GeoScience and GeoEngineering@DUSEL

[dusel.org]

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…. and many, many others from the BGE DUSEL Community

December 14, 2010

[dusel.org; Deep Science, 2007]

Outline

- Societal Imperatives for Geo-Science and Geo-Engineering (Needs)
- Science Drivers (Objectives)
  - Underground Universe (Physics and Astrophysics)
  - Dark Life (Biology)
  - Restless Earth (Geoscience)
  - Ground Truth (Geoengineering)
- DUSEL Initial Suites of Experiments (Approaches)
  - Distributed Experiments [FiberOptic/EcoHydrol/Drilling/Transp. Earth]
  - Facility-Based Experiments [CO2/THMCB/Frx]
  - Cavity Experiments
- Facility Layout with Experiments
- Future Benefits of DUSEL? (Outcomes)

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**
  - Aquifer Remediation

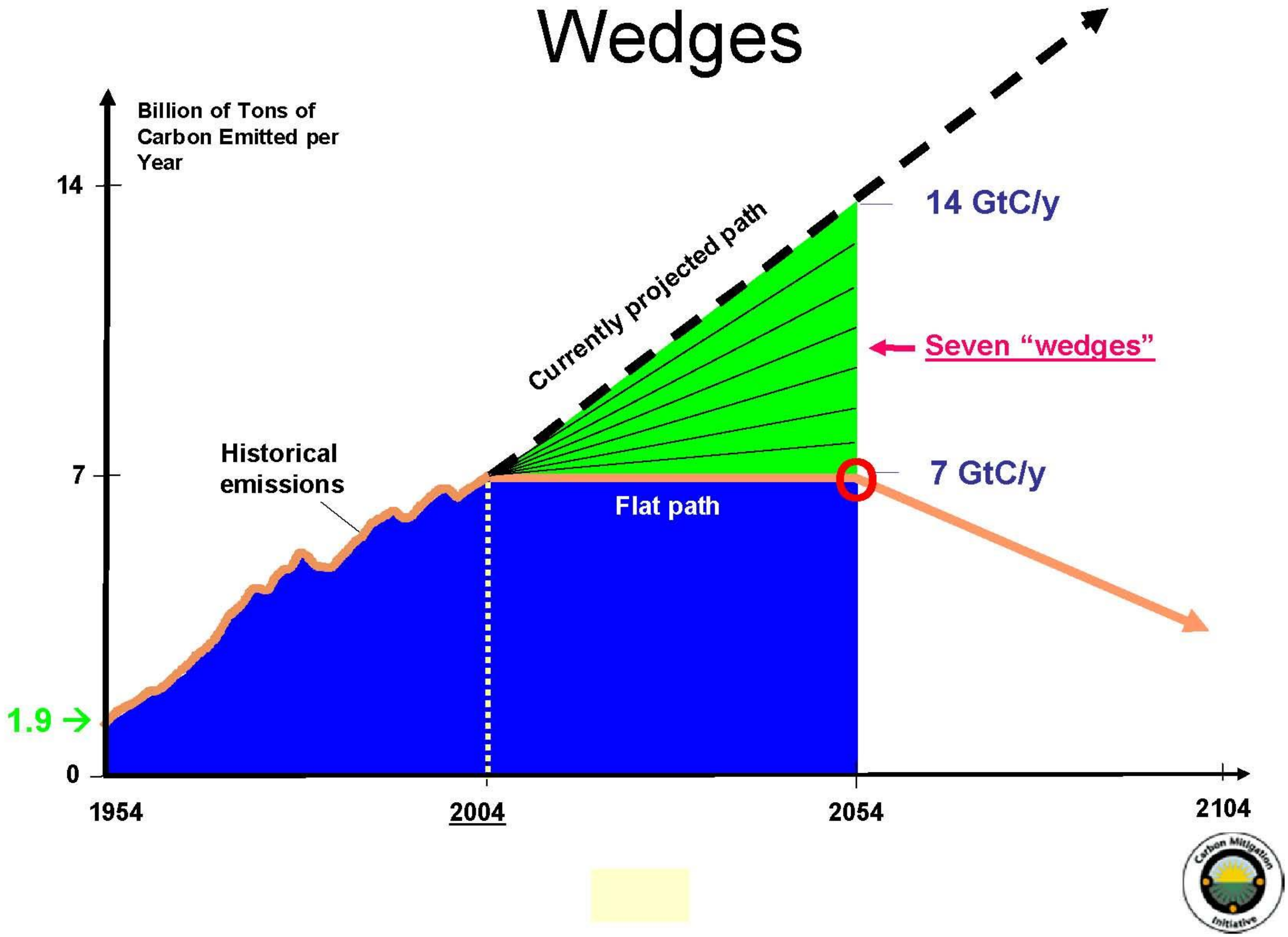
Mainly GeoHydrology

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

Mainly GeoMechanics

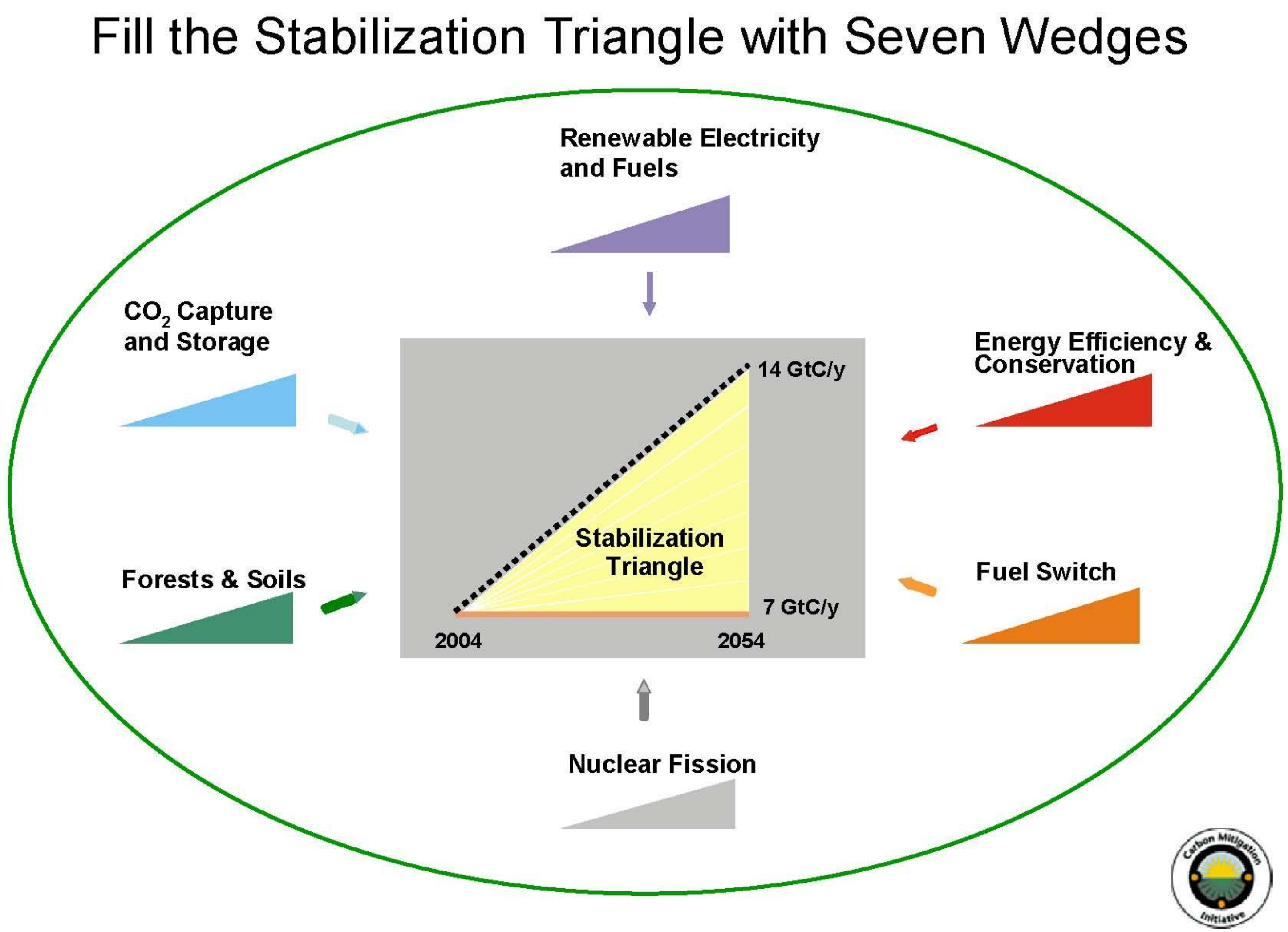


Capacity Needs – Stabilization Wedges



[**Rationale in:** Pacala & Socolow, *Science*, 2004, www.stabilisation2005.com/day3/**Socolow**.pdf]

Capacity Needs – Stabilization Wedges



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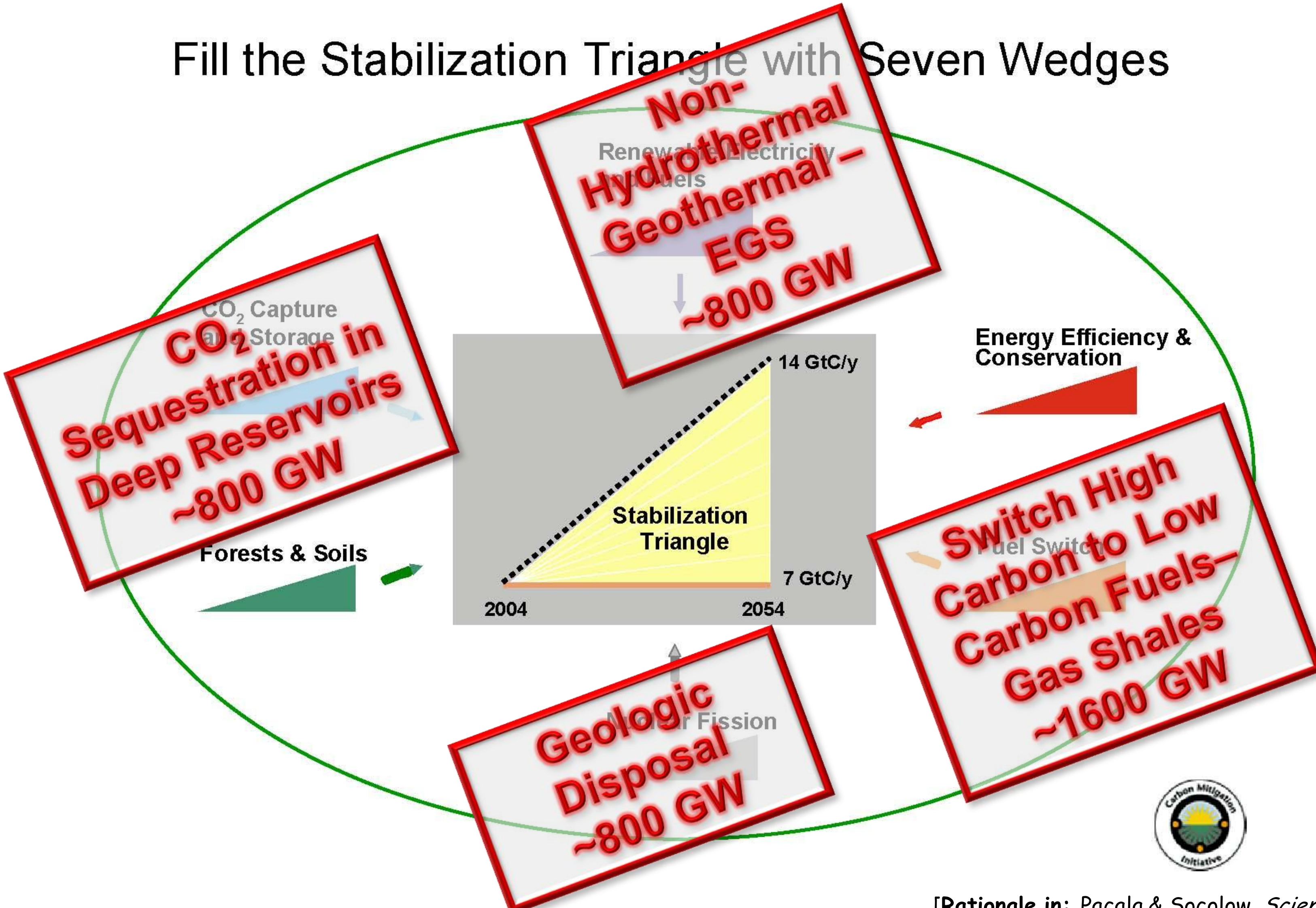

