Geoscientists to Probe Abandoned Gold Mine for Microbes and Dangerous Chemicals

Introduction

While the Homestake mine's 8000 feet of overlying rock provide neutrino physicists shielding from cosmic rays of outer space, geoscientists will scurry throughout the 350 miles of criss-crossing tunnels to probe inner space for the system of fractures that are the conduits for water that support deep microbial life and transport chemicals. Geoscientists will have unprecedented three-dimensional access to explore the complex subterranean space filled with folds, faults, and fractures that limit engineering predictability for civil construction, resource extraction, and contaminant transport. The Homestake mine provides the special opportunity for geochemists, geomicrobiologists, geophysicists, hydrogeologists, and geomechanicists to study synergistically the same four-dimensional (space and geohistory) terrane. The scientific problems to be solved are the effects of spatial scale in fractured and jointed systems; the coupled effects of mechanical, hydrological, biological, and chemical processes throughout geologic time; the development of techniques to identify and characterize the physical response of geological systems:

(List is unedited from Joe Wang's NUSL-Earth Science White Paper of June 2002. The first three bullets appear also in the Hydrogeology-Science working group draft.)

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

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

[3] **Do recharge flows to great depths for sustainability evaluation of groundwater supply?**
Direct measurements of the interactions between subsurface processes and atmospheric variations can determine the damping mechanisms, propagation of episodic infiltration events, and redistribution of percolation fluxes throughout the

rocks. The assessment of sustainability at fractured hard-rock sites is especially relevant for many communities located on bedrocks with scarce water resources. A de-watering zone is an example of a **critical zone** (vadose zone or unsaturated zone), as discussed in Section 3. Understanding the critical zone around the underground facility will be beneficial for evaluation of many other fractured sites.

[4] **Can the deep facility as a whole be used as an observatory to image the earth structure, as a platform for deep drilling to measure crustal stresses, and for finding life forms under extreme conditions?**
The quiet setting at depth and the feasibility of further drilling from the underground facility are positive attributes for deep imaging and deep sampling. Rock deformation under crustal stresses and survivability/growth of diverse bacteria species are key to fundamental understanding of the deep crustal environment. Remote sensing with seismic and other geophysical techniques is not only pertinent to earth structure imaging but also to monitoring of distant events.

Geomechanics Science Plan

Geomechanics is the study of forces and deformations in the earth as they exist in the present and as they can be reconstructed through geologic history. The formation of fractures, folds, and faults are coupled with fluid flow and geochemical reactions. These processes can lead to ore concentrations, influence regional hydrogeology, and affect construction conditions within the rock mass. An important goal of geomechanics research is to understand the stress and deformation history of the rock mass and how that history affects fracture patterns that govern the flow of groundwater and transport of chemical species. Obtaining the physical and engineering properties of rock masses from geophysical remote sensing is necessary for resource exploration and construction applications. The central outstanding issue that cross cuts between geomechanics and hydrogeology is the scale dependence of fractures. Therefore, the priorities of the geomechanics science plan are to elucidate the state of stress and stress history of the Homestake mine, obtain a three-dimensional fracture map of the mine, and perform active thermal stress tests within the mine.

Rock Mechanics at Homestake (Bill Pariseau 8/20/02)

Experience at Homestake

My contribution here is based on a long running interest in rock mechanics and a sequence of projects at the Homestake Mine that began in 1982. Our[1] first project

[1]Homestake Mine personnel, Bureau of Mines personnel from the Spokane Research Center and many of my rock mechanics students at the University of Utah.

concerned stability of relatively large stopes[2] (60,000 tons or so)[3] between the 6950 and 7100 Levels (6950 to7100 ft below ground surface). The large stopes we studied initially were about 150 ft high, 50 ft in breadth along the vein and 50 to more than 80 ft in width across the vein. Four such stopes were involved in the study that lasted several years. These stopes are roughly comparable in size to proposed excavations for neutrino detection, as is the depth.

We were eventually able to obtain quite good correlations between displacement measurements and finite element model calculations in this first study at the Homestake Mine. Regression analysis of calculated on measured displacements gave correlation coefficients of 0.85 or so, which is outstanding in the realm of rock mechanics and rock engineering. Measured displacements were obtained from multiple position borehole extensometers; a simple elastic-plastic finite element model was used to calculate corresponding displacements induced by mining. In this regard, our first model effort, undertaken with great confidence in our knowledge of physical laws, failed to produce even the proper algebraic sign of some displacements. With some humility, we began a systematic review all aspects of the modeling effort and to pay close attention to details of input data, especially to geology, rock properties, initial stress state and mining sequence.

The model required the usual: satisfaction of stress equilibrium, strain-displacement relations (small strain) and elastic stress-strain relations. Yielding was possible; associated flow rules were used for elements stressed beyond the elastic limit. Fortunately the site was dry, so water was a non-factor. The site was also lacking in any obvious jointing. So we felt quite strongly that rock mass displacements should be consistent with the basic requirements in the finite element model and therefore focused on the input to the model rather than the model itself.

We considered the folds on folds and plunging nature of these folds from mine maps (plan views) and sections (vertical view) and then traced the major contacts between the Poorman, Homestake and Ellison formations in plan and section. We then drafted finite element meshes over these sections and digitized all. We attempted to maintain adequate mesh refinement by insisting on at least five elements across the narrow dimension of stopes whose eventual boundaries were also incorporated into the meshes. With practice, one can digitize about three points per minute. In this regard, we have looked for and attempted automatic mesh generation but did not succeed with the limited resources available.

We reviewed all the previous stress measurements that we could acquire. Some were made with doorstoppers and some with Bureau of Mines bore hole deformation gages. Eventually, we used Hi-Cells (three-dimensional borehole gages) for determining

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[2]Stopes were mined by Avertical crater retreat@, the VCR method.

[3]During the last years of the mine, 6000 tons was often a mining target and mechanized cut and fill the mining method of choice

premining stresses. Data from the Denver Research Center of the Bureau of Mine was especially helpful because of measurements made on different levels that give the vertical stress gradient. We also attempted a horizontal gradient determination but concluded it was within the noise of the data and therefore indeterminate. These data lead to principal stress formula for *in situ* stress at the mine. In these formulas, the vertical stress is the major principal stress (compression positive) while the horizontal stresses are less compressive and appear to be parallel and normal to folding. Additional stress measurements have been made since that suggest some rotation of principal stress with depth.

Homestake drilled three holes in the study area that were mutually orthogonal and transected each of the three formations. Well-developed foliation indicated anisotropy, so the holes were oriented perpendicular to the foliation, down foliation dip and along foliation strike. Laboratory testing at the South Dakota School of Mines and Technology produced elastic moduli, unconfined compressive strength and tensile strengths from the drill core. These laboratory data formed the basis of an orthotropic elastic model with orthotropic strengths. Nine independent elastic moduli and nine strengths for three formations amount to 54 properties for our simple elastic-plastic (time-independent) model. These data were uniformly reduced with two scale factors, one for elastic moduli and one for strengths, that were determined by model calibration using mine measurements and guidance developed from two simple strain to failure and energy at failure rules.

By examining the blasters data, we were able to determine excavation boundaries as mining progressed lift by lift and thus to know the mining sequence during the VCR project. This situation was not always the case in other studies where correlations were less.

Attention to detail paid off in the form of a reliable finite element model for subsequent parameter studies of alternate stope layouts and extraction sequences. Rules for deep level VCR stopes evolved from these analyses. The same lessons were applied to later projects including the Ross Pillar Project much higher in the mine (about 3500 Level) that assisted recovering millions of dollars high grade ore near the Ross Shaft where mining was previously prohibited.

Some consequences of our experience for NUSL rock mechanics research and neutrino detector construction are:

1. Accuracy of geologic data on the scale of interest is essential. In mining, relatively closed spaced ore definition drilling provides such accuracy. There is a suggestion that a region away from mined ground and in the Yates member of the Poorman be used to host neutrino detectors. This region would need to be explored in acceptable detail prior to excavation planning, layout and sequencing. In particular, one would need to ascertain the absence or location of shear zones that appear in the mine, hard and abrasive porphyry intrusives and graphitic schist, all of which are potential sources of excavation instability. Figure 1 shows a plan view of a mining level that contains previous mined

stopes (pink), possible future stopes (brown) and folded Poorman, Homestake and Ellison formations which are indicative of geologic complexity at the mine. A coarse, two-dimensional finite element mesh is also shown in the figure.

