Subsurface Imaging and Sensing – Transparent Earth Team

Steven Glaser (glaser@berkeley.edu), working group herdsman

The task of this working group is to help craft proposal modules for subsurface imaging and sensing, viewed in the widest sense. Our job for the April 20th meeting in Lead is to assemble an Initial Suite of Experiments module, and to leave with a straw-man outline of our proposal. Our work will also serve as the core of the NSF S-4 proposal due June 30, 2008. Our module for the Preliminary Design Proposal will be included in the comprehensive Major Research Equipment and Facilities Construction (MREFC) proposal to build and commission a DUSEL. The MREFC proposal will be submitted in December 2009 and will include a complete justification of the science and a reasoned definition for feasibility of construction and execution.

There are about 10 working groups in the geomechanics/geohydrology /geobiology areas. The working groups have been established by three earth science members – Derek Elsworth, T.C. Onstott, and Larry Murdoch – who are members of the DUSEL Experiment Development Committee (DEDC).

Setting the stage

We can image deep space and the formation of stars, but at present we have great difficulty imaging even tens of meters into the earth. We want to develop the Hubble into, not away from, the earth. The Subsurface Imaging and Sensing – Transparent Earth working group will develop and refine the science necessary to image the earth at many scales, use these abilities to gain understanding of the rock and rock mass, and to leverage these discoveries into engineering tools. Our team applies a wide variety of physical behaviors to perform this imaging. The physics, however, relies on derived measures, and our analyses are most often cast as an inverse problem. The proposed suite of experiments combines the power of a number of methodologies to provide strong constraints on the necessary inversion, and allows us to bring our images into sharper focus. The Homestake is the only facility that allows this multi-scale and multi-physics campaign to peer into our complex earth.

Providing a usable experimental infrastructure

Towards the full Homestake Transparent Earth Observatory – installation and operation of a full complement of seismic, tilt, and EM instrument stations. We are developing a deep in situ seismic observatory that will move us closer to the realization of rapid imaging of dynamical geo-processes at depth. The frequency bandwidth of 1 Hz to 1 KHz that is being recorded by the array, allows a wide variety of monitoring and characterization studies. We have two three-component stations currently installed – in a 500 foot deep bore beneath the slurry pump house, and in a 50 ft deep bore on the 2000 foot level. There is a tilt-meter installed at the 2000 level station. With the current NSF funding, the plan is to install, at a minimum, three stations on the

2000, on the 2600, and on the 4000. We plan to install a tilt meter at each station. Additional funding will need to be found to carry out this full scope of work.

What We Will Do

- Install and operate a permanent seismic observatory illuminating the volume of the Homestake Mine: The facility will be open to all users, e.g. seismic tomography researchers. The observatory will be unique in that the mine volume is surrounded (sides and bottom) and penetrated by hundreds of deep bore holes, many of which can be reentered. The observatory will operate on a local (internal and external to the mine volume), regional, and global scale.

- The basic observatory array will consist of at least twenty-four seismic/tiltmeter/ gravimetry stations, each operated by a control and data capture appliance. This trio of transducers will have the sensitivity to accurately measure strain induced by barometric pressure and earth tides. The stations will be linked by fiber Ethernet links with IEEE1588 service. Each station will serve a local network of wireless Motes that will monitor the near-by section of the mine for CO2, CO, methane, O, temperature, relative humidity, air-flow velocity, and intrusion alert. The Mote network can easily extend kilometers from the station, and will locally process and relay data from fields of MEMS-based parameter sensors. The station will provide the needed services for IP, SP, active EM, and ERT imaging.

- The Homestake transparent earth observatory will integrate with the USGS, and the LIGO geo-team to enhance the experience of all stake-holders. The USGS Albuquerque office will look to move the RSSD array into Homestake. LIGO will integrate arrays of two types of innovative tiltmeters, Barone-type horizontal accelerometers, several STS-2, and a fleet of Nanometrics instruments. Further instrumentation will include long period interferometers to measure wall movement with respect to an inertial mass in the 0.1-10 Hz frequency band.