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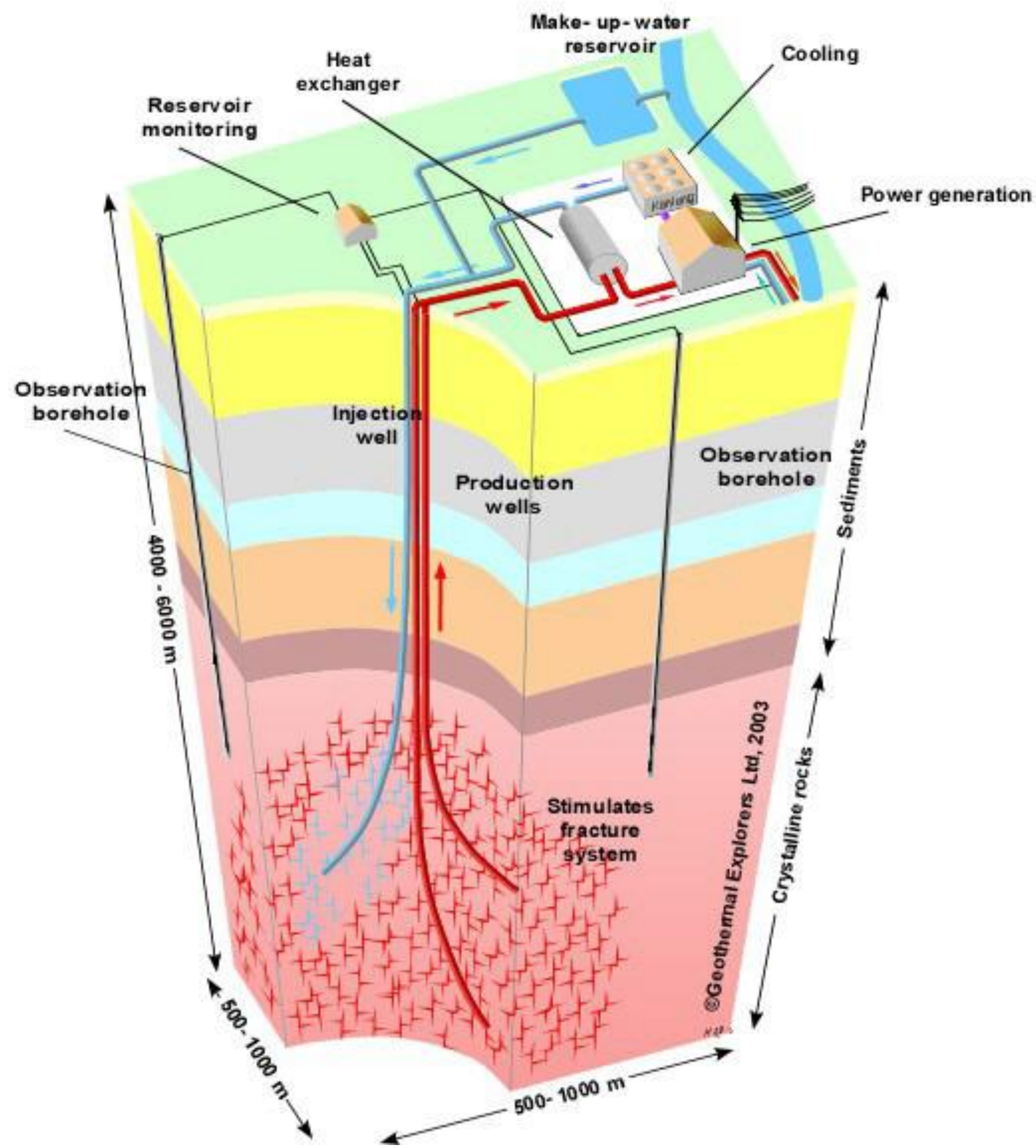
Zero Carbon Solution? Enhanced Geothermal Systems

Types
- Hydrothermal (US: 10^4 EJ)
- EGS (US: 10^7 EJ; 100 GW in 50y)
- Heat pumps

Requirements
- Geothermal gradient
- Natural/induced fracturing

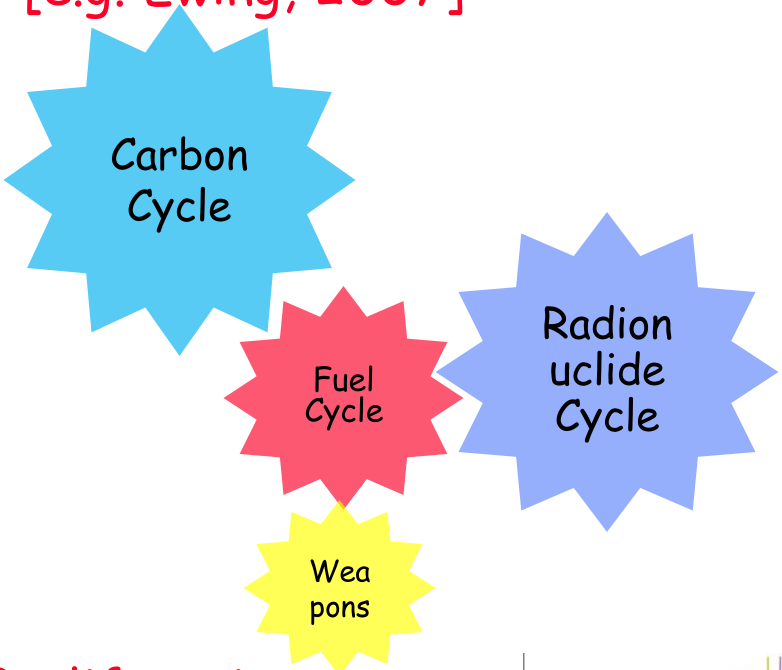
Attributes
- Large scale
- Sustainable
- Peak load available
- Virtually emission free
- Small surface footprint

Challenges
- Prospecting (characterization)
- Accessing (drilling)
- Creating reservoir
- Sustaining reservoir
- Environmental issues – e.g. induced seismicity



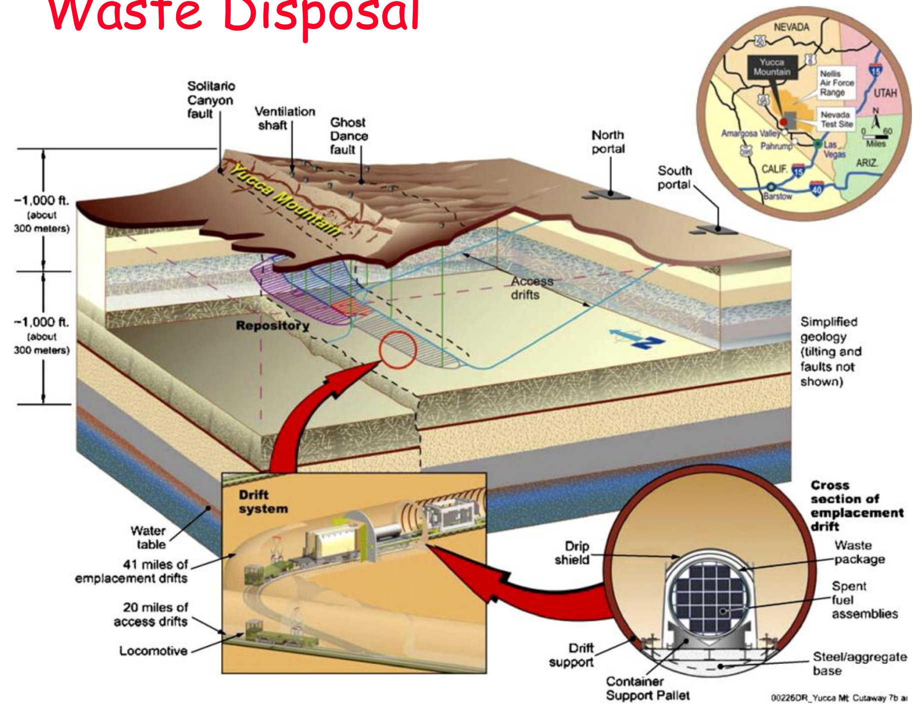
Zero Carbon Solution? – Nuclear Power

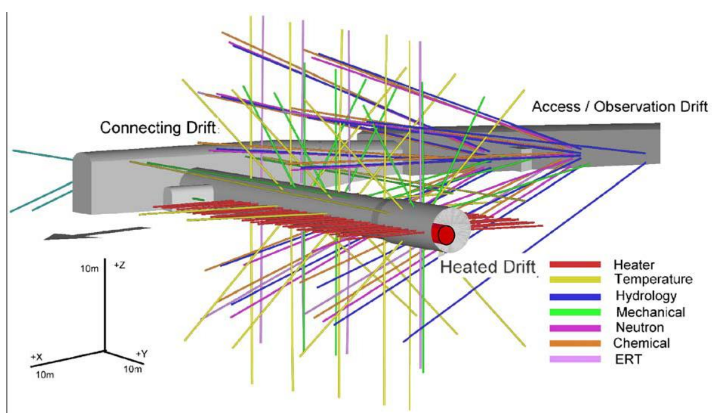
Connected Cycles
[e.g. Ewing, 2007]