2. Anisotropy associated with foliation is important to rock mechanics at the Homestake Mine. Properties data used in formulating rock mechanics hypotheses should take into account the directional character of the individual rock formations. Of particular importance in laboratory measurements is the direct determination of shear moduli and strengths which are often merely estimated from measurements of Young=s moduli, Poisson=s ratios, and uniaxial compressive and tensile strengths, respectively. Although some fracture mapping was done, there seems to be no well-defined joint sets that dominate rock mass behavior. Tacit assumptions of jointed, isotropic rock block models need to be treated with caution until reliable mapping of accessways and exploration drill holes is done. Figure 2 shows foliation in the back of a drift in the Poorman formation and the role of dipping, foliated formations in asymmetrical mining-induced damage to a small drift. The Homestake formation tends to be much less anisotropic, while the Ellison is similar to the Poorman. This anisotropy appears in noticeable differences in stability between drifts along strike and crosscuts perpendicular to the foliation.

3. Instrumentation, especially borehole extensometers, provide reliable data for model calibration, updating and monitoring and should be planned and installed in advance of excavation. Such instrumentation should be grouted in the hole and provide mechanical reading for backing up electrical readout and data acquisition when power outages or component failures occur. Figure 3 shows installation of a multiple point borehole extensometer in a downhole and an instrumented cable bolt in an up hole as well as some of the model and measurement results. In our experience, readings of less than about 2 mm.(0.05 in.) tend not to be reliable; correlation coefficient tended to a constant values above 2 mm of relative displacement induced by mining. The reason is shown in the regression data of computed on measured displacements in Figure 3. Small measurements clustered near the origin have little effect on trend.

4. Stress measurement data including gradients are important but have yet to be done with rock anisotropy in mind. In this regard, micro-shearing along the foliation is often considered to be an important mechanism of deformation. This diffuse shearing is considered to be responsible for the lack of well-defined joint systems and the Anormal@ state of stress (vertical stress equal to unit weight times depth, horizontal stresses less than vertical stress). Stress measurement data should be collected with the aid of three-dimensional, temperature compensated stress gages in advance of neutrino detector excavation design and construction and reduced with a proper anisotropic data reduction scheme. Figure 4 shows a stage in stress measurements and a stress gauge. Such instrumentation is capable of strain measurement involving the detection of parts per million in a harsh underground environment.

Opinion

In my opinion, design of neutrino detector excavations should be done with two objectives: (1) safe, stable excavations for the life of projects and (2) advancement of rock engineering science. The two go hand in hand because measurements in advance of design and during construction can serve both objectives. Essential tasks include: development *a priori* of site criteria, adequate site exploration of geology, laboratory testing for rock properties and joint properties (if present), stress measurements before excavation. These data should aid in selection of suitable numerical modeling approaches. Design should then consider excavation sequencing and instrumentation layout in close association to maximize sensitivity.

Because of the relatively long life of detector excavations (25 yrs or so) and associated accessways, consideration should be given to time-dependent rock mass behavior. We have collected some data that could be used for this purpose beginning June, 1994, and continuing but additional readings need to be made to maintain the data collection and generate time-dependent displacement data. In this regard, the Ross Shaft experienced time-dependent closure for more than 60 years with significant consequences for mine operations. Time-dependent mechanism(s) of rock mass motion at all scales, beyond the mine, mine-wide, stope and drift scale to laboratory test specimen scale would be a fruitful area of research, in my opinion.

The question of scale seems to arise frequently in rock mechanics discussions and has been posed within the NeSS rock mechanics already. Conventional wisdom in rock mechanics asserts the existence of scale effects. The issue is an interesting one because it often defies concise formulation. We do not actually think that physical laws change with scale, but rather are ability to apply them seems hampered by considerations of material laws and impediments to implementation. We often observe brittle behavior at the laboratory scale but more plastic-like deformation at the scale of mine openings and then again brittle behavior at the scale of large faults. The discrete nature of all numerical models further restricts our vision and raises the issue of representative volume elements (RVE) and possible heterogeneity at various RVE scales and how to pass information back and forth between scales, necessity bore of the fact that computers will never be big and fast enough to allow tracking of details. The situation points out the need to keep science and engineering closely connected in research efforts because improved engineering designs must come from more reliable modeling procedures that include input data definition and output interpretation.

A national underground research facility at the Homestake Mine offers an unprecedented opportunity to advance rock engineering and science because of the potential for collecting experimental data over a very large rock mass. The opportunity to integrate physical measurements related to rock mechanics with geophysical, hydrological and biological probes is unique and comes at very low cost. Access for experimental measurements from surface to a depth of 8000 ft over an even larger lateral extent would permit undertaking research investigations that would put the U.S. in the forefront of research. However, the window of opportunity will not stay open indefinitely; the time to act is now.

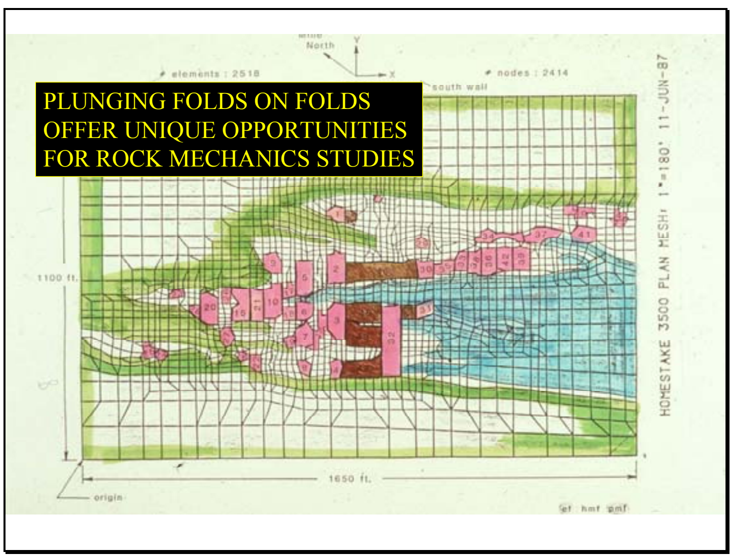

Figure 1 showing folded, plunging metasediments and complications of mining geometry for rock mechanics studies.

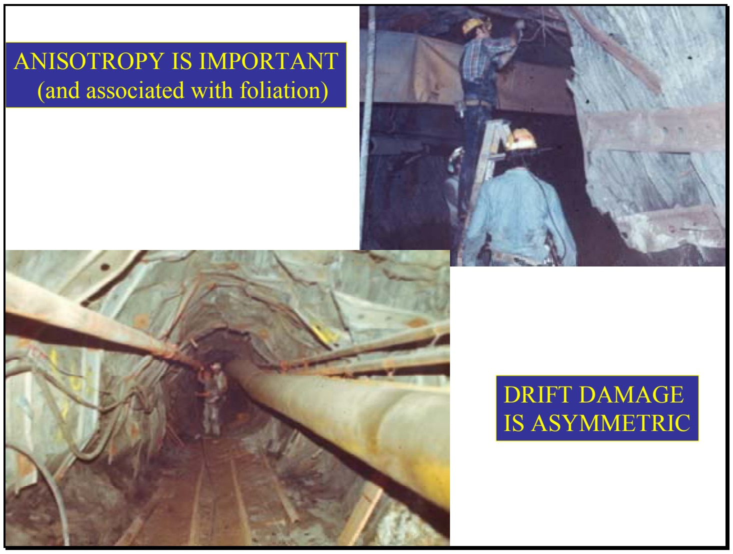

Figure 2 illustrates the role of anisotropy and its importance to opening design.
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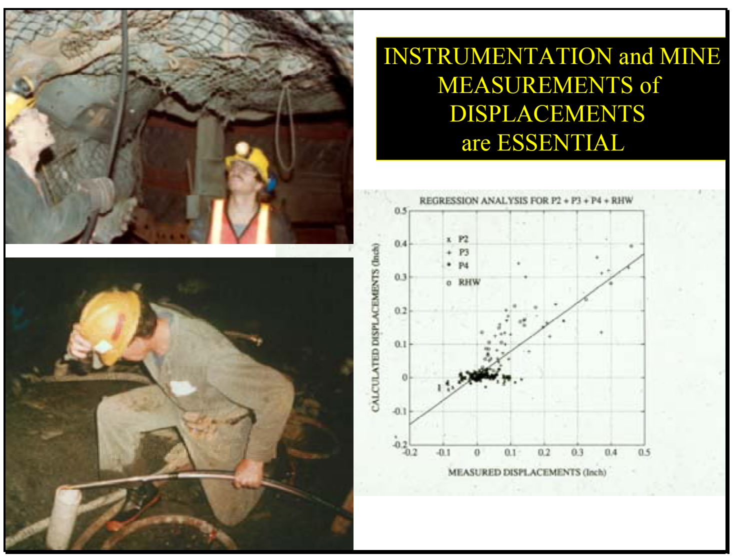

Figure 3 shows some borehole instrumentation and results finite element modeling in comparison with measurements.

