Deep Underground Science and Engineering Program Planning and Technical Requirements: Geo-Engineering Perspectives/Needs

Derek Elsworth & EarthLab Contributors

(Including contributions by.....C. Fairhurst, P. LaPointe, M. Mauldon, J. Monsees, E. Sonnenthal, S. Kesler, B. McPherson, T.C. Onstott, T. Phelps, W. Roggenthen, H. Wang, ...and T. Doe, and many many others.....)

Synthesis of Prior, NESS and EarthLab discussions?

NSF-EarthLab Report: www.earthlab.org

NSF-ARMA-Engineering Research Opportunities in the Subsurface Report: www.armarocks.org/documents/NeSSReport.pdf

NSF-ARMA Workshop on DUSELs – Johannesburg SA, 2003. www.armarocks.org/documents/Dusel2004.pdf

Road Map for Presentation

- Background and Introduction
- Current Case for DUSEL
- How DUSEL Can Fit These Needs
  - What is special about DUSEL?
  - What kind of experiments could be done?
  - What kind of experiments have been done?
- What Questions Remain Unresolved? ....For working groups?
- Basic Technical Requirements for DUSEL Modules?
- What Will be Done in 20 years?

Background and Introduction

EarthLab Deliberations

[Steering Committee and contributions by many… many others……]

	Science	Engineering
GeoBiology	Onstott	
GeoChemistry	Kesler	
GeoHydrology	McPherson	Elsworth
GeoMechanics	Wang	Fairhurst
GeoPhysics	Roggenthen	

Natural Processes……Intervention/Construction

Needs in Geo-Engineering Innovation – “Evolutionary?”

(after Jim Mitchell: NRC:COGEE, Opportunities for Research and Technology Innovation)

Characterization (in space and time)

(Faster, more reliable, less expensive, more information)

High-level Analysis (in space and time)

(Faster, more reliable, less expensive, more accurate)

- Understanding Natural/Augmented Processes
- Performance of structure

Improvement Methods

(what you do with the new data?)

Monitoring Response

(During and post-construction)

Remedial Actions

Current Case for DUSEL

- Societal Needs
- Scientific & Engineering Merit
  - Scale Effects – overriding theme....related to...

1. Complex coupled process interactions (THMC-B)
2. Rock deformation and state of stress – Influences on rock engineering
3. Role of fractures on hydraulic and mechanical behavior
4. Flow and transport in the deep subsurface

Scientific Rationale

Societal Imperatives

- Resource Recovery
  - Petroleum and Natural Gas Recovery
  - In Situ Mining
  - HDR/EGS
  - Potable Water Supply
  - Mining Hydrology
- Waste Containment/Disposal
  - Deep Waste Injection
  - Nuclear Waste Disposal
  - CO_2 Sequestration
  - Cryogenic Storage/Petroleum/Gas

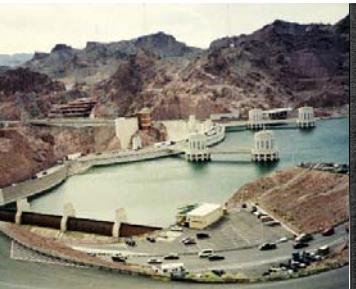
Both GeoHydrology and GeoMechanics

- Site Restoration
  - Acid-Rock Drainage
  - Aquifer Remediation

Mainly GeoHydrology

- Underground Construction
  - Civil Infrastructure
  - Mining
  - Underground Space
  - Secure Structures

Mainly GeoMechanics



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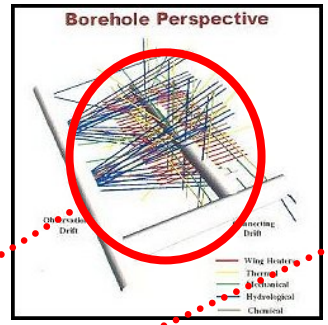
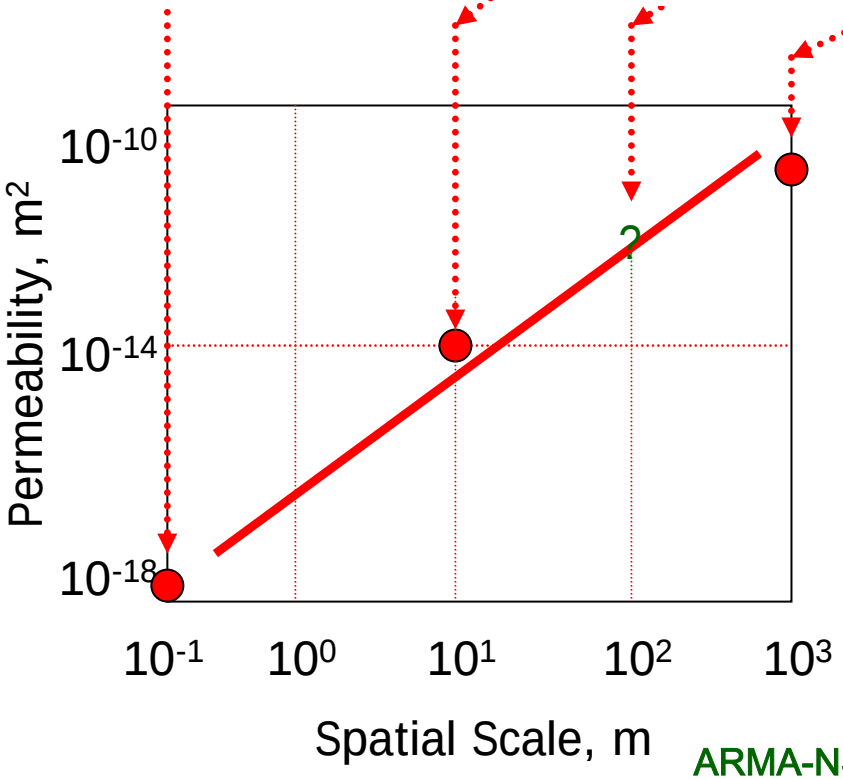
Scale Effects in Geo-hydrology – Space and Time

