either in the periphery of the potential heated zone, or in an area that will be heated gradually over many years. Specific lab experiments and modeling to predict and understand system evolution, which will evolve as data are collected and interpreted.

6) Expansion of heater array and monitoring/collection boreholes. Long-term experiments in heated and unheated rock mass could include reactive transport, CO_2 injection, and other tests in specific regions.

A schematic diagram for a design of a planned (but not performed) test in volcanic tuffs is shown below for the working group to start thinking about a potential experimental configuration.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Space Requirements

(1) Approximately a 50 x 40 x 40 m “block” for planar heater array experiment, with larger potential region for ambient experiments
(2) Surrounding adits/tunnels for observation and imaging boreholes, electrical, controlling, and monitoring equipment
(3) Subsurface (Mobile laboratory could be employed) and surface laboratories for sample storage/analyses.

Approximate Timeline (to be coordinated with 4850 level Sanford Lab and DUSEL Development):

2008-2009 Block selection after dewatering operation at deep sites, sample collection and analyses for evaluating basic design and test considerations. Preliminary modeling to evaluate test designs

2010-2012 THMCB block experiment design and instrumentation

2013- deep and large block testing

EXPECTED RESULTS

It is expected that this experimental facility will provide the earth sciences community an unprecedented facility to test many hypothesis regarding coupled THMCB processes over a wide range of spatial scales and over time periods longer than any other experiments have had the opportunity to investigate. A few of the questions that have been posed are: What are the effective reaction rates between minerals and fluids in fractured rock? How does the chemistry of fluids and minerals affect the mechanical behavior of fractures, sealing and permeability evolution under stress? At what rates under specific flow and temperature conditions are metals mobilized through water rock-interaction, transported, and concentrated through sorption and/or mineral precipitation? How do microbiological communities in rocks evolve and migrate in fractured rock undergoing changes in temperature and geochemical environment? How does mineralogical and permeability heterogeneity at small scales affect the compsition of fluids at a larger scale and how can the effective reaction rates be interpreted from the fluid compositions?

The experiment will be unique, because it is not aimed solely at a specific engineering goal, such as a CO_2 sequestration, nuclear waste isolation, or enhanced geothermal system behavior, as other experiments have been, but will be set up from the scientific perspective of understanding the wide range of physical, chemical, and biological processes taking place in a well-controlled and instrumented rock mass. High performance computer simulations of these coupled phenomena will advance in concert with the experiment, providing a “groundtruth” to which fundamental concepts can be developed, and tested. It is expected that a wide range of fundamental and applied studies will be performed, supported by various sources, and published in the scientific and engineering literature.

POTENTIAL TEAM MEMBERS

Eoin Brodie (LBNL) - Microbiological population dynamics, sensors for biological responses as a function of environmental conditions
Susan Carroll (Lawrence Livermore Nat. Lab) - Experimental determinations of fundamental kinetic rates of minerals and engineered materials
Mark Conrad (LBNL) – Stable isotope chemistry
Ed Duke (SDSM&T) - Mineral chemistry, petrology, geology, educational liason with SDSM&T
Derek Elsworth (Penn State Univ.) - Thermo-hydro-mechanical-chemical process models and

experiments, fracture mechanics, and pressure solution

Barry Freifeld (LBNL) - Hydrology, experimental design, in-situ measurements for temperature, pressure, permeability, mineralogy, chemistry, fluid collection, and remote data acquisition

Bob Lowell (Virginia Tech) – Hydrothermal systems and modeling, multiphase flow, permeability evolution in the oceanic crust

Mack Kennedy (LBNL) - Noble gas isotopes, crustal transport of fluids and heat, geothermal systems

Kate Maher (Stanford University) - Radiogenic isotope measurements to infer effective reaction rates in geologic systems

Brian Mailloux (Barnard College) - Bacterial transport, ^{13}C and ^{14}C signature of DNA, arsenic geochemistry

Mark Reed (Univ. of Oregon) - Fluid compositions in ore systems, characterization of secondary minerals, fluid inclusions

Jonny Rutqvist (LBNL) - Thermo-hydro-mechanical (THM) processes and modeling

Eric Sonnenthal (LBNL) - Coupled THMC processes and modeling, geochemistry

Nicolas Spycher (LBNL) - Aqueous geochemistry, metal speciation and reactive transport, thermodynamic geochemical models

Carl Steefel (LBNL) - Reaction transport model development, pore-scale modeling and experiments, reaction rates in geological systems, geochemistry

Joe Wang (LBNL) - Multiphase flow, field site evaluation, experimental design and measurements, relation to site-scale hydrological processes

COLLABORATION STRATEGY

We envision that the collaboration will have spokesperson(s) rotated among participants. Each organization will seek funding for specific tests and tasks individually or collaboratively from agencies and industry. The collaboration will interact with other NSF and DOE programs or initiatives to use Homestake DUSEL facility for coupled process studies, and related problems in hydrogeology, geophysics, geochemistry, ecology/microbiology, and rock mechanics and geoengineering.

REFERENCES AND SUPPORTING DOCUMENTATION

(to be added)