Figure 4 shows a task done in preparation for installation of a 3D stress gauge (insert) that detects strain in parts per million despite the harsh environment.

Scaling Behavior of Fractures and of Heterogeneity in Rock (geometric, hydraulic, mechanical, seismic, geochemical) (Laura Pyrak-Nolte)

Working in the subsurface requires an understanding of physical processes that occur on multiple length and time scales. Here is an example: "Fracture geometry for instance, has many length scales. For example, areas of contact have specific radii. Apertures have specific heights. Correlated fracture geometry has correlation lengths. All of these specific length scales can be compared to the wavelength of the seismic probe (or other geophysical probes), as well as the length scale over which the probe samples. In addition, chemical interactions between pore fluids and the fracture walls occur locally on the sub-micron scale but affect wave propagation occurring along the length of the fracture, a length scale of hundreds of microns to meters or more. For a fracture partially saturated with gas and water, the distribution of these two fluid phases is affected not only by the intrinsic lengths of the fracture geometry but also by time-dependent processes that alter the local capillary pressure which controls the phase distribution." (from Pyrak-Nolte, 2002)

It would be important for each group to make sure that their investigations measure/observe the same length/time scales as the other groups. Each group can still focus on their individual interest but it should be working towards some goal.

Part of this theme on scale is directly linked to heterogeneity. Some statements should be made on how important it is determine if measurements made in the laboratory are important to understanding field scale measurements/processes. This requires an understanding of how microscopic behavior affects macroscopic measurements, and the effects of local heterogeneity. In general, the physical properties of a heterogeneous

system must depend on scale. It is not clear what fraction of the research is focused on the field scale & what portion is focused on linking the field to the laboratory.
The seismic portion of the wish list seems to be mainly passive, i.e. acoustic emissions. I think that both passive and active (e.g., crosshole) should be used to investigate current modeling/theories or laboratory results on wave propagation in fractured media to the field scale, as well as theories that link the seismic response of fractures to the hydraulic response of fractures.

The importance of three-dimensional fracture network characterization within the Homestake mine (Steve Martel and Michele Cooke)

Fracture systems are of paramount importance in the strength and hydrology of rock masses in virtually all locations and at a broad range of scales of size and time. The three-dimensional architecture of the fractures at the Homestake mine must be characterized to intelligently design, safely construction, and effectively operate a major underground physics facility.

Fractures serve as conduits and/or barriers to subsurface fluid flow, so they are of tremendous importance in the flow of groundwater, hydrocarbons, ore-forming fluids, and geothermal fluids. Fracture distributions, and how we think of them, also influence strongly how we design exploration strategies for the subsurface. Nonetheless, we still have much to learn about the geometry of fracture systems, the processes that create them in the Earth, and how they conduct fluids and heat. To date our most sophisticated characterizations of fracture networks in the subsurface typically involve extrapolating information gained from surface exposures, borehole observations, and inferences drawn from geophysical methods. These methods, however, have some distinct limitations, especially when applied separately. Surface exposures commonly are obscured by soil, vegetation, or water, and in many cases fractures formed near the surface are superposed on those that formed at depth. Boreholes sample relatively miniscule volumes of rock, making characterization of large fracture networks problematic. Existing borehole and surface geophysical methods are unable to detect fractures below certain size thresholds, and they commonly cannot detect details that illuminate how fracture systems develop. The Homestake mine, with its 350 miles of tunnels, offers an unprecedented opportunity to characterize a subsurface fracture network in three dimensions over a wide range of depth (8,000'), to further our understanding of how fractures develop in three-dimensions, and to distinguish between fractures that develop near the surface from those that develop at depth. Furthermore, outstanding questions such as the role of rock heterogeneities, anisotropy ("layering"), and nearby structures on fracturing can be tested at the mine. The access to well-exposed, extensive, three-dimensional exposures would make a tremendous contribution to our understanding of fractures in rock.

A three-dimensional characterization of fractures could rely in part on existing maps, but detailed mapping done specifically to target the fractures would be essential. This is because mapping done for other purposes commonly screens out observations that are vital to understanding the origin and development of fracture systems.

Accurate and detailed information on fracture locations, sizes, orientations, and physical characteristics would be invaluable for testing, improving, and developing new hydrologic methods and new non-invasive geophysical methods for subsurface characterization. Innovations developed and tested at Homestake would provide for more effective and more efficient characterization of subsurface fracture networks in aquifers, economically viable hydrocarbon reservoirs, and ore bodies. An important point to note is that the geophysical evaluations would naturally be done in conjunction with direct observations rather than separately. This would have a very positive synergistic effect, not just on technique development, but also in fostering interdisciplinary collaboration among geologist, geophysicists, specialists in rock mechanics, and hydrologists.

The Homestake mine also offers some unusual educational opportunities for earth science and engineering students. The perspective gained from rock exposures <u>within</u> the Earth substantially broadens the traditional perspective obtained from exposures <u>on</u> the surface of the Earth. Students would also benefit tremendously by observing and participating in collaborative, cross-disciplinary research.

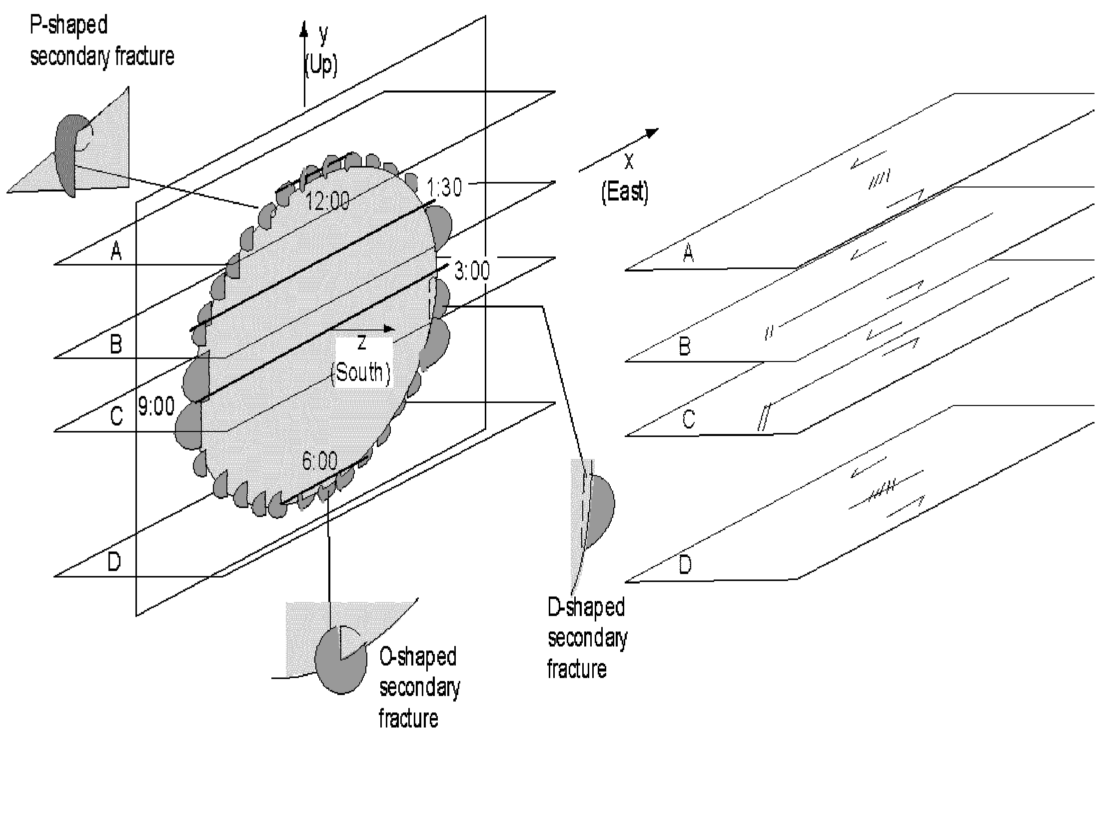

Fig. 1 - Idealized fracturing around a penny shaped fault in 3-D, along with the appearance of the fault and fractures in "2D" cuts at various levels through the fault.