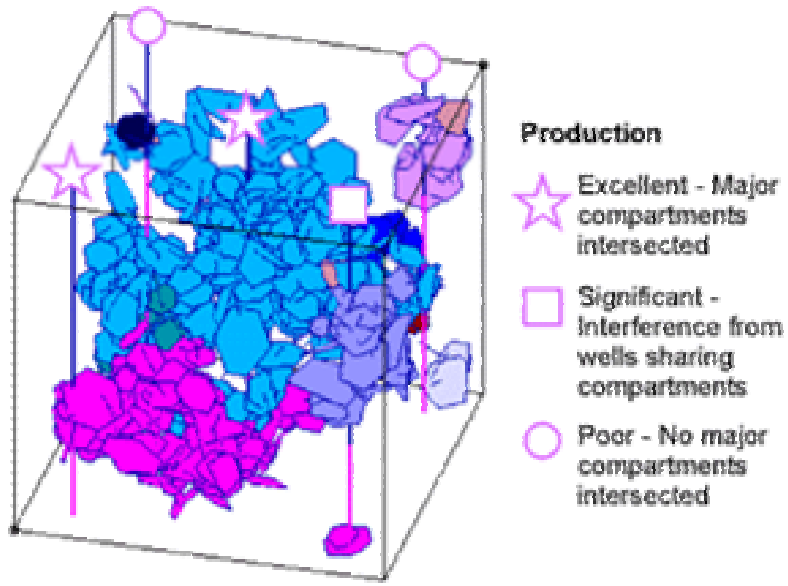


Lab scale

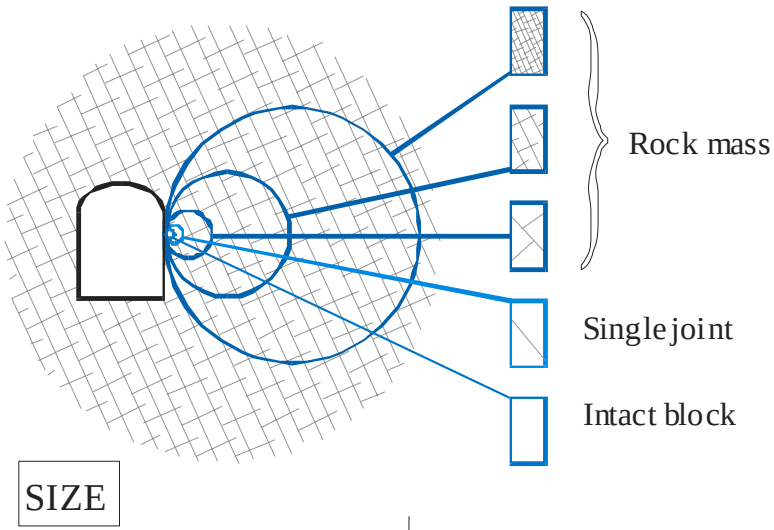
Field scale

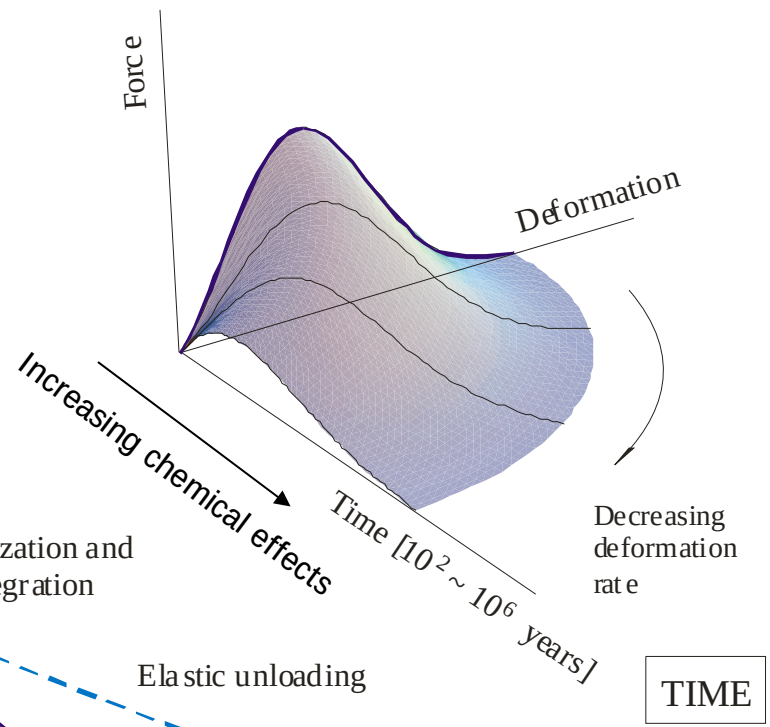
Regional scale

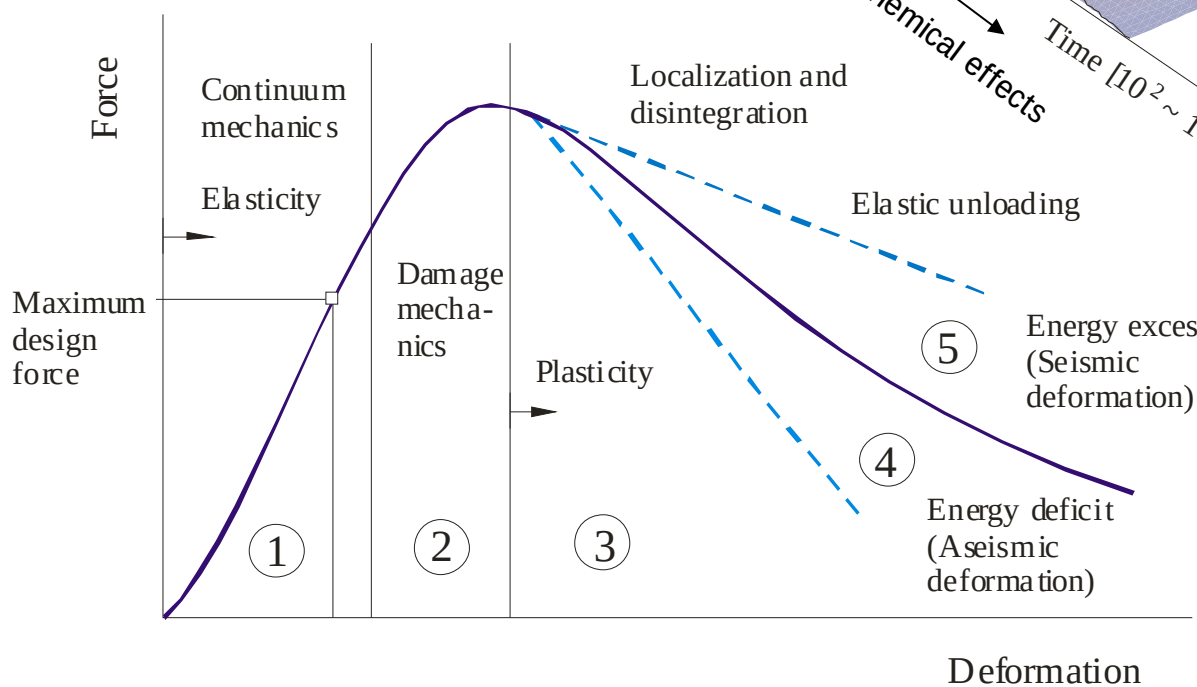




Scale Effects in Geo-Mechanics – Space and Time







Complete Load-Deformation Behavior

[Courtesy: C. Fairhurst]

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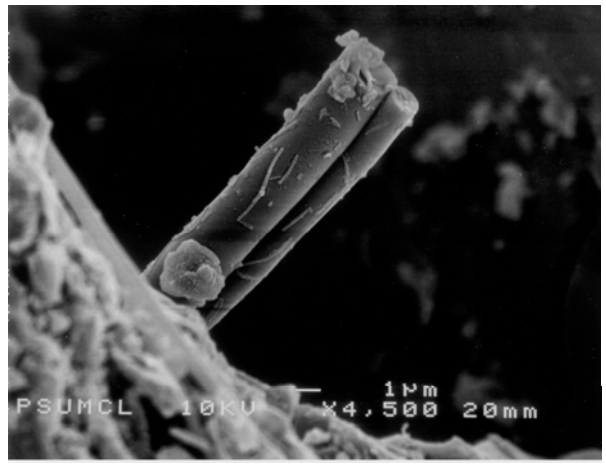
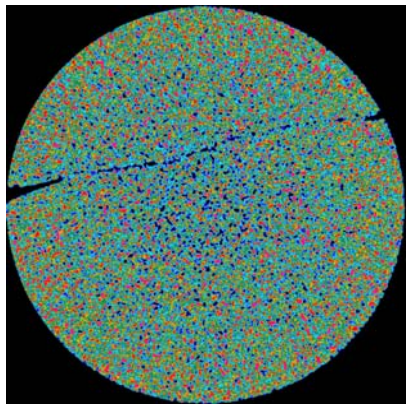
Complex coupled process interactions (THMC-B)

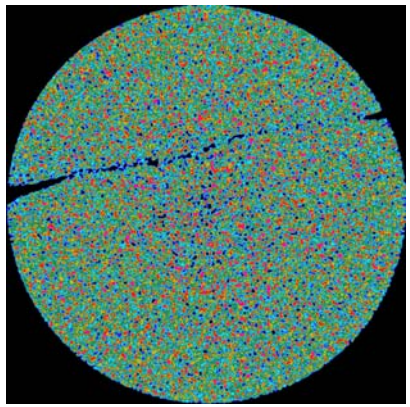


Solid- & Fluid-Environment Interaction

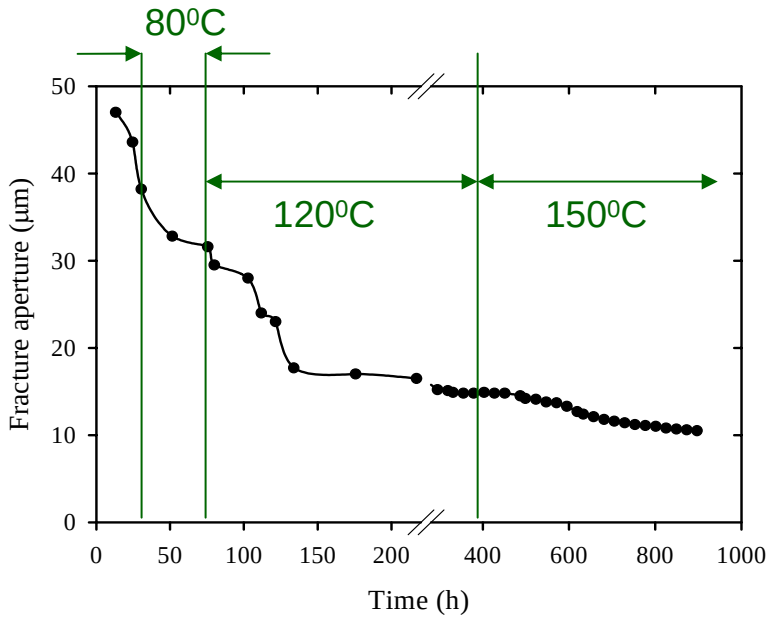
- Models of Fracture Development
- Coupled Processes
  - THM
  - CB
  - THMCB



80^{0}C



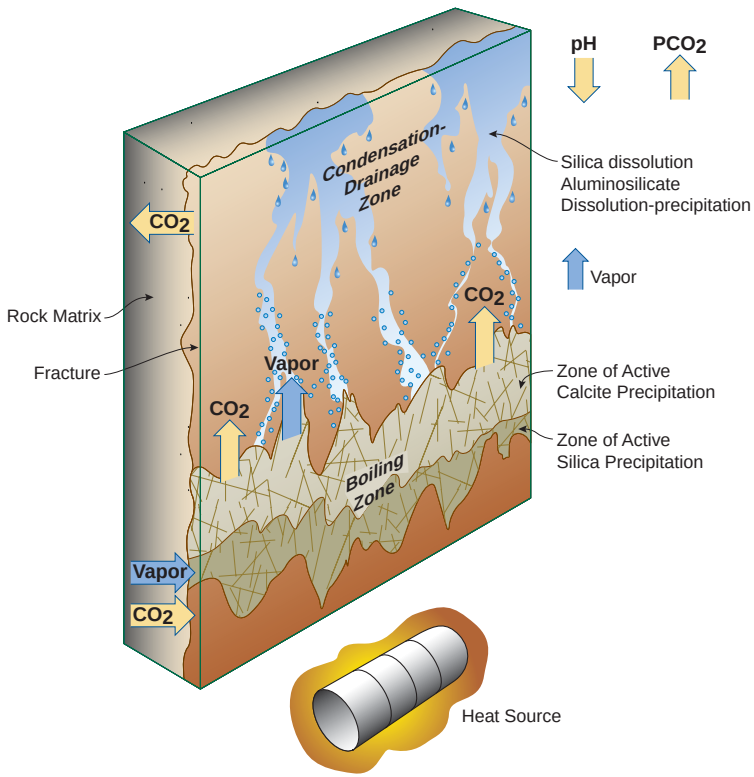
120^{0}C



Importance of Large-Scale In-Situ Experiments

- Validation of coupled reaction-transport conceptual and numerical models requires well-controlled *in-situ* experiments (not found in nature)
- Effective reaction rates are controlled by the hierarchy of scale of fluid flow - e.g., flow in a fracture, through the fracture network, and flow between the rock matrix and the adjacent fractures
- Reaction-transport processes can be strongly coupled to permeability changes from rock mechanical processes and can affect rock deformation as a result of changing mineralogy, permeability, and the chemical environment at fracture tips
- The Drift-Scale Test at Yucca Mountain has been used to study coupled thermal-hydrological-chemical-mechanical processes in unsaturated fractured tuff
- However, different geological and chemical environments can result in different system evolutions

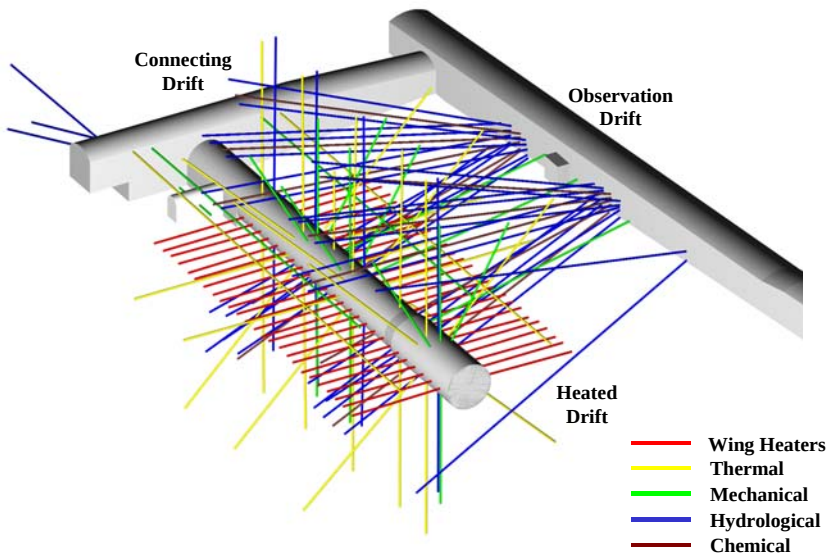
Example of thermal-hydrological-chemical processes in boiling unsaturated fractured rock



[Courtesy: E. Sonnenthal]

Coupled Thermal, Hydrological, and Chemical Processes in the Drift Scale Test at Yucca Mountain