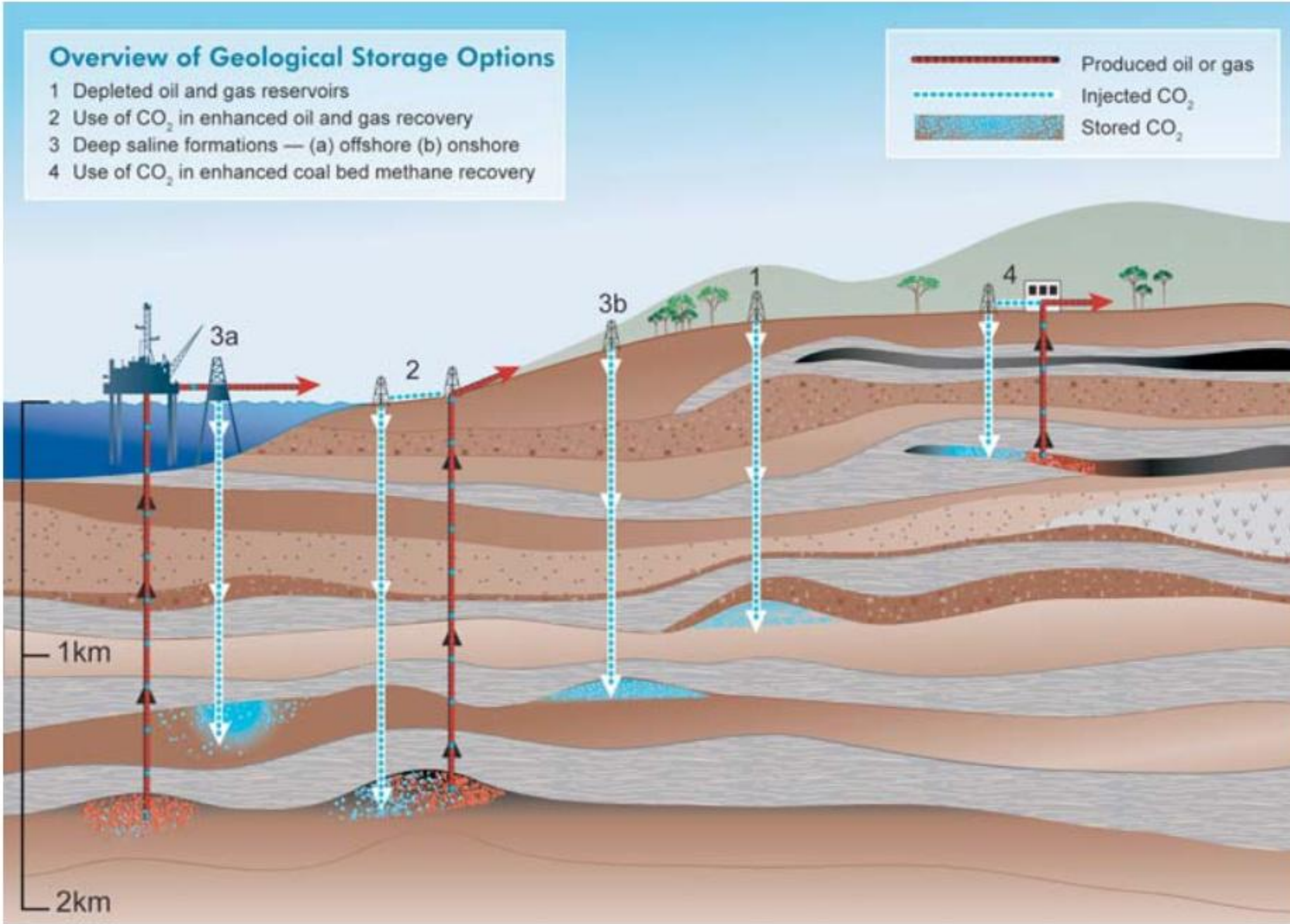


Proliferation

Waste Disposal

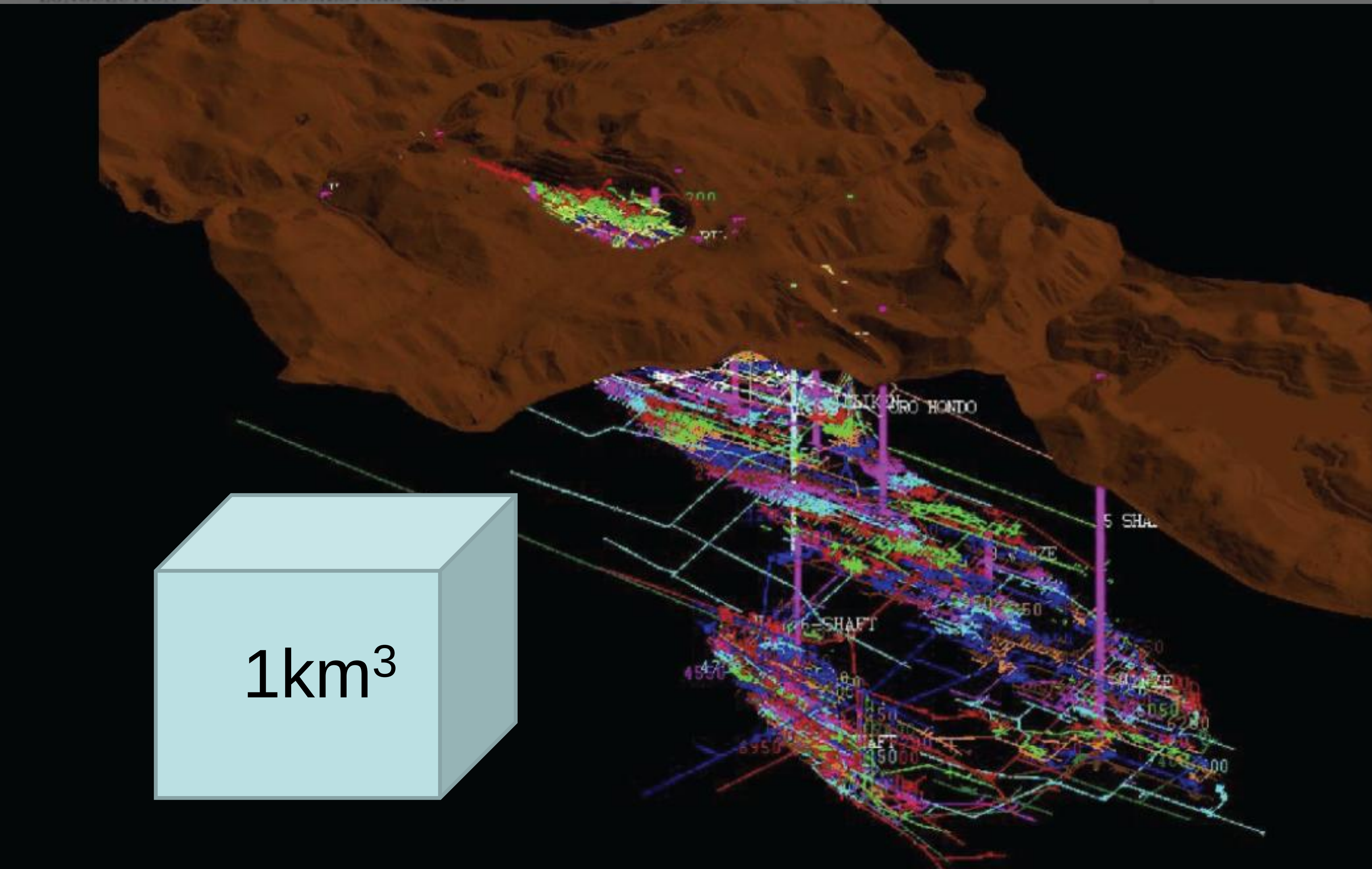






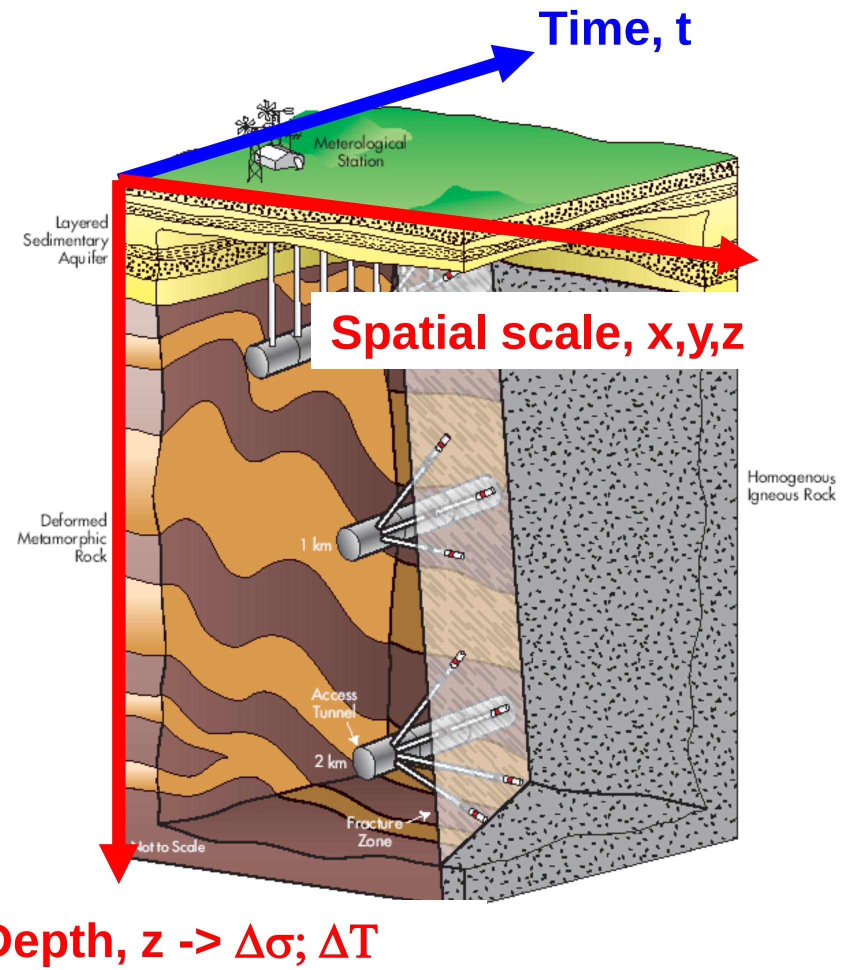
Courtesy of CO2CRC, http://www.co2crc.com.au/

Facility – Sanford/Homestake Laboratory



Principal Attributes of a DUSEL

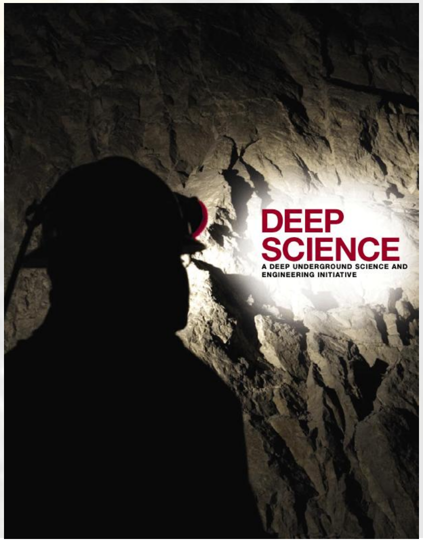
- Broad access to an opaque block of rock (~km-scale)
- Depth and hence elevated stresses and temperatures
- Long-term occupancy, hence continuity



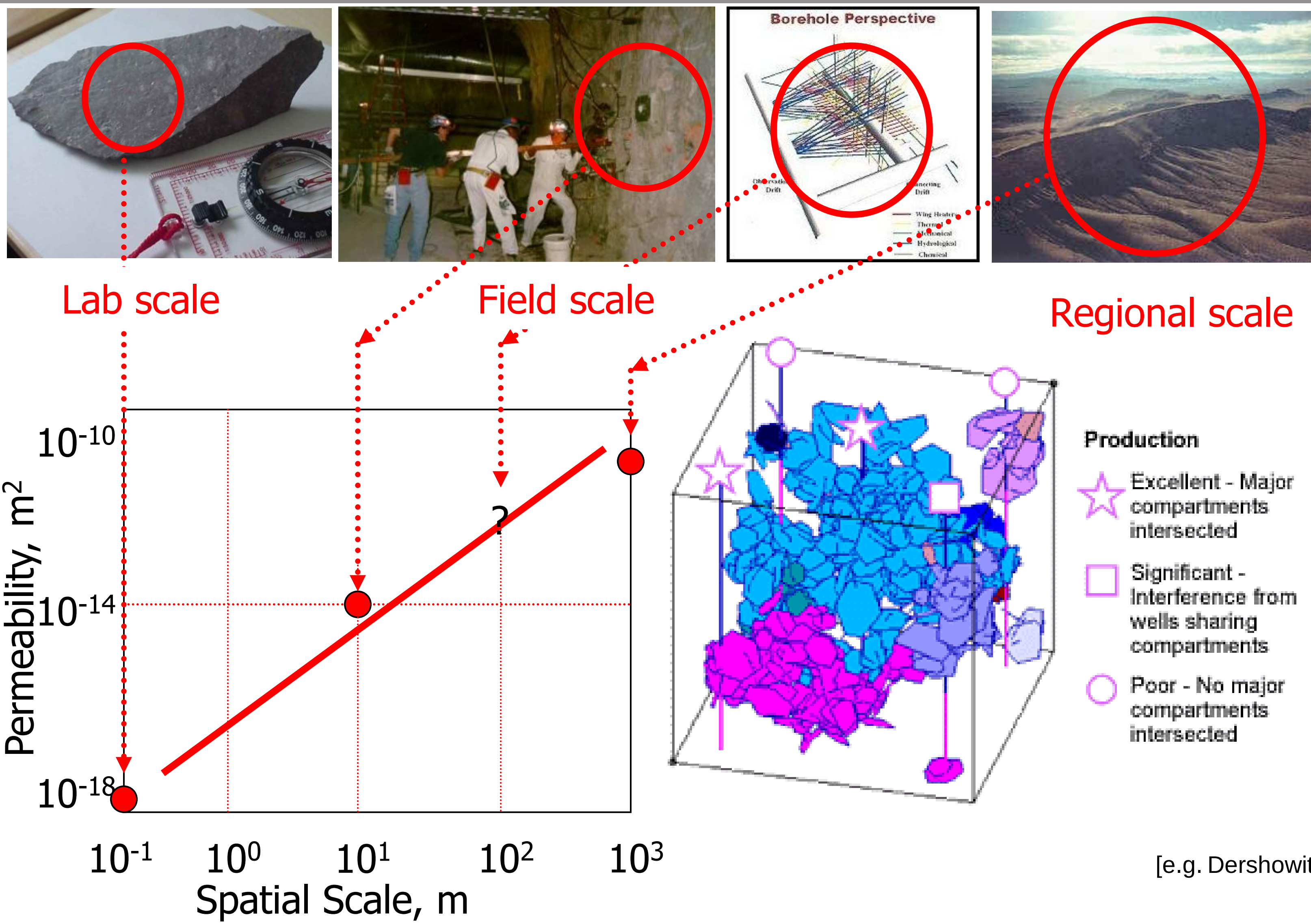
Science Drivers (Objectives)

Biology, Geosciences, Engineering – S1 Science Drivers

- 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?
  - Can we view complex underground processes in action?
  - Can we forewarn of earthquakes?
- Ground Truth (Geoengineering)
  - What lies between boreholes?
  - How can technology lead to a safer underground?
  - How do we better harness deep underground resources?