Fig. 2: Tail cracks and a fault in a flat outcrop.

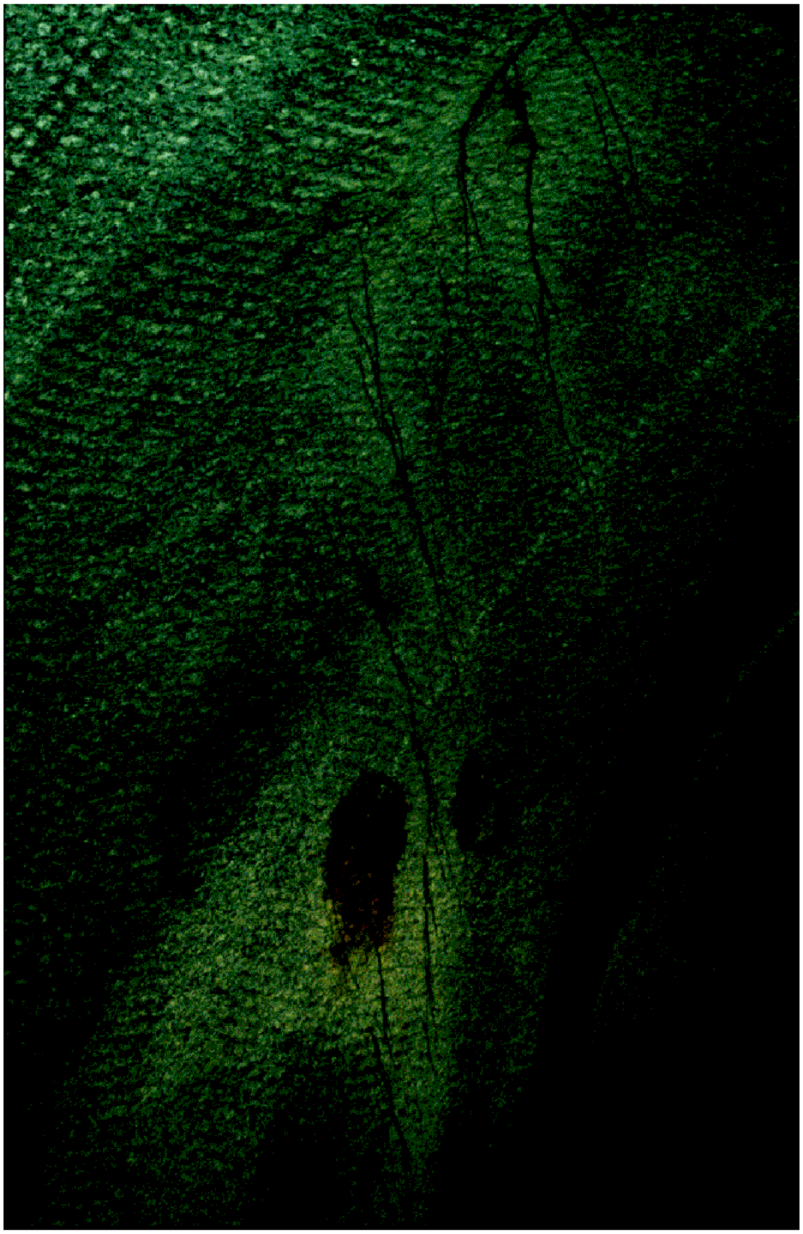

Fig. 3: Tail cracks in the walls of a cylindrical smooth bore tunnel (Grimsel) and a fault in the tunnel roof. Note the red rust stains along the tail cracks. This picture could be reconstructed from an inclined cut through the fault of Fig. 1.

Fig. 4:   Fault_zone_alteration. This shows how apparently minor variations in fault geometry are associated with pronounced changes in hydrothermal alteration, and presumably fluid flow.

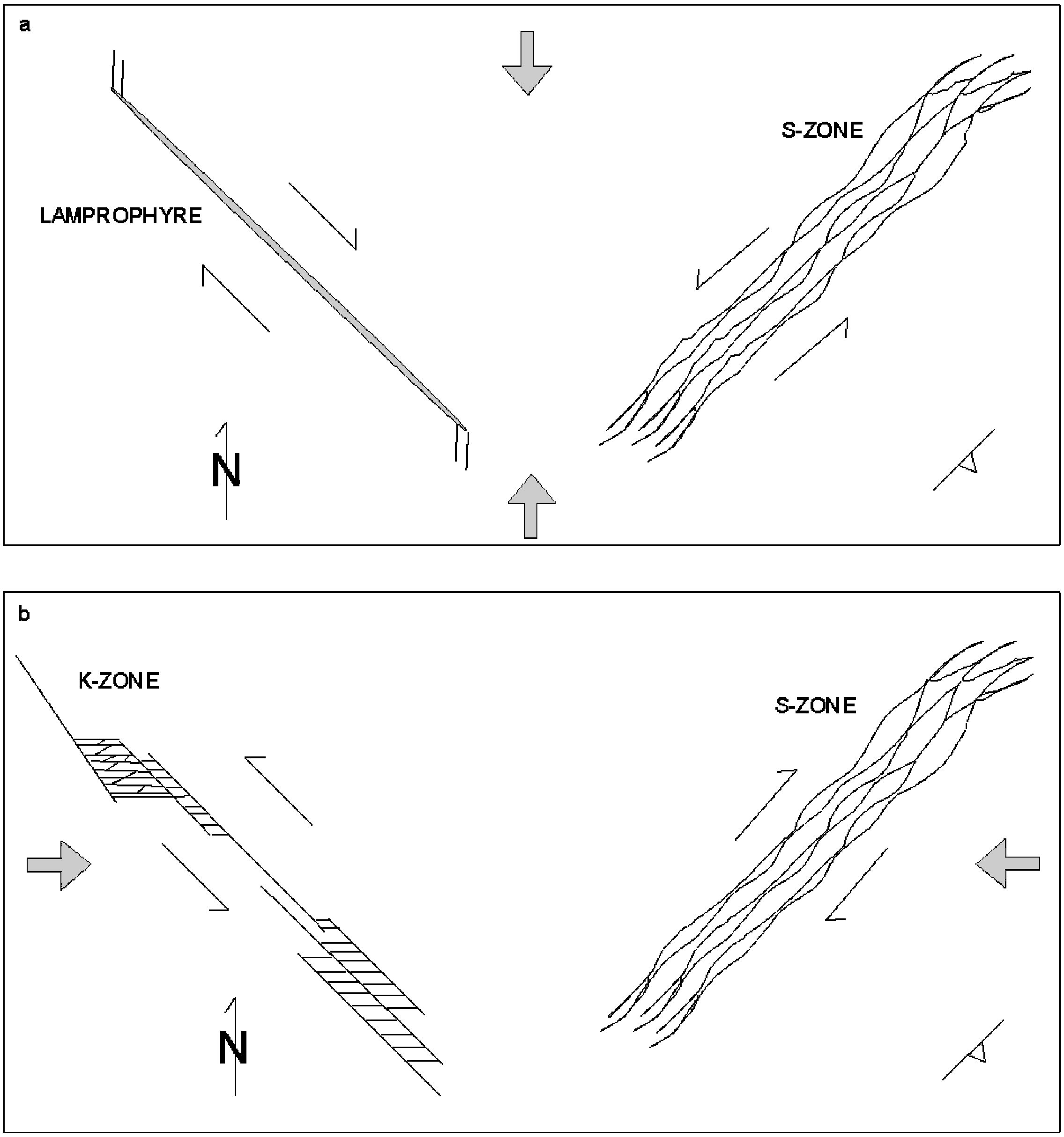

Fig 5: Fault zone or shear zone structure can be heterogeneous and/or anisotropic, so fluid flow could be expected to be heterogeneous and/or anisotropic too. (a) one stage of deformation: Lamprophyres (essentially dikes of basaltic composition) evolve into faults and slip. Tail cracks form near the ends. The picture of the tail cracks with the rust stains (Fig. 3) is where a tunnel intersected the dike-turned-fault near the fault end. S-zone. A shear zone, with fractures along the foliation in the metmorphosed granite of the lab. (b) a different stage of deformation K-zone: A fault zone that formed from pre-existing fractures (the pre-existing fractures were probably joints). This is very

reminiscent of the faults in the Sierra (Fig. 4). S-zone. The shear zone of the upper figure. I found evidence for right-lateral slip on some of these zones, and left-lateral on others. I suggested there might have been two different episodes of slip.

