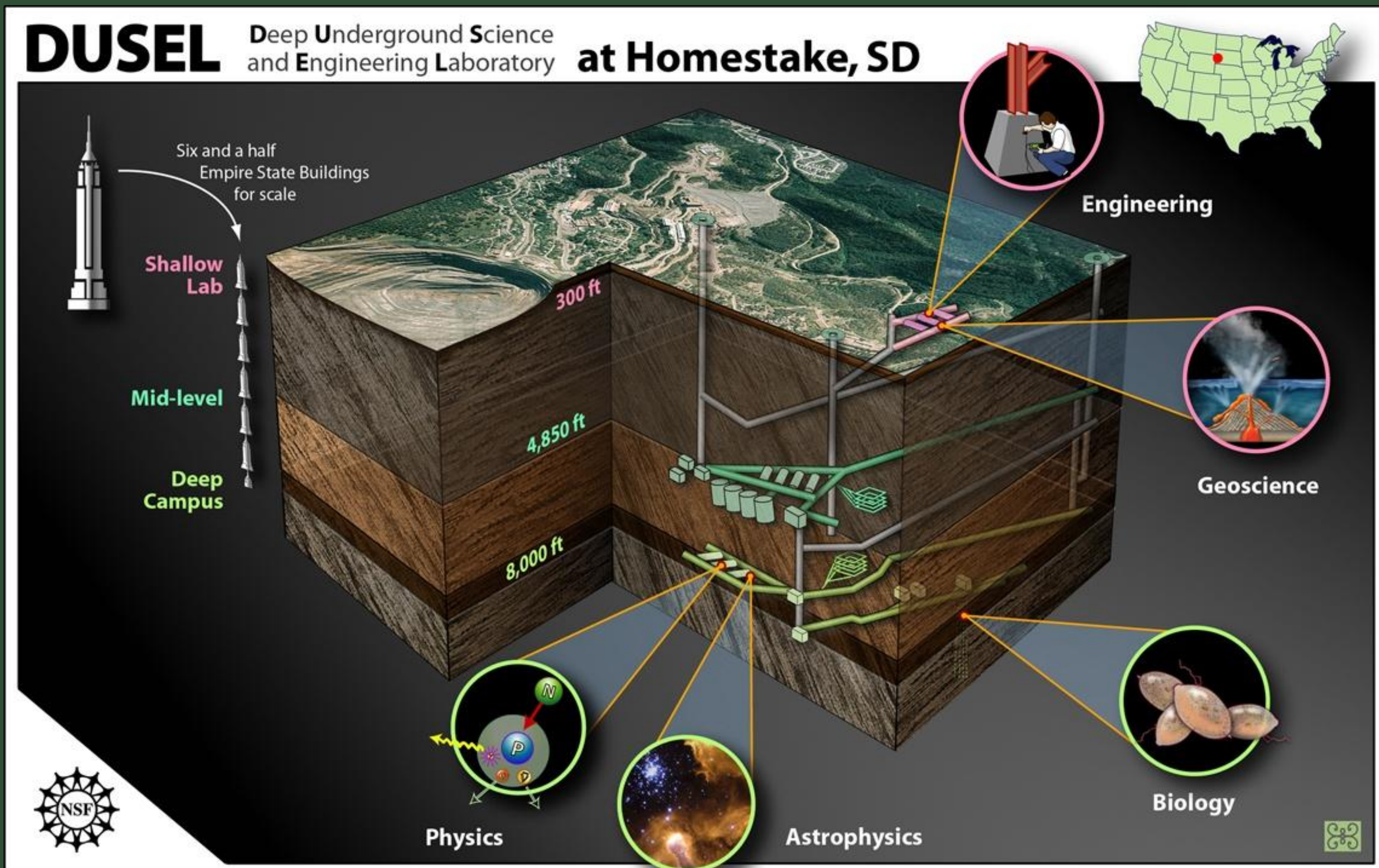
DUSEL Experiment Development and Coordination (DEDC)

NSF Visit

March 19 & 20, 2008

Steve Elliott, Derek Elsworth, Larry Murdoch, Tullis C. Onstott and Hank Sobel



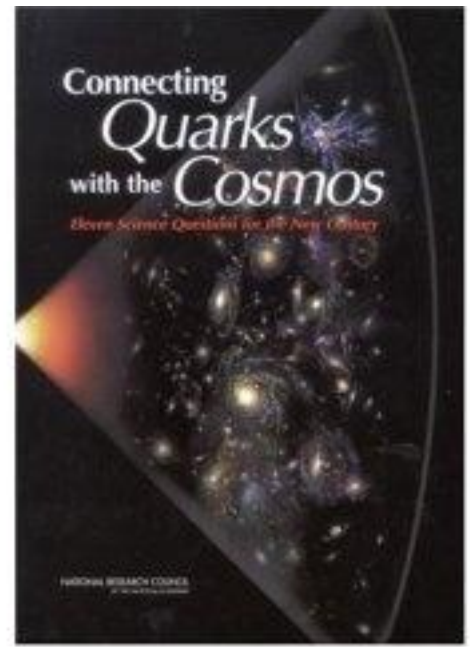
Purpose

- Broadcast recent activities towards the development of a deep underground science and engineering laboratory (DUSEL)
- Share science opportunities with the research and academic community beyond those already engaged within DUSEL-related activities
- Solicit input from NSF regarding how DUSEL can best serve their needs and the needs of their research constituencies

Outline

- Why DUSEL?
- Recent Path and Current Status of DUSEL
- Societal Imperatives for Geo-Science and Geo-Engineering
- Overview of Proposed DUSEL Science Plan (Objectives)
  - Underground Universe (Physics and Astrophysics)
  - Restless Earth (Geoscience)
  - Dark Life (Biology)
  - Ground Truth (Geoengineering)
- What Will Be the Benefits of DUSEL? (Outcomes)
- The Path Ahead

Physics and Astrophysics Grand Questions



- Coverage of the grand questions
  - What is the Dark Matter?
  - Exploration and exploitation of neutrinos to uncover the origin of mass and matter, and to understand the sun
  - Are protons really stable?
  - Origins of the Elements?
- Why study the Universe from 1-2 miles underground?
  - Surface `noisy'… physics signals of interest are like a whisper in Manhattan traffic
  - Interesting particles of astrophysical origin easily penetrate… $1/10^{13}$ interact when passing through the *whole earth* !
- Detectors as pure and massive as possible

Recent Evolution of DUSEL

- 2000: Homestake closure announcement. Meeting with Earth science and physics communities
- 2001: Underground Science Meetings; Earth science, physics and geomicrobiology workshops
- 2002: NSF visit, ARMA/NRC and NeSS meeting
- 2003: ARMA-NSF and EarthLab reports
- 2004: NSF S-process announcement, S-1 workshops
  - Inaugural Workshop – Berkeley August 2004
  - GeoScience and GeoEngineering – Blacksburg November 2004
  - Bio- and Geo-sciences – Boulder January 2005
  - Synthesis – Minneapolis June 2005
- 2005: S-2 applications,
  - H-H selection + 2, AGU townhall, S-2 workshops
- 2006: CDR-100 for S3 & S-1 Reports
- 2007: CDR-250 for S-3
  - Homestake Site Selection
  - Establish DEDC and Design Initial Suite of Experiments
- 2009 MREFC Application
- 2011 Initial Suite of Experimentation

Scientific Rationale & Societal Imperatives

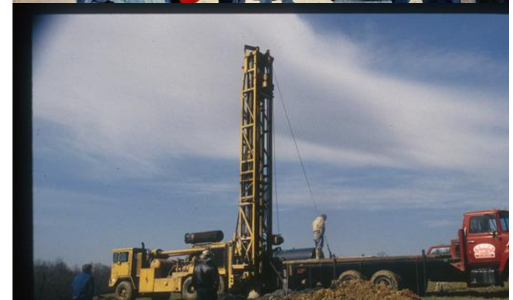
- **Resource Recovery**
  - Petroleum and Natural Gas Recovery
  - In Situ Mining
  - HDR/EGS
  - Potable Water Supply
  - Mining Hydrology
- **Waste Containment/Disposal**
  - Deep Waste Injection
  - Nuclear Waste Disposal
  - CO_2 Sequestration
  - Cryogenic Storage/Petroleum/Gas
- **Site Restoration**
  - Aquifer Remediation
- **Underground Construction**
  - Civil Infrastructure
  - Mining
  - Underground Space
  - Secure Structures

Both GeoHydrology and GeoMechanics

Mainly GeoHydrology

Mainly GeoMechanics

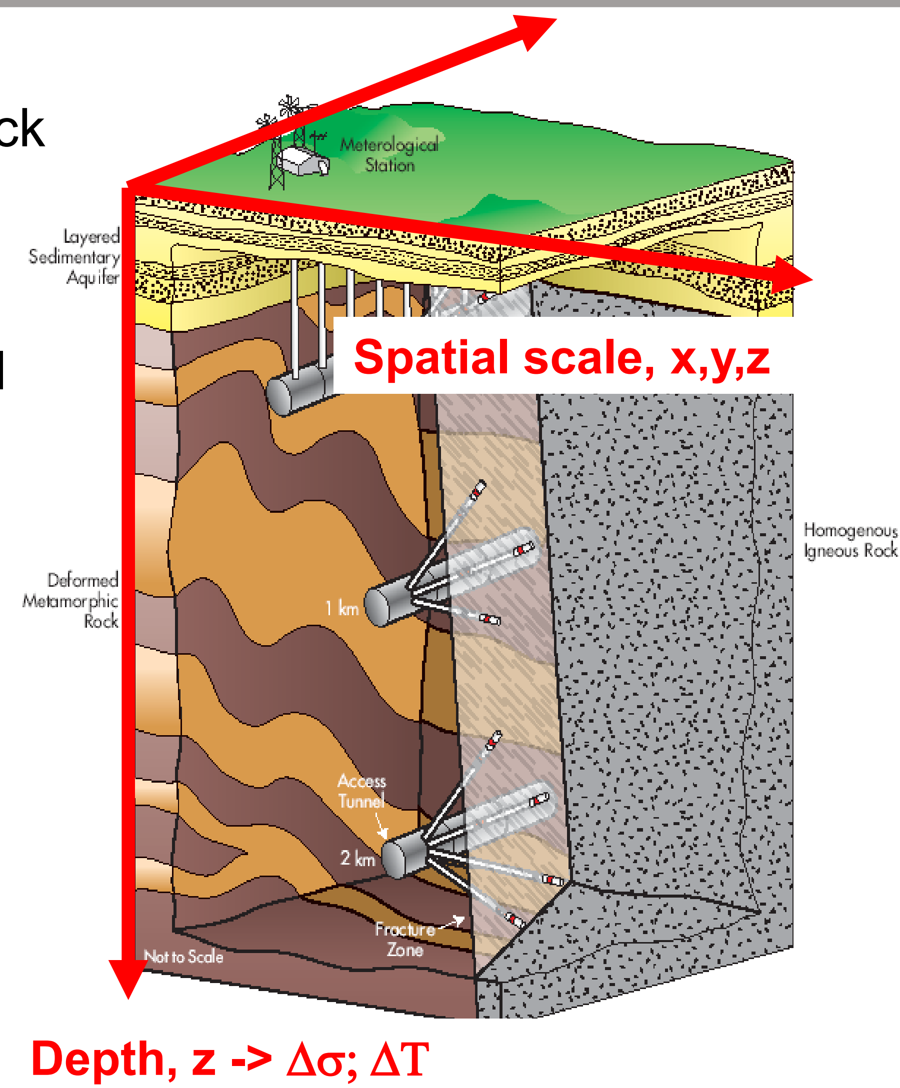




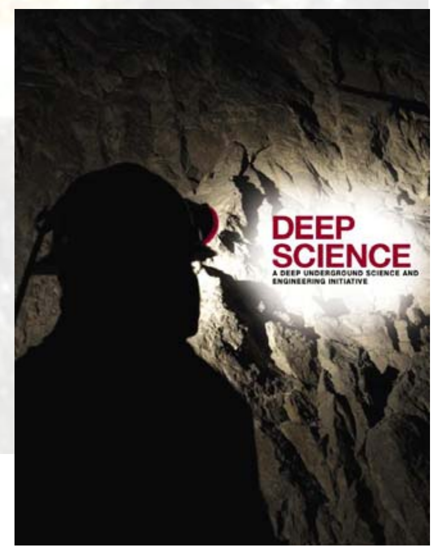
Why DUSEL?

- 4D - Experiments within a block of rock (~km-scale) at depth and at *in situ* temperature and stress.
- Access to fluids and gas with minimal contamination for molecular studies.
- Capabilities to characterize the rock block at multiple scales.
- Access to controlled energy sources.
- Proximal access to clean laboratory, fabrication facilities and unique technologies.



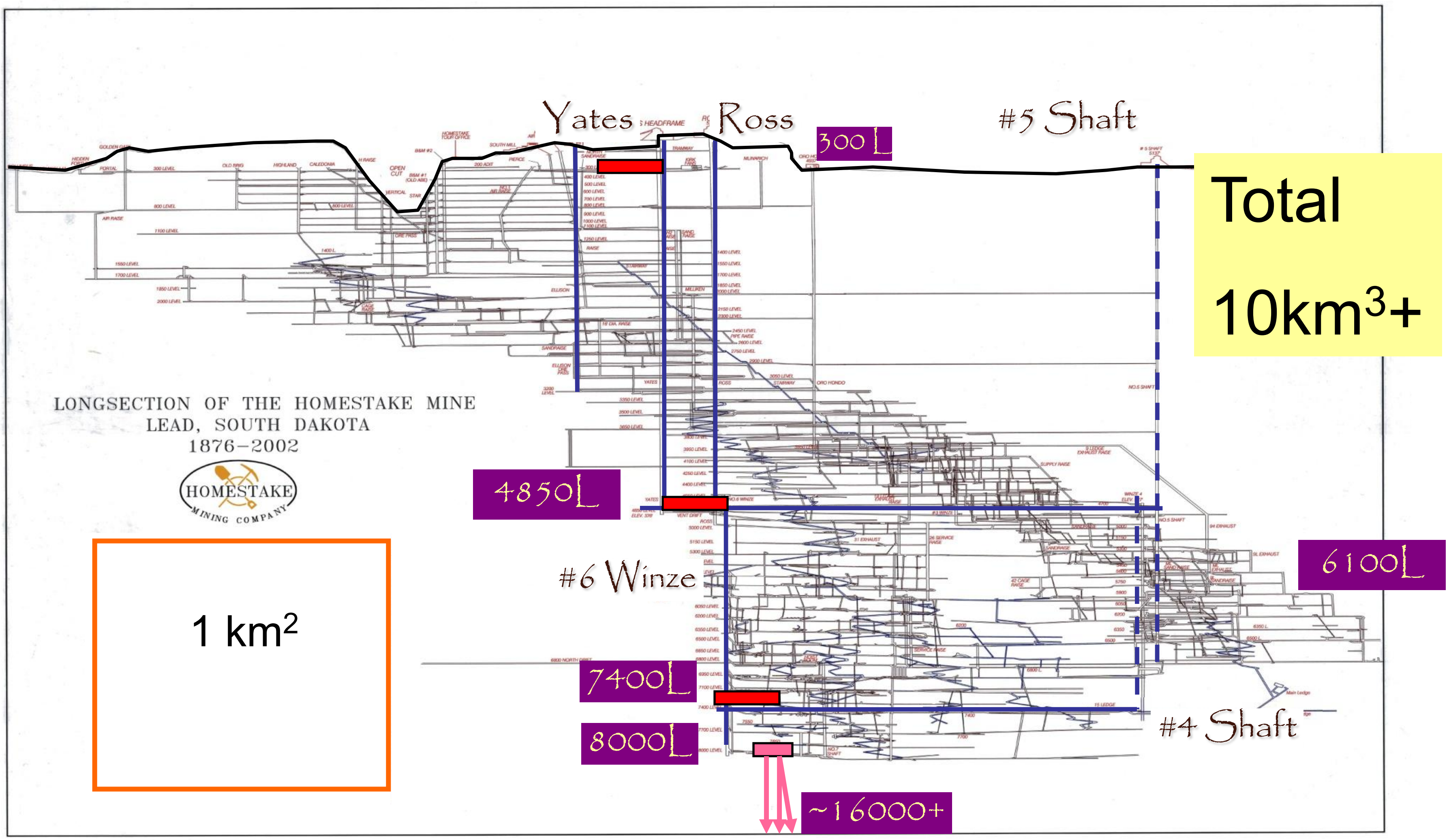
The Geo-Universe – Science Questions

- Dark Life (Biology)
  - How deep does life go?
  - Do biology and geology interact to shape the world underground?
  - How does subsurface microbial life evolve in isolation?
  - Did life on earth originate beneath the surface?
  - Is there life on earth as we don't know it?
- Restless Earth (Geosciences)
  - What are the interactions among subsurface processes?
  - Are underground resources of drinking water safe and secure?
  - Can we forewarn of earthquakes?
  - Can we view complex underground processes in action?
- Ground Truth (Geoengineering)
  - What lies between boreholes?
  - How can technology lead to a safer underground?
  - How do water and heat flow deep underground?

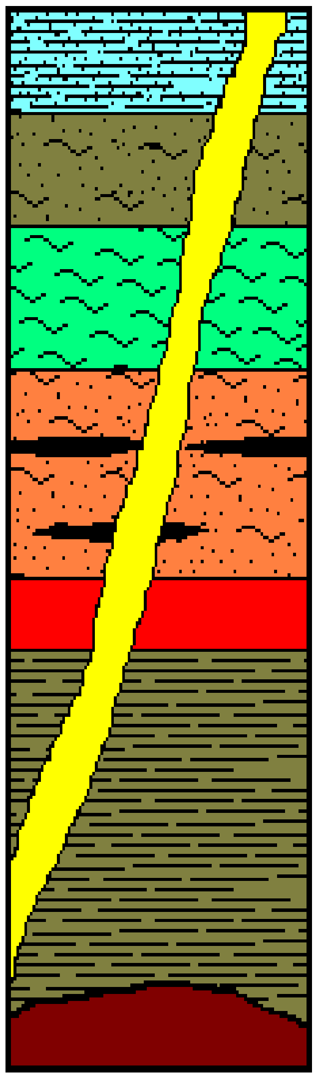


Bio-Geo-Eng Laboratory

Campus + Whole-mine activities (60 levels)



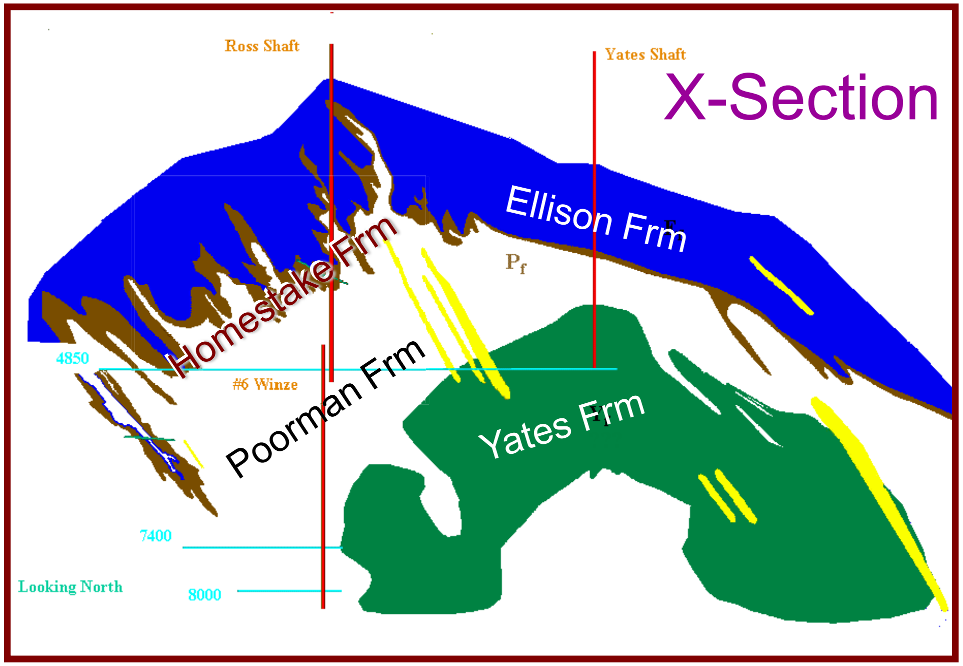
Site Conditions: Proterozoic Stratigraphy

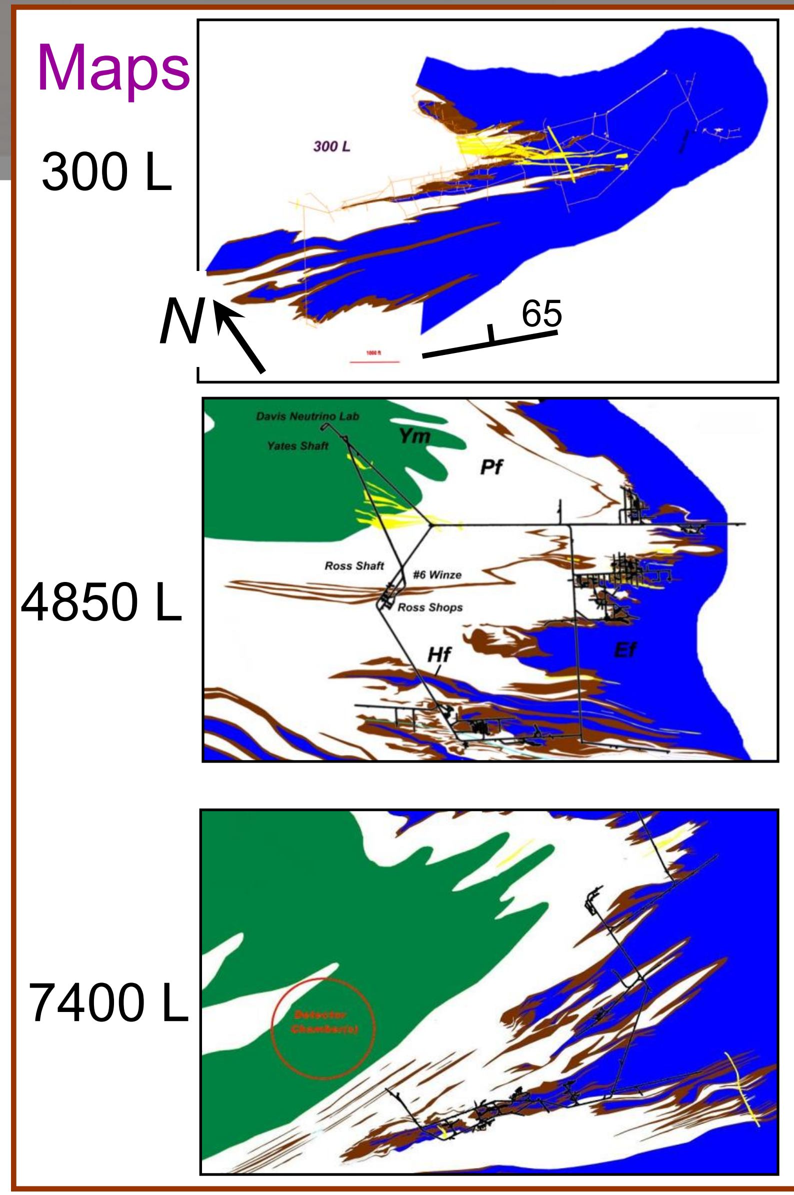


- **Grizzly Formation** - Metagraywacke, sericite-biotite schist
- **Flag Rock Formation** - Biotite-sericite schist, graphitic phyllite
- **Northwestern Formation** - Biotite-qtz-sericite-garnet schist
- **Ellison Formation** - Quartzites, Sericite-biotite schist and phyllite
- **Homestake Formation** - Grunerite/Siderite schist, chert
- **Poorman Formation** - Sericite-biotite carbonate phyllite
- **Yates Unit** - Hornblende-plagioclase schist and amphibolite

Greenschist→Amphibolite grade

Conditions: Geology





- Subsurface geology is complex, well-known.
- Structure: Isoclinal folds, shear zones, general dip 65° NE. Later joint set.
- Wide range of rock compositions at every level.

Active Processes and Site Conditions

Processes

- Flow
- Transport
- Deformation
- Reaction
- Diversity
- Activity
- Evolution

Conditions

- Large Scale
- Large Stress
- Detailed and Controlled Access
- Long Duration
- Physical, chemical and biological heterogeneity

Example ISE: Induced rock deformation processes

- Fracture propagation
- Fluid flow in networks
- Deformable fractures
- Faulting
- Scaling of fracture energy

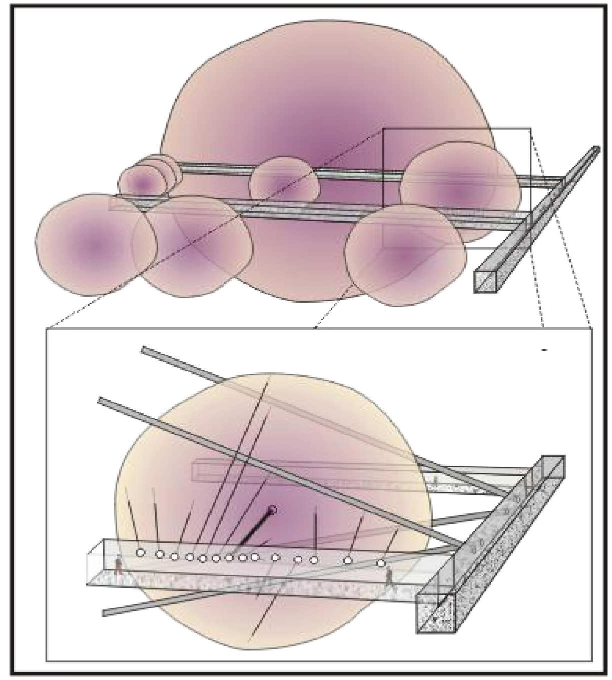
- Propagation of fault in intact rock
- Gouge development
- Friction laws
- Fault reactivation
- Corresponding seismic response
- Fluid effects…..

San Andreas Fault, Carrizo Plain, CA

Approach

Create idealized fractures for basic processes, then move to natural fractures

- Hydraulic fracturing to evaluate Mode I propagation
- Change stresses using thermal technique→"designer fractures"
- Small stress change
  - a. stress and permeability (up to critical stress)
  - b. create cross-cutting hfrx→development of percolating networks
- Large stress change
  - a. slip on existing fractures
  - b. gouge development
  - c. fault growth



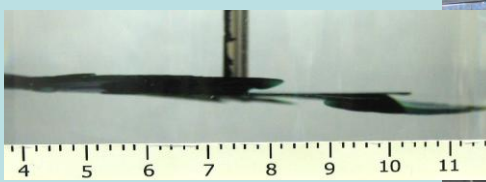
Use well understood/designed fractures and fracture networks to:

- Characterize scaling of fracture energy

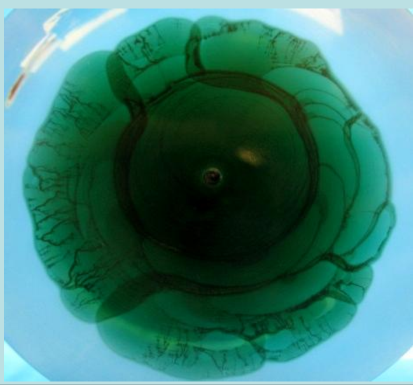
  1 m – 10^2 m; (10^3m?)
- Determine displacement during pressure change
  - a. stiffness vs. aperture
  - b. pressure dependent permeability
  - c. diagnostic tool (e.g. in situ fracture network characterization)

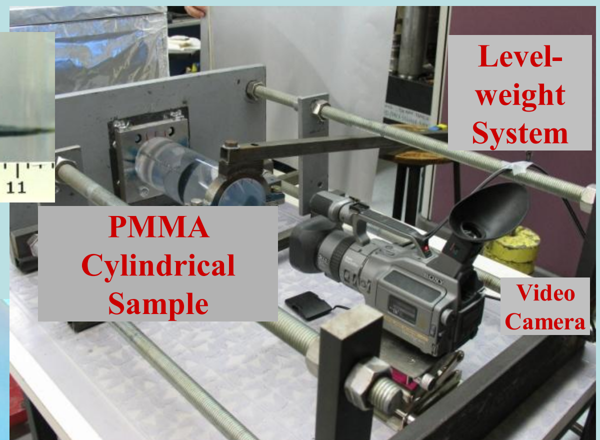
Fracture Propagation

Side View

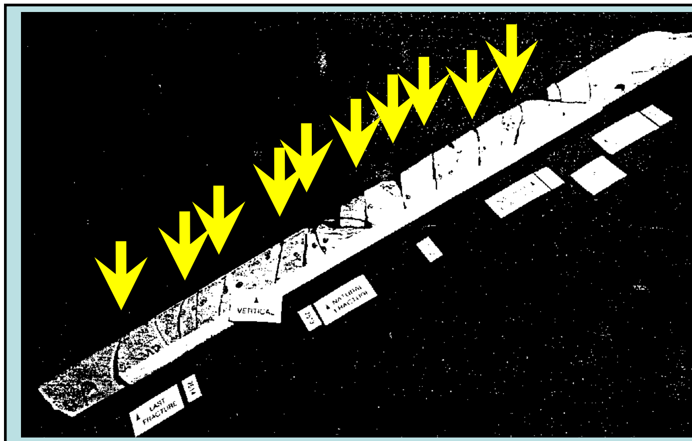


End View





Hydraulic fracture with segments at leading edge created in laboratory [*Germanovich et al*. 2007]

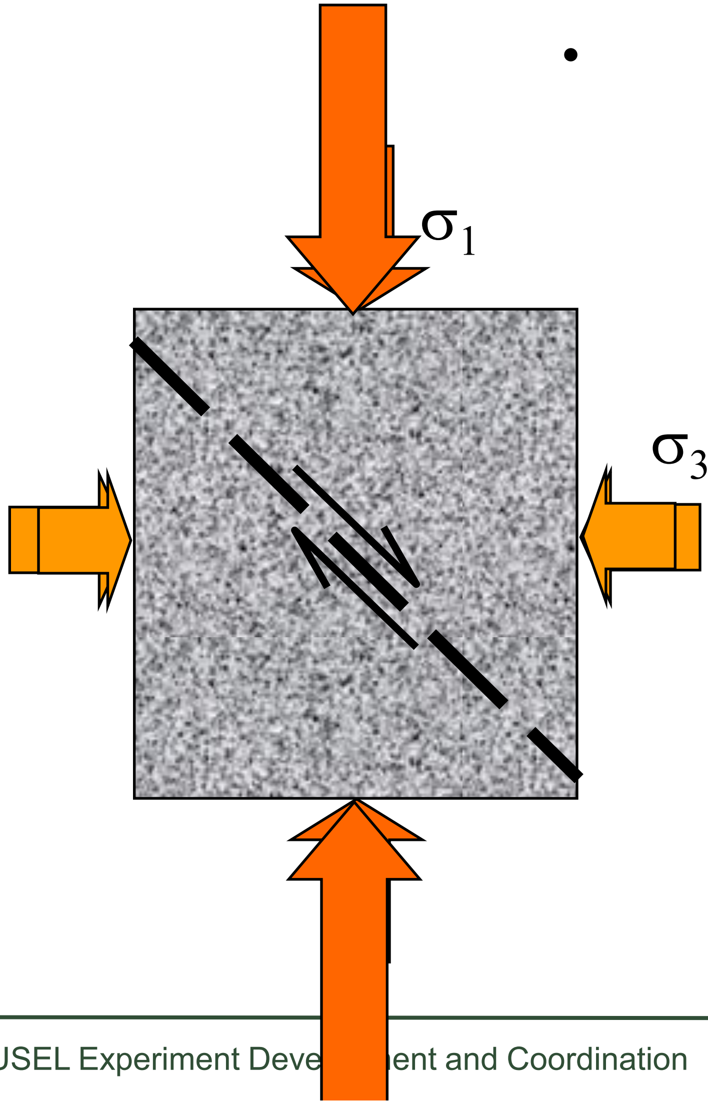


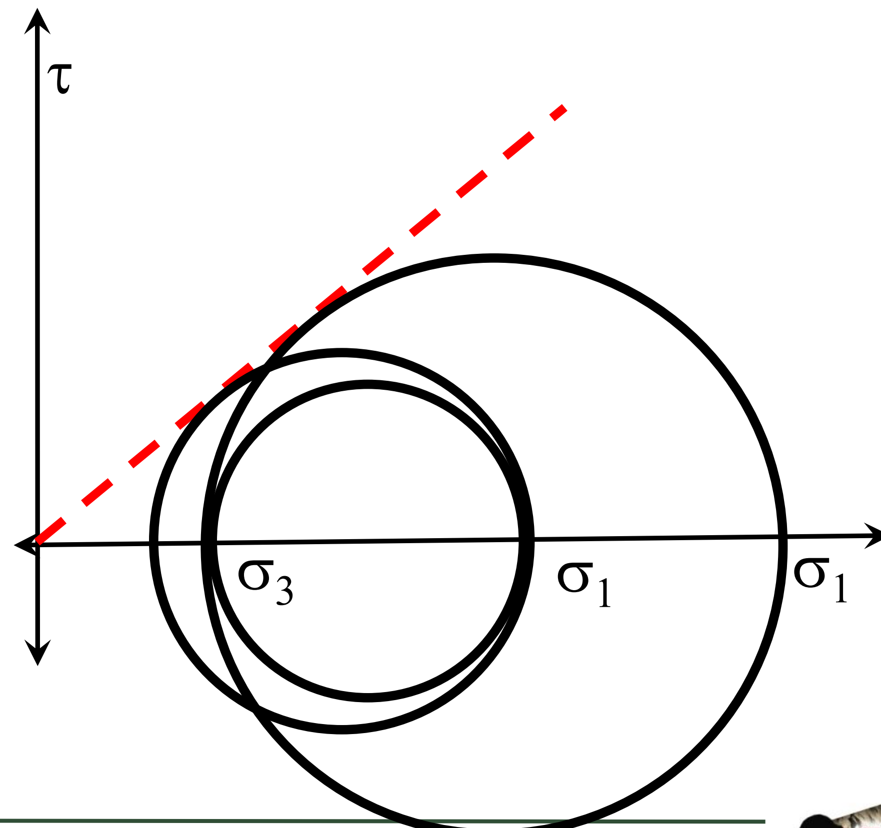
Core from front of a hydraulic fracture. Piceance basin near Rifle, Colorado, 7150 ft depth [*Warpinski et al.*, 1993]

Segmentation at fracture tip appears to dominate energy requirements for propagation → depends on size and confining stress. Need experiments.

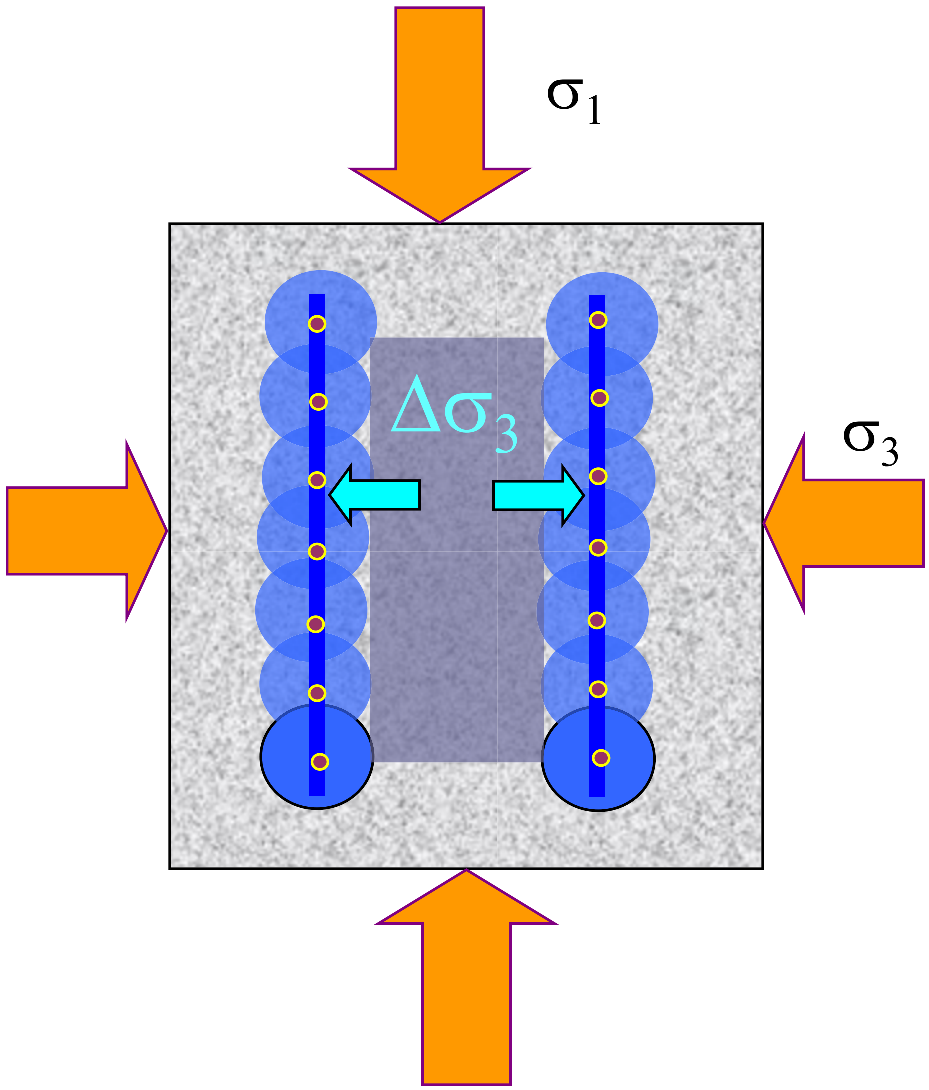
Faulting

- Utilize large, natural in-situ stresses
- Create failure by *reducing* existing load





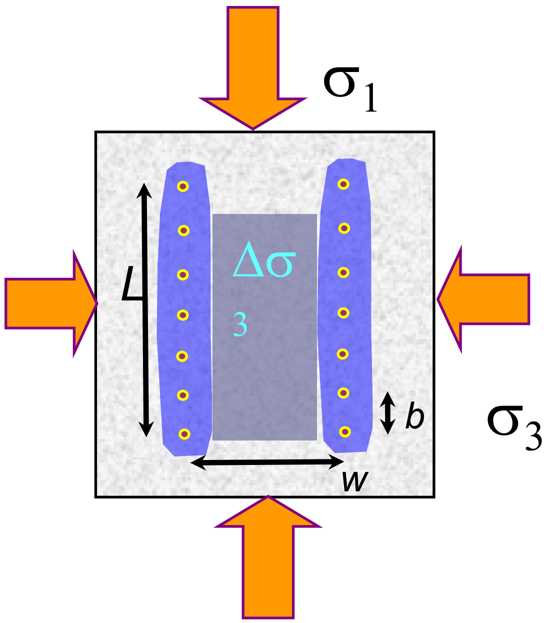
Concept



1. Create a pair of parallel lines of boreholes normal to σ_3
2. Cooling by ΔT reduces σ_3 and allows controlled modification of stress state between lines
3. Reduce σ_3 between boreholes until failure occurs

Could it work?

Preliminary modeling



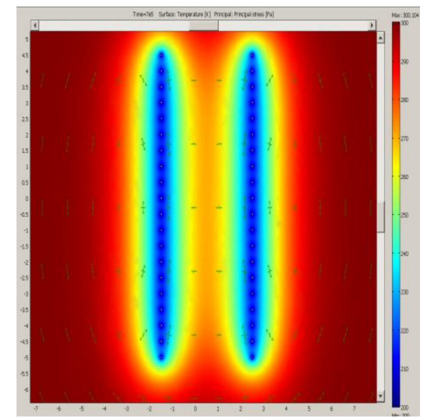
Will the stress change enough to cause faulting?

$$\Delta\sigma_3 = \frac{2\alpha\Delta T\sqrt{D_T t}}{L} = -22\ \text{MPa}$$

$$\Delta\sigma_{3\,failure} = -17\ \text{MPa}$$

Will it be fast enough to be practical?

$$t \approx \frac{1}{D_T}\sqrt{\frac{b}{\alpha\Delta T}} = 13\ \text{days}$$



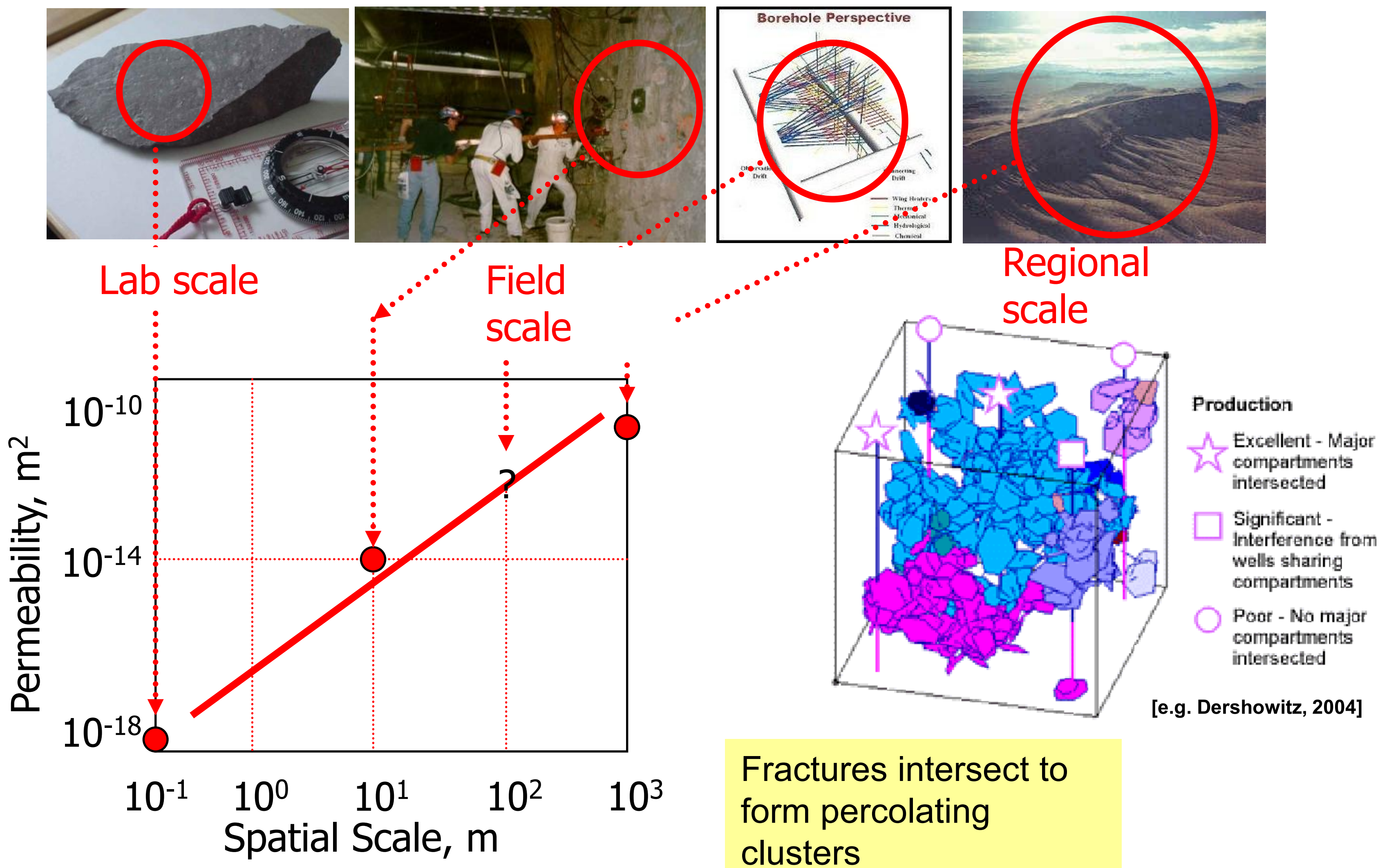
Numerical analyses

Assume
Depth: 1 km

E: 10^{11} Pa
ΔT: 10^2 K
α: 10^{-5} K^{-1}
D_T: 10^{-6} m^2/s
ρ: 2600 kg/m^3
b: 1m
σ_1: 25 MPa
σ_3: 23 MPa
w: 3m
L: 10m

Feasible to create small faults in intact rock to study earthquake triggering at DUSEL. Need range of stresses, rock types; time to develop

Fractures and Scaling of Permeability

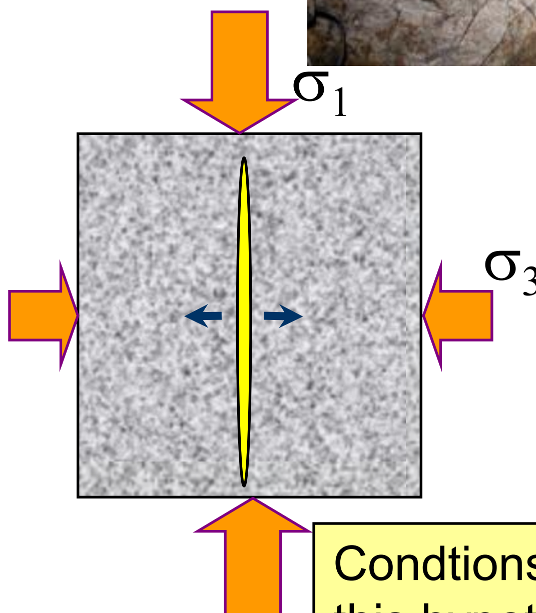


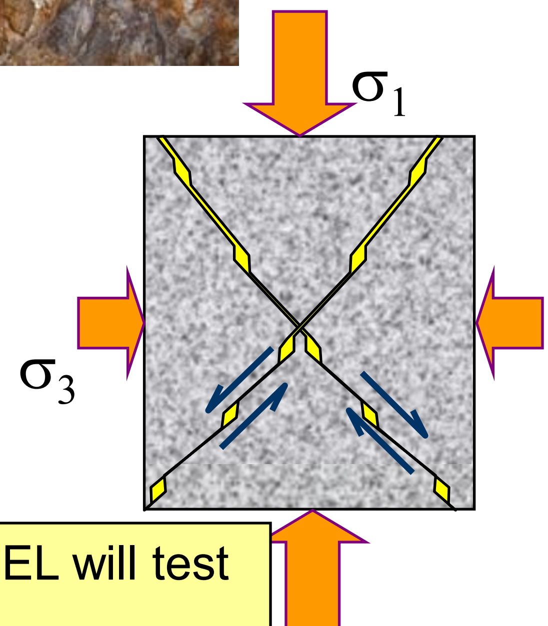
Fractures intersect to form percolating clusters

Fracture permeability and stress

How do fractures develop into cluster of connected networks?

How does state of stress affect properties?





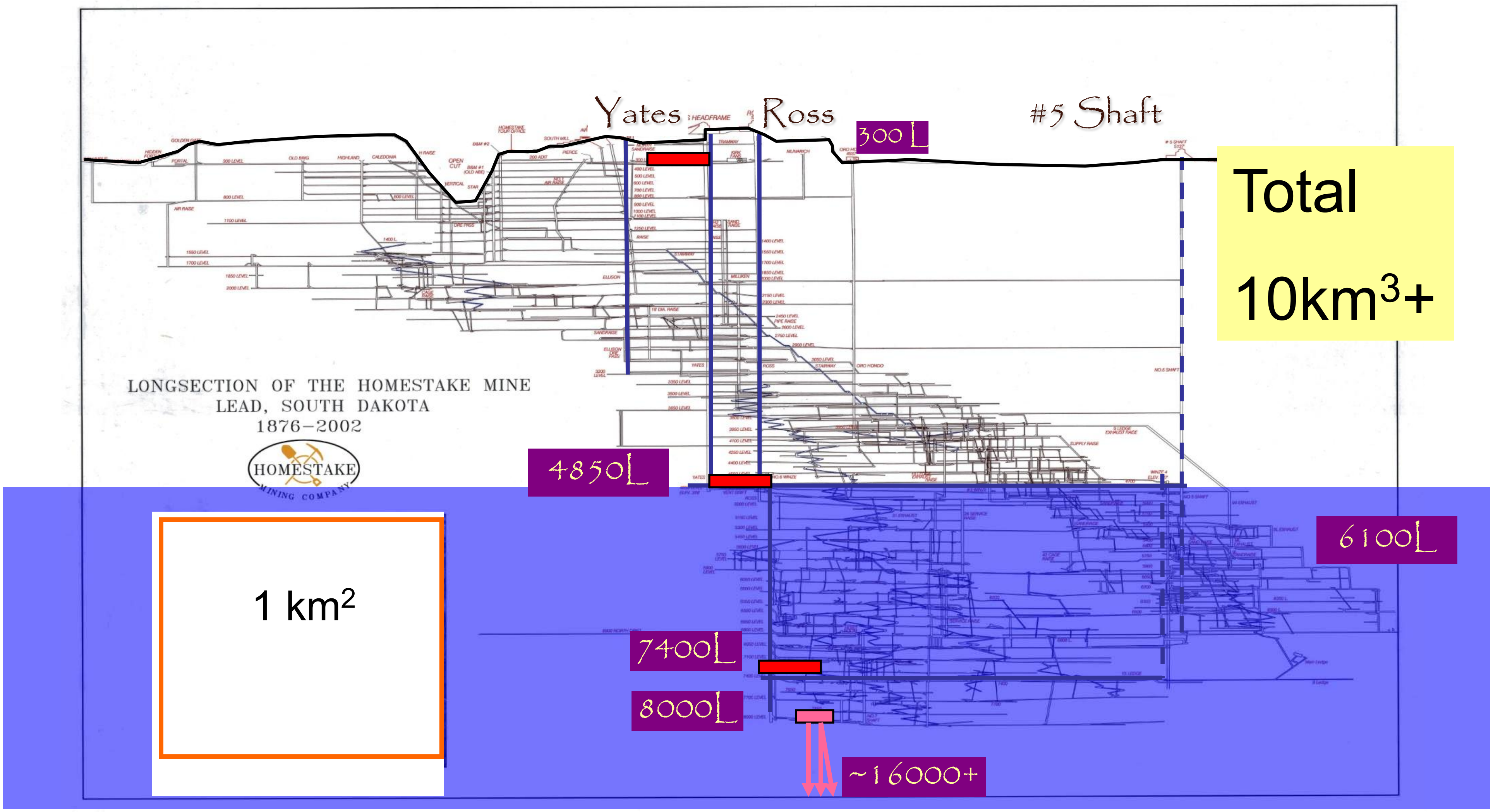
DUSEL dewatering = 1000 m change in water level;

10 MPa change in effective stress.

Condtions at DUSEL will test this hypothesis

Bio-Geo-Eng Laboratory

Campus + Whole-mine activities (60 levels)



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- Transport
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- Reaction
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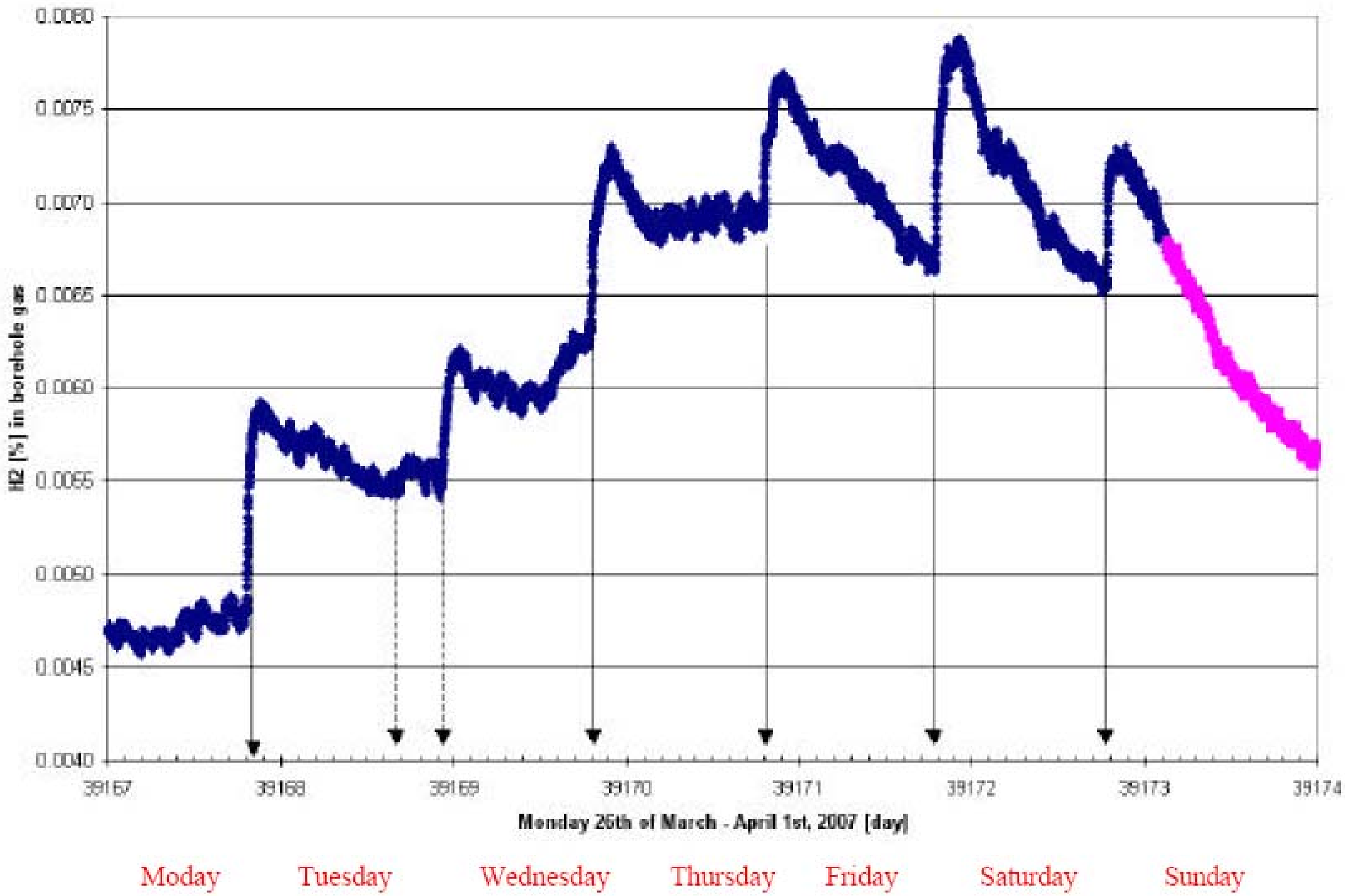
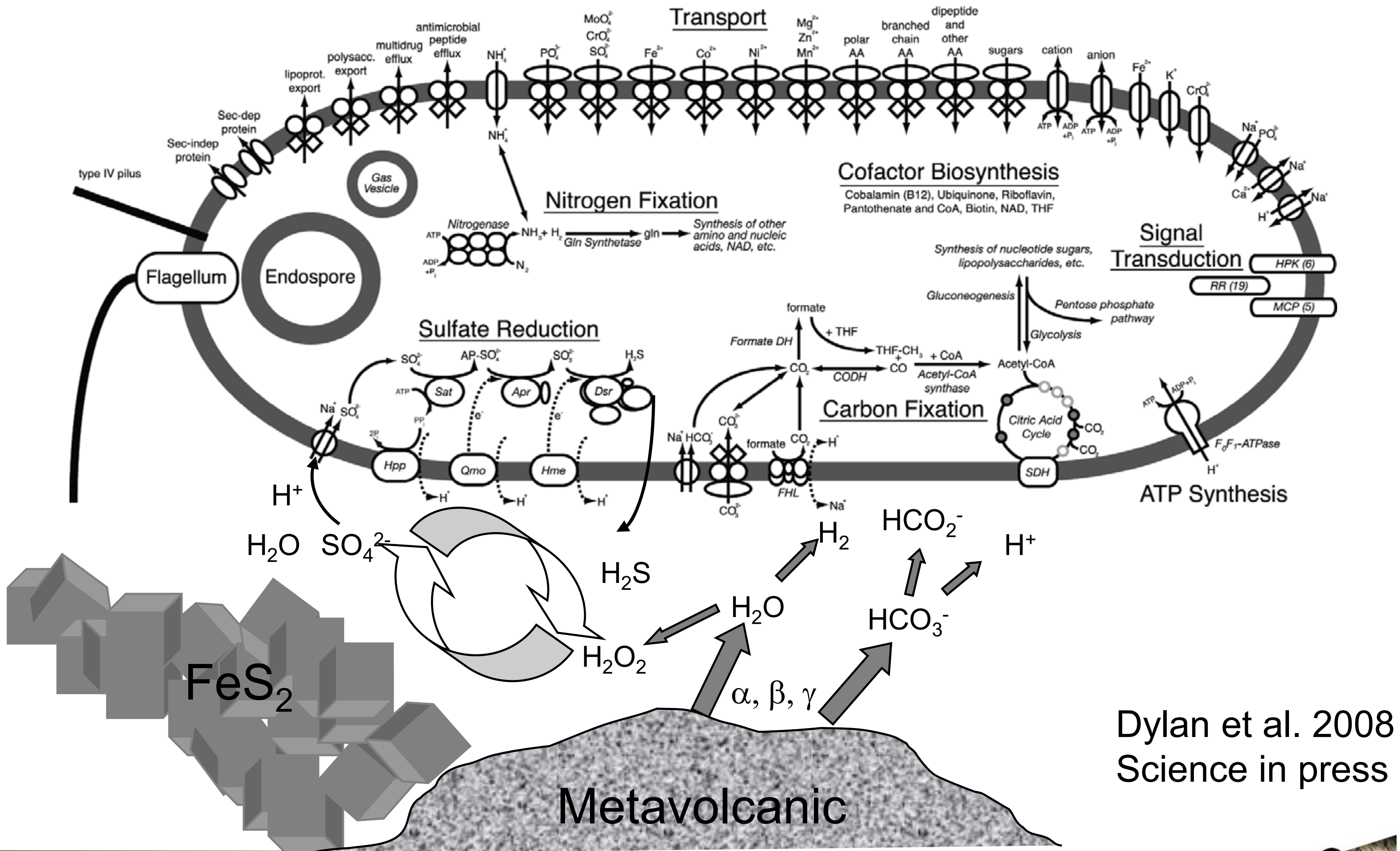
How do biology and geology interact?



H_2 Generation from H_2O reacting with fractured SiO_2

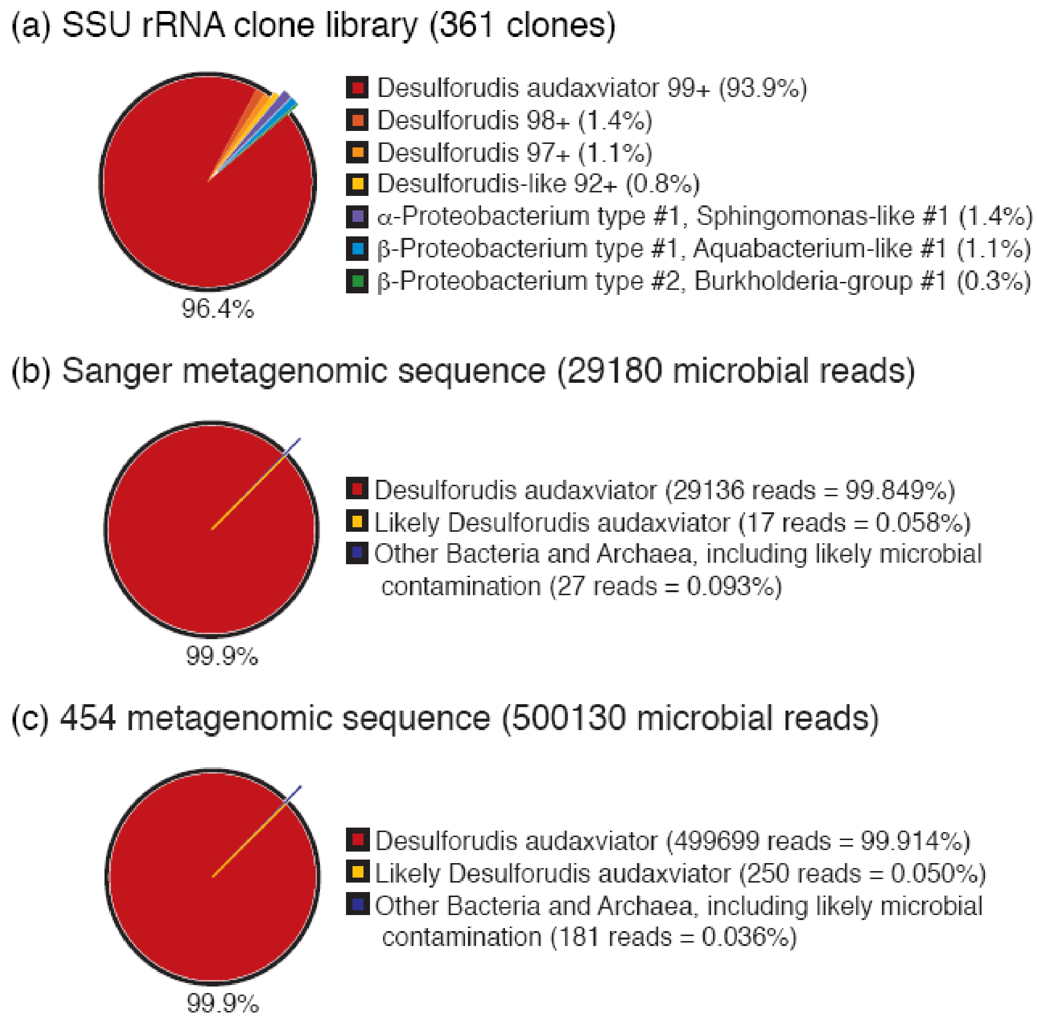
First metagenome from 3 km depth



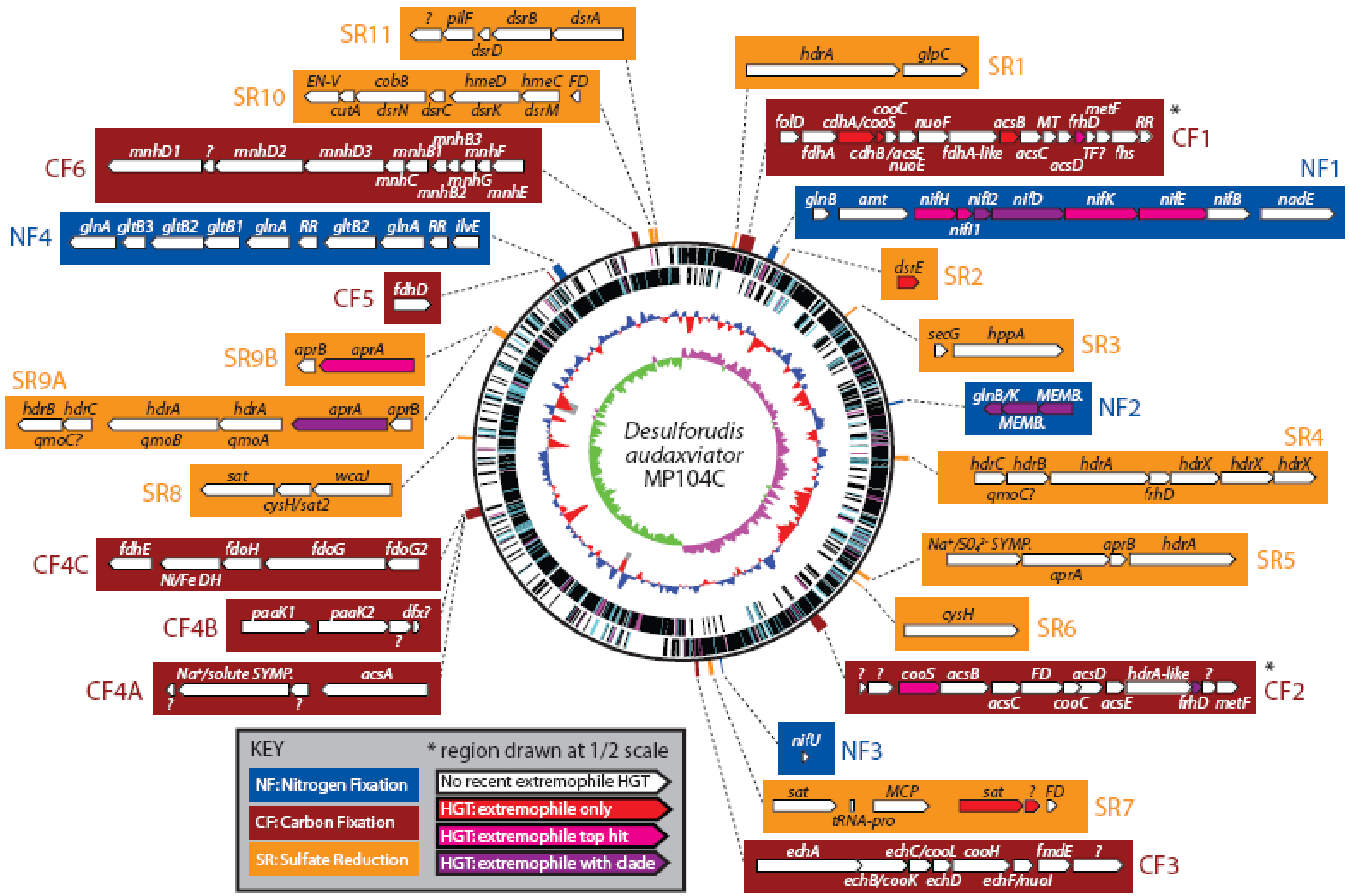
Dylan et al. 2008
Science in press

Single organism biomes

- 10,000 liters of fracture water
- 10^{11} cells
- 99.9% of DNA from *D. Audaxviator*

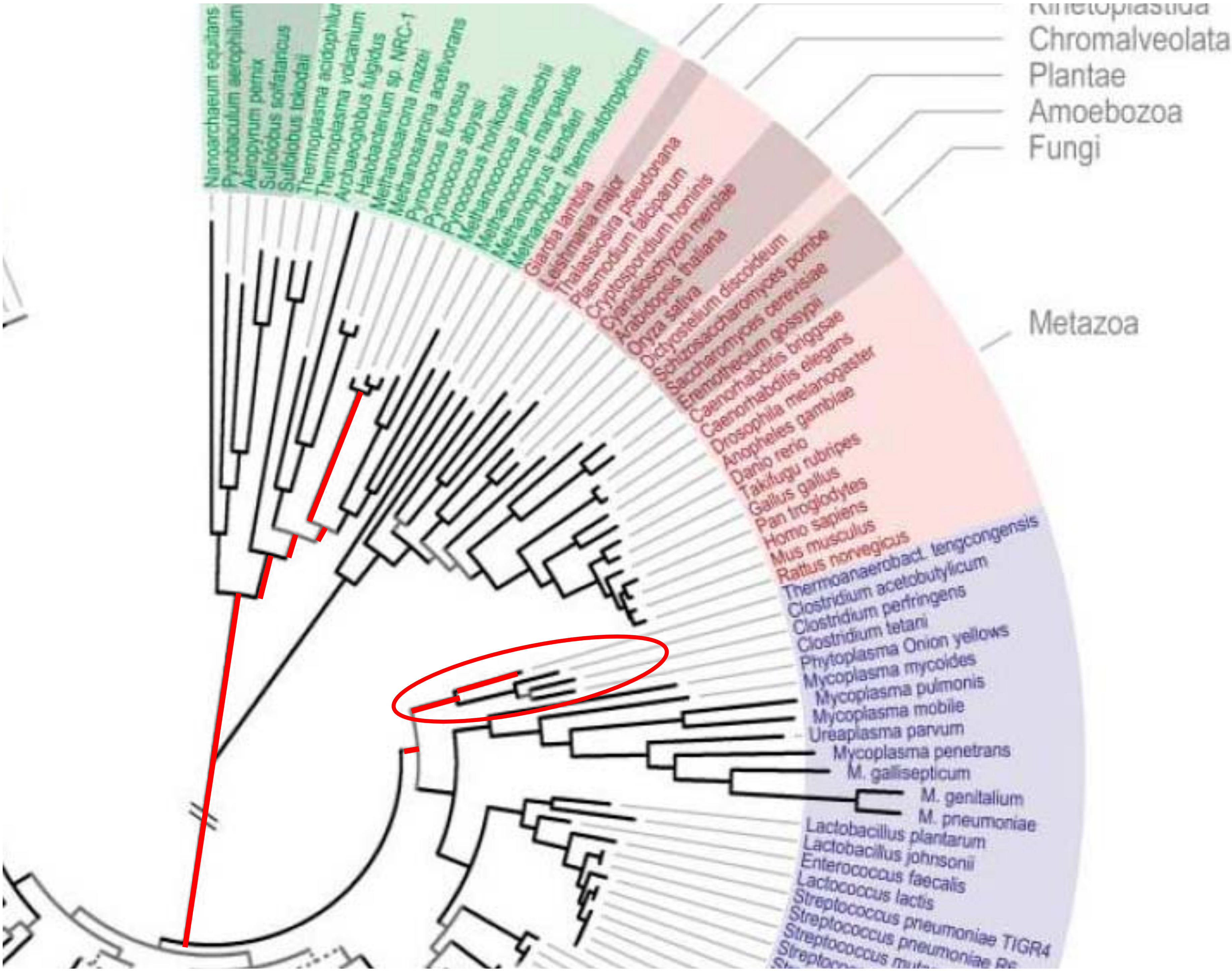


How does subsurface life evolve?

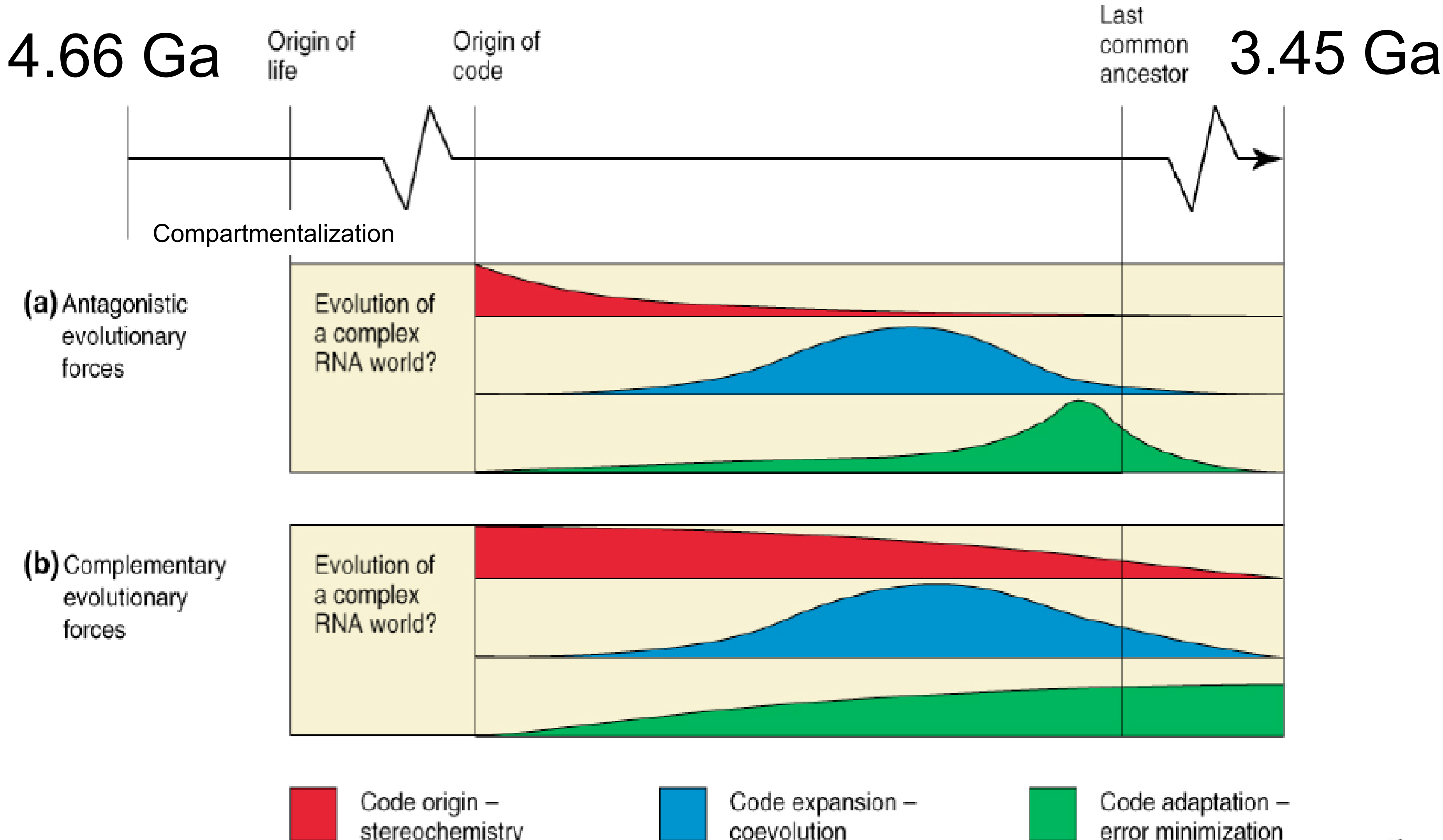


Deep subsurface evolution

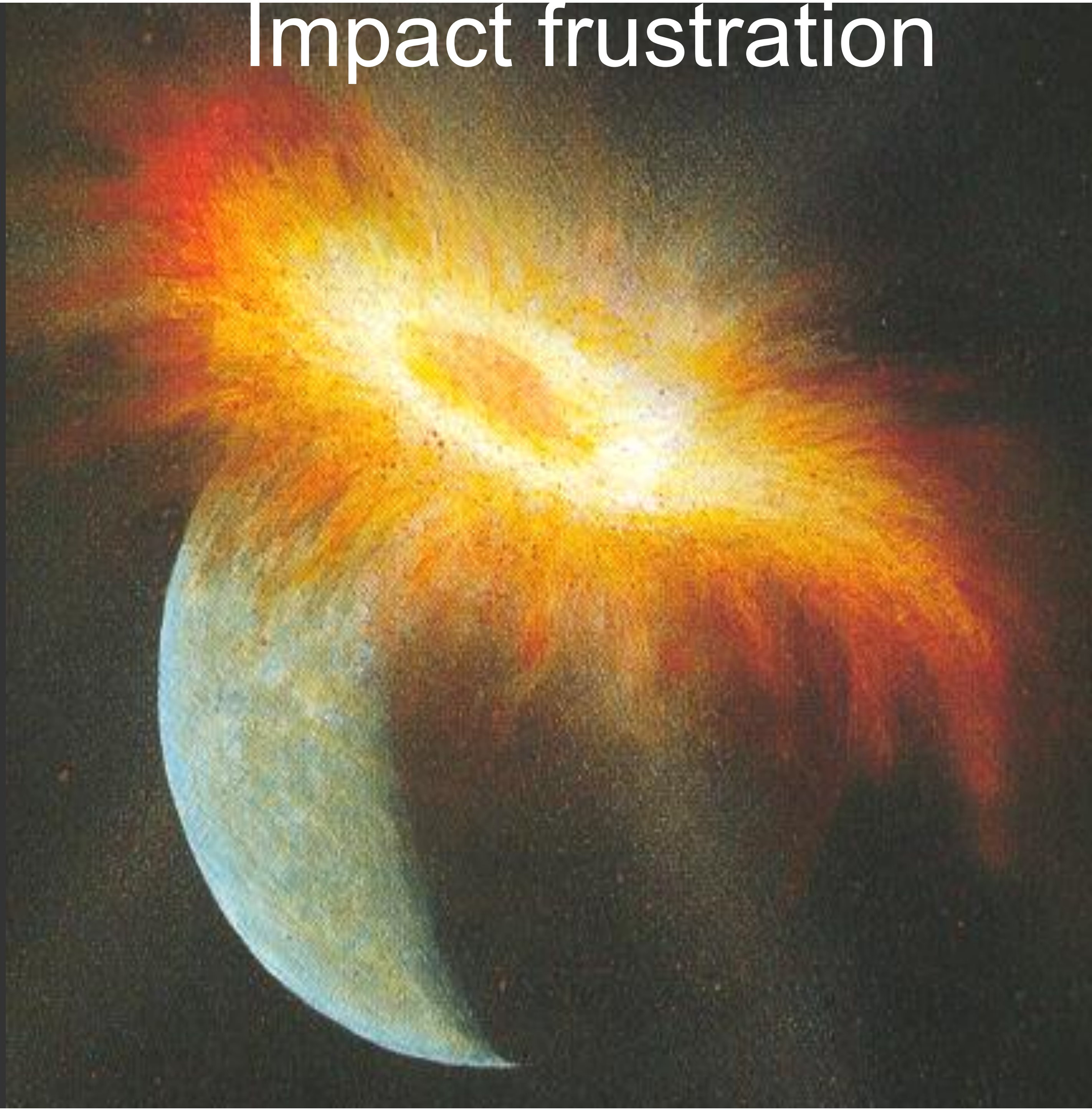
- N_2 fixation genes may have originated from *Methanobacterium thermoautotrophicus* neighbor found in some fractures by HGT.
- Two clustered regularly interspaced short palindromic repeat ("CRISPR") regions that are used for viral defense occur in the genome with adjacent CRISPR-associated genes ("CAS"), some of which are horizontally shared between *D. audaxviator* and archaea.
- Is HGT occurring by transduction or conjugation?
- 10^{11} cells are clonal - only 0.0014% of bp's show polymorphism, almost 60 fold less than the rate of 0.08% found for the unusually homogeneous *Leptospirillum* group II population from Iron Mt. acid biofilm community.
- Amino acid analyses indicates average age of ~1000 years (for the proteins).
- AA consistent with geochemically constrained respiration rates, but are subsurface populations evolving very slowly compared to surface life?


Chromalveolata
Plantae
Amoebozoa
Fungi
Metazoa
Nanoarchaeum equitans
Pyrobaculum aerophilum
Aeropyrum pernix
Sulfolobus solfataricus
Sulfolobus tokodaii
Thermoplasma volcanium
Archaeoglobus fulgidus
Halobacterium sp. NRC-1
Methanosarcina mazei
Methanosarcina acetivorans
Pyrococcus furiosus
Pyrococcus abyssi
Pyrococcus horikoshii
Methanococcus jannaschii
Methanococcus maripaludis
Methanopyrus kandleri
Methanobact. thermautotrophicum
Giardia lamblia
Leishmania major
Thalassiosira pseudonana
Plasmodium falciparum
Cryptosporidium hominis
Cyanidioschyzon merolae
Arabidopsis thaliana
Oryza sativa
Dictyostelium discoideum
Schizosaccharomyces pombe
Saccharomyces cerevisiae
Eremothecium gossypii
Caenorhabditis briggsae
Caenorhabditis elegans
Drosophila melanogaster
Anopheles gambiae
Danio rerio
Takifugu rubripes
Gallus gallus
Pan troglodytes
Homo sapiens
Mus musculus
Rattus norvegicus
Thermoanaerobact. tengcongensis
Clostridium acetobutylicum
Clostridium perfringens
Clostridium tetani
Phytoplasma Onion yellows
Mycoplasma mycoides
Mycoplasma pulmonis
Mycoplasma mobile
Ureaplasma parvum
Mycoplasma penetrans
M. gallisepticum
M. genitalium
M. pneumoniae
Lactobacillus plantarum
Lactobacillus johnsonii
Enterococcus faecalis
Lactococcus lactis
Streptococcus pneumoniae TIGR4

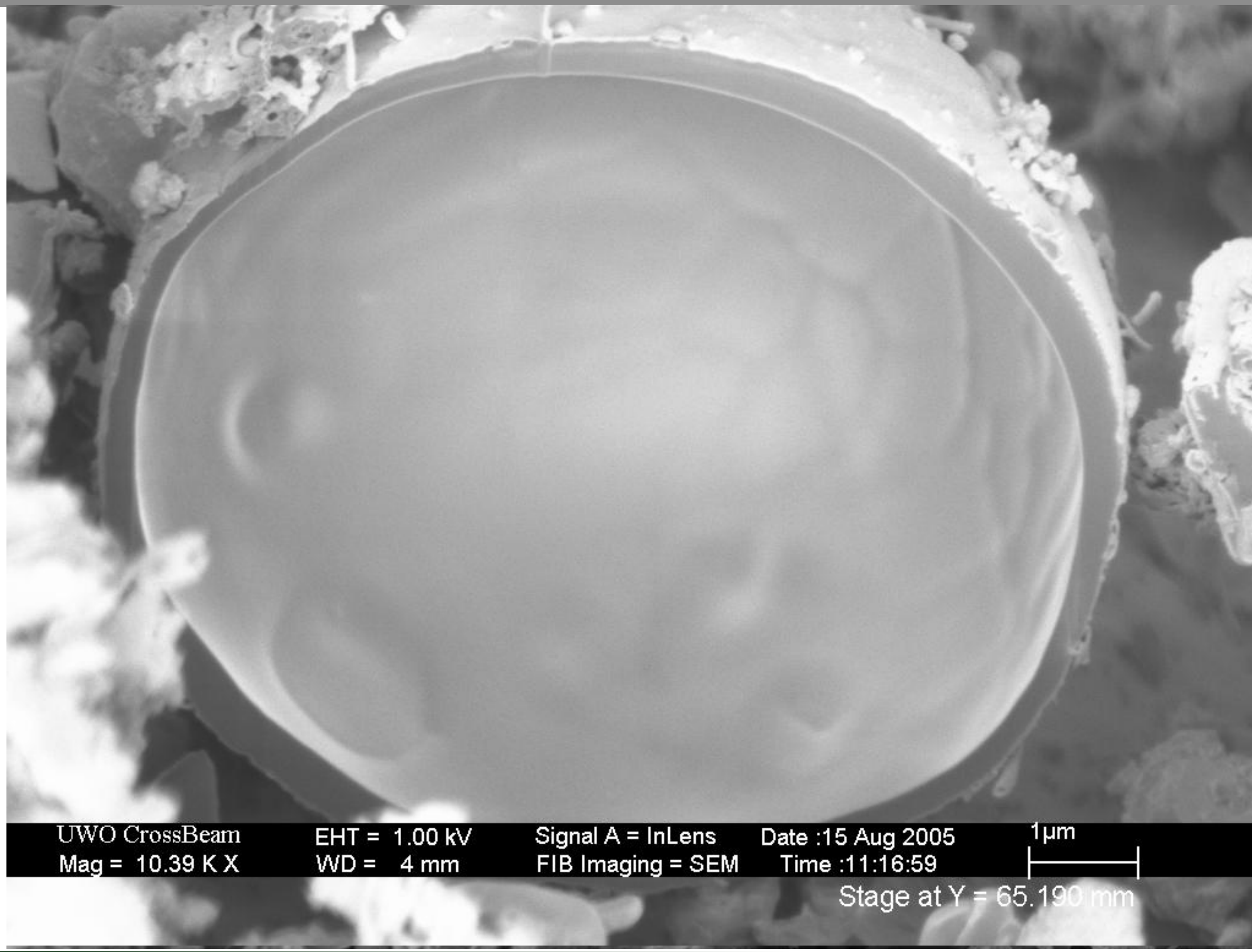
Subsurface life include the deepest roots
Origin of Life



Impact frustration



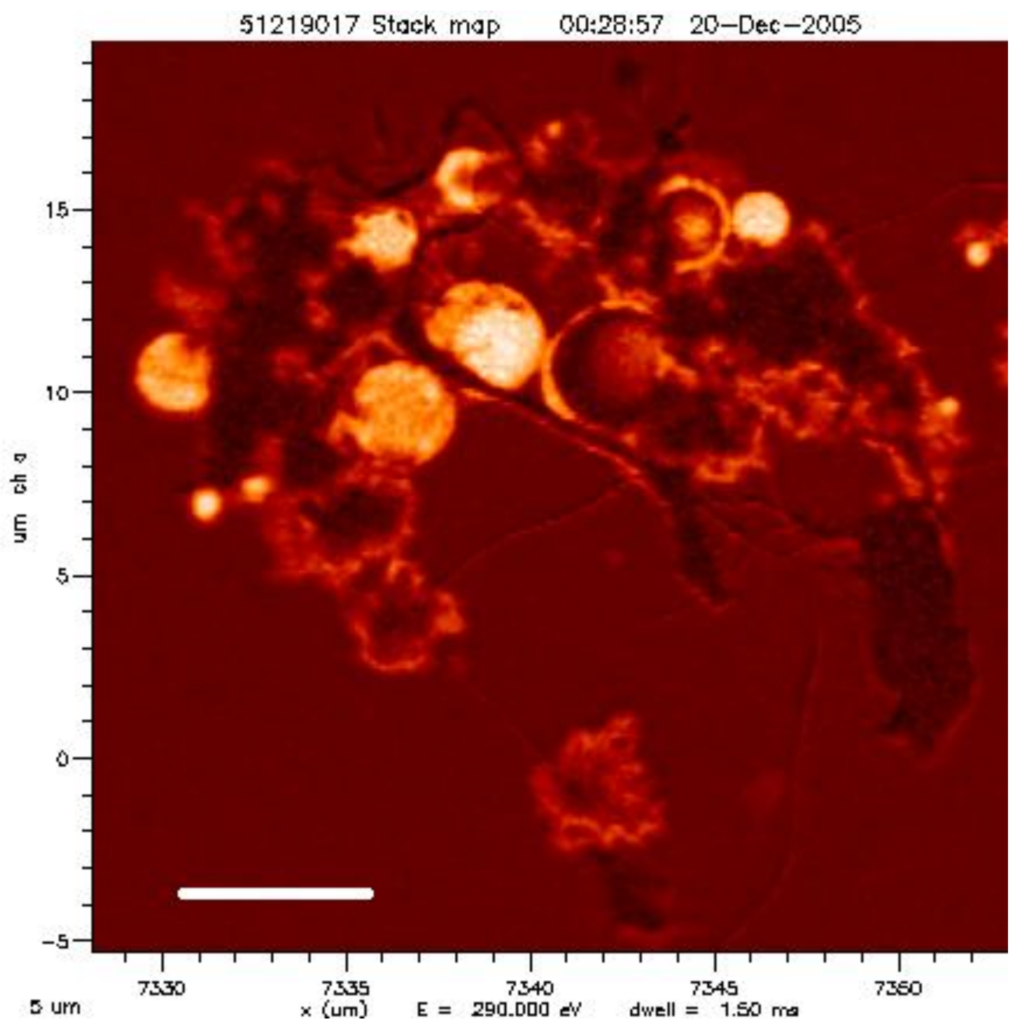
Did life originate beneath the surface?

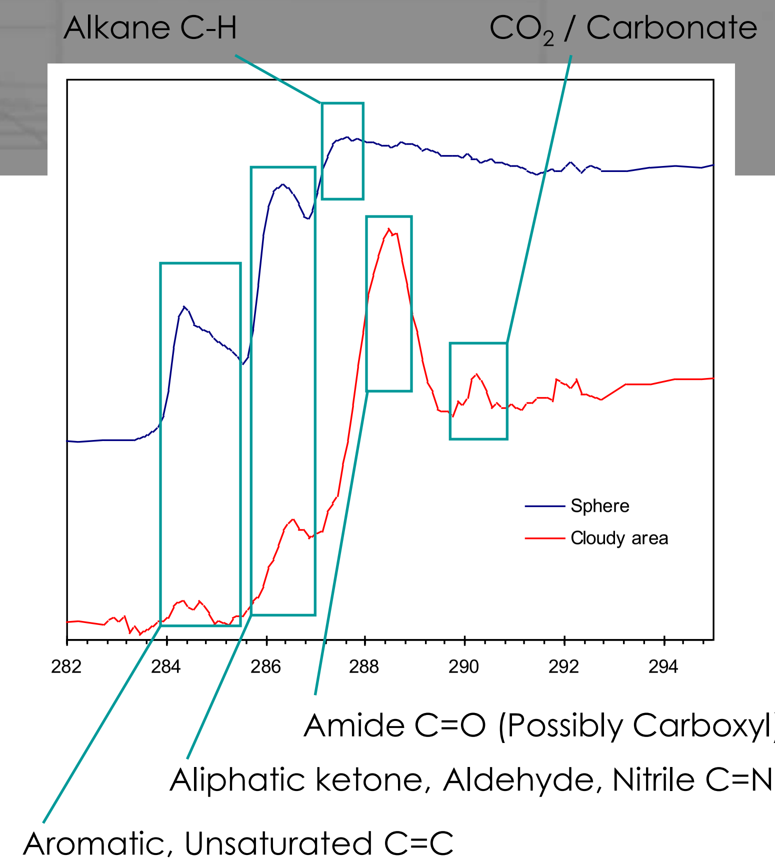


Scanning Transmission X-ray Microscopy (STXM) Results

Microsphere Sample 550-1

Michael Hay and Satish Myneni, Princeton University

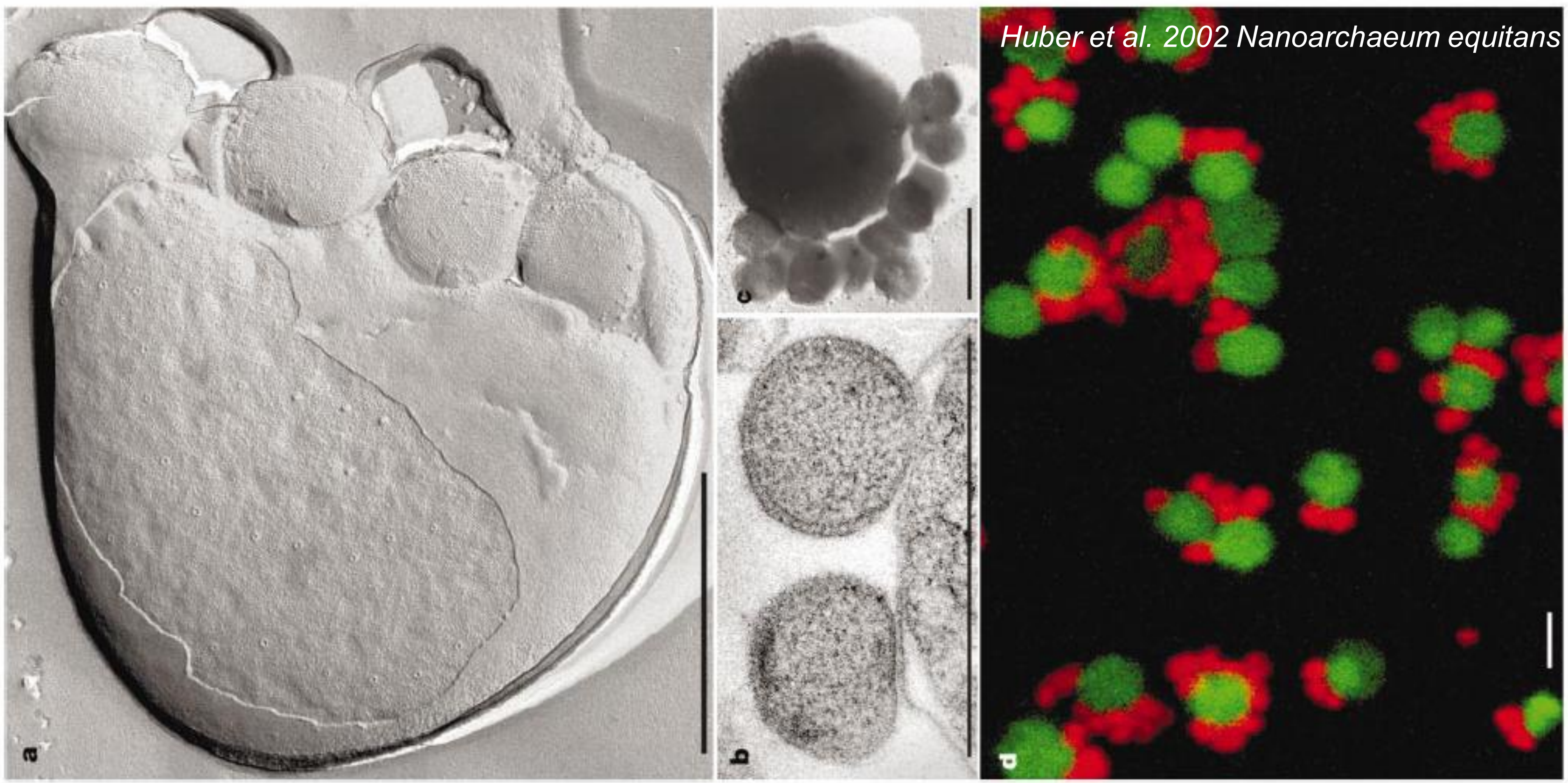




- Microspheres: High aromatic / alkene content
- More amide / carboxyl in cloudy regions
- Filaments contain less C overall (data not shown)

How deep does life go?
Is there life not as we know it?

The DUSEL ultra-deep observatory will set several instrumented boreholes down to the known temperature limits of life. Ultra-low contamination is achieved through the use of the Cherenkov detector water supply system and controlled ventilation.

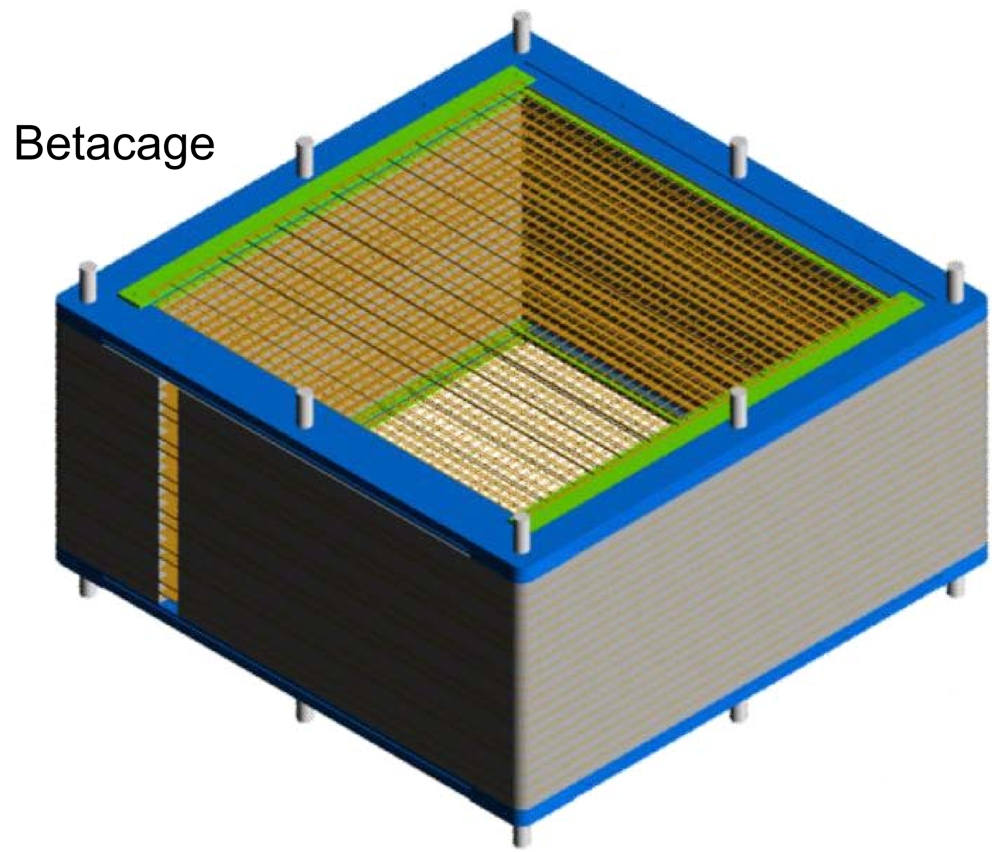


Huber et al. 2002 Nanoarchaeum equitans

A marriage of physics and molecular approaches

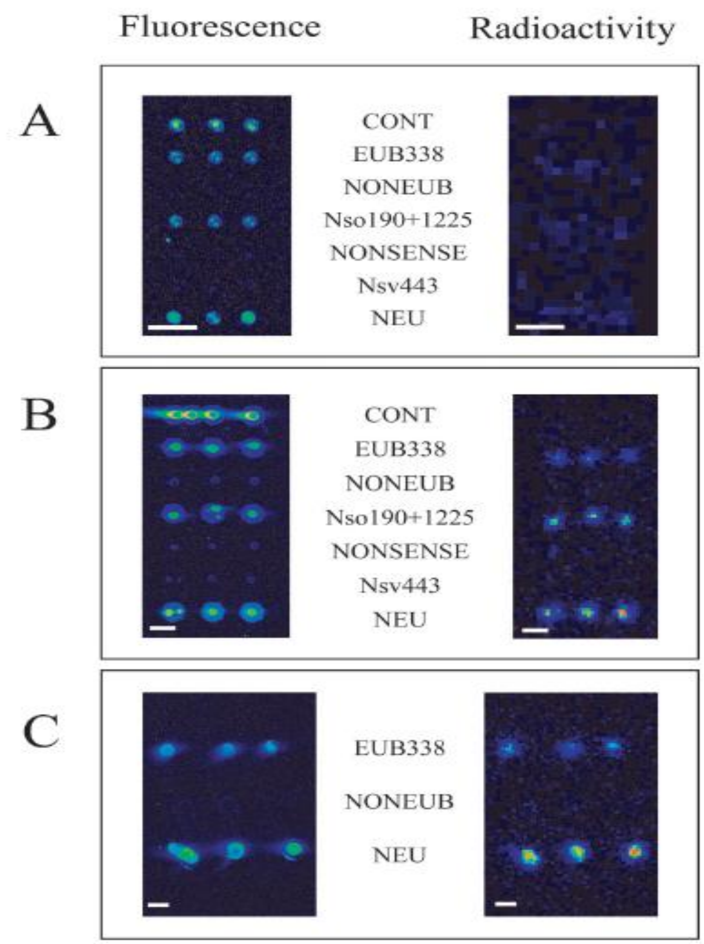
How to detect weak signs of life?

Underground Ultra-Low Level Counting Facility



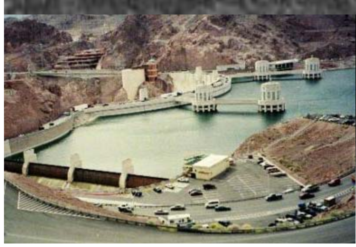
Poinar et al. 2006

Microarrays

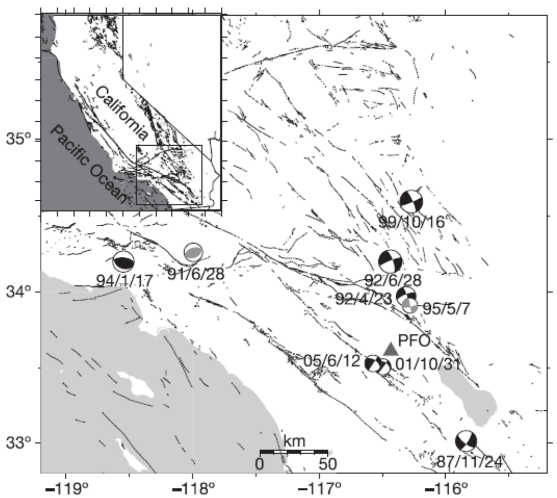


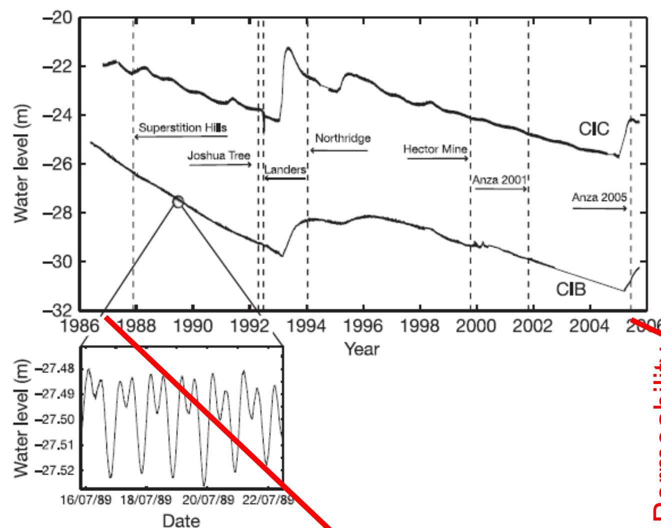
Adamcyzk et al. 2003

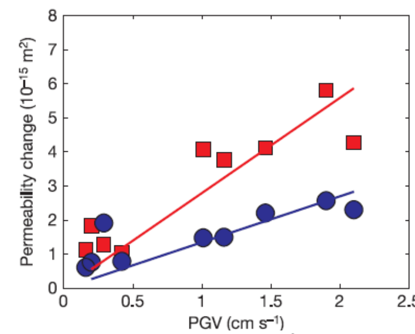

Cellulose-degrading thermophiles isolated from SUSEL – more to come through baseline characterization

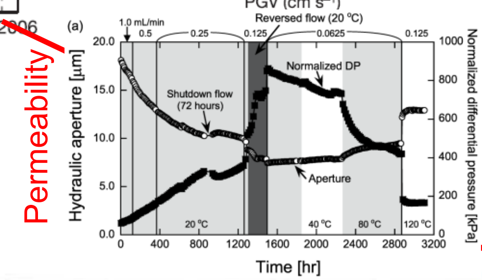


Scale Effects in Hydrology – Space and Time

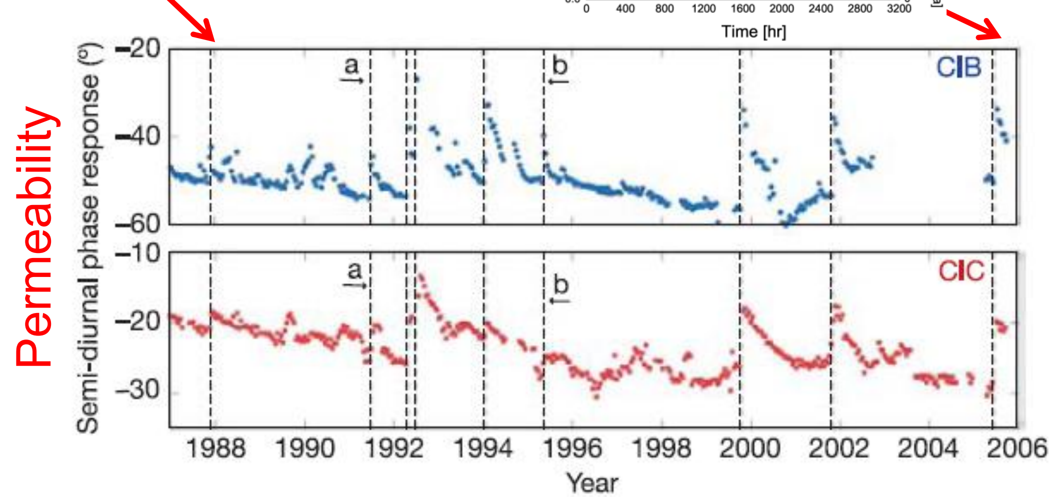






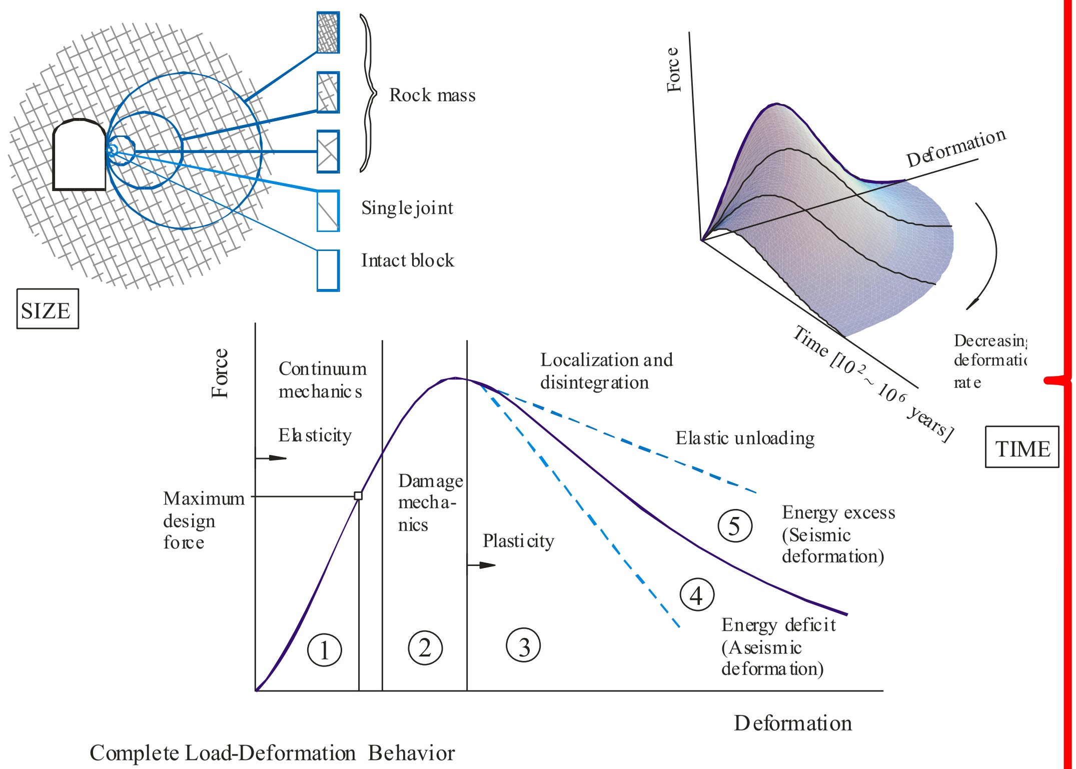


- Remote earthquakes trigger dynamic changes in permeability
- Unusual record transits ~18y
- Sharp rise in permeability followed by slow “healing” to background
- Scales of observations:
  - Field scale
  - Laboratory scale
  - Missing intermediate scale with control



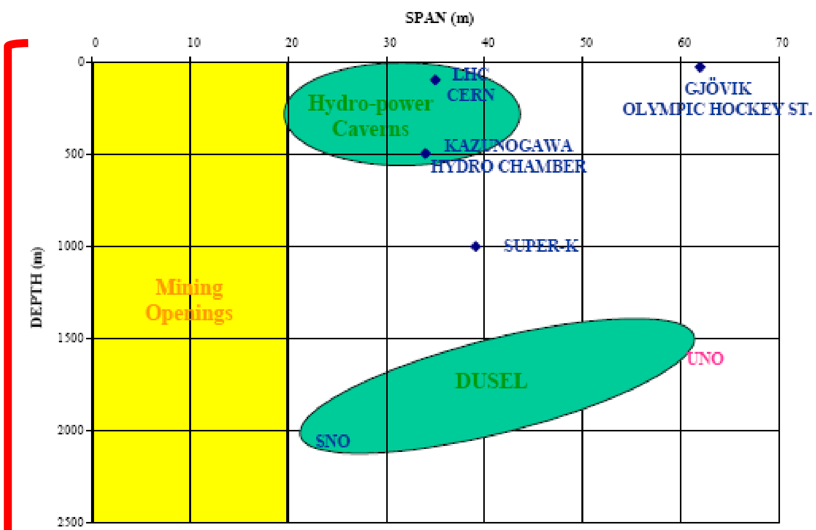
[Elkhoury et al., Nature, 2006]

Scale Effects in Geomechanics – Space and Time

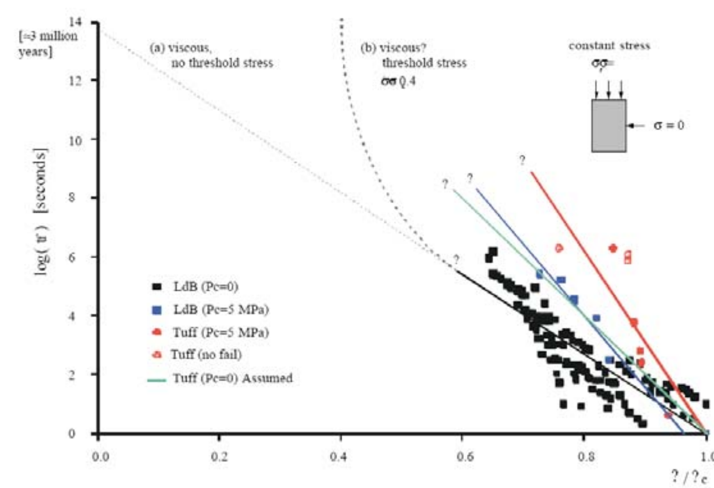


[Fairhurst, 2004]

TIME



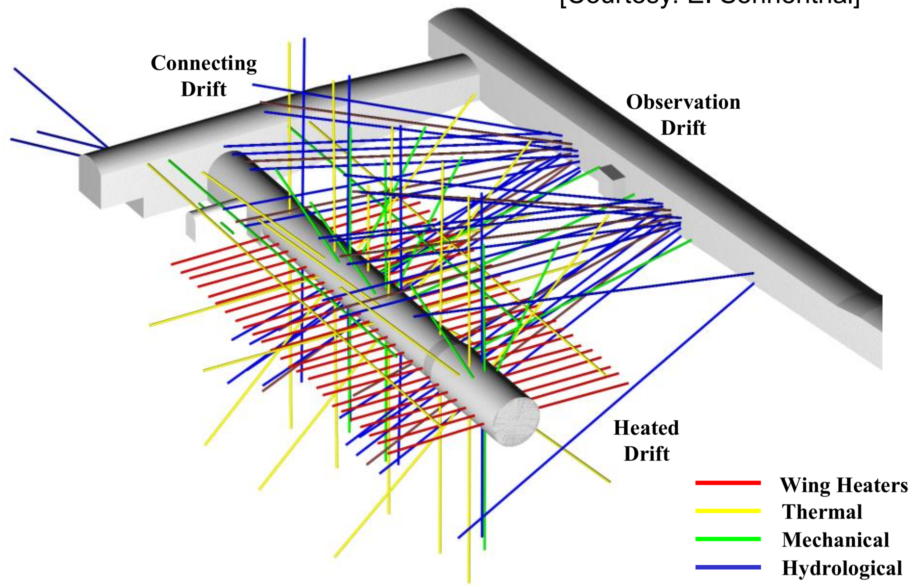
[Elsworth and Fairhurst, NSF-S1, 2007]

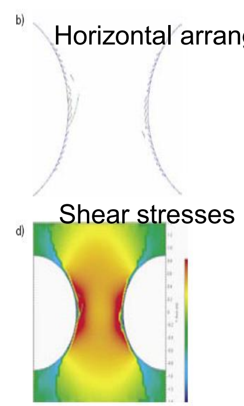


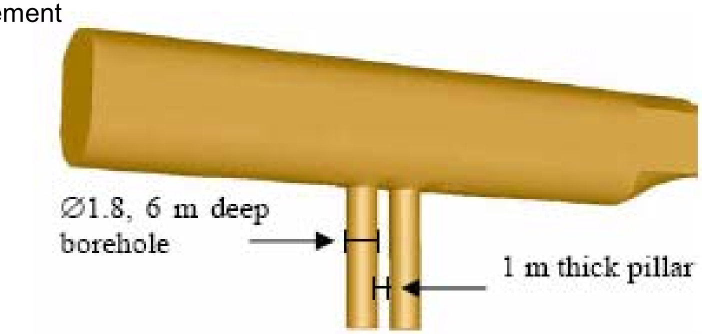
Coupled Thermal, Hydrological, Mechanical and Chemical Processes

- 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

[Courtesy: E. Sonnenthal]



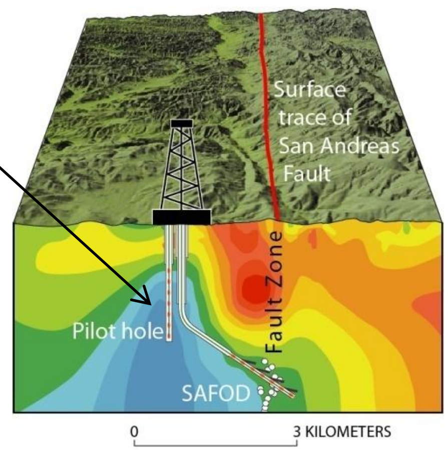


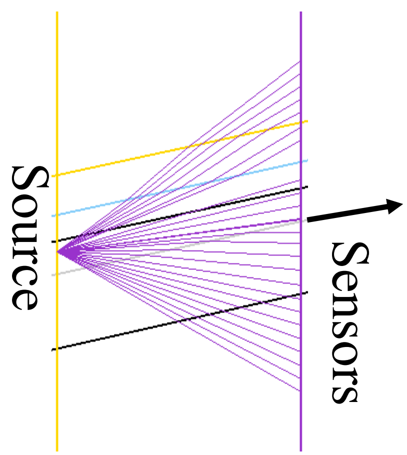


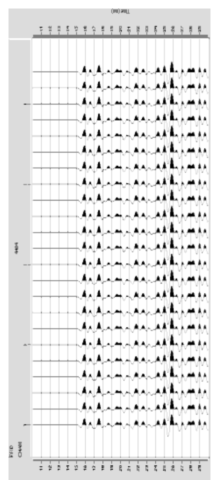
[Rinne et al., SKB, R-04-04, 2004]

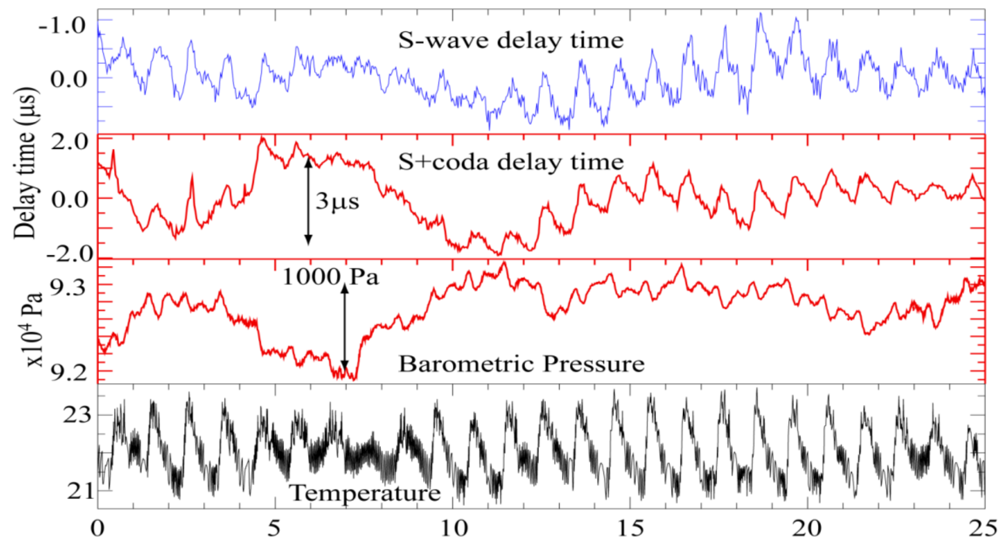
Imaging for Constitutive Behavior

Crosswell:
1.1 km deep
~12 m apart









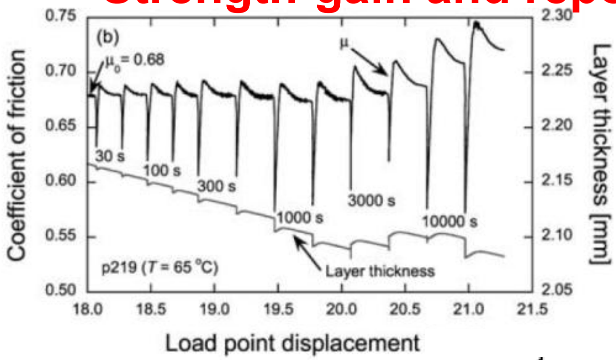
Result: Velocity change: 3.0E-4;
Stress sensitivity: 3.0E-7 Pa^{-1}

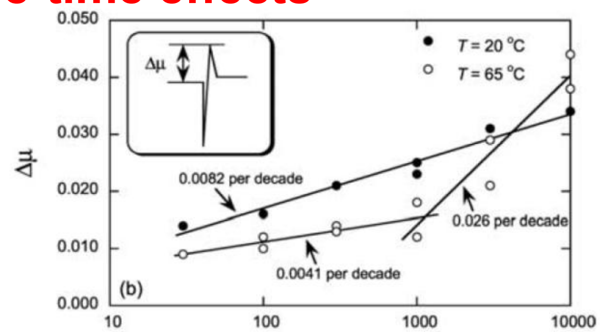
- Goal: In-situ monitoring of stress changes using seismic travel time change
- Motivation:
  - Earthquake ‘Prediction’
    - Tectonic stress change
  - Reservoir Management
    - Fluid Pressure via effective stress
    - Subsidence via stress and strain changes
- Need calibration signal to determine stress sensitivity: Barometric pressure or Earth tides

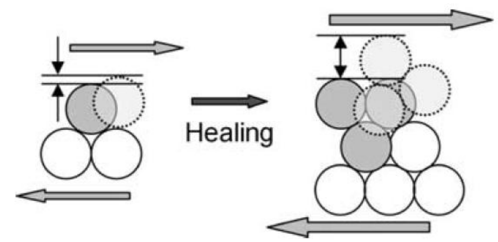
[Majer et al., 2007]

Scaling of Seismic Activity

Strength-gain and repose-time effects

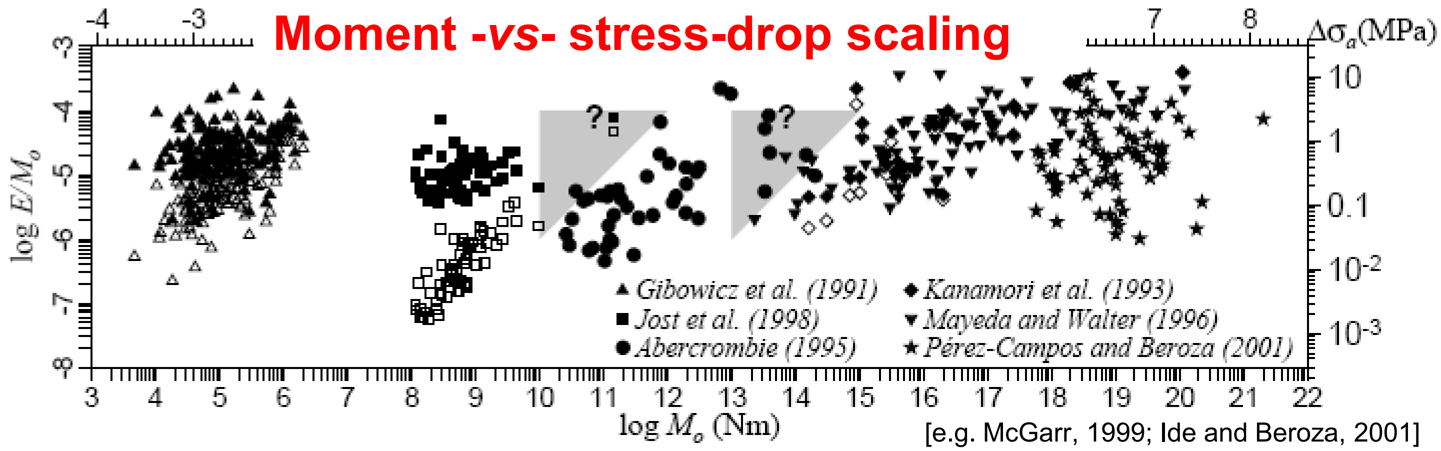






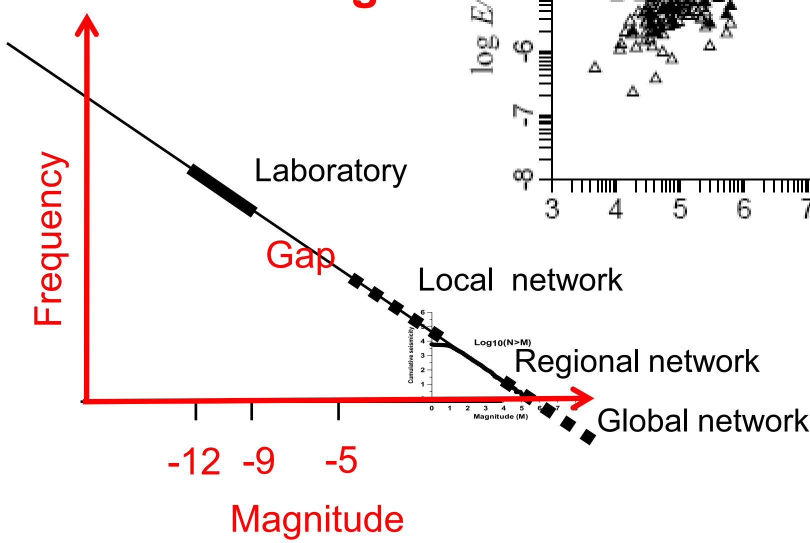
[e.g. Yasuhara et al, 2005]

Moment -*vs*- stress-drop scaling



[e.g. McGarr, 1999; Ide and Beroza, 2001]

b-value scaling



[e.g. Korneev, 2007]

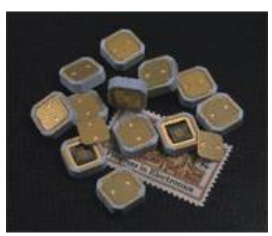
Scale dependencies

- Strength-gain and repose-time effects
- Moment stress-drop scaling
- b-value scaling

Sensor Deployment

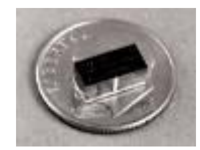
Environmental Variables

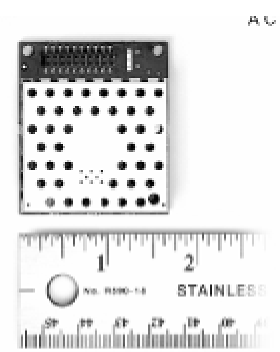
- Temperature
- Barometric pressure
- Relative humidity (0 ~ 100%)
- Gases
  - NO_x, SO_x, CO, CO_2,...
  - pH
- Soil moisture content (TDR, FDR, capacitive)
- Wind velocity and direction (5-pitot design)
- Light intensity (wavelength selective)



Mechanical Variables

- Acceleration and derivatives
- MEMS retro-mirror interferometer
- Micro-RADAR (movements)
- Tilt
- GPS
- Rate gyro
- Magnetometer
- Quantitative acoustic emission





[e.g. Glaser, 2007]

What Will be Done in 20 years?

LONGSECTION OF THE HOMESTAKE MINE

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
  - ……………….




The Path Ahead - Initial Suite of Experiments, Bio-Geo-Eng

Current Working Groups

Ambient rock deformation processes, Herb Wang, University of Wisconsin

Induced rock deformation processes, Leonid Germanovich, Georgia Tech

Ambient flow, transport, diversity, activity and evolution, David Boutt, U. of Mass

Induced flow, transport, diversity, activity and evolution, Eric Sonnenthal, LBNL

Underground construction and environment, Charles Fairhurst, U. Minn.

CO_2 Sequestration, Joe Wang, LBNL

Resource extraction, Jean-Claude Roegiers, U. Oklahoma

Subsurface imaging and sensing, Steve Glaser, UC Berkeley

Ultra-deep biological observatory, Tom Kieft, New Mexico Tech

Baseline characterization and monitoring, Steve Martel, University of Hawaii

The Path Ahead – DEDC Timetable

Proposed Project Timetable			
			2008
	Pre-workshop:	Invite proponents, solicit initial input, plan workshop agenda	March 10th
		Complete initial agenda and one-page white paper	April 1st
	Lead ISE Workshop:	Craft working group and ISE modules: objectives, approach, expected results	April 20
		Present strawman outline at close of workshop - plan S-4 proposals	April 22
	NSF S-4 Proposal:	Submit S-4 proposals for initial critical design elements of ISEs	June 30th
	ISE e-Workshop	Potential teleconference to assess progress in ISE proposals and integrate ISEs	October
		S-4 funding available from NSF	expected October
	Grantees Meeting and Workshop	Summary of design progress and recruitment of further community involvement into development of ISEs, including those that were submitted for S-4 but didn't receive funding	December
			2009
	ISE e-Workshop	Potential teleconference to assess progress in ISE proposals and integrate ISEs	March
		Preliminary Design proposals for ISEs due	May
	Grantees Meeting:	Final report on ISE design for incorporation into CDR/MREFC	May
		Initial Suite of Experiments selected and announced	July
	ISE Workshop	Writing workshop as input for MREFC submission	October
	MREFC:	Assembly of MREFC and submission for review by NSF's NSB	December
2010		MREFC submitted to Congress	March
2011-2016		ISEs begin	

DUSEL Attributes

- DUSEL will represent an important facility with unparalleled attributes:
  - Long term access to site (long term response of structures and active processes)
  - Access to unusual depth for important initiatives in deep science (bioscience)
  - Broad access to a large volume of rock (scale effects and transparent Earth)

- A facility for world-class science and engineering science in:
  - Biology
  - Geosciences
  - Engineering

- Important societal impacts:
  - Construction
  - Energy and sustainability
  - Resource recovery and sustainability
  - Natural Hazards…..

DUSEL Experiment Development and Coordination (DEDC)

NSF Visit

March 19 & 20, 2008

Steve Elliott, Derek Elsworth, Larry Murdoch, Tullis C. Onstott and Hank Sobel