

Deep Underground Science and Engineering Program

Planning and Technical Suggestions: Biogeosciences

Presented by:
Tommy J. Phelps

Contents drawn extensively from
Derek Elsworth (Geo-Engineering presentation) and EarthLab
Biogeoscience Contributors along with ideas and concepts gleaned from
>300 co-authors at >100 institutions

Road Map for Presentation

(similar to the talk by Derek Elsworth on Geo-Engineering)

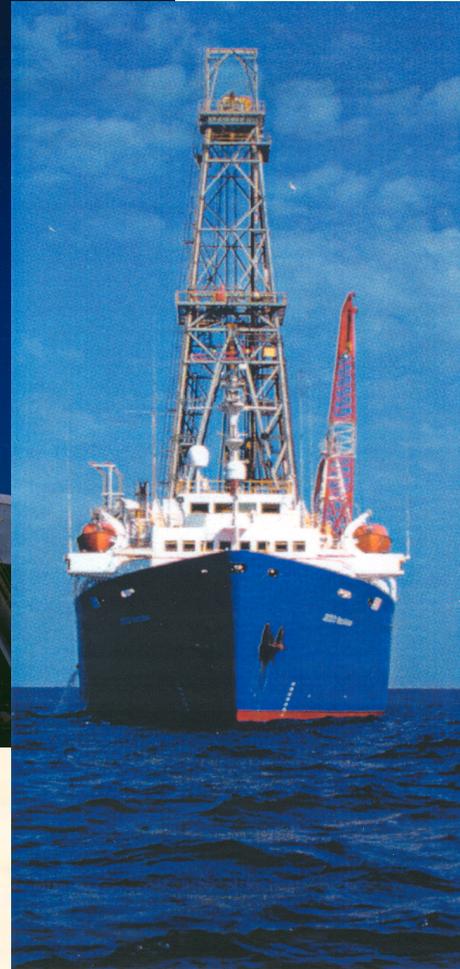
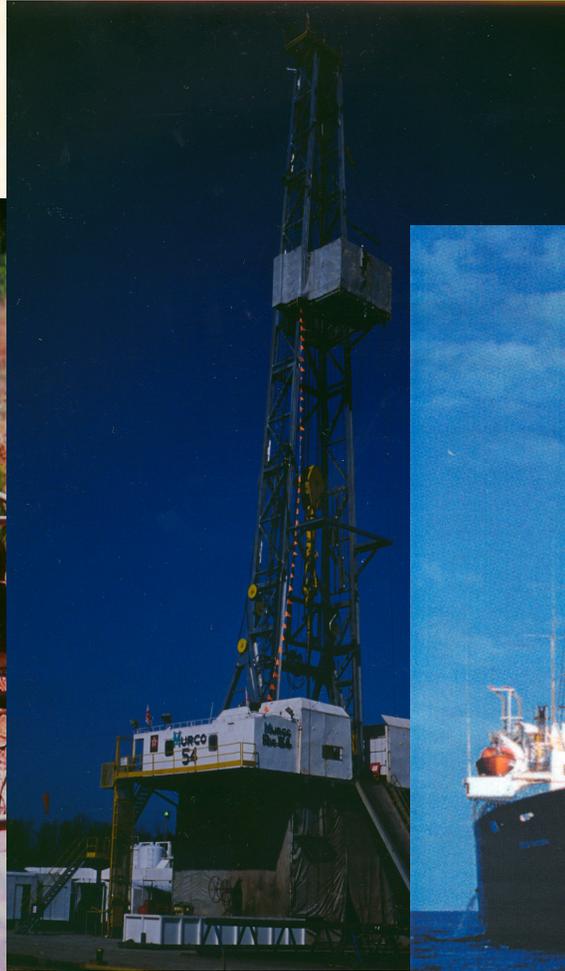
- Background and Introduction
 - What kind of experiments have been done?
 - What have we learned?
 - What is planned in near future?
 - What kind of experiments would we like to do?
- Current Case for DUSEL
- How DUSEL Can Fit These Needs
 - What is special about DUSEL?
 - What kind of experiments could be done?
- What Questions Remain Unresolved?For working groups?
- Basic Technical Requirements for DUSEL Modules?
- What Could be Done in 20 years?