Is the Homestake Mine Critically Stressed? (Zoback)

- Is the crust penetrated by Homestake mine critically stressed as we've found elsewhere at great depth, even in stable intraplate areas? (Note that we've developed a broad suite of stress measurement tools for arbitrarily-oriented boreholes and stress fields that should be applicable. This, of course, would be fundamental for many other studies as well.)
- Flow through critically-stressed faults is dominant process at many sites we've studied in both scientific boreholes and in oil and gas reservoirs around the world. Is the same thing true for flow through fractures and faults intersecting Homestake mine? This research represents a linkage between rock mechanics and hydrogeology but as the rock mechanics chair, I'll let you make whatever contact might be appropriate with tht group.
- Stabilization of failure around tunnels, shafts and wellbores. This is a critically-important problem in many contexts but, to my knowledge, has never been adequately addressed. Comprehensive stress measurements (which I think are now feasible), coupled with good rock mechanics data, should enable a new generation of models to be developed addressing this question

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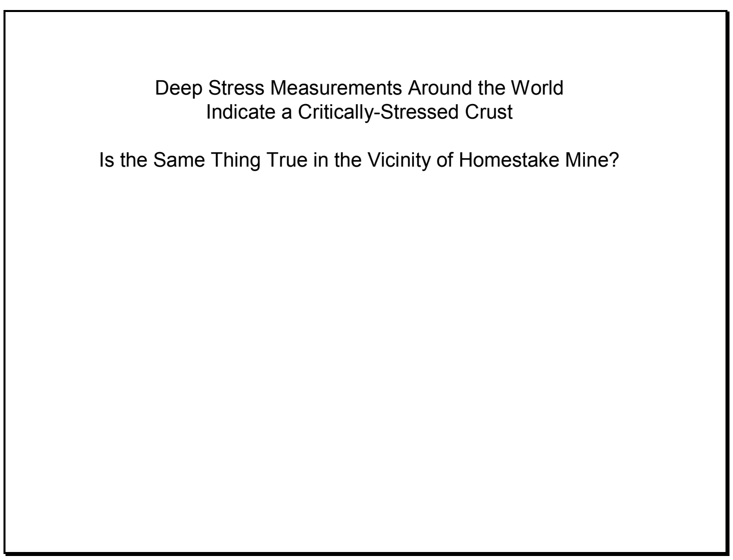

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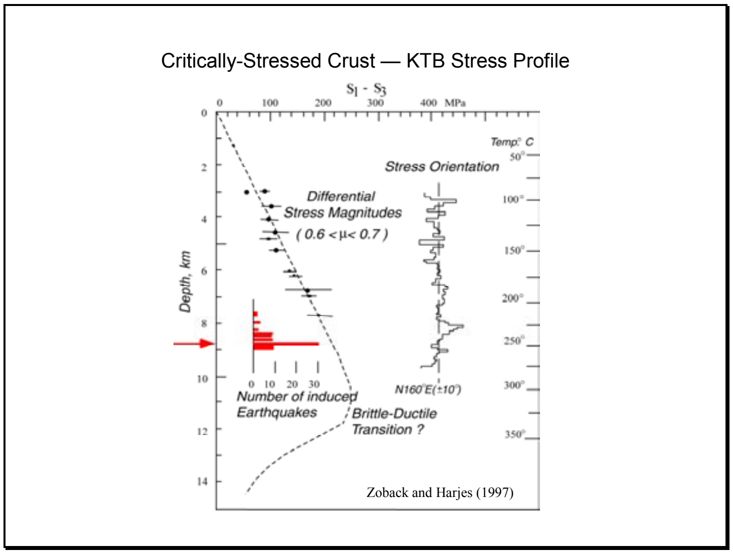

Figure 1-10 – Stress data collected in the KTB borehole to ~8km depth. Measured stresses are quite high and consistent with Coulomb faulting theory and friction coefficients of ~0.7 and injection of water at 9 km depth triggered earthquakes at extremely low perturbations of the ambient, approximately hydrostatic pore pressures (after Zoback and Hayes, 1998).

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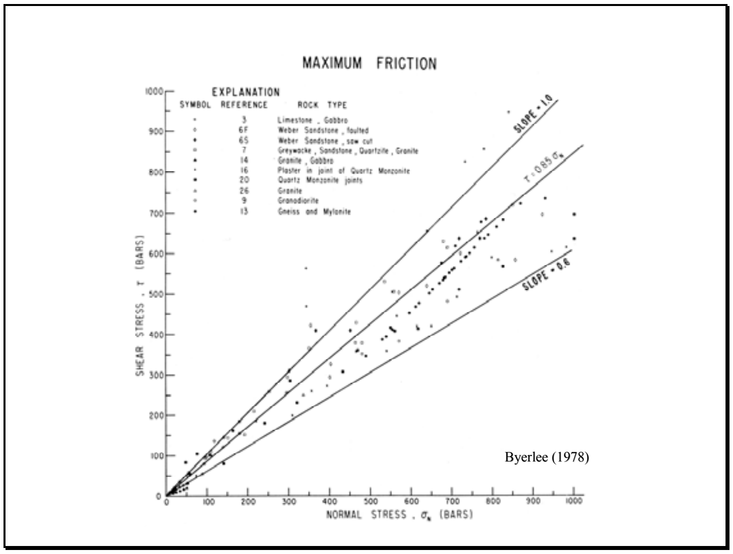

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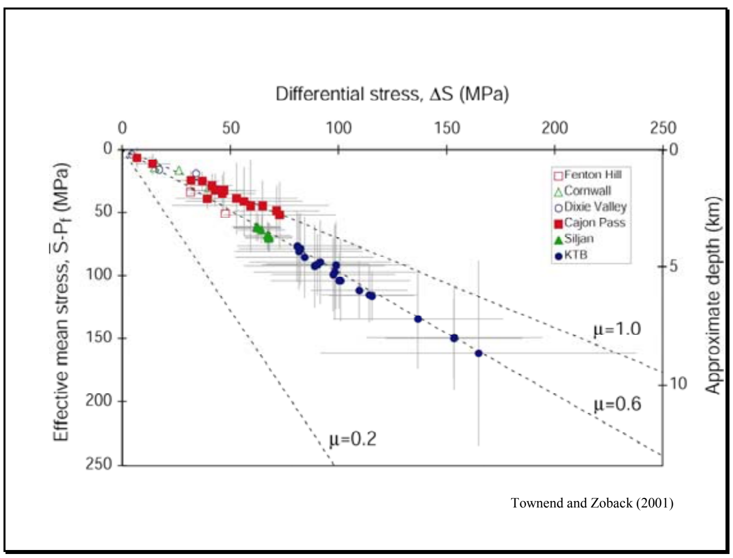

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Over the Past 5 Years, we have developed a number of new techniques for determination of the complete stress tensor in three dimensions based on observations of borehole wall failures

- **These techniques have entered into widespread usage in the petroleum industry in highly deviated and horizontal wellbores**
- **Coupled with hydraulic fracturing (to determine only the least principal stress) these techniques have successfully been used to determine the complete stress tensor in numerous oil and gas fields around the world**
- **They can be easily adapted for use in core holes drilled at various orientations from mine shafts and tunnels**

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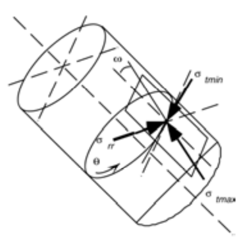
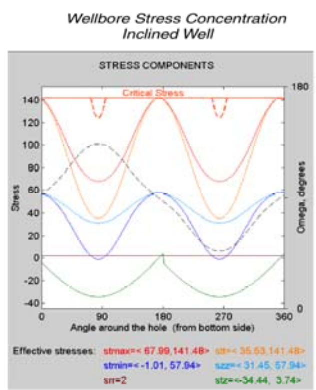
Borehole Wall Stresses for an Arbitrarily Oriented Hole