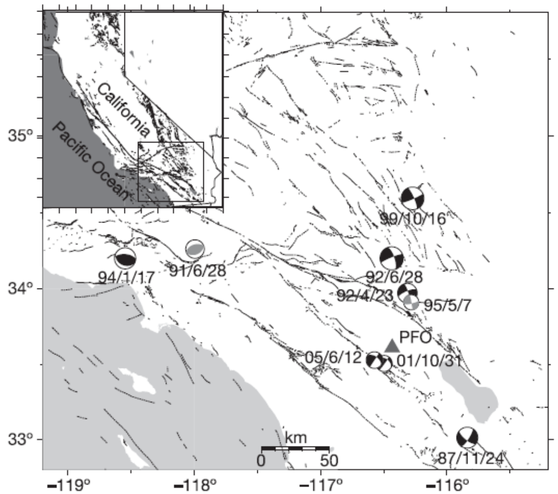


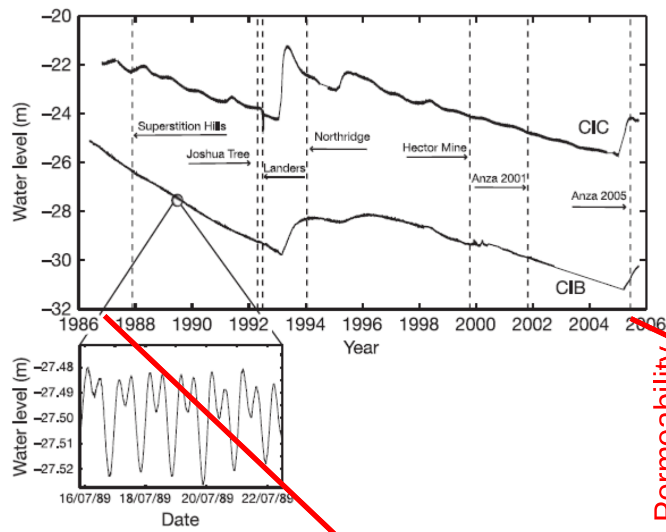
Scale Effects in Hydrology – Space and Time

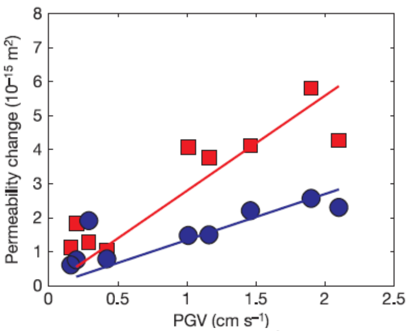


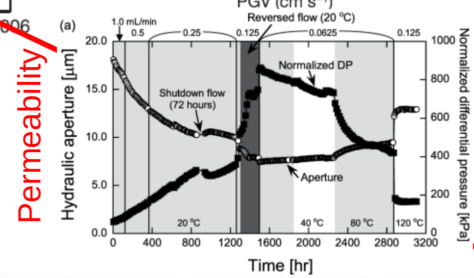
[e.g. Dershowitz, 2004]

Scale Effects in Hydrology – Space and Time

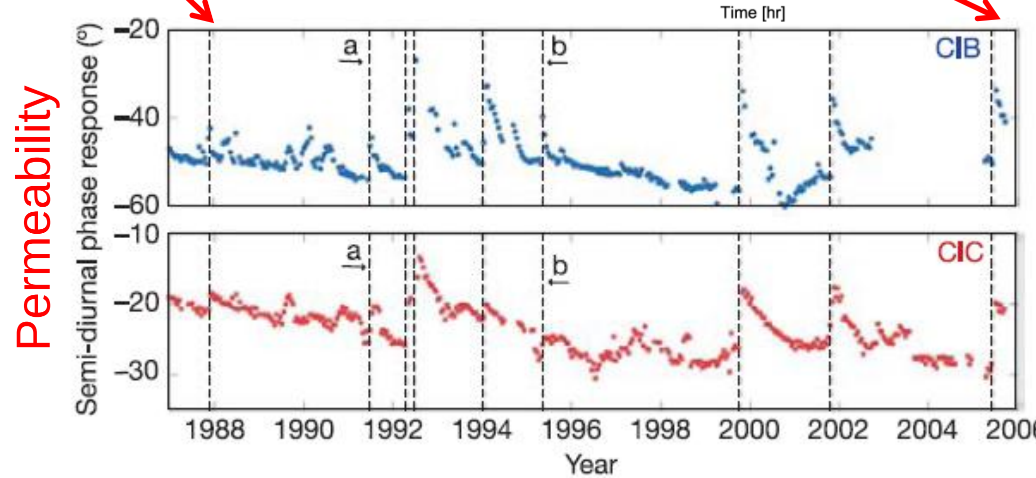








- Remote earthquakes trigger dynamic changes in permeability
- Unusual record transits ~8y
- Sharp rise in permeability followed by slow "healing" to background
- Scales of observations:
  - Field scale
  - Laboratory scale
  - Missing intermediate scale with control

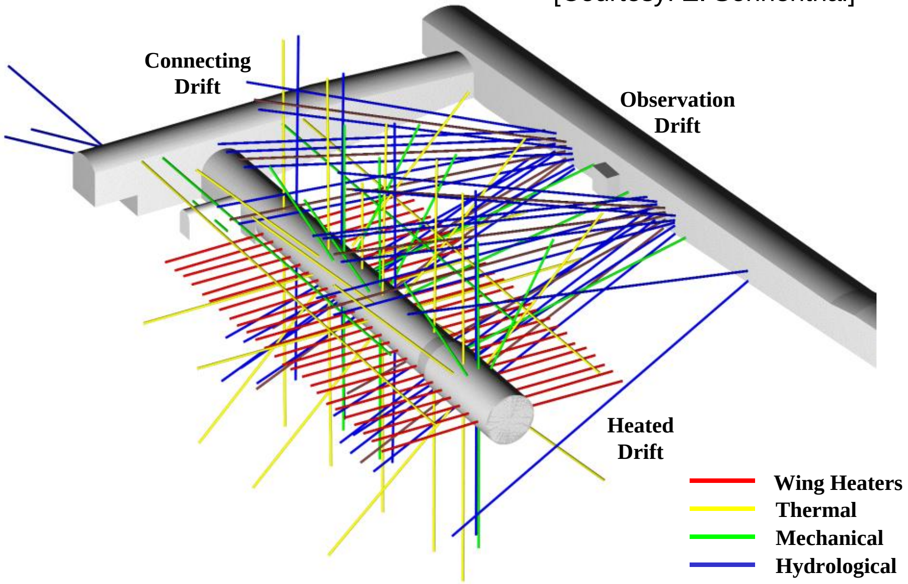


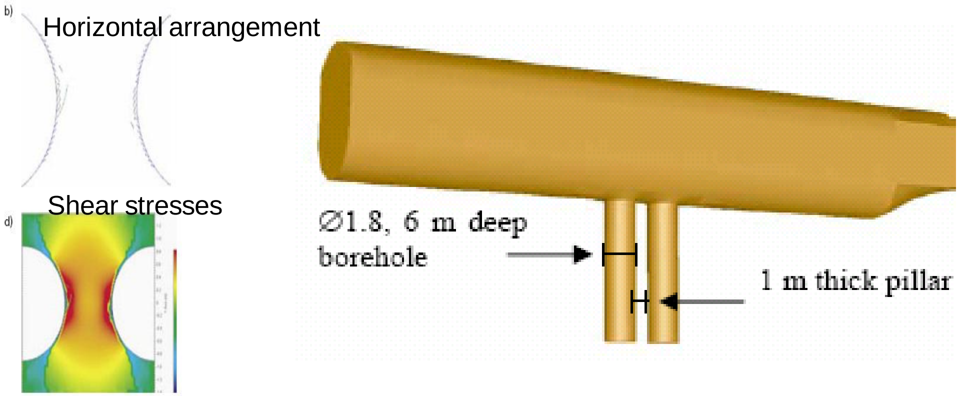
[Elkhoury et al., Nature, 2006]

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]

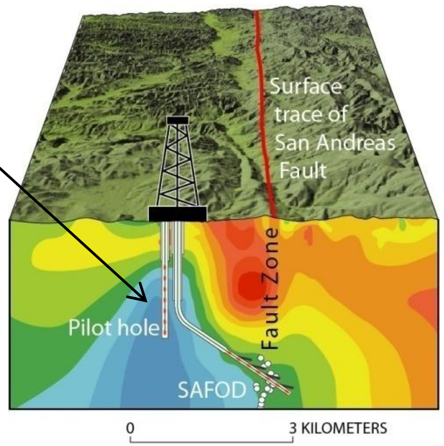


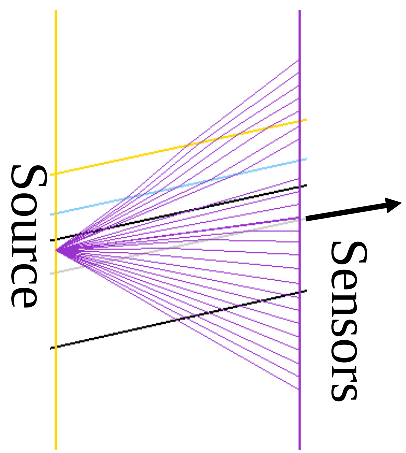


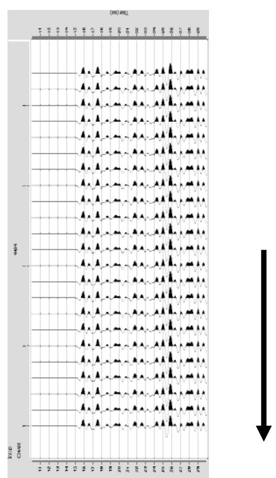
[Rinne et al., SKB, R-04-04, 2004]

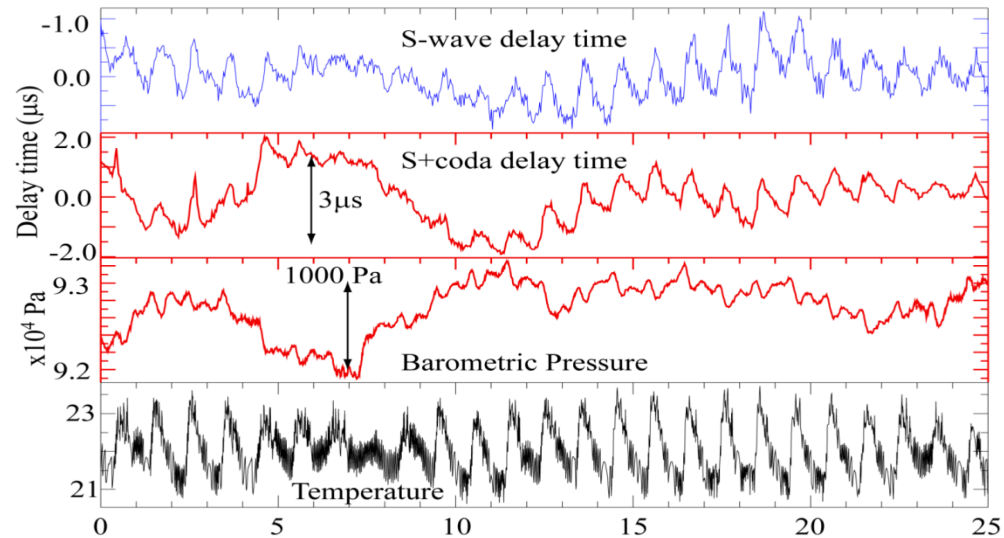
Imaging for Constitutive Behavior

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 Process Understanding
    - 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]

Proposed Initial Suite of Experiments (Approaches)

Biology-Geosciences-Engineering Summary Experiments

LONGSECTION OF THE HOMESTAKE MINE

Distributed Experiments

CMMI Fiber-Optic Monitoring of R. Masses	Wang (UWM) + 6 others	**[CMMI+GEO]**
S4 Deep EcoHydrology	Boutt (UMass); Kieft (NMT); Wang (UWM) + 8 others	**[CMMI+GEO]**
S4 Subsurface Imaging and Sensing	Glaser (UCB) + 19 others	**[CMMI+GEO]**

Facility-Based Experiments

S4 CO_2 Sequestration (LUCI)	Peters (Princeton); Oldenberg/Dobson(LBNL) + 6 others	**[CMMI+CBET]**
CMMI Coupled THMCB Processes	Sonnenthal (LBNL) + 6 others	**[CMMI+GEO]**
S4 Faulting Processes (FRX)	Germanovich (Georgia Tech) + 7 others	**[CMMI+GEO]**

Cavity Experiments

S4 Cavern Design for DUSEL	Einstein (MIT); Bobet (Purdue) + 8 others	**[CMMI+GEO]**

→ have a strong interactions with Physics research

DISTRIBUTED EXPERIMENTS [FIBEROPTIC/ECOHYDROLOGY/DEEP DRILLING/TRANSPARENT EARTH]

Fiber-Optic Strain and Tilt Monitoring of Rock Masses in Large Underground Facilities - GEOX™

Geoscience Goals

- How do rock masses deform as a function of spatial scale over long times?
- How does the static deformation field measured by strain sensors relate to microseismicity?
- How are the deformation field and fracture flow coupled?