Earth's Subsurface Microbial Ecology

- *The biosphere extends deep into the subsurface*
- *Limited by geothermal gradient and nutrient flux*
- *Biomass generally low relative to the surface*
- *Distribution is very patchy and heterogeneous*
- *Rates of community metabolism very low*
- *Volumetrically largest part of the biosphere*

Todd Stevens, Pacific NW National Laboratory





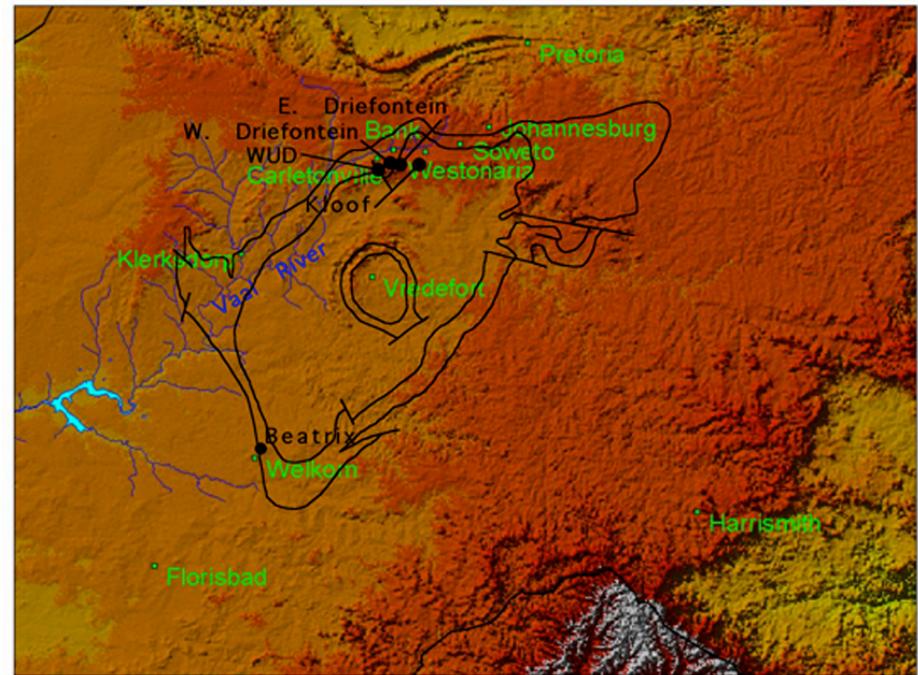
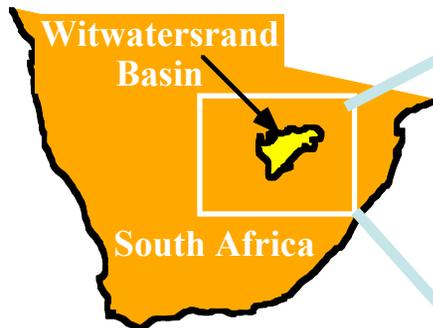
In the 1980's deep subsurface research used truck mounted rigs: DOE, USGS, & EPA

Investigations typically focus on piggy-backed opportunities: often industry-government collaborations, NSF (LExEn and Microbial Observatories) IODP, NASA, (DOE?)