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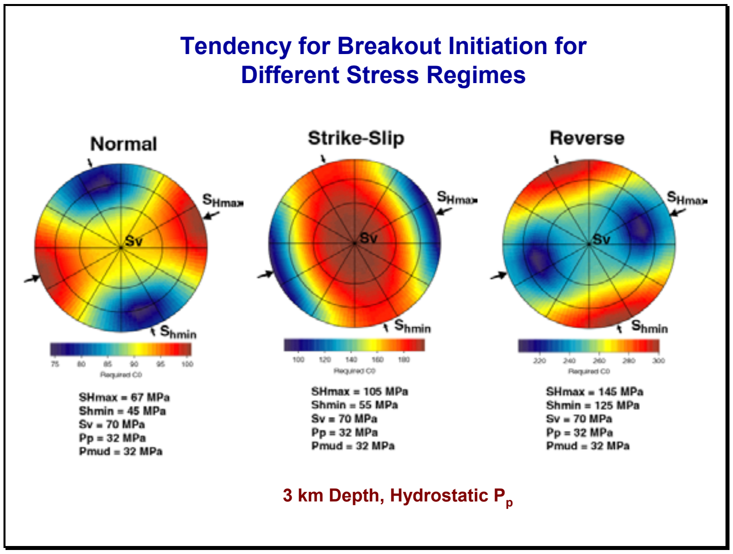

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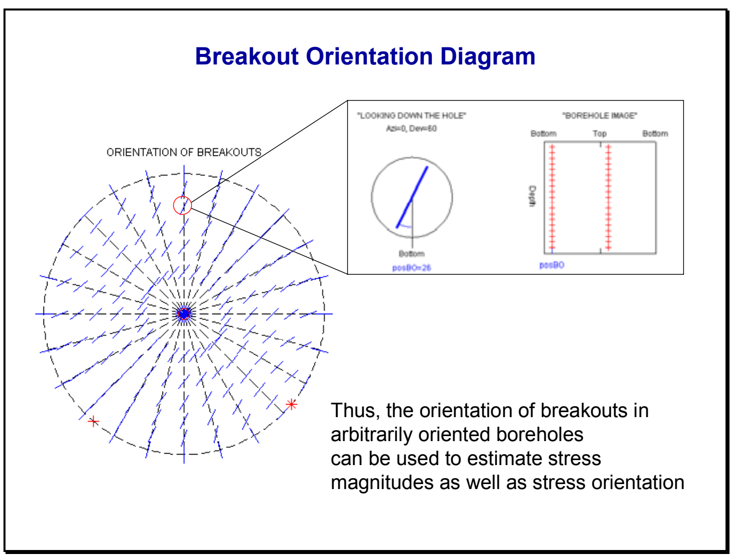

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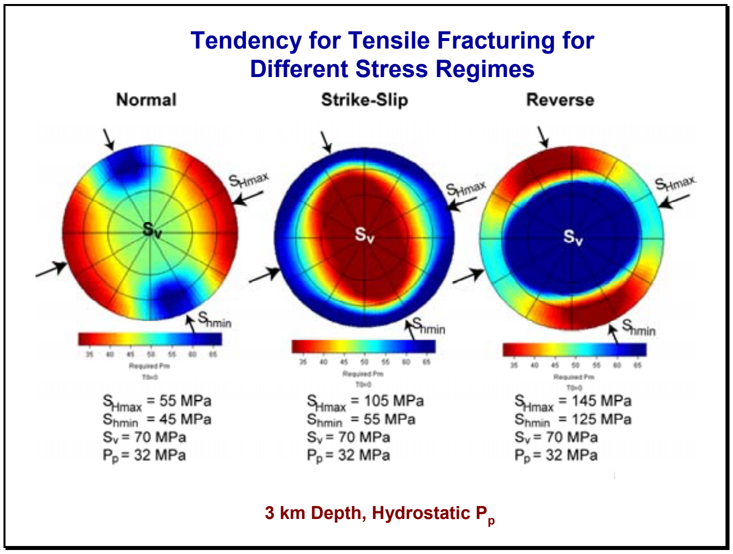

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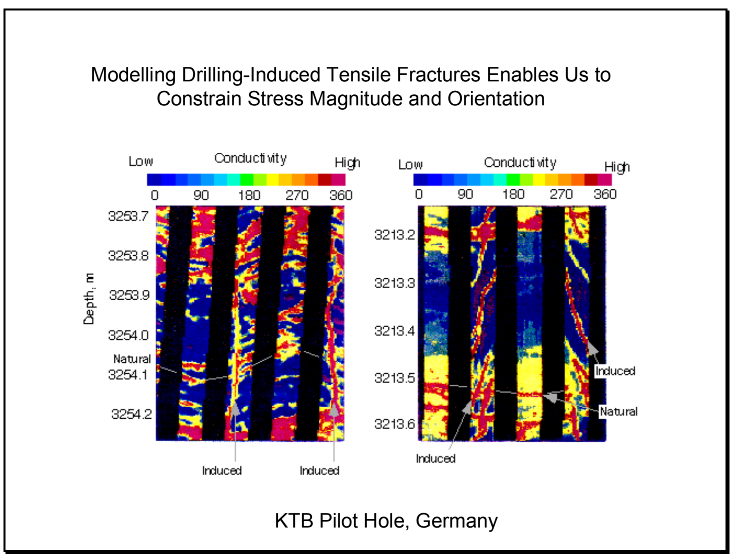

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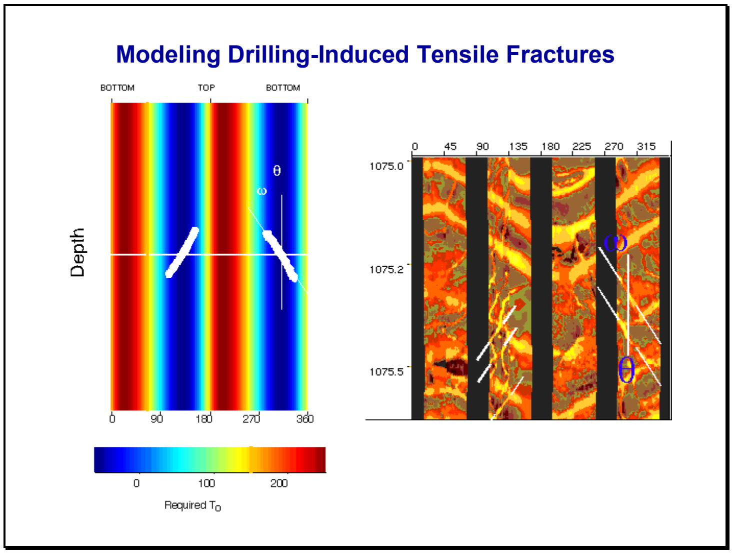

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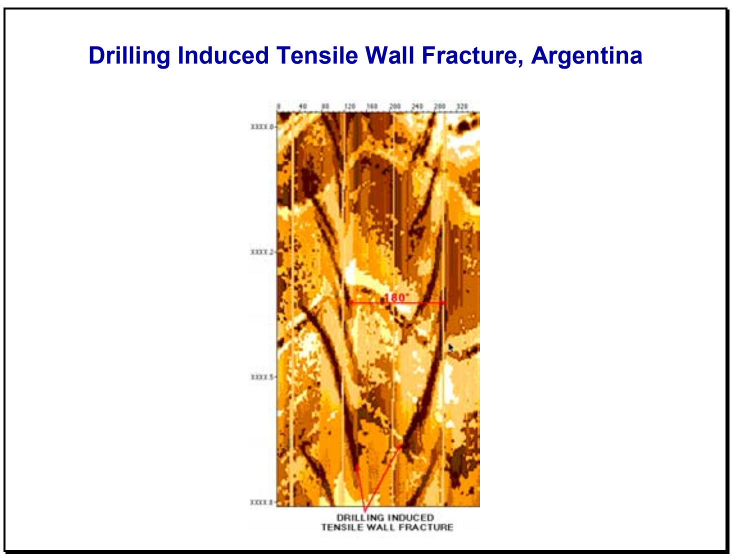

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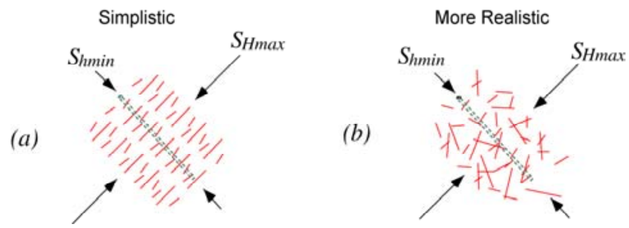
Understanding Flow Through Fractures in the Earth

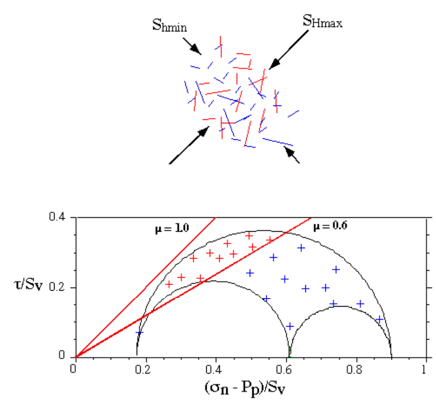
At many locations around the world, fluid flow is dominated by critically-stressed faults



Is the same thing true at depth in the vicinity of Homestake Mine?