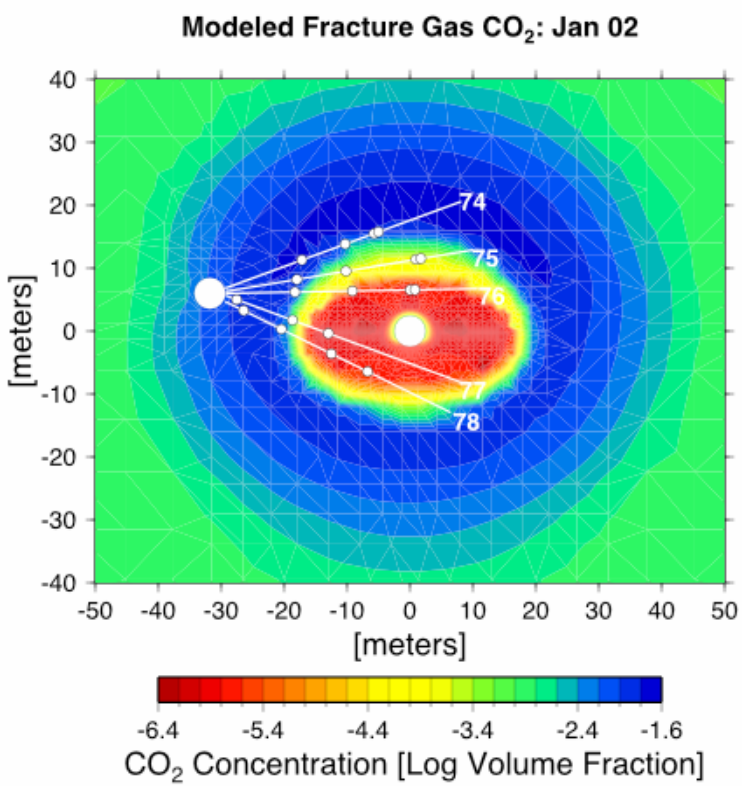
- Purpose of the test is to evaluate coupled thermal, hydrological, mechanical and chemical processes surrounding the potential repository
- Dimensions: ~ 50 meters long by 5 meters in diameter
- Electric heaters activated Dec. 1997, turned off Jan. 2002
- Maximum drift wall temperature reached ~ 200°C
- Water, gas, and rock samples collected from boreholes for geochemical and isotopic studies
- Reaction-transport modeling performed prior to and during test (examples on following slides)

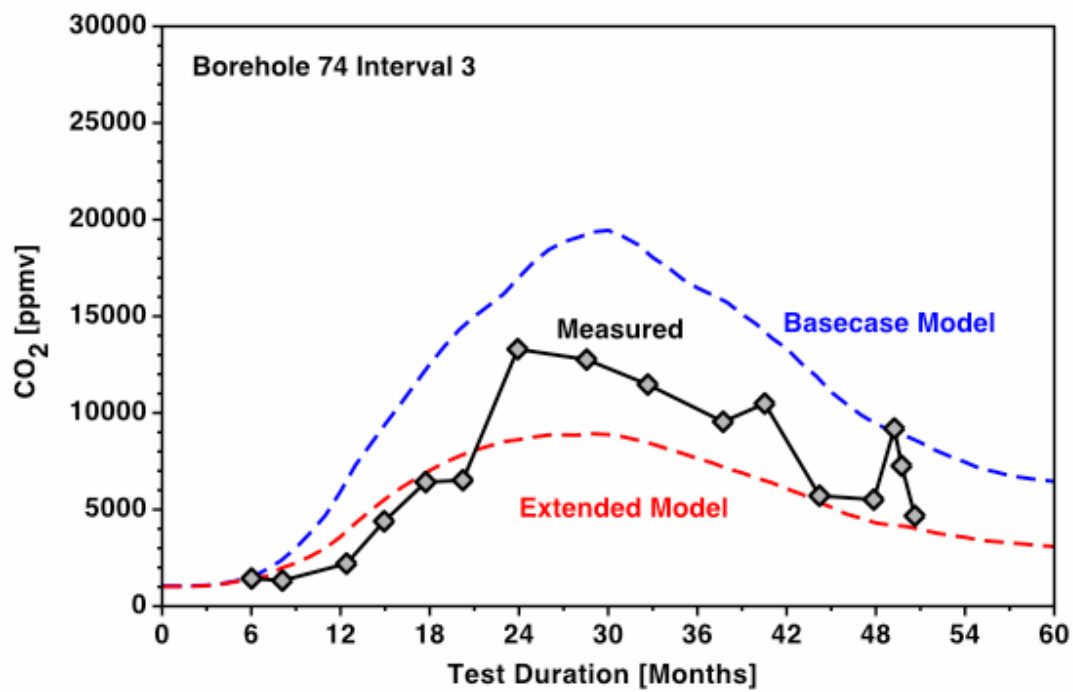


[Courtesy: E. Sonnenthal]

CO_2 Evolution in the Drift Scale Test

- CO_2 concentrations in vapor migrating through fractures reflects coupled processes of boiling, vapor condensation, diffusion and reaction of flowing fracture water with calcite coatings on fracture walls
- Reactive transport models using alternative geochemical systems are tested against measured gas concentrations (figure on right)





[Courtesy: E. Sonnenthal]

Current Case for DUSEL

- Societal Needs
- Scientific & Engineering Merit
  - Scale Effects – overriding theme....related to...

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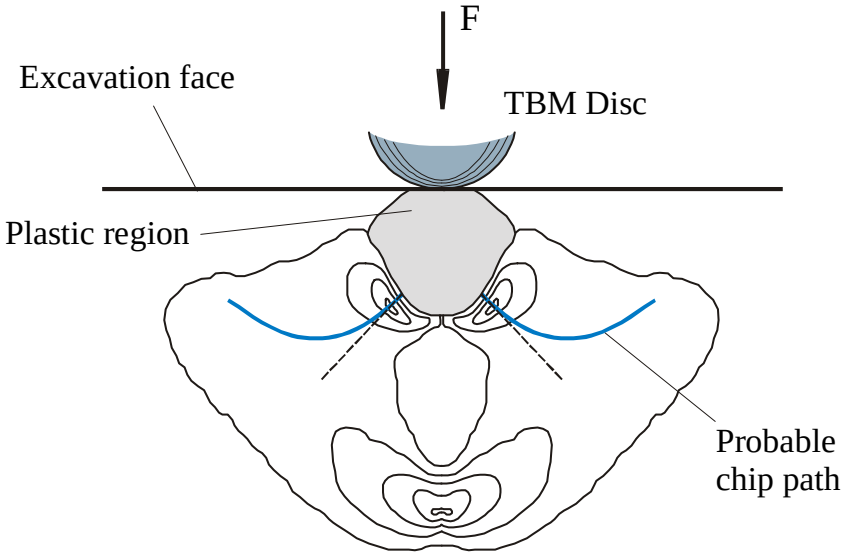
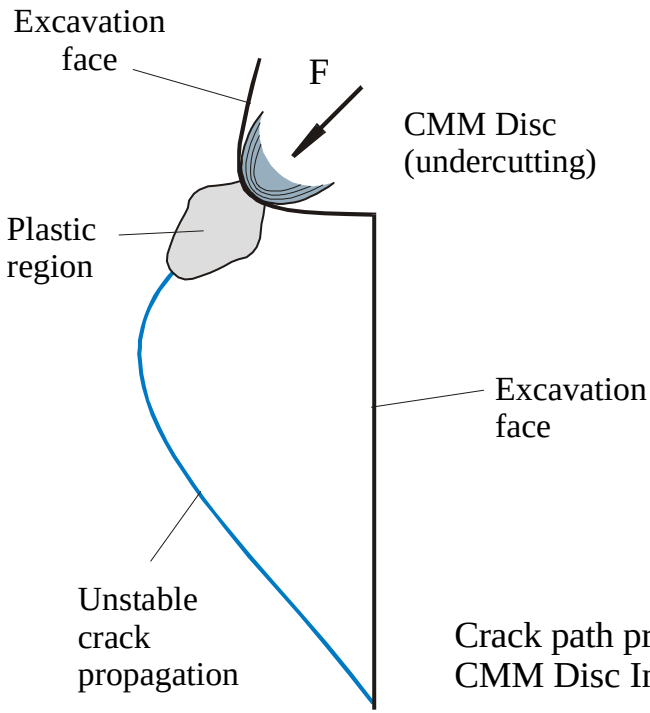


Stress distribution beneath a TBM Disc Indenter
after the stable vertical crack has developed



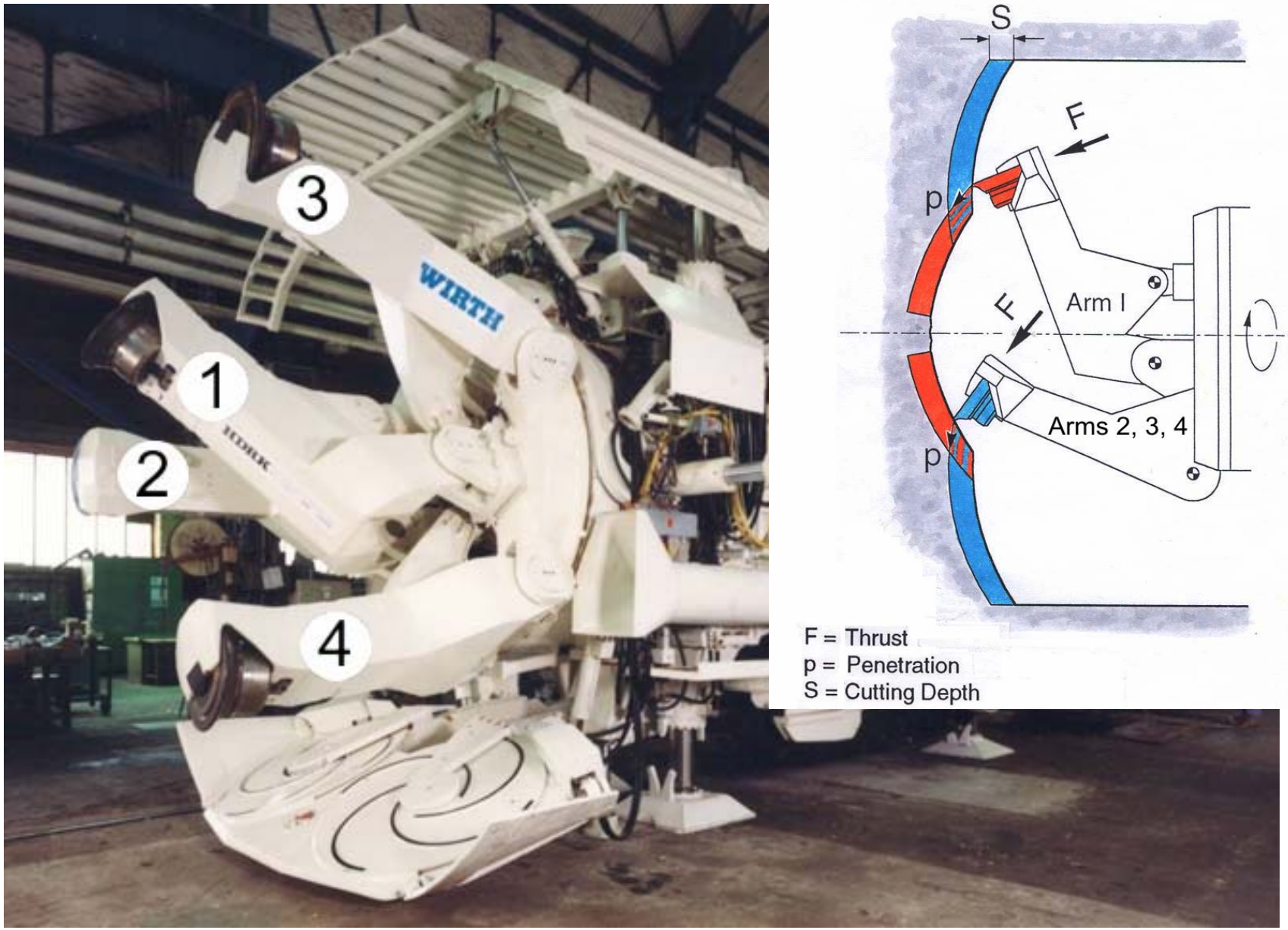
Crack path produced by
CMM Disc Indenter