Geoengineering Goals

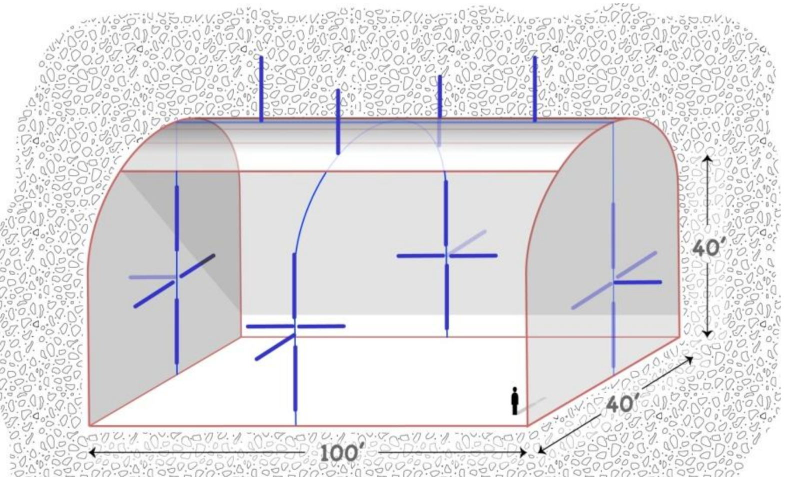
- Large cavity engineering
- General mine monitoring, and safety – How is the mine “breathing?

Technology Goals

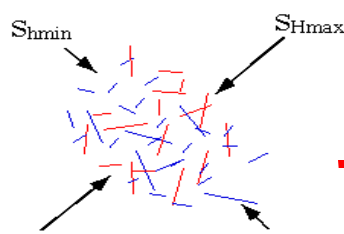
- Determine rock properties that control rock deformation over multiple scales of length and time
- Advance the technology of characterizing rock deformation
- Perform long-term (decadal) structural health monitoring (SHM) of DUSEL.
- Integrate deformation sensors with other physical and chemical fiber-optic sensors into a laboratory-wide environmental and safety monitoring system

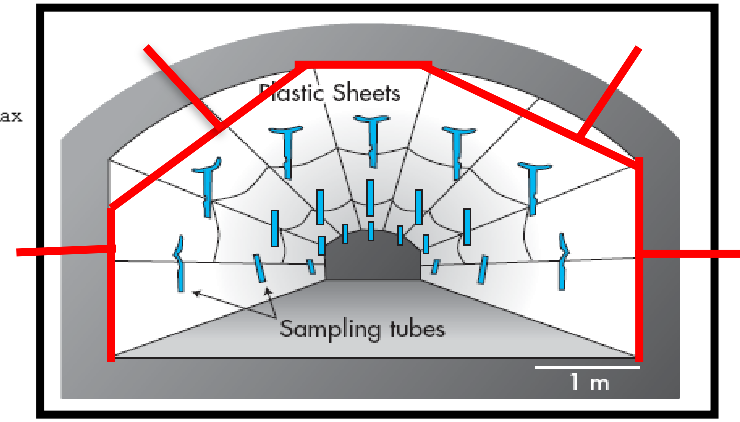
GEOX^{TM} -Experimental Layout

Large Scale Deformability

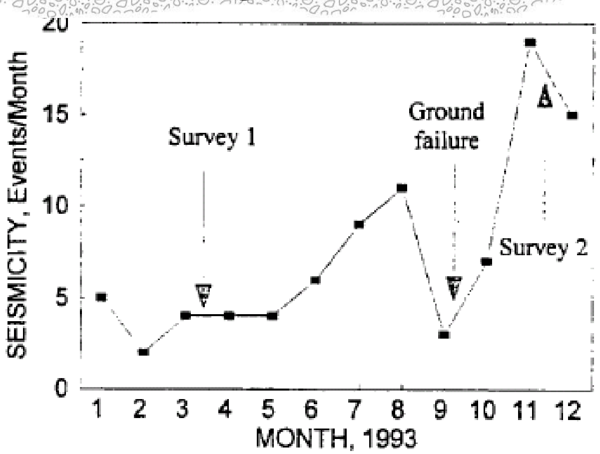


Linking Deformability and Permeability



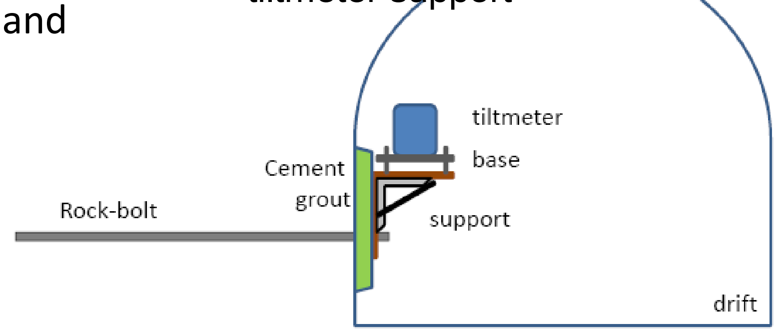


Monitoring Deformation and Acoustic Events



Events with magnitude >0.5 recorded by Friedel et al. between 7100 and 7250 levels

Experimental arrangement at 2000L using rock bolts for tiltmeter support



Subsurface Imaging and Sensing

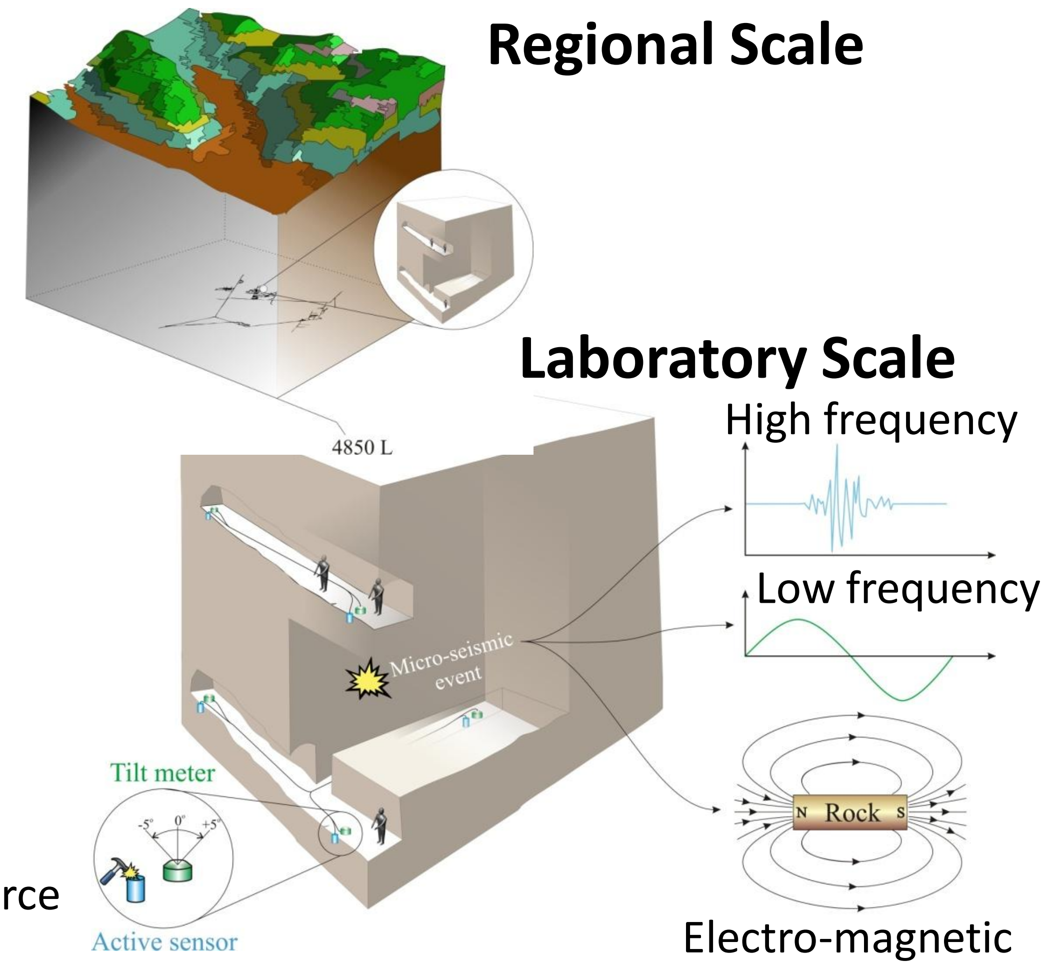
Geoscience Goals

- Constrain source mechanisms
  - Full 3-D coverage
  - Proximal and enveloping measurements
  - Strong coupling
  - Ultra-low-noise environment
- Potential to take seismology from a 10+% to a 1% science

Geoengineering Goals

- Condition monitoring of experiments for: stress, energy, deformation, failure modes…….

Measure the Rock State?