Slide 14

Permeable Fractures and Faults are Critically Stressed



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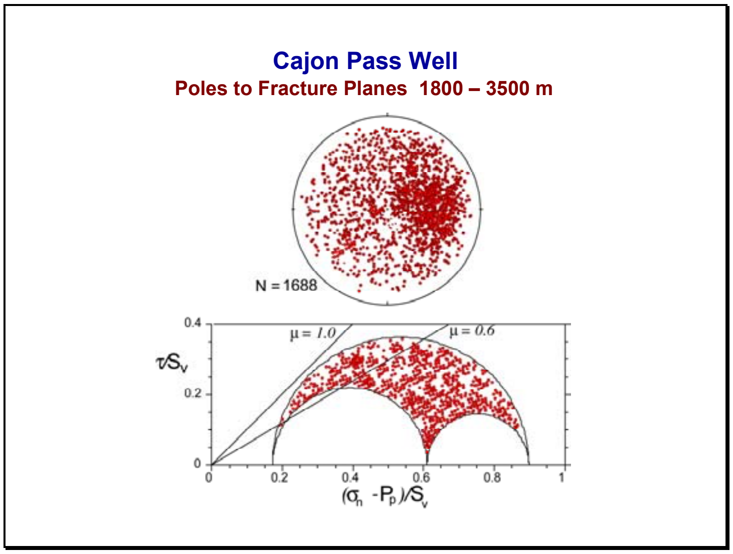

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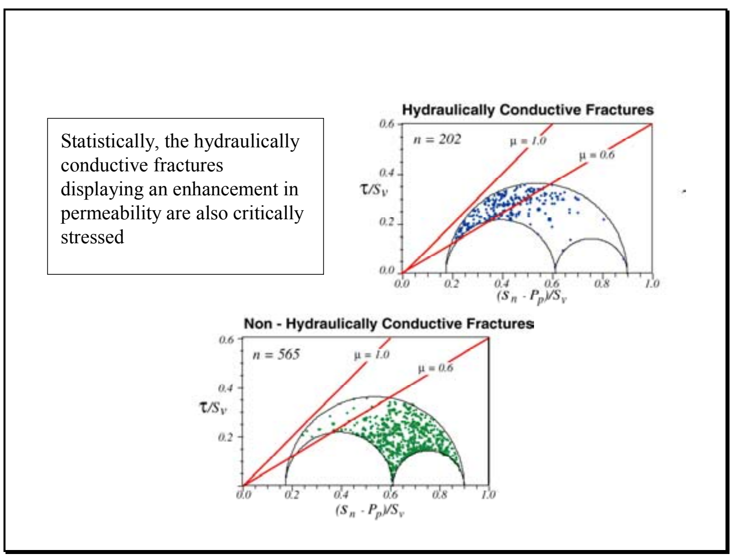

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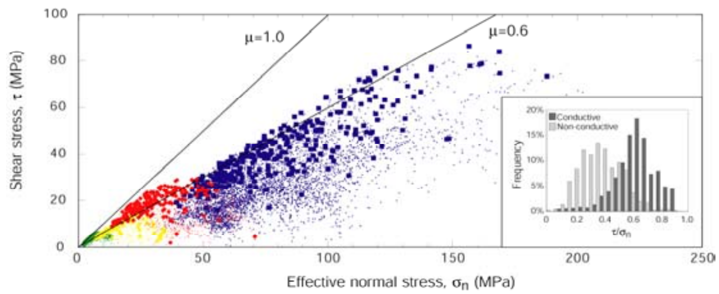
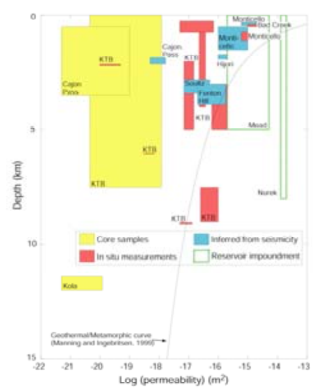
Permeable fractures/faults (filled symbols) are critically-stressed
Impermeable fractures/faults are not



Zoback and Townend (2001)

(Data from NTS, Long Valley, Cajon Pass, KTB)

Slide 18



Townend & Zoback (2000)

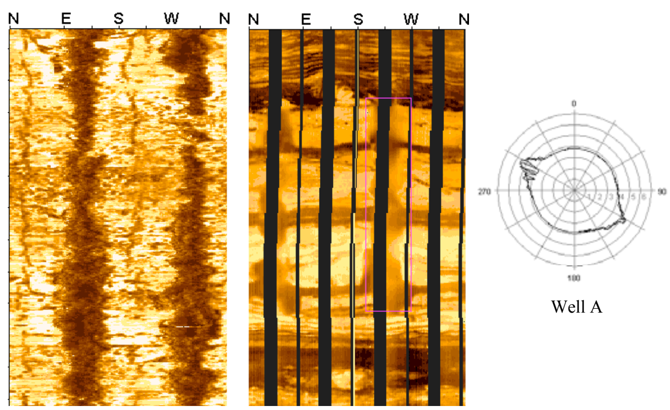
- Permeable faults/fractures are critically-stressed
- High permeability maintains hydrostatic pore pressure
- Hydrostatic pore pressure results in high crustal strength

Slide 19

Detailed Stress Measurements Before and After Excavation, Coupled with Detailed Rock Mechanics Studies and Modelling Has the Potential to Contribute Significantly to Knowledge of How Failure Stabilizes Around Tunnels, Shafts and Wellbores as Strain Energy is Absorbed Through Inelastic Deformation

Slide 20

Compressional Wellbore Failure



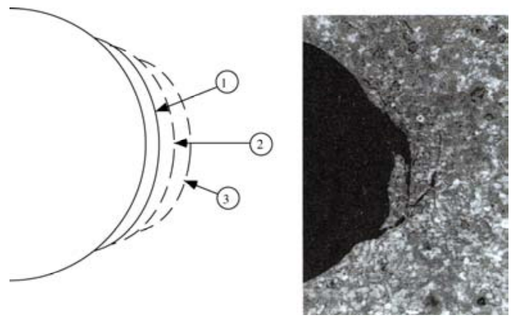
Well A

UBI Well A

FMI Well B

Slide 21

Breakouts Deepen with Successive Episodes of Failure



In nature, failure stabilizes much faster than elastic theory would predict

Active Experimentation (OU group)

DRILLING OPTIMIZATION

Dr. Jean-Claude Roegiers and Dr. Richard Hughes, The University of Oklahoma
Dr. John Osnes, Respec

Goal: To develop 'downhole' intelligence in order to optimize penetration rate.

Background: The petroleum and geothermal industries are developing ever deeper and more difficult reservoirs requiring unique and expensive drilling facilities. Daily rates in excess of \$100,000 are not unheard of. Although automation is slowly being applied in the field, it consists mostly of data transmission to a central location; hence, mainly monitoring a series of measured parameters. But as far as weight on bit, torque, and mud circulation are concerned, trial-and-error is still the approach used in the field. Moreover, when the rate of penetration drops below a certain economic limit, it is usually left to the crew to decide upon the potential cause; often leading to pulling the drilling string to the surface. When completing 15,000 ft+ wells, such a measure corresponds to approximately a loss of one day for the roundtrip.

Proposal: Recent developments in fiber optics have resulted in the possibility not only to 'see and illuminate' the dark environment, but also to measure pressure, temperature, fluid and particle velocities. It would, therefore, be feasible to develop a downhole 'package' having the capabilities to make decisions, based on the data collected downhole. For example, if an unusual high pressure gas zone is encountered and is detected, it is quite conceivable that some downhole packers could be inflated, isolating the zone. The drilling process would then stop and a signal would be sent to the surface requesting further action. This would definitely increase safety. By the same token, the visual aspects could detect the efficiency of rock comminution and adapt the drilling parameters to encourage shear or tensile failure rather than compressive crushing.