Note: Tensile crack can not propagate
until plastic region reaches critical size

Disc tip radius	CMM Indenter Force (N/mm of contact length)			
	S = 25 mm	S = 50 mm	S = 100 mm	S = ∞
6 mm	1,700 (74%)	2,310 (100%)	2,700 (117%)	3,000 (130%)
8 mm		2,500 (100%)	3,150 (126%)	(3,500?) (140%?)
12 mm		3,150 (100%)	3,600 (114%)	4,200 (133%)

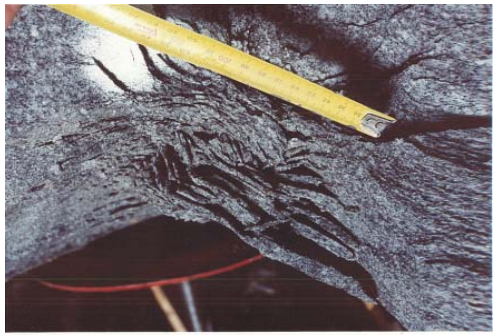
Note: Indenter Force Increase is small for large increase in cutting depth S.

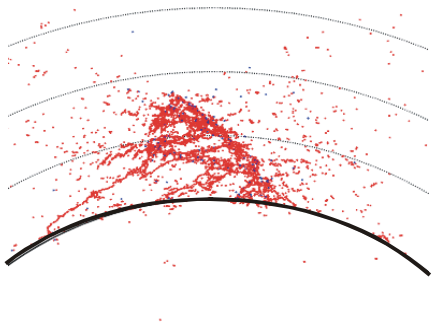
Comparison of chip formation in classical TBM and in CMM (undercutting) [Courtesy: C. Fairhurst]

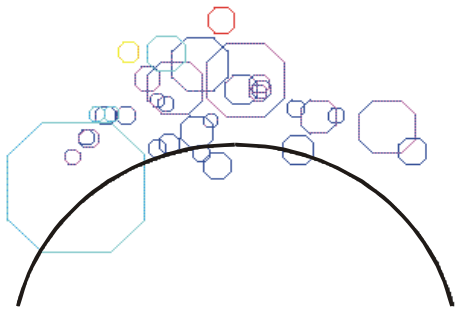


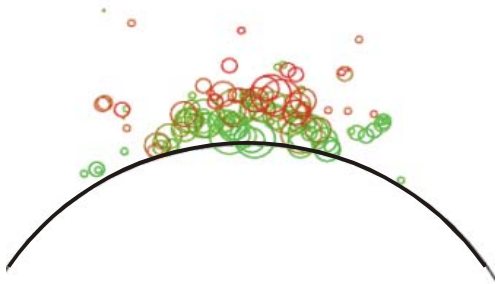
WIRTH-HDRK Continuous Mining Machine (CMM) [Courtesy: C. Fairhurst]

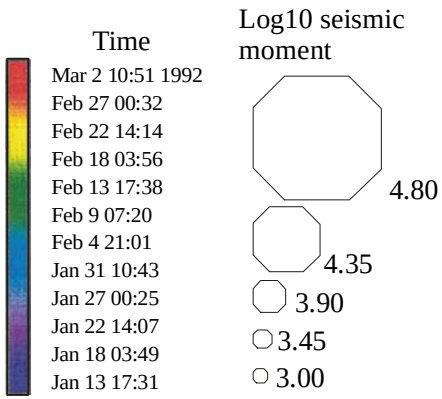
Rock cuttings produced by CMM [Courtesy: C. Fairhurst]

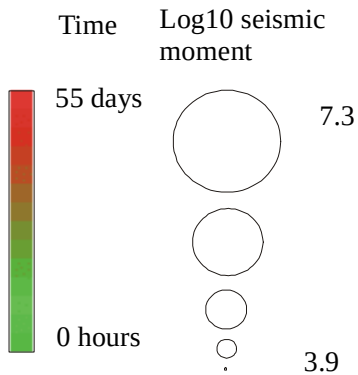












Breakout PFC analysis

[Courtesy: C. Fairhurst]

Current Case for DUSEL

- Societal Needs
- Scientific & Engineering Merit
  - Scale Effects – overriding theme....related to...

1. Complex coupled process interactions (THMC-B)
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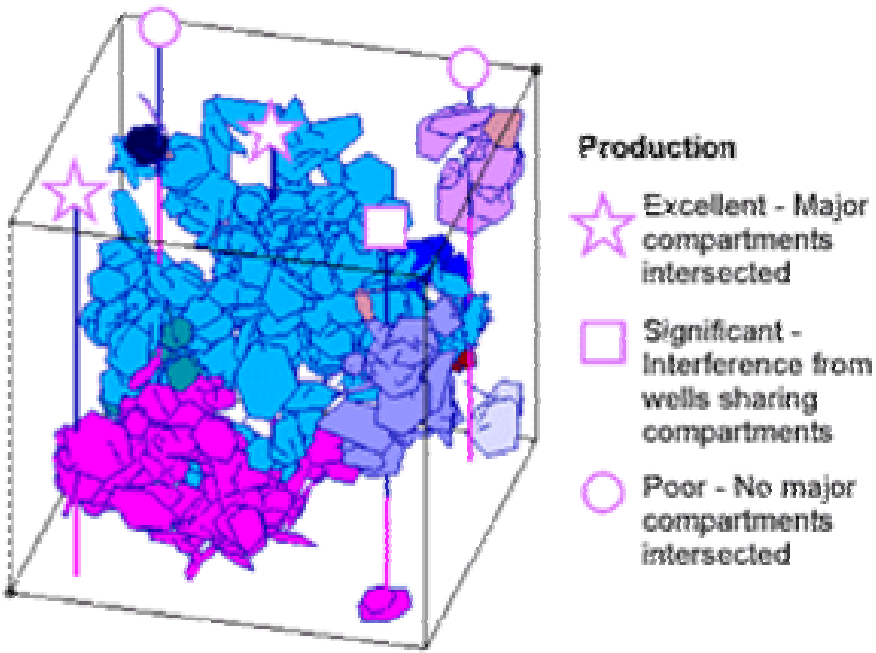
Role of fractures on hydraulic and mechanical behavior

Mechanical and Transport Behavior

- Connectivity of Fracture Networks
- Multi-phase Flow
- Particulate (Colloid/Bacterial) Transport



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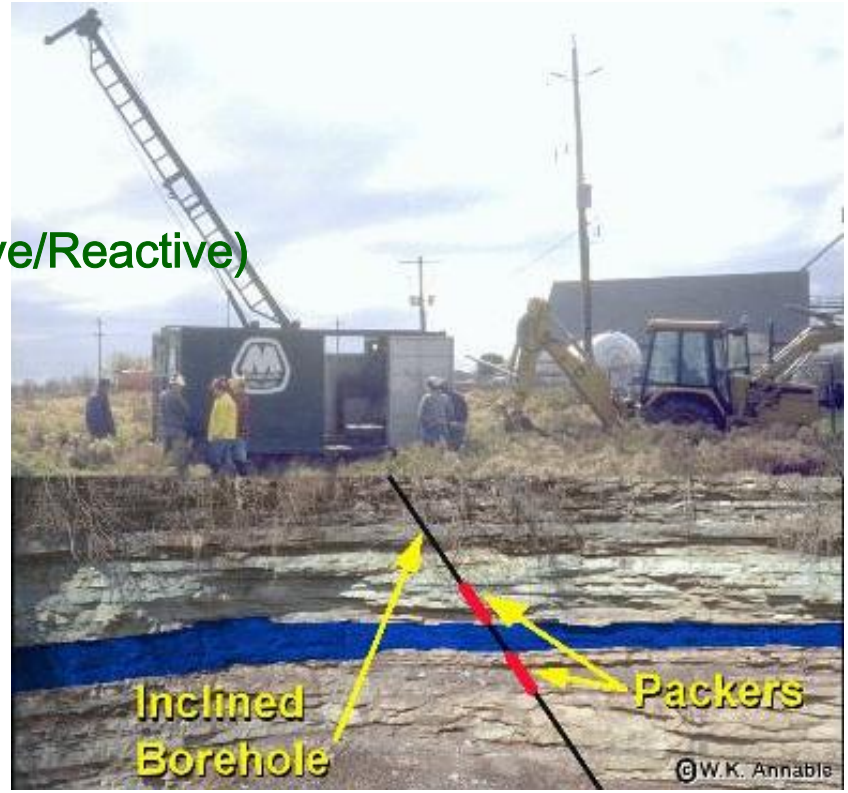
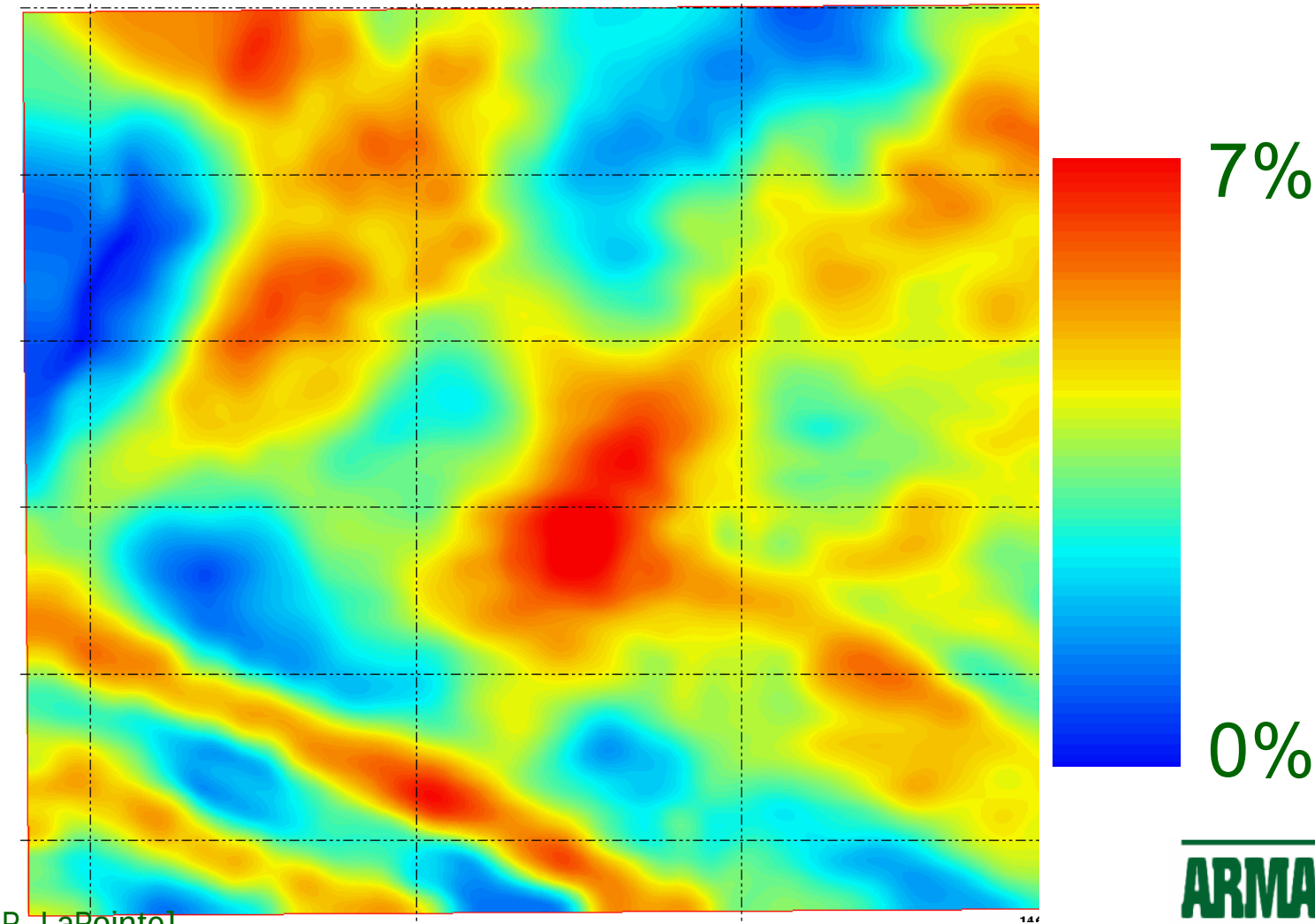
Flow and transport in the deep subsurface