- The subterranean-installed array will be supplemented by a matrix of surface boreholes containing sondes to various depths. We will either locate existing and plugged holes or have the SDGS drill holes for us.

- As the stages of work unfolds, further stations will be strategically deployed so as to visualize rock mass response due to falling water table, excavation of drifts and laboratory modules, and excavation of the large chambers.

- Image rapid dynamic changes in the rock mass: There will be many local and distant sources of seismic dislocations. Among them are microseisms from stress realignment during the current dewatering process, from excavation and construction activity present and future, from various other forms of rock mass damage, and from local, regional and global tectonics.

Steven Glaser, UCB; Bill Roggenthen, SDSMT; Lane Johnson, LBNL; Gary Pavlis, IU

Installation of the Rapid City long-period station at the Homestake. The USGS Albuquerque Seismological Laboratory (ASL) operates and maintains two major seismic networks, and houses USGS facilities for testing seismic instrumentation, in particular the RSSD array 20 km south-west of Lead. This instrumentation will complement the several frequency and amplitude scales operating at DUSEL by Glaser. ASL will evaluate the seismic background noise within the mine; if the Homestake site is quieter than the current location, ASL would push to relocate the station to the mine. The first step will be to install temporary seismic equipment in at least two locations in the mine, as deep as possible. The equipment would be left to record ground motions for several months, with the data telemetered back to ASL over Ethernet. If the in situ noise level is acceptable, ASL will use DUSEL for testing seismological instrumentation. ***Lind S. Gee, scientist-in-charge at the USGS Albuquerque Seismological Laboratory.***

Rock motion observation and mapping for the LIGO Experiment*; **The LIGO experiment will join forces with the Transparent Earth observatory to provide a richer and finer observations to both teams. The LIGO experiment requires extremely accurate measurement of invert motion and tilt. LIGO is currently designing two types of tiltmeters so as to separate common from individual sensor noise. The performance will be compared with a pair of purely horizontal accelerometers, produced by Fabrizio Barone in Salerno. Subtracting the seismic signal from the total signal will be a nice breakthrough. LIGO will be able to integrate several of their custom tiltmeters and Barone accelerometers to the observatory. LIGO will install three STS-2 instruments in the tunnel during the summer. Further instrumentation will include long period interferometers to measure wall movement over time. ***Riccardo DeSalvo, CalTech; Vik Mandic, UMN

EM Passive Imaging as a Hazards Assessment Methodology. At present, sudden rock mass deformation events are systematically monitored to evaluate distribution and relaxation of stresses in mines. The data are used as an early warning system for impending ground stability failure and rock bursts. Evaluation of electromagnetic (EM) emissions associated with rock deformations and failures offers an alternative or complement to microseismicity. EM emissions are a form of fracto-emissions (i.e., the sudden release of energy in the form of transient waves in a rock mass subjected to stress change). EM emissions generate signals in a large frequency range that have the potential to characterize rock burst events and to complement microseismicity data (i.e., EM waves are transparent to nonconductive faults and antennae do not need to be physically coupled to the rock formation). EM emissions have been used in the past to develop precursor systems for earthquakes and mines, but with little success as the mechanisms for the generation of emissions remain elusive. This elusiveness is caused in part by low signal-to-noise ratio events that prevent the proper characterization of dominant physical mechanisms.

We propose the development of a new excavation monitoring system based on the complementary interpretation of microseismic and EM emissions in a quiet electrical environment. The DUSEL environment gives the opportunity to study the basic science of the problem, as well as the deformation and failure processes of rock masses. This project will study

EM emissions at different scales to bridge the gap from the science of the phenomena to the engineering implementation of hazard assessment methodology. These scales include:

(a) Material scale (mm to cm): understand and characterize generation mechanisms in the Homestake mine rocks and minerals (e.g., charge acceleration, piezoelectricity, charge separation, fracture charges, fracture-atmosphere interaction, etc.).

(b) Fracture scale (dm to m): In-situ EM emission monitoring of deformation/failure across fracture planes caused by the increment of shear stresses and/or the reduction of effective stresses (e.g., fluid injection).