Homestake Mine: The advantages of having access to a well-defined underground research facility are obvious as the mine will allow the validation of the concepts developed in this project. Boreholes could be drilled between drifts using this “intelligent drilling” technology, providing additional geological information. The geologic formations at Homestake would lend themselves more directly to deep, hard rock formations such for geothermal reservoir exploration; however, application in the petroleum industry would not be a great extension of the work.

Lithology Recognition from the BHA Vibrations

Dr. Malgorzata B. Ziaja, Montana Tech
Dr. Richard Hughes and Dr. Jean-Claude Roegiers, The University of Oklahoma
Dr. John Osnes, Respec

Goal: To develop tools and techniques to allow the detection of lithology changes while drilling using the vibrations from the drill string bottomhole assembly. An additional goal is to use this lithology information to control drilling parameters to ensure that the drilling is being conducted safely and in an economically optimal manner.

Background: An understanding of rock properties is fundamental in civil, mining and petroleum engineering. In the petroleum industry, the knowledge of rock properties is essential for hydrocarbon resource estimations, drilling process design, oil and gas production optimization, and enhanced recovery operations. Thus, problems related to rock classification, rock bit selection and performance optimization and wellbore stability are essential for the optimal and economic management of natural resources.

Most of the recent developments have been made in drill bit design through the utilization of new materials that extended the life of the bits and allow their application to harder and more abrasive formations. Drilling problems associated with excessive bit vibrations have been recognized. Moreover, the developments in bit design have not eliminated the most severe problems that occur while drilling through changing lithologies. The only way to successfully drill such boreholes is to adjust parameters (for instance, weight-on-bit, rotational speed or pump pressures) during drilling. In addition, industry has recognized an increased need for extended-reach and horizontal drilling to improve productivity and reduce cost. Thus, directional bit-steering becomes a crucial need. At present, downhole measurements allow detection of excessive bit vibration only. No method has been developed to detect formation changes while drilling so that appropriate drilling parameters can be adjusted to steer the bit. As a result, sudden and unexpected bit damage and/or unnecessary tripping operations often occur.

Results of experiments using a single polycrystalline diamond compact (PDC) cutter, performed at Montana Tech, have shown that it is possible to predict bit performance under given conditions by measuring the forces and moments at the bit face. These forces and their dynamic characteristics could also be estimated based on vibrations of the bottom-hole assembly. It has also been demonstrated that the drilling force dynamics associated with the cyclic nature of rock destruction while drilling is directly related to rock lithology. By implication, if the variations in cutting forces could be detected and interpreted in real time, then a new and useful diagnostic tool would be available during drilling. As a result, it would be possible to detect the changes in rock drillability, as well as to differentiate the changes in rock properties from the changes in bit wear and well conditions. In order to take advantage of this possibility, a dynamic model of rock/bit interaction incorporating the bottom hole assembly vibrations as a function of bit design, rock lithology, drilling parameters and well conditions needs to be developed.

Proposal: In order to develop the dynamic rock/bit interaction model it is necessary to use different bit designs in different rock lithologies using variable drilling parameters and well conditions. An instrumented, down-hole diagnostic sub that allows measuring temperature, wellbore pressure, weight-on-bit, rotational speed and torque, as well as bit displacements and accelerations would need to be designed and built. The proposed methodology of data analysis would use a neural network to identify material lithology where the inputs are operational parameters, well conditions and bit design characteristics. At the same time, an analytical analysis would be required to develop a dynamic bit model accounting for the stress distribution in the bit body and in the rock at the rock/bit cutter interface as a function of the bottomhole assembly characteristics. For this, the IDEAS software could be used to model the reactive forces, displacements and accelerations. Simulations could be run to verify both the model of the bit and the model(s) of rock failure. The developed models could then be used in the neural network analysis as the additional input data that should provide better drilling process predictions. The developed methodology of rock lithology identification should also significantly improve bit performance and assist in optimization of drilling process based on data from offset wells.

Homestake Mine: Lithology and rock properties while drilling are very difficult to identify because access to the rock material being drilled is generally only available through small cuttings, logs and cores obtained or analyzed after the well has been drilled. Since rock properties and rock behavior are a function of the depth and geological conditions, the processes, which depend on rock properties are very difficult to design and/or control. Thus, the majority of the research has been limited to rock sample testing under simulated in-situ stress and temperature conditions, studying the effect the rock properties have on the tools used in the field and studying the stability of the wellbores and underground openings. Most of this research aimed at studying the effect of rock properties on the different rock-dependent processes cannot find practical applications. This is due to the limited scope of the individual projects, limited laboratory or field data available and/or lack of the specific conditions for verification of the theoretical solutions. Usually, laboratory tests are very expensive and do not reproduce the full-scale processes. On the other hand, in the field some parameters are not measured or recorded. Also, the range of the field data is limited to cases with optimal and/or reasonable operational conditions and cases where an extreme change in the magnitudes of some of the parameters is not allowed. For most of the research, it is required to follow the very specific scenarios of the tests. Usually, such scenarios are not of practical interest. Also, some of the tests need to have the results from several if not many wells, which causes the research to be very expensive and time consuming. Moreover, some of the test conditions may not be comparable and/or complete, thus useless for new developments.

Access to different levels in a mine (depth of 1,000 ft, 4000 - 8,000 ft, and 8,000 - 16,000 ft) allows testing different rock lithologies under the different in-situ conditions.

Drilling relatively short, thus less expensive wells, allows fast testing of different bits while applying variable operational parameters. It is also extremely important to have the possibility of rearranging test scenarios including allowing repeat tests.

SEE-AHEAD OF THE BIT

Dr. Jean-Claude Roegiers and Dr. Richard Hughes, The University of Oklahoma
Dr. John Osnes, Respec

Goal: To develop the technologies required to probe the rock formations ahead of the drilling bit in order to avoid costly surprises.

Background: One of the most expensive remedial workovers in the petroleum and geothermal industries results from encountering unexpected geological conditions such as a fault, an overpressured horizon, etc. Such conditions always result in cost overruns in order to save the well, or can even result in loosing the well altogether. In addition, an unexpected rise of gas bubbles through the mud column can jeopardize the safety of the drillers by causing devastating fires on the rig floor. Attempts have been made by the tunneling industry to investigate geological conditions prevailing ahead of boring machines. Deep Penetrating Radar and Acoustic Tomography, for example, have had limited success in providing the engineers with advance warning, sufficient to adapt the support system to the new conditions.

Proposal: It is proposed to review the different existing seismic, electric and magnetic technologies; especially their assumptions and limitations with respect to depth of penetration as well as accuracy with respect to formation characterization. Some technologies will probably have to be extended to determine some specific important characteristics such as strength and roughness. In addition 'miniaturization' will play an important role in order to apply such technologies, or combination thereof to deep oil and gas drilling.

Homestake Mine: The obvious advantage of having access to a deep three-dimensional mine consists in the fact that surface drilling can be conducted from any drift to validate the theoretical developments as well as testing the concepts via mineback operations. In addition, drilling deep boreholes from the surface will allow researchers to tackle and solve problems related to data transmission to the surface by using wireless technology.

PROPAGATION OF HYDRAULIC FRACTURES

Dr. Jean-Claude Roegiers and Dr. Richard Hughes The University of Oklahoma
Dr. Gary Callahan, Respec

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

Background: From outcrop observations and the few mineback field experiments, it is well known that in-situ discontinuities affect the propagation of hydraulically induced fractures. In general, the resulting geometry reveals an offset of a certain magnitude which is, presently, impossible to predict. On one end of the scale, this offset can be infinite; in which case the induced fracture is "contained". This would be the ideal situation if one wants to keep stimulation treatments within the producing reservoir, avoiding growth into the upper and lower barren barriers. On the other end of the scale, the offset could be nil; in which case the induced fracture has essentially “ignored” the presence of the preexisting discontinuity. This is ideal if one considers the problems associated with the transport phenomena, especially the placement of the associated proppants. In other words, the petroleum industry would like the fracture to be contained in one direction, while avoiding offsets in the other perpendicular propagation direction.

About thirty years ago, a number of preliminary laboratory tests where performed on composite parallellipipeds which revealed that the ‘arrest’ criterion was very much a function of contrasts between the properties of the materials. Later on, some coalbed methane projects involved mining the hydraulic fracture back and revealed both containment and offset, speculating that the behaviour of the discontinuity played the most important role as well as the pumping rate. Thus far, no theoretical approach has been able to provide sufficient guidelines for field treatments.

Proposal:

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

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

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