Characterization of Mechanical & Transport Properties

- Hydraulic Methods
- Tracer Methods
  - Natural
  - Forced
    - Aqueous (Conservative/Reactive)
    - Thermal
    - Particulate
- Geophysical Methods
- Drilling Methods

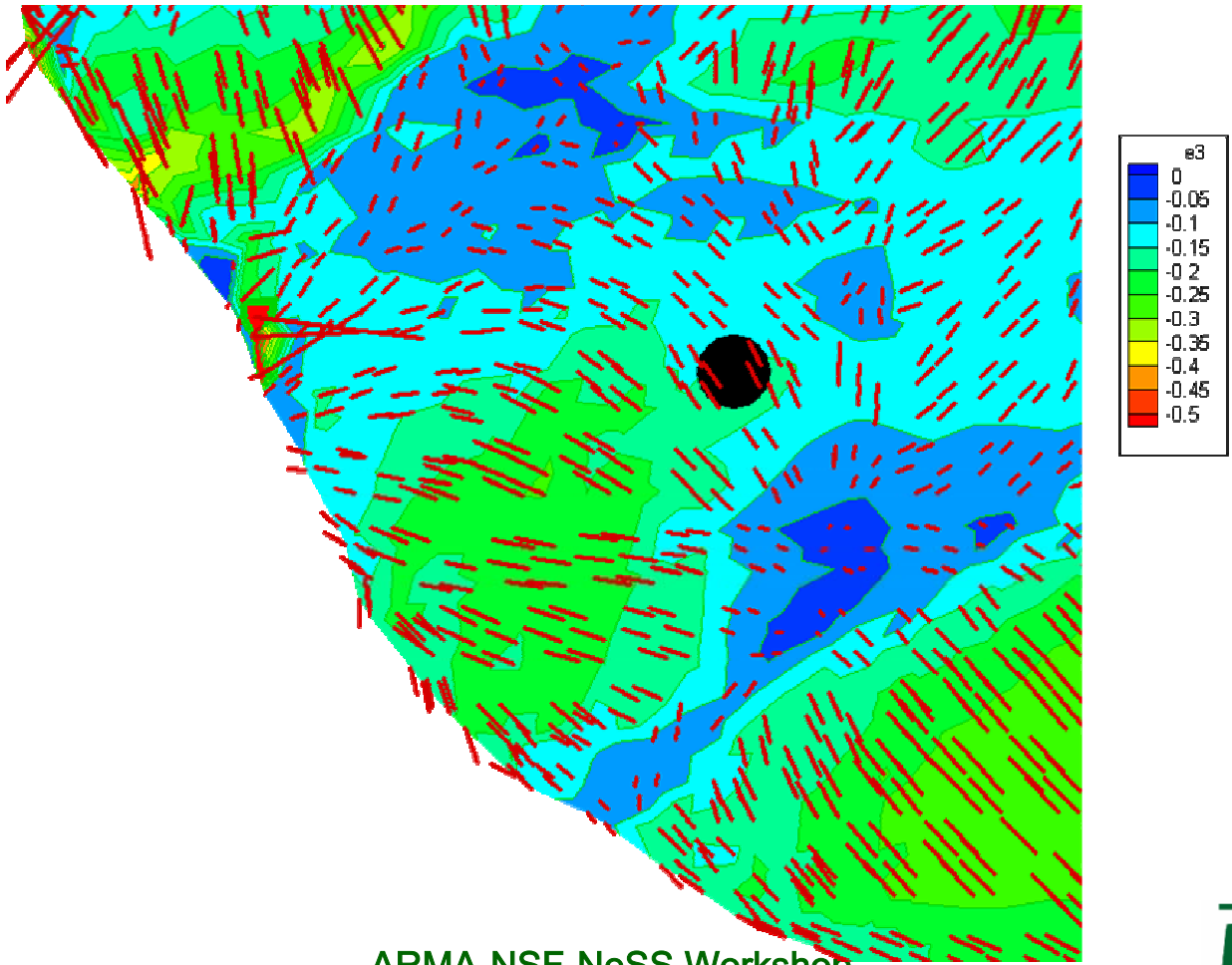


We think that this image might be telling us something about fracture orientations and intensity, but it is not clear what



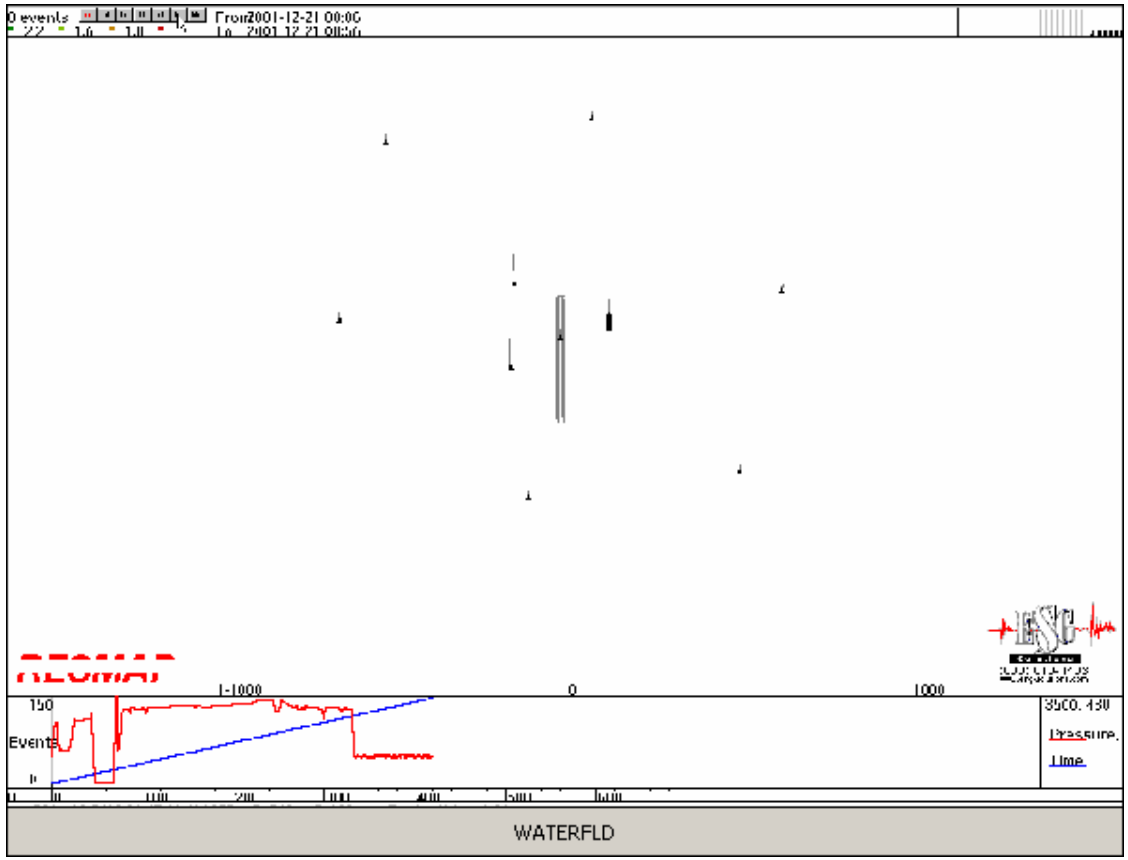
[Courtesy: P. LaPointe]

What we would like to be able to do is to accurately infer the fracture pattern, so that wells could be sited and completed to enhance numerous recovery processes



[Courtesy: P. LaPointe]

Geophysical Methods - Waterflood Acoustic Events

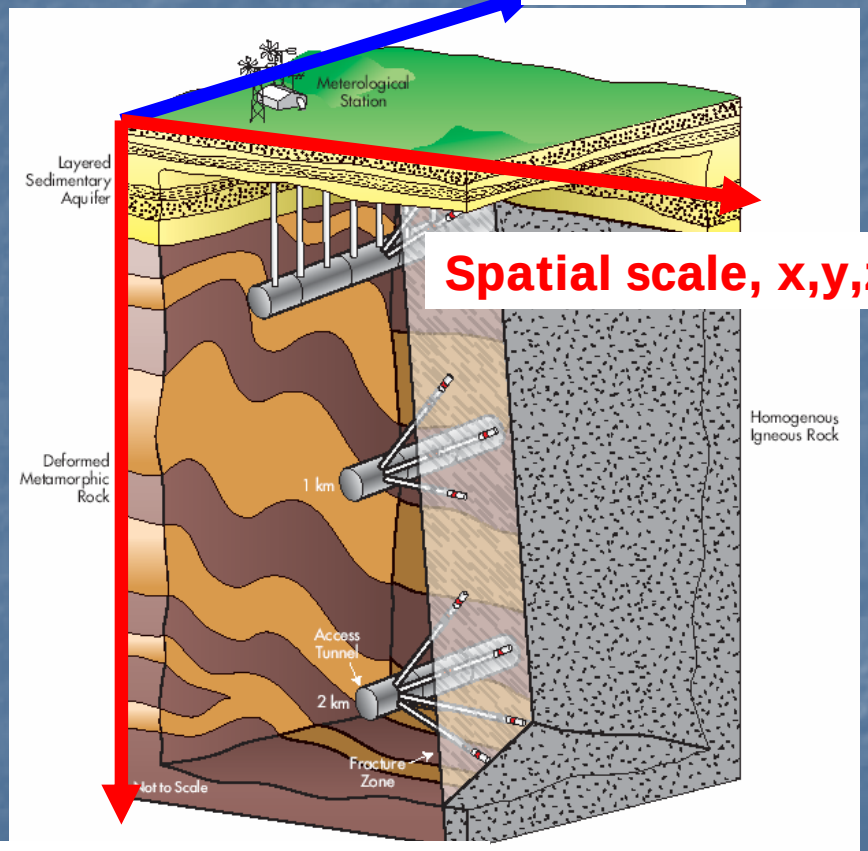


[Courtesy: P. LaPointe]

How DUSEL [May] Fit These Needs

- What's so special about DUSEL?
- What kind of experiments could be done?
- What kind of experiments have been done?