Active Source

FACILITY-BASED EXPERIMENTS [CO_2/THMCB/FRX]

LUCI - Geologic Carbon Storage – Science Drivers

Objectives

•Mechanisms for migration, reaction, and trapping of CO2 in underground aquifers or reservoirs

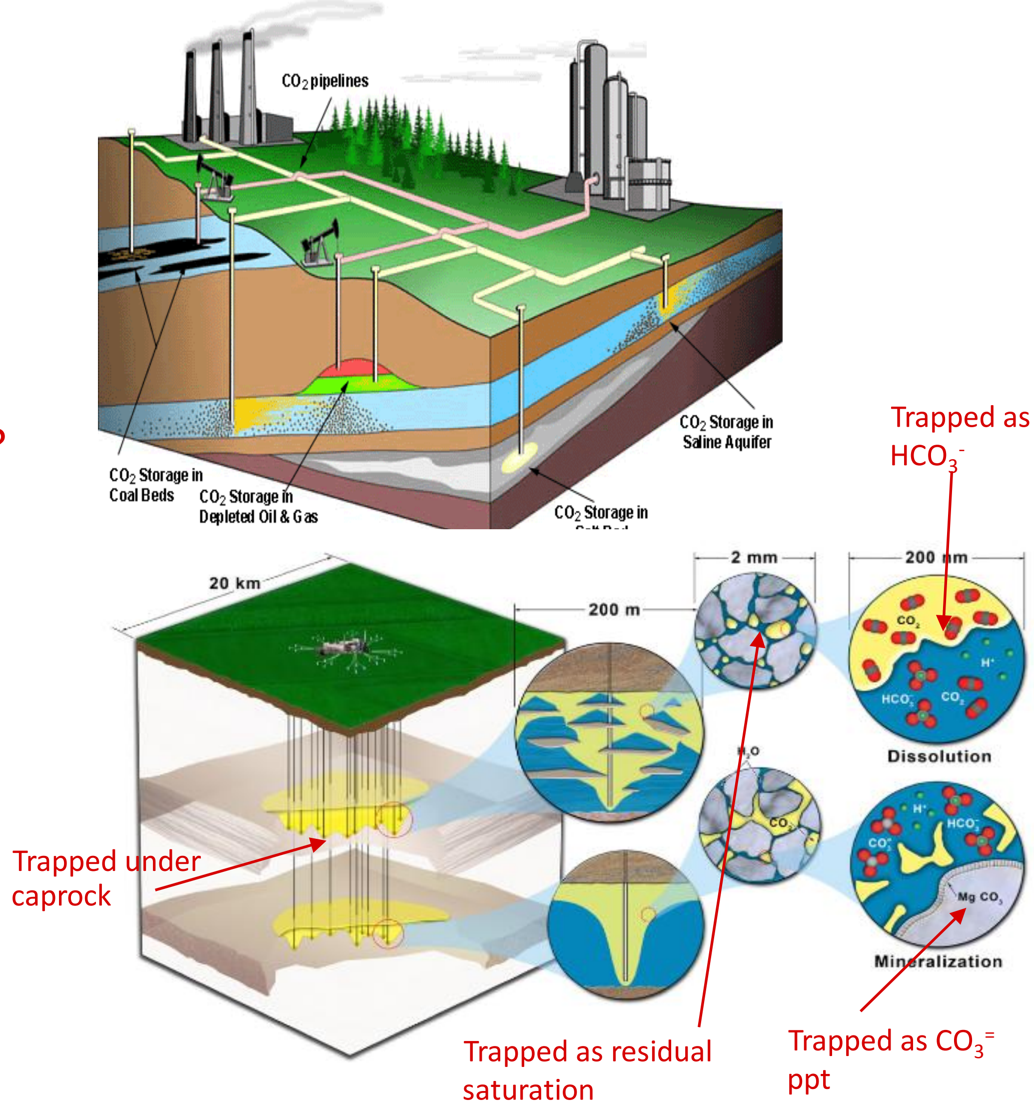
- Will CO_2 flow accelerate due to increasing buoyancy?
- Will Joule Thomson cooling and other processes mitigate buoyancy?

•Interactions of CO_2 with caprocks and well cements.

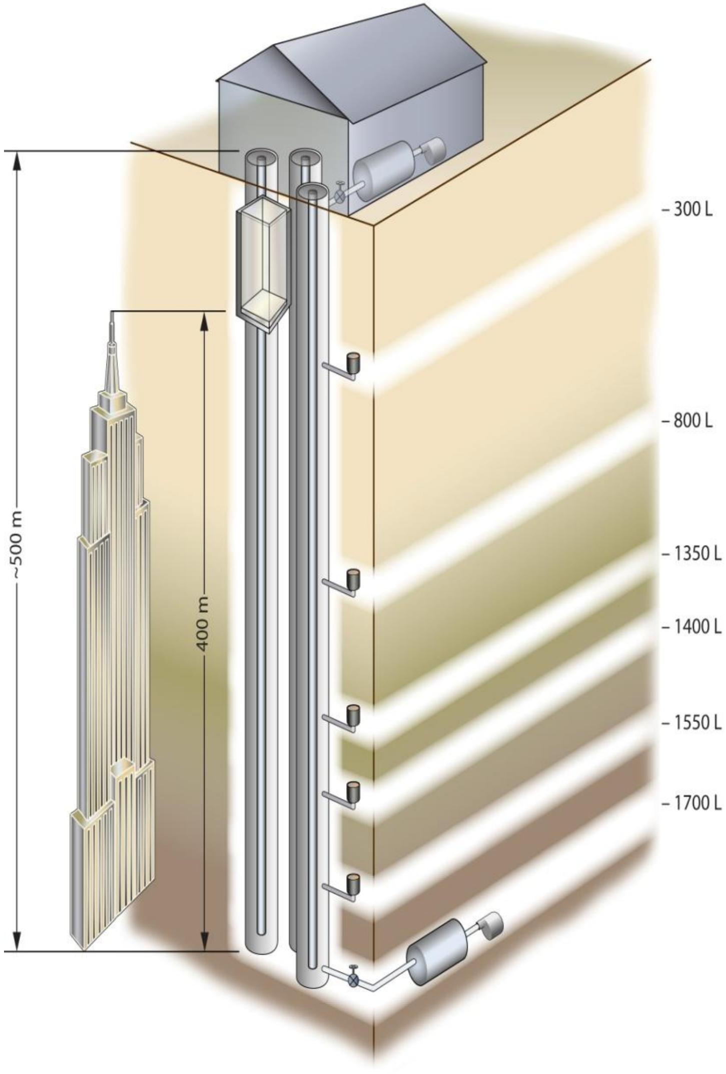
- Will acidic fluids enlarge flow pathways or cause them to self-seal?

•Metabolic potential in caprock shales.

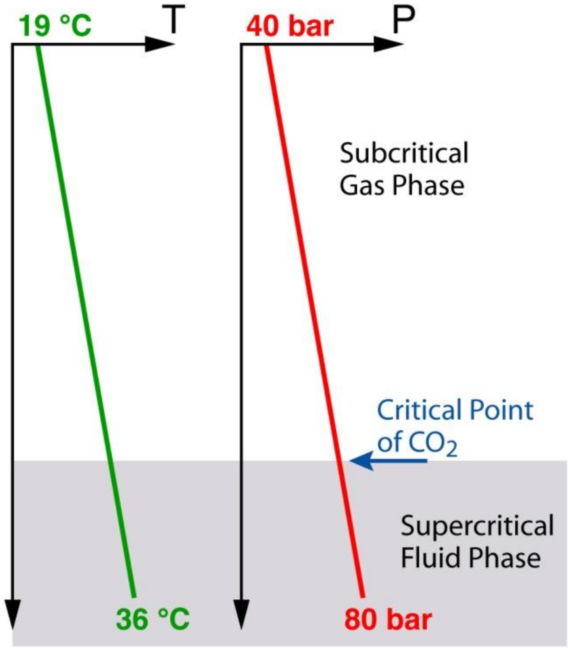
- What are the effects of anaerobic, thermophilic microbial communities on CO_2 conversion to CH_4 and carbonate?



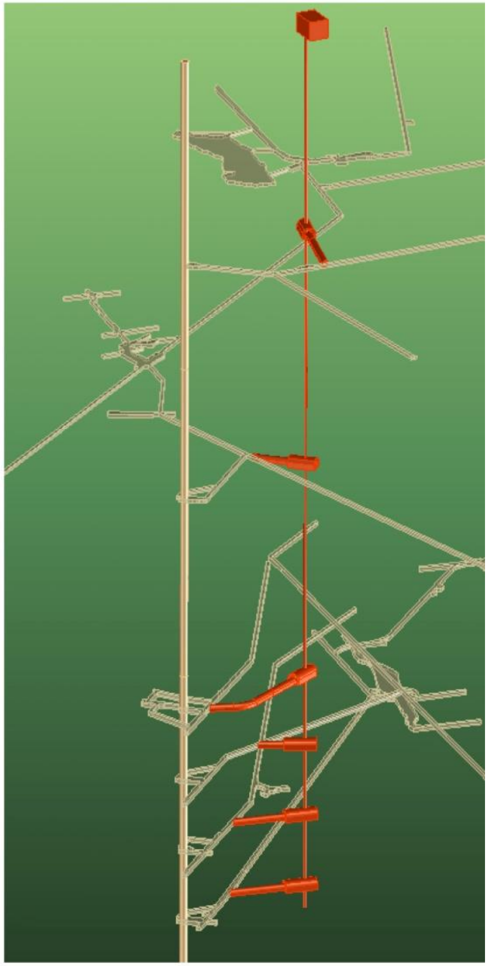
LUCI - Geologic Carbon Storage – Experimental Layout



Conceptual Design for
DUSEL CO2 Laboratory



- Long Pressure vessels filled with sedimentary materials
- Vertical bored raise ~3 m in diameter, 500 m in height
- Access at two or more intermediate drifts



Transport and Reaction Processes Experiment – Science Drivers

Key Scientific Question:

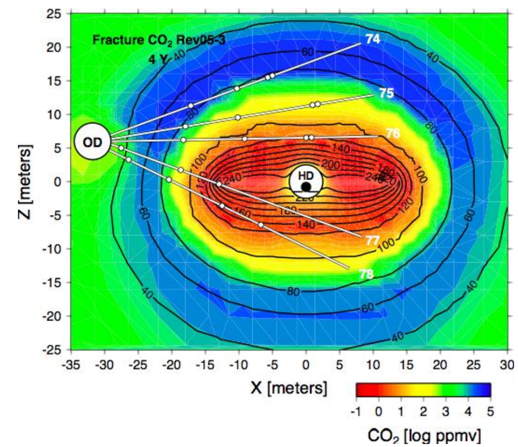
How do mechanical and transport properties evolve and influence fluid chemistry and microbial populations?

Intellectual Merit:

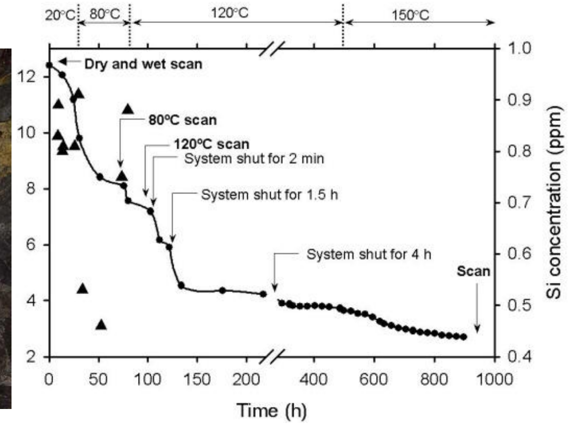
Advance understanding of fault zones, geothermal reservoirs, magmatic-hydrothermal systems, ore mineralization, radioactive waste, other.

Process interactions and feedbacks are scale-dependent, complex and often enigmatic - requiring large-scale well-controlled *in-situ* experiments to understand response.

Modeled concentration of chemical species around heater



Permeability-drop in fracture with chemical reaction and collapse



Transport and Reaction Processes Experiment – Experimental Layout

Experimental Approach

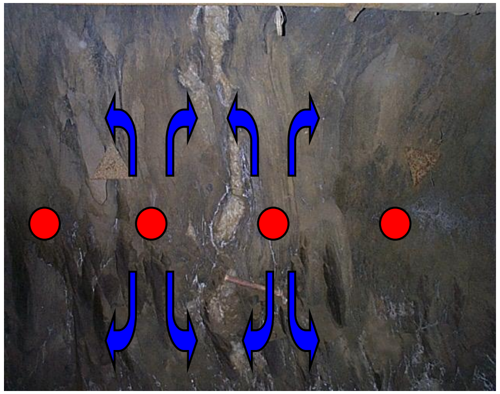
a.) characterize site, b.) install infrastructure
c.) heat d.) monitor e.) core samples
d.) excavate (*mine back*) and describe.