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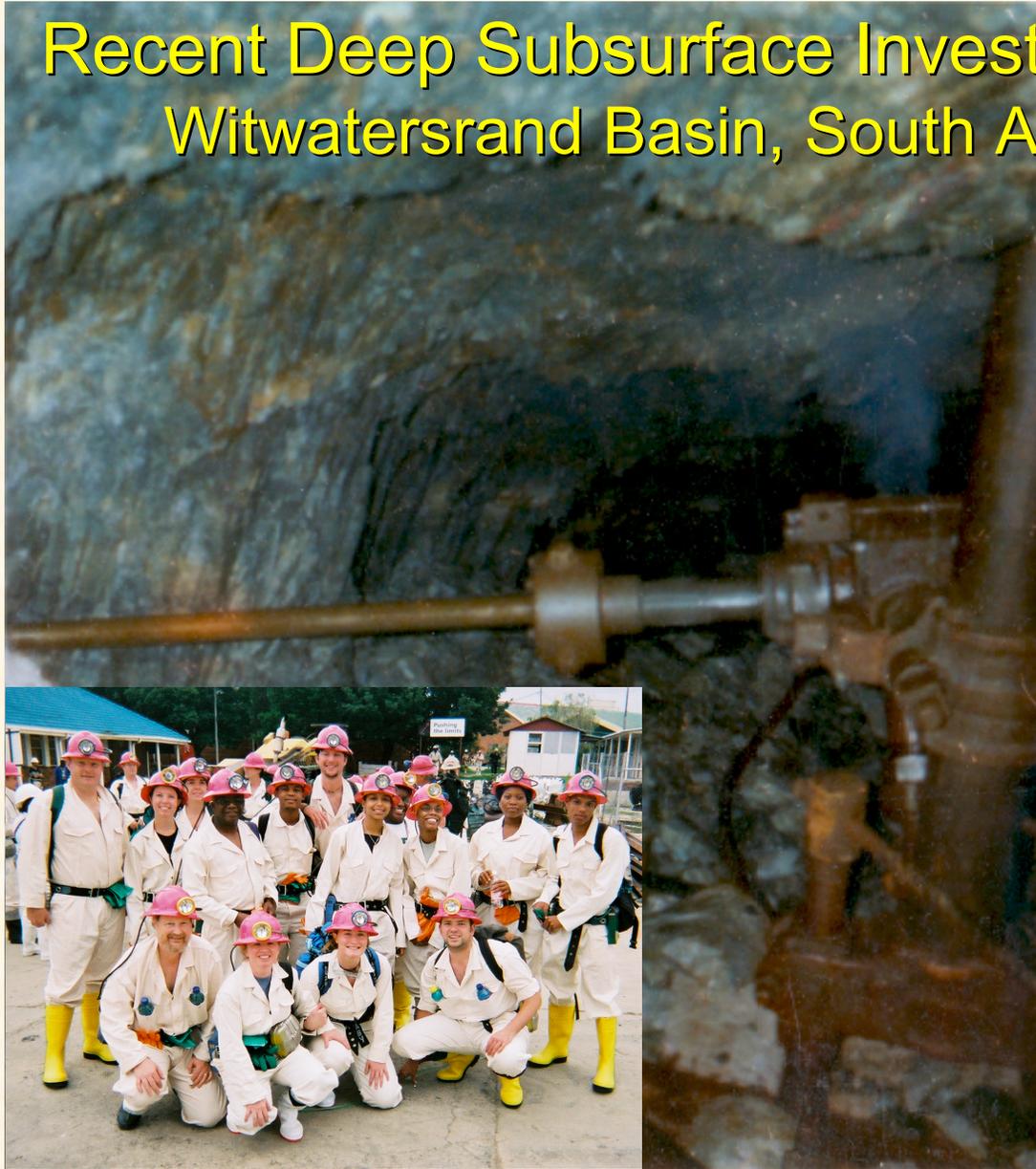
Recent Deep Subsurface Investigations Witwatersrand Basin, South Africa



- NSF and NASA funded: Highly successful collaborations with University of the Free State (UFS)
- US-S.A. seven week workshop for disadvantaged undergraduates
- **Problematic Issues: Access, Safety, Infrastructure, Site or Sample Control, Supply Lines, Export Controls, Customs, Biodiversity Regulations, Liability, Cost, Poor Gov-Ind.-Institutional Commitment, Distant Location**



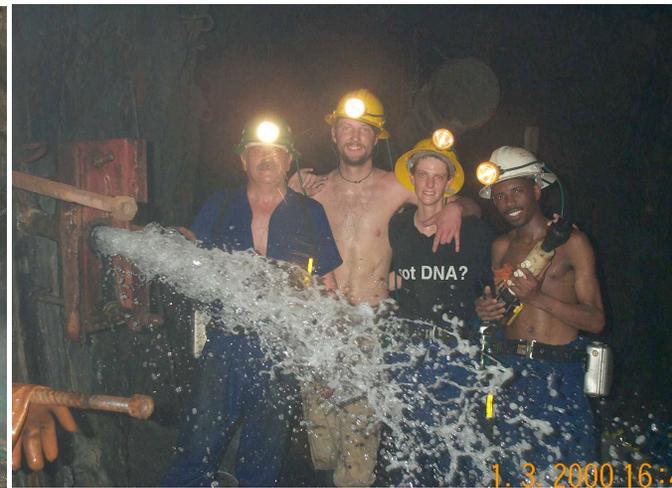
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