What's so special about DUSEL?



Time, t

Spatial scale, x,y,z

Depth, z -> $\Delta\sigma$; ΔT

Principal Attributes

1. Unusual spatial scale
2. Long-term access
3. Depth gives stress and thermal regimes……

..and others

Geology different from waste disposal sites?

Underground Science Laboratory
Priority Attributes of EarthLab

- Long-term access to large (20 cubic km) volume of subsurface
- Diverse chemical and physical environment (rocks, structures, hydrology, fluids)
- Geological features well characterized in 3-D
- Host rocks to 120°C (at ~5 km), water-filled fracture system
- Ability to access this environment through drill holes, underground workings, and observatories
- Ability to modify environmental loads (thermal, stress, chemical tracers, hydraulic conditions..)
- Community access to archive of data/samples if mine chosen as DUSEL

How DUSEL [May] Fit These Needs

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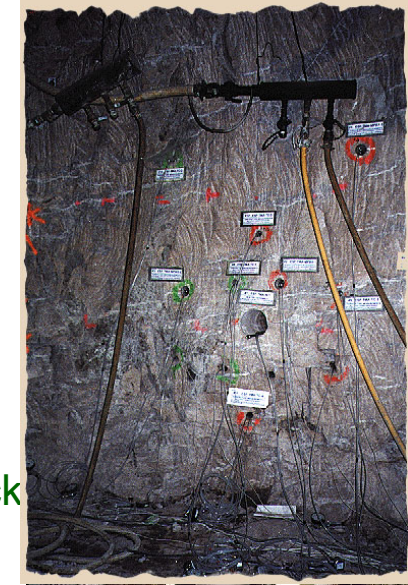
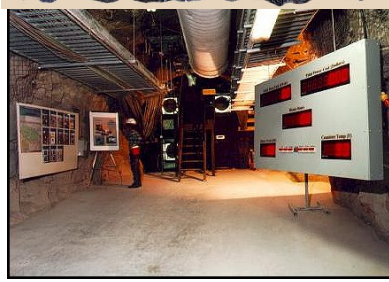
Science & Engineering Needs (Cont'd)





Imperatives

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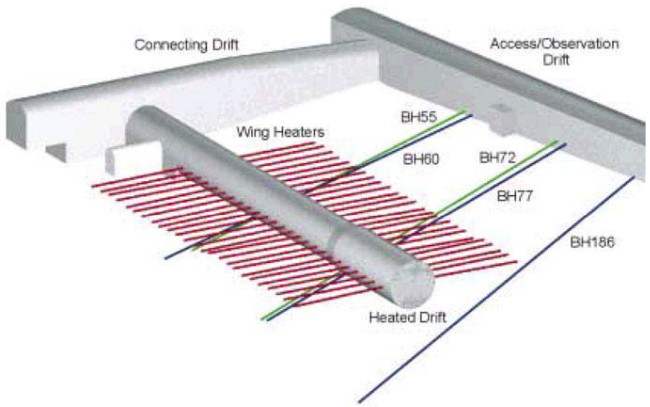
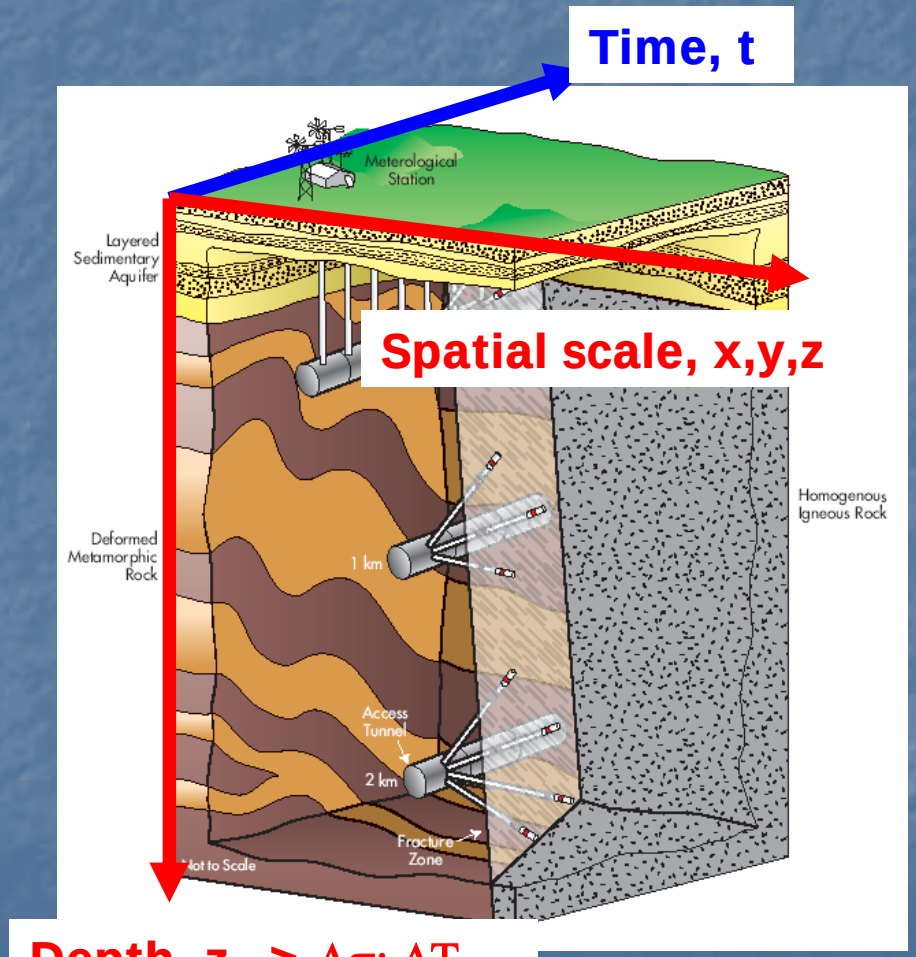
Approach

- Run-of-Mine/Facility Experiments (HCB)
- Experiments Concurrent with Excavation of the Detector Caverns (HM)
- Purpose-Built Experiments (THMC-B)
  - Large Block Tests/Observatories...
  - Mine-By and Drift Structure Tests



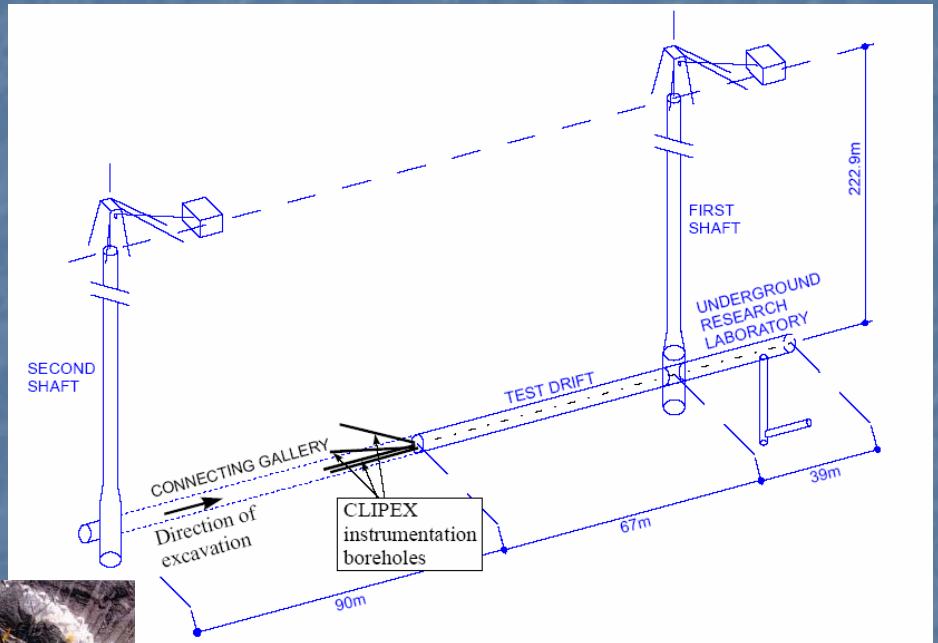
Run-of-Mine/Facility Experiments



- Access to very large block
- Characterization
- Scale effects and heterogeneity
- Variable stress, temperature
- .....

Experiments Concurrent with Excavation [of the Detector Caverns and other access..]

- Characterization
  - Prediction and corroboration
- Scale effects on Processes in EDZ:
  - Mechanical
  - Hydraulic
- Others.....



e extension of the underground laboratory at Mol (Belgium)

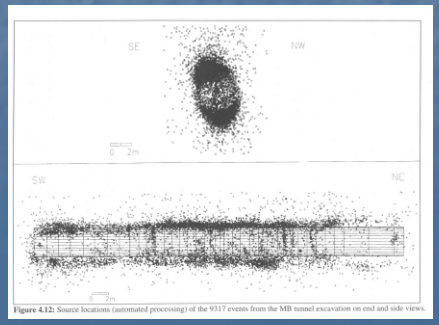


Figure 4.12: Source locations (automated processing) of the 9317 events from the MB tunnel excavation on end and side views.

http://www.lassondeinstitute.utoronto.ca/young/research/url/mineby.html

http://www.euridice.be/downloads/Andra-1299-jdba.pdf

Purpose-Built Experiments

Large Block Tests

[behavior of the pristine envt.]

- Engineering equivalent of scientific observatories
- Characterization
- Scale effects on processes in pristine environment:
  - Mechanical
  - Hydraulic
- Confirm predictions and corroborate models by exhumation
- Others.....