(c) Rock mass scale (Hm to km): Construction of the DUSEL testing infrastructure will be used as a test bed for the generation/evaluation/monitoring of EM emission at the mine scale. The EM emission monitoring study will be complemented with data from the Homestake mine seismic monitoring system. ***Dante Fratta – University of Wisconsin-Madison***

Experiments made possible by the proposed Homestake infrastructure

Examining seismic sources from micro to macro through multi-sensor inversion; Lane Johnson, LBNL, Steven Glaser, UCB;

The basic science of the effect of multi-scale earth heterogeneity on seismic wave propagation; Gary Pavlis, Indiana

Stress Monitoring with high precision seismic travel time measurements*; This experiment will explore the field measurement of temporal variations in subsurface stress through continuous monitoring of seismic travel times between boreholes. Time-varying stress is a fundamental property associated with many of the dynamic processes studied in geosciences, including rock fracturing, fluid transport and earthquake dynamics. Numerous laboratory studies over several decades have shown that seismic velocities clearly exhibit stress dependence, usually attributed to changes in the physical characteristics of cracks (e.g. crack density, crack orientation). A long term (months to years) monitoring of travel time variation, with concurrent monitoring of important hydrologic properties such as water level, is required to definitively demonstrate the remote measurement of stress changes induced by barometric pressure and earth tides. Long term monitoring will allow repeated measurement of externally-induced stress changes and will allow us to identify the level of dynamic stress sources (e.g. pore pressure changing effective stress) which can be monitored. A larger scale test will allow investigation of the scaling of travel time accuracy with distance and frequency content. Success will indicate potential new applications of seismic monitoring for important DOE programs such as contaminant remediation and CO_2 sequestration. An order-of-magnitude increase above expectations of crosswell seismic measurement is possible. ***Tom Daley, LBNL; Paul Silver Carnegie Institute; Fenglin Niu, Rice

Transparent Earth: 3D, Time-Lapse Seismic Tomography for Imaging Overburden Changes due to Dewatering. This project will use induced seismicity to generate a three-dimensional, time-lapse image of changes within the rock mass due to dewatering. Local earthquake tomography will be used with the many, small seismic events to generate the images. This is a novel, immature method that holds great promise for passively imaging changes within the earth. Tomograms generated from seismic data collected by the observatory will yield time-lapse three-dimensional images of structural changes within the rock mass. Seismic data from the dewatering will provide the needed seismic signals. These tomograms will then be used in concert with numerical modeling efforts to gain a deeper understanding of structural changes within the rock mass, with the ultimate goal of providing a tool that will forecast changing conditions prior to rock failure. Subsequent monitoring, as a separate project, will image changes within the rock mass due to cavern excavation. ***Erik Westman, Virginia Tech***

Computer Aided Geoscientific Interpretations of Long-Term Multi-Dimensional Geophysical Monitoring Data. Passive and active seismic monitoring in the uppermost part of the continental crust (<30km) will help to understand hydro/geological and geophysical processes. A seismic network installed at the Earth's sub/surface can monitor mechanic rock properties in space and time. It is proposed to monitor, visualize, and interpret long-term changes of geophysical properties and the evolution of the seismicity. Data interpretations will be supported by modern cyber-enabled expert systems that explore and sort through multi-dimensional and often complex data. The result will be multi-parameter tomographic image interpretations. ***Christian Klose, Columbia Univ.***

Viewing into rock with EM. Spatial/temporal variability in fluid mass flux will be measured by time-lapse gravity measurement. This would build on the baseline (pre-pumping) survey performed by the USGS. A suite of gravimeters will be placed with the accelerometer-tiltmeter stations that are part of transparent earth so as to further constrain the problem with surface and subsurface deformations measured by the tilt meters.

Combining surface/borehole resistivity and induced polarization (IP) measurements will provide static site characterization, as well as a means of monitoring the changing water table. The non-polarizing IP electrodes will also be used for self-potential (SP) studies. SP will also be used to provide a three-dimensional image of the subsurface as the water level drops. The experiment will use strings of SP electrodes inserted into several boreholes and/or tunnels. This experiment will provide information on preferential drainage pathways. Above the water table the electrodes might have to be grouted into place.