- **Hydrothermal Convection**
- **Biological Gradient Experiment**
- **Effective Reaction Rates**
- **Geothermal Stimulation Experiment**

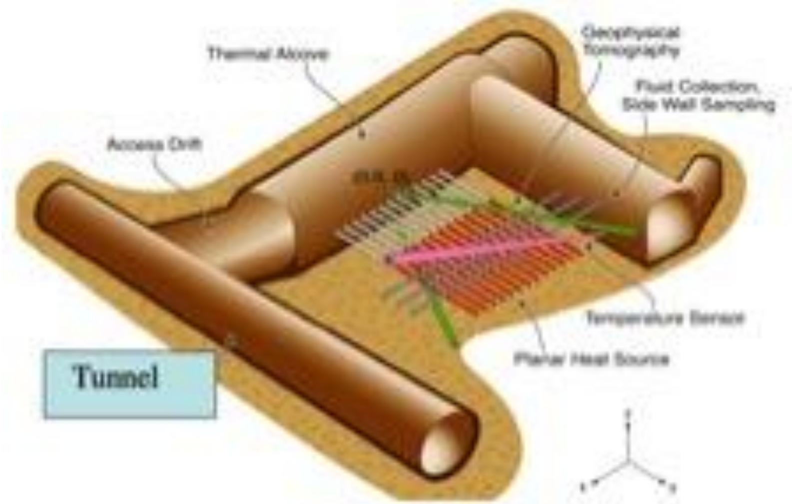
THMCB S4 Tasks

- Select candidate rock mass and tunnel complexes based on geological, mineralogical, hydrological and fracture data
- Preliminary design, refined through the following steps of characterization and pre-test modeling:
  - Laboratory experiments
  - Modeling
  - Evaluation of new technologies
- Development of **WBS**
- Working group meetings to refine design and costs

Ellison Formation & Heaters



Experimental Layout

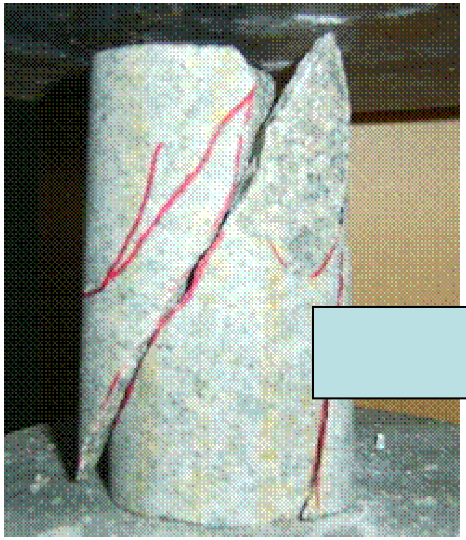


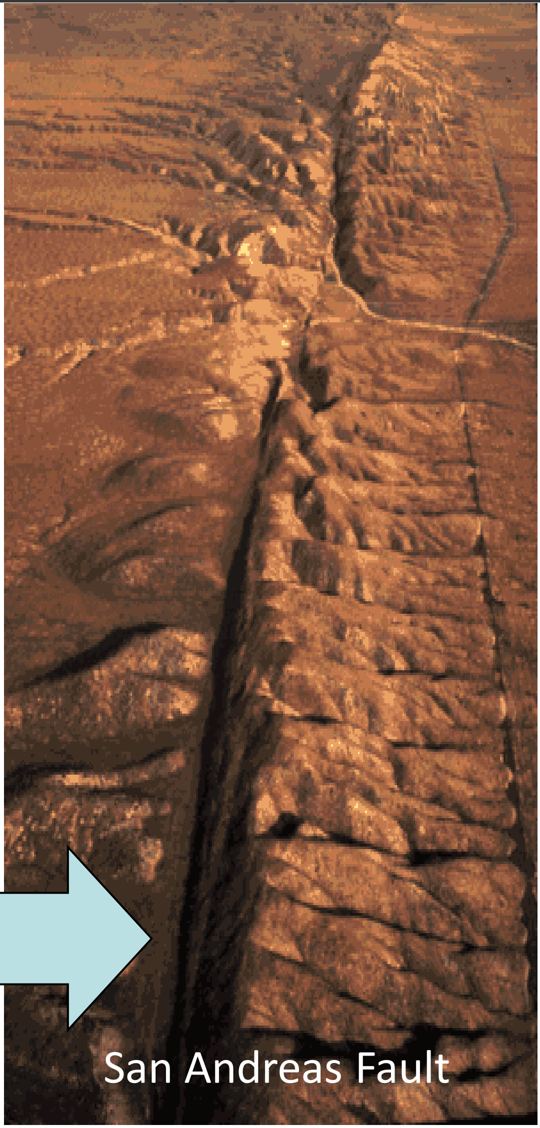
Faulting Processes Experiment – Science Drivers

Hypothesis: Faulting processes change with scale, so small laboratory experiments are incomplete representations of real faults. Larger experiments are needed to advance understanding of faulting.

Faulting Processes

Propagation in intact rock
Gouge development
Friction laws
Fault reactivation
Corresponding seismic response
Fluid effects
Microbial interactions
Sealing and healing
many others….

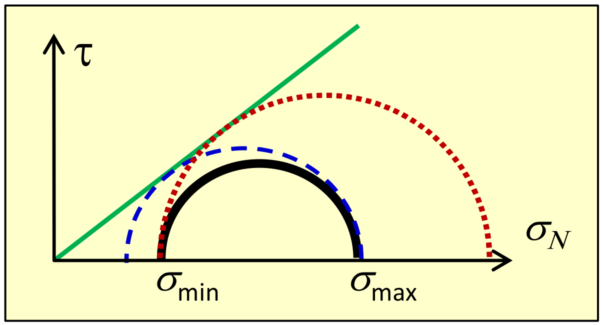


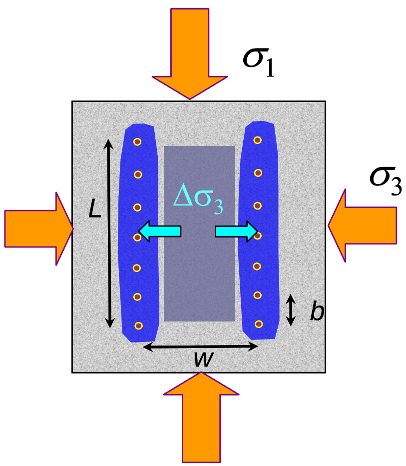


Faulting Processes Experiment – Experimental Layout

Approach

- Faulting by either increasing or decreasing stress

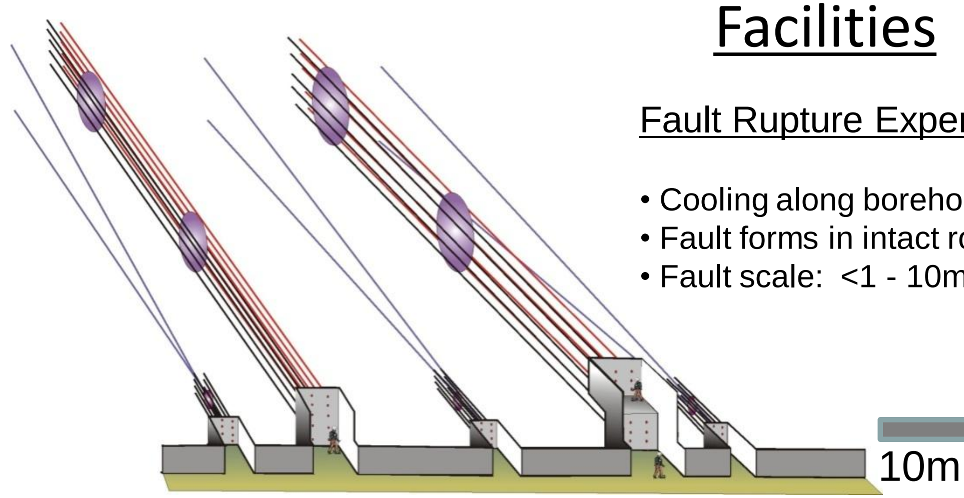




Cooling two rows of boreholes to change stress→ cause faulting

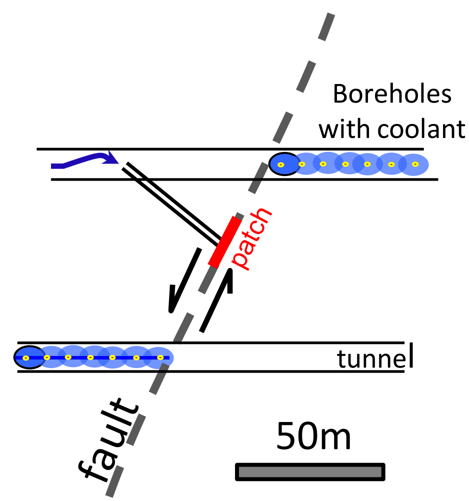
Facilities

Fault Rupture Experiment



- Cooling along borehole arrays
- Fault forms in intact rock
- Fault scale: <1 - 10m

Slip Propagation Experiment



- Cooling on 2 levels to increase shear stress.
- Inject water to initiate slip.
- Slip nucleates on patch
- Patch grows until unstable
- Critical patch size ~ 1m, so need block 10-100m

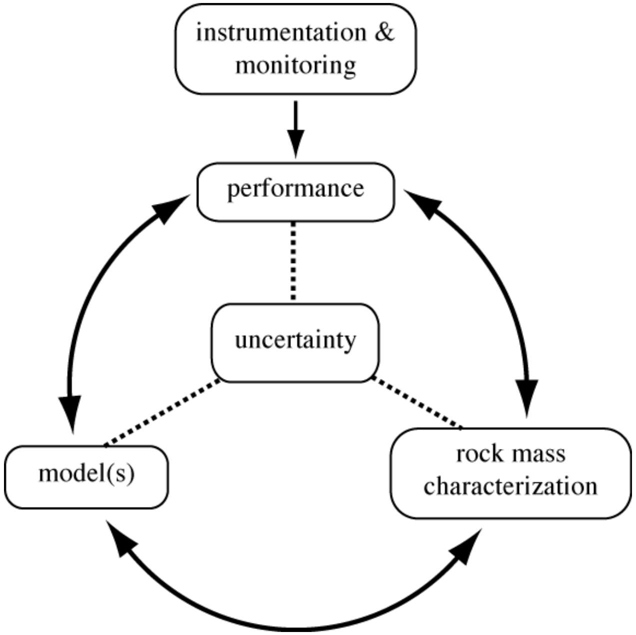
CAVITY EXPERIMENTS

Cavern Design and Instrumentation – Science Drivers

Vision:

Determine spatial- and temporal-scale behavior of rock masses for design, construction and long-term performance control of large caverns.

Concept:



Integrated Suite of Experiments

Rock mass characterization

- Fracture Network Characterization
- Digital-Reconstruction of Tunnel Walls
- New Models for Geomechanical Characterization
- Stochastic Characterization of Rock Properties

Scale effects & model(s)

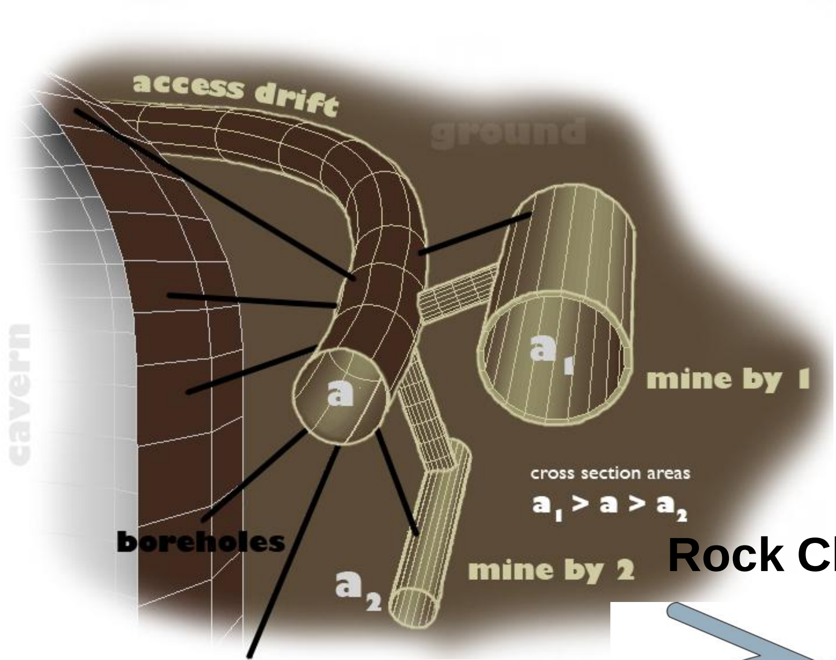
- Geophysical Evaluation of Damage Mechanisms
- Novel Excavation Techniques for Stress Relief
- Scale Effects and Mine-By Experiments
- Mine Pillar Scale Effects
- Engineering of Fractures in Discontinuous Rocks