Mine-By and Drift Structure Tests

[behavior of the drift (tunnel) structure]

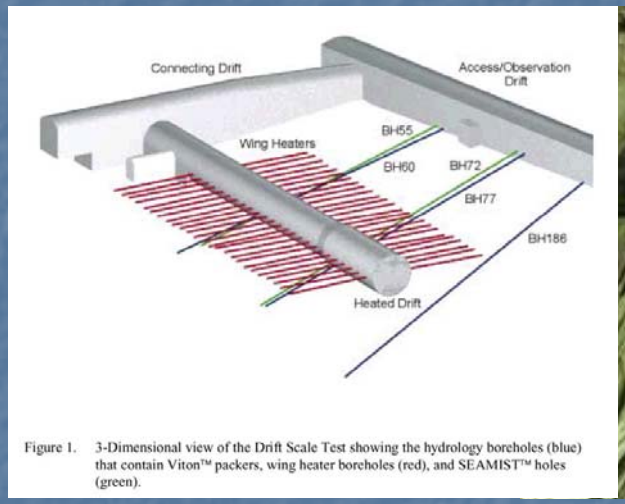


Figure 1. 3-Dimensional view of the Drift Scale Test showing the hydrology boreholes (blue) that contain Viton™ packers, wing heater boreholes (red), and SEAMIST™ holes (green).

- Infrastructure installation and durability
- Detonations and lifeline survivability
- Excavation efficiency studies
- Others.....

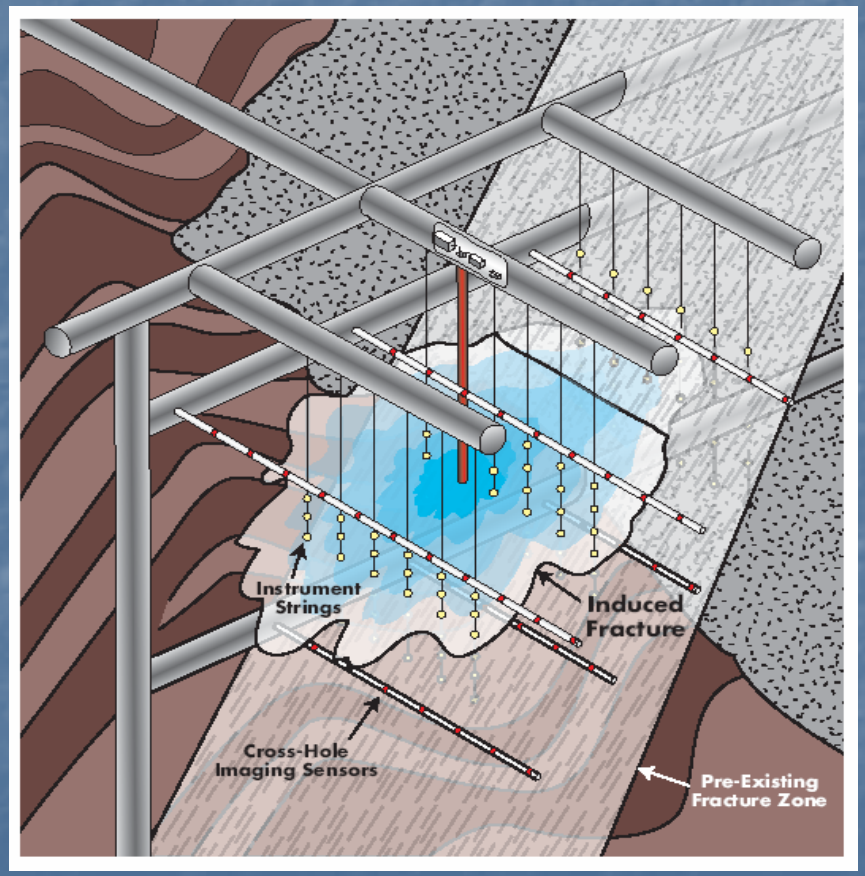
EarthLab... Proposed Experiments

- Deep Flow and Palaeoclimate Laboratory and Observatory
- Induced Fracture Processes Laboratory
- Deep Coupled Processes Laboratory
- Ultra-deep underground observatory for biological and biogeochemical education and research
- Deep seismic observatory

EarthLab Report to NSF, 2003.

Induced Fracture Processes Laboratory

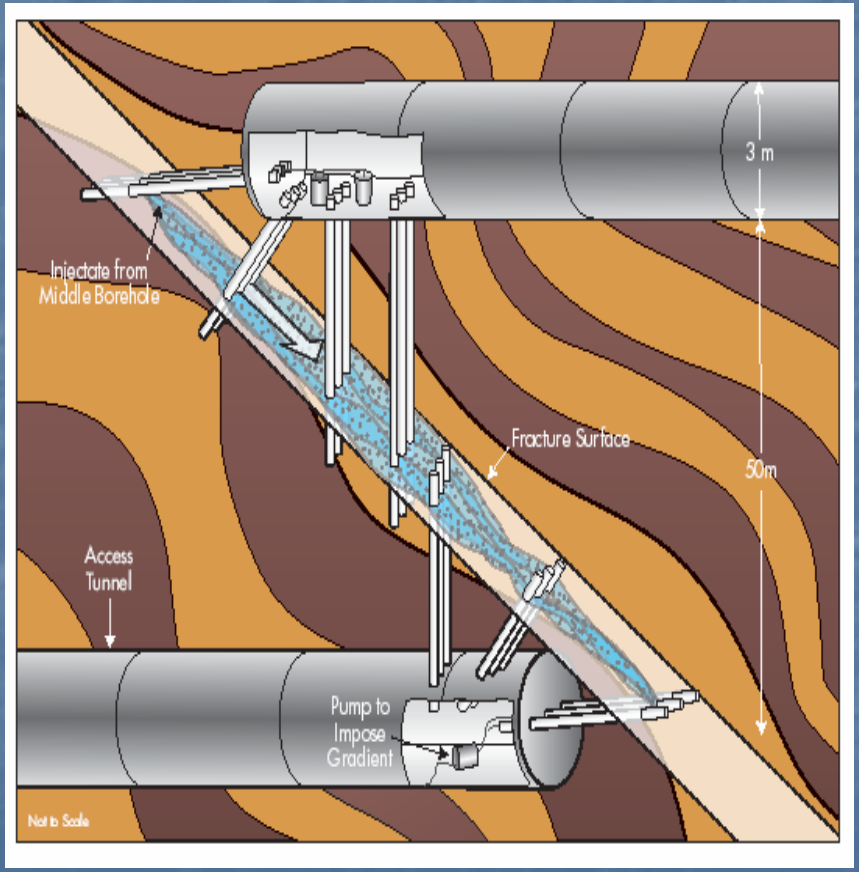
- Evaluate and refine models of fracture initiation and propagation
  - Resource recovery
  - CO2 sequestration
  - Waste isolation
- Examine effects on proximal fluid flow and transport including proppants
  - Wellbore interaction effects
  - Pressure solution in fractures
  - Examine roles of different propellants
- Examine roles of fractures in bacterial colonization
- Examine the long-term stability and durability of underground openings



http://www.earthlab.org/

Deep Coupled Processes Laboratory

- Characterize coupled-processes that affect critical environmental engineering, and complex subsurface Earth processes
  - CO2 sequestration
  - Waste isolation
  - In situ mining
  - Mineralization and ore body formation
- Characterize coupled processes under ambient conditions
- Chemical fate and transport including dissolution/precipitation and modification of mechanical and transport parameters
- Multiphase flow and transport
- Microbial colonization

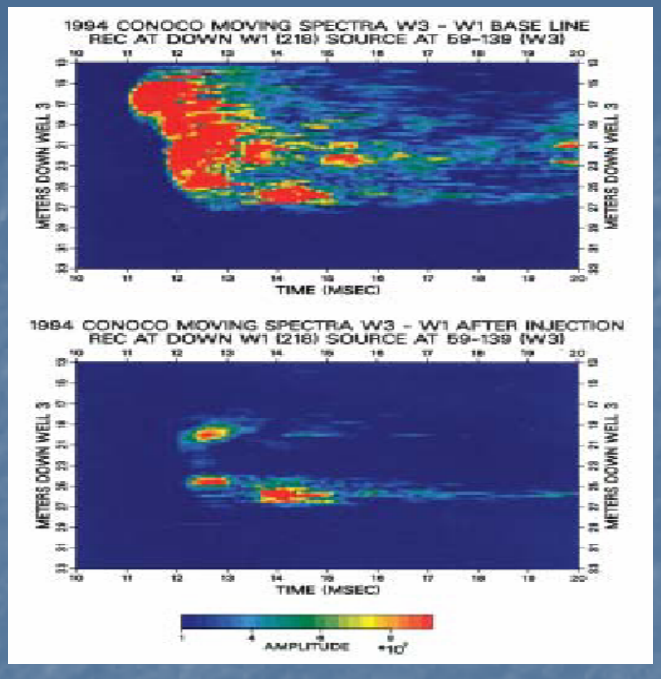


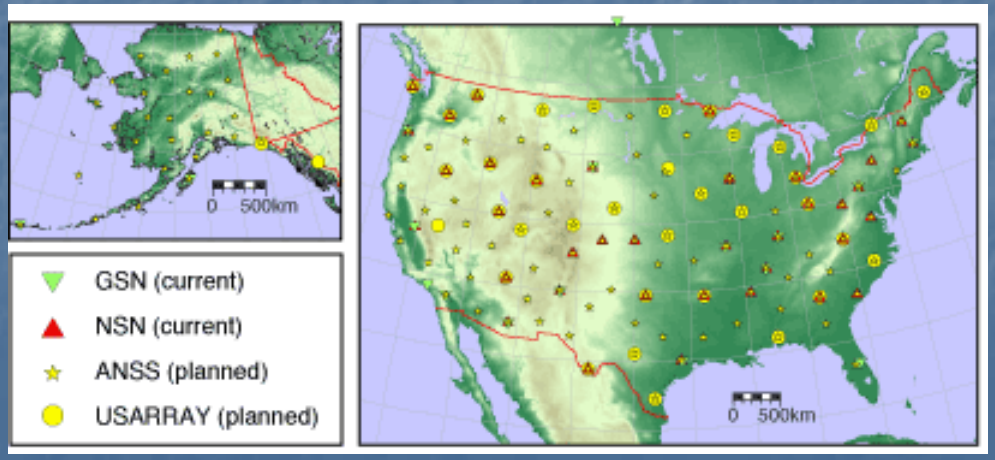
http://www.earthlab.org/

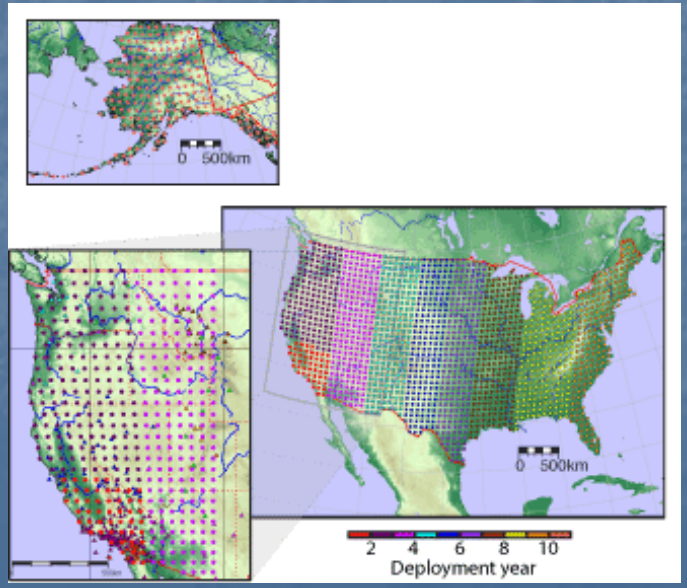
http://www.earthlab.org/

Deep seismic observatory

- Investigate physics relating fracture formation to seismic wave propagation
- Monitor local and global seismic events and mining seismicity
- 3D array of ~60 broadband stations
- Complement transportable and permanent components of USArray







http://www.earthscope.org/usarray/

http://www.earthscope.org/usarray/

How DUSEL [May] Fit These Needs

- What's so special about DUSEL?
- What kind of experiments could be done?
- What kind of experiments have been done?