The subsurface access at Homestake allows the use of active EM techniques to image into the rock surface. Methods to be tried include pulse/transmit down-hole or in tunnels and electrical resistance tomography (ERT) with varying transmitter pulse time so as to measure IP.

High-frequency natural-field electromagnetics (piezoelectric effects) can be tested for locating the active zone where the electromagnetic sensors should be positioned. This is a natural imaging technique to use in conjunction with the microseismicity observatory to be installed in and around the mine. Ground-penetrating radar and small-loop TDEM surveying will be included to further constrain drilling/blasting/fracture imaging. ***Victor Labson, Paul Bedrosian, Bob Horton, and Burke Minsley; US Geological Survey, Denver.***

Geomicrobial optical logging detectors (GOLD). A series of optical borehole loggers, or a single mega-logger if feasible, will be developed that will perform hyper-spectral imaging of the borehole wall and measure bacterial concentration, mineralogy, organics, temperature, and oxygen concentration. The borehole tools will allow for the monitoring of time-dependent microbial and short-scale geologic processes and provide valuable in situ stratigraphic data to supplement core analyses, especially where instances of missing or damaged core sections make such studies difficult. Incorporated into these instruments will be a sampling/inoculation tool to allow for the recovery and/or manipulation of particularly interesting sections of the borehole wall for further study, enabling a series of microbiological studies. Including gene transfer studies, hydrological studies, and nutrient manipulation studies. The borehole tools that will be developed are autofluorescence spectroscopy, Raman spectroscopy, borehole camera, temperature and oxygen sensors, and the sample acquisition/deposition instrument. ***Nathan Bramall, Carol Stoker, Buford Price, Louis Allamandola, John Coates, Andy Mattioda, NASA and UC Berkeley***.

Roles played in a variety of proposed DUSEL projects

Multi-time scale evaluation of the mechanical response of large cavities. The project will use the excavation of each cavity as a large laboratory test with monitoring of the stress and deformations paths over time. The observations will be made over an extended period of time, from short-term, i.e. excavation, to long-term phenomena, i.e. stress corrosion, creep. This will be accomplished by heavily instrumenting the rock surrounding the excavations and using geophysical methods for visualization and quantification of damage mechanisms internal to the rock. The value added is to couple mechanical processes with geophysical measurements, and vice-versa. ***Antonio Bobet, Purdue.***

Large cavern design. The dominant cause of construction problems underground is the encounter of an unexpected "bad ground". Within the context of an underground construction contract, unexpected bad ground often result in major delays, cost overruns, equipment abandonment and even project termination. Under current design practices, predictions of ground conditions in a variable ground mass are inherently unreliable. Geophysical imaging can provide for continuous imaging of the construction volume and reveal the variability of the geologic structures, material properties and fluids in their full natural complexity. Geophysics offers the potential to deliver a superior spatial characterization of the construction ground mass, notably including information on the location and extent of pockets, lenses or layers of atypical, extreme or simply "bad ground" conditions. ***Christopher Laughton, FNL.***

Tiltmeter Measurements to Evaluate Coupled processes of water flow and rock deformation. Fluid flow and deformation of rock are important to processes ranging from the production of resources from reservoirs, to the inflation of magma chambers prior to a volcanic eruption, or the build-up of fluid pressures prior to earthquakes. The proposed project will advance understanding of coupled fluid flow and deformation processes by characterizing the deformation resulting from dewatering of the mine. This will be accomplished using several integrated measurement techniques, including tiltmeters deployed at the ground surface. The proposed plan is to deploy three transects of six tiltmeters at the ground surface overlying and in the vicinity of the mine. The tiltmeters will be mounted in shallow water-tight enclosures, monitored for background signal, and then monitored during and following dewatering. Preliminary analyses suggest that dewatering will cause deformation resembling a ridge and trough, with the maximum slope on the order of 10^{-4}. Signals of this magnitude can be measured using robust, electrolytic tiltmeters. The tiltmeter data will be used with measurements of deformation fields at discrete times determined using InSAR, as well as with tiltmeter measurements made within the mine. ***Larry Murdoch Clemson University***