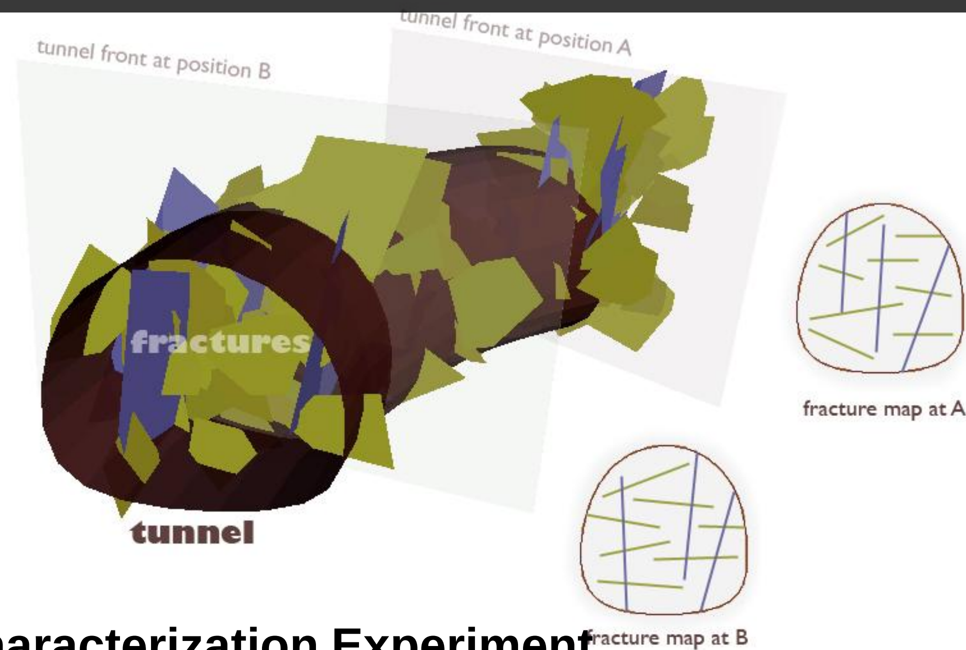
Performance & model(s)

- Optimizing the Locations of DUSEL Caverns
- Cavern Design and Monitoring
- Risk Assessment

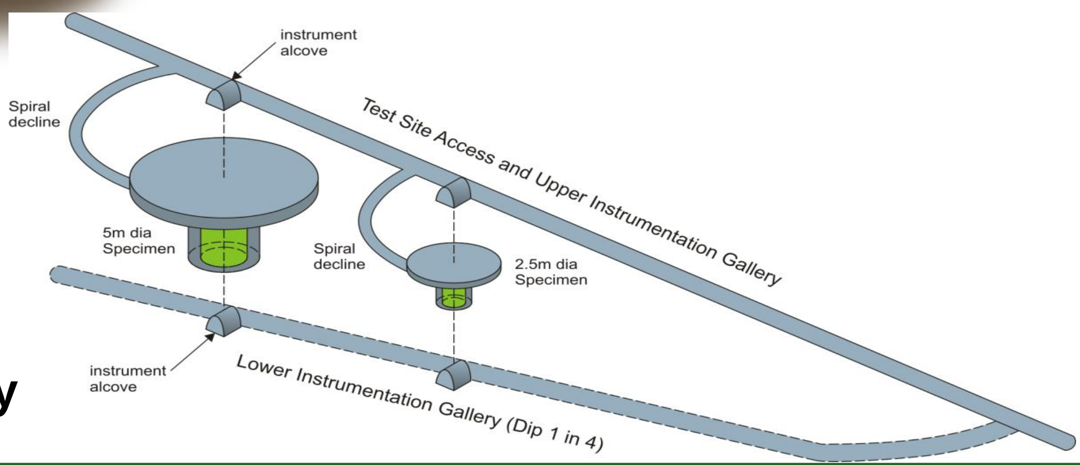
Cavern Design and Instrumentation – Experimental Layout

Sensor Array and Mine-By Tunnels



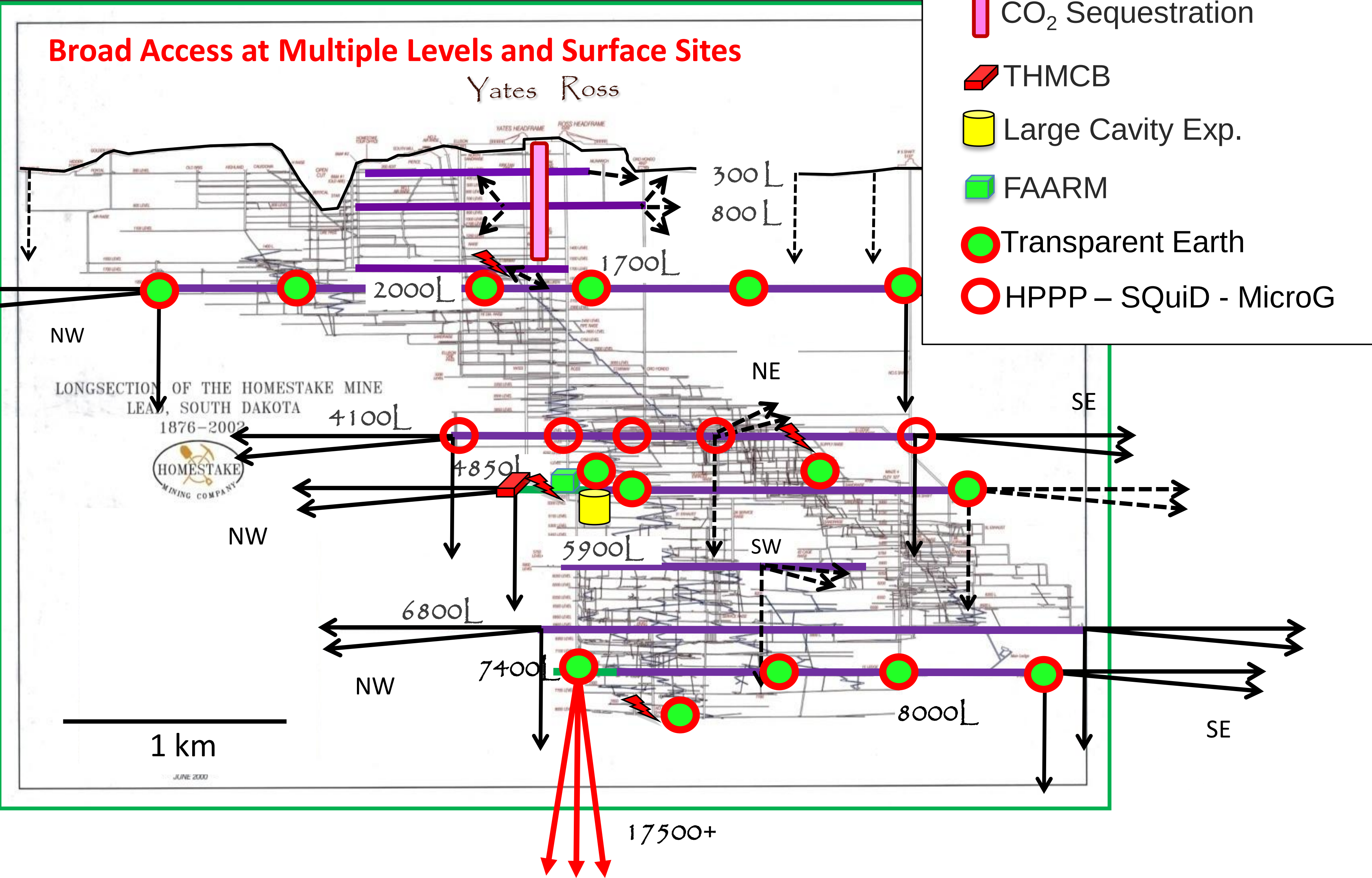


Rock Characterization Experiment



Rock Strength Facility

Experimental Layout



Future Benefits (Outcomes)

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**
  - Aquifer Remediation

Mainly GeoHydrology

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

Mainly GeoMechanics

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
  - ………………




Anticipated Contributions of DUSEL

The Dynamic Earth – *What are the crucial processes that control the dynamic evolution of the crust? These include discovery of:*

- How faults slip
- How deep rocks and fluids interact and evolve
- How rock mass behavior evolves and differs at scale and at depth

Resource Recovery, Sequestration Science and Sustainability – *What are the crucial processes and features that limit the effective recovery of resources and the safe sequestration of wastes in the deep subsurface? These include:*

- Discovery of complex process interactions that are currently poorly-observed *in vivo* and therefore poorly understood
- Defining critical factors that affect the safe sequestration of CO_2 in deep geological reservoirs

Construction Engineering in the Deep Subsurface – *How do we better characterize the subsurface to enable faster, cheaper, safer and more resilient construction in the subsurface? This includes:*

- Defining the effect of geological heterogeneities on rock mass behavior at depth and the resulting risk from characterization uncertainties
- Developing innovative design, construction and risk-analysis approaches for deep underground structures

Concluding Remarks- DUSEL Attributes

- DUSEL will represent an important facility with unparalleled attributes:
  - Long-term uninterrupted access to site
    (long term response of structures and active processes)
  - Access to unusual depth for important initiatives in deep science
    (physics and bioscience)
  - Broad access to a large volume of rock
    (scale effects and transparent Earth)
- A facility for world-class science and engineering science in:
  - Physics and Astrophysics
  - Sub-surface Science and Engineering
- Important societal impacts:
  - Energy and sustainability
  - Resource recovery and sustainability
  - Natural Hazards
  - Construction…..
- Promote cross disciplinary endeavor – biology, geosciences and engineering

Decadal Contributions [1]: The Dynamic Earth – *What are the crucial processes that control the dynamic evolution of the crust? These include:*

Discovery of how faults slip

- What are mechanisms for nucleation, triggering and reactivation?
- How does slip on one fault trigger remote failure on another with relatively small dynamic stresses? How does fault strength and permeability evolve?
- And how does this affect slip reactivation?

Discovery of how deep rocks and fluids interact and evolve

- How does permeability evolve in the deep crust?
- What factors control the competition between mechanical, hydrological, chemical and thermal agents that increase permeability and those that staunch it?
- What factors control these competitive rates at growing length scales?
- What are the important interactions of mechanics, chemistry and microbial populations on this evolution?
- How do microbial communities migrate in fractured rock in response to chemical and thermal gradients and how does deep crustal fluid flow affect the population distributions?

Discovery of how rock mass behavior evolves and differs at depth

- What is the role of different space (nm to km) and time scales (μs to decades).
- How does rock deformation partition from long baseline behavior (InSAR and GPS) to short- (tiltmetry and seismicity)?

Decadal Contributions [2]: Resource Recovery, Sequestration Science and Sustainability – *What are the crucial processes and features that limit the effective recovery of resources and the safe sequestration of wastes in the deep subsurface? These include:*

Discovery of complex process interactions that are currently poorly-observed *in vivo* and therefore poorly understood

- How do mechanical, transport and reactive properties vary from nanometer to kilometer scales?
- How do we effectively image these processes in real time using available current and new geophysical tools?
- What are the most effective methods of harvesting heat from fractured geothermal reservoirs while minimizing induced seismicity?
- What constraints may be placed on reactive or heat-transfer surface area by physical, chemical, isotopic and other methods.

Defining critical factors that affect the safe sequestration of CO_2 in deep geological reservoirs

- How will fingering driven by capillarity and by reaction control migration in reservoirs and repositories?
- Will Joule-Thomson cooling inhibit the upward migration of liquid CO_2 relative to reduced buoyancy?
- How do these processes evolve at different length-scales?
- What are the roles of microbial biota in these processes?
- How do trapping mechanisms of CO_2 evolve with time and over varied length- and time-scales?
- What is the long-term prognosis for secure trapping and effective isolation?

Decadal Contributions [3]: Construction Engineering in the Deep Subsurface

– How do we better characterize the subsurface to enable faster, cheaper, safer and more resilient construction in the subsurface? This includes:

Defining the effect of geological heterogeneities on rock mass behavior at depth and the resulting risk from characterization uncertainties

- What are the relationships between stress and strain in the shallow crust?
- How do we image in the subsurface to define the form, the location and the constitutive characteristics of these heterogeneities?
- What controls stress evolution and how effective is rock stiffness as a proxy for *in situ* stress?
- What acoustic and electromagnetic signatures allow us to better constrain processes complicit in the fracturing of rock?

Developing innovative design, construction and risk-analysis approaches for deep underground structures