[Courtesy Tom Doe: NRC COGEE presentation of August 2003]

What kind of experiments have been done?

- What is going on with radwaste research facilities over past 25y?
  - Granite
  - Clayrock
  - Salt & Tuff
- What are the scientific issues and accomplishments
- .....

What Questions Remain Unresolved? ....For working groups?

(Joint with Tommy Phelps)

- Attributes of different geo-environments

  what can be done optimally....what cannot?
- Coordination of activities
- Define incompatibilities
- Integrate site-characterization with project

Attributes of different geo-environments

Sci/Eng Focus	Relevant Attributes
Overall/Geo/Eng	Low-high stress Low-high thermal gradient Small-large site volume Homogeneous-heterogeneous Unfractured-fractured Ramp access – shaft access
Geo-biological	Sterile-teeming
Geo-chemical	Reactive-inert High-low electrochemical flux
Geo-hydrological	Permeable-porous to non-porous/fractured
Geo-mechanical	Brittle-ductile Low-high stress
Geo-physical	Aseismic-Seismic

Define Incompatibilities

- Explosions & blast mechanics::AFM
- Radio-labeled tracers [or interred radioactive waste?!?]::radiation detection experiments
- Deep-hot-wet environment::getting anything done
- .....

Basic Technical Requirements for DUSEL Modules?

.....For working groups to decide.....?

Conditioned by ....
..... The excellence of the science...
.....The relevance of the engineering....
.....types of experiments needed....

Complementary [not competitive/duplicative] with current URLs and IDP studies

Separated-from or integrated-with detector sites/caverns?

Broad community consensus of important issues

What Will be Done in 20 years?

Never make predictions, especially about the future....

Sam Goldwyn Mayer

Heavier than air flying machines are impossible.....

Lord Kelvin, President, Royal Society, 1890-95.

- Digital/transparent/glass Earth for characterization of structure <u>and</u> properties
  (Faster, more reliable, less expensive, more information)
- Transparent prediction of processes
  (Faster, more reliable, less expensive, more accurate)

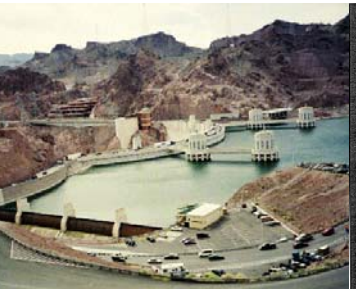
  ..... especially those that contribute to:
  - Complex THMCB interactions
  - Post-peak behavior of rocks

.....and therefore affect the performance of natural processes and engineered structures..... In space and time.....

What will we need to do better in 20 years?

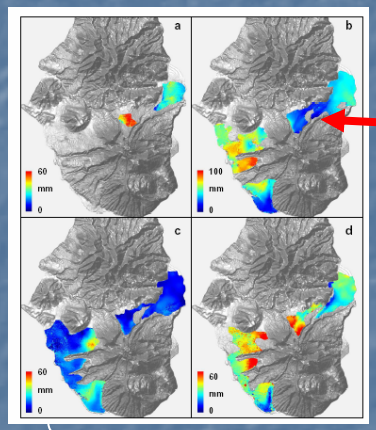
Grand Challenges…..

- Resource Recovery
  - Locate resource
  - Access quickly and at low cost
  - Recover 100% resource at chosen timescale
  - No negative environmental effect
- Waste Containment/Disposal
  - Characterize host at high resolution
  - Access and inter quickly at low cost
  - Inter completely or define fugitive concentration output with time
- Underground Construction
  - Characterize inexpensively at high resolution
  - Excavate quickly and inexpensively
  - Provide minimum support for maximum design life
  - ……



Rapid and Non-invasive Fine-scale Characterization of Material Characteristics

Non-invasive distributed measurements

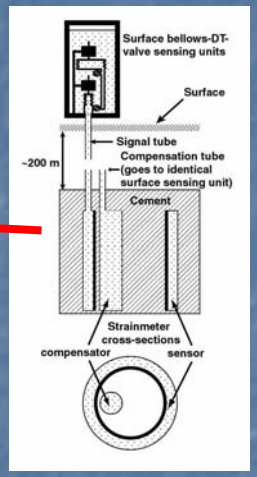


e.g. INSAR

Passive and Active Geophysics

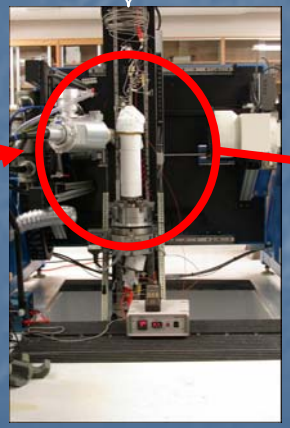
Other?

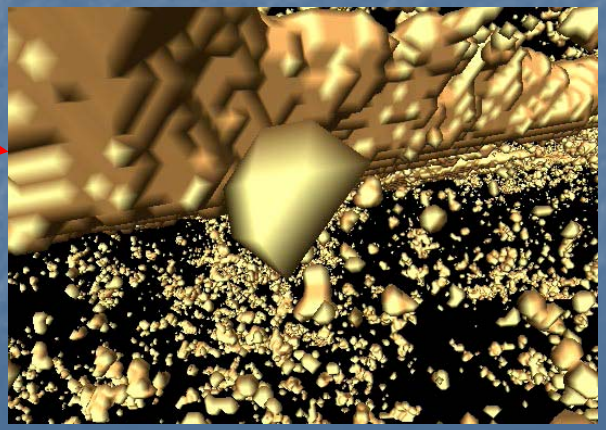
Invasive point measurements



e.g. Strainmeters

Tilt, CGPS





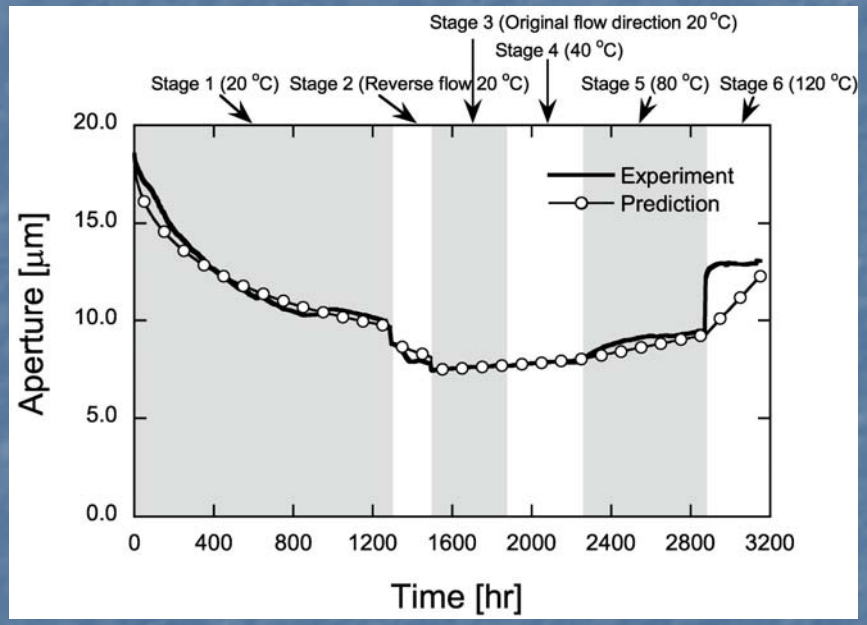
Structure -> Spatial scale effect

Complex Phisio-Chemical THMCB -> Temporal scale effect

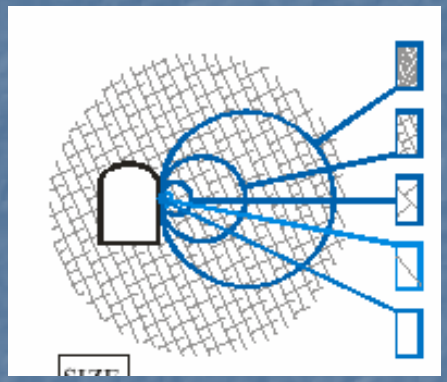
Complex Coupled THMC Processes

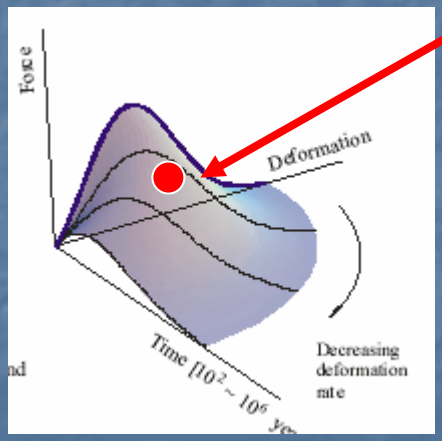
- Fine-scale resolution of influence of physical and chemical interactions of fluids and rock on properties, e.g. reactive chemistry in a stressed environment on physical hydrology……

Cold …… to …….Hot



Rock Fracture and Post-peak Failure Behavior – Time to Failure?





- Analysis: Since Galileo?
- Characterization
  - Structure
  - Initial Conditions
  - Constitutive Relationships
- DUSEL Offers:
  - Long occupation
  - Large-scale lab

Rock Fracture and Post-peak Failure Behavior

- Drilling and excavation efficiency
- Minimal excavation support
- Security and vulnerability of structures
- Earthquake mechanics
  - Second-order friction effects
  - Role of fluids
  - Mechanisms of healing

Underground Science Laboratory
Potential for Scientific and Engineering Innovation

- Genetic materials, microorgansisms with novel capabilities, biotechnology applications
- Instrumentation for monitoring/mapping in extreme environments (subsurface MEMS/NEMS imaging/sensors), applications in exobiology & underground mine mapping (robotics, lasers)
- Environmental remediation technologies (contaminated groundwater)
- CO2 sequestration field testing (leakage, impact)
- Drilling & excavation technology (rock engineering, structural support of rock masses)
- Natural resource exploitation and development

EarthLab Report to NSF, 2003.

That’s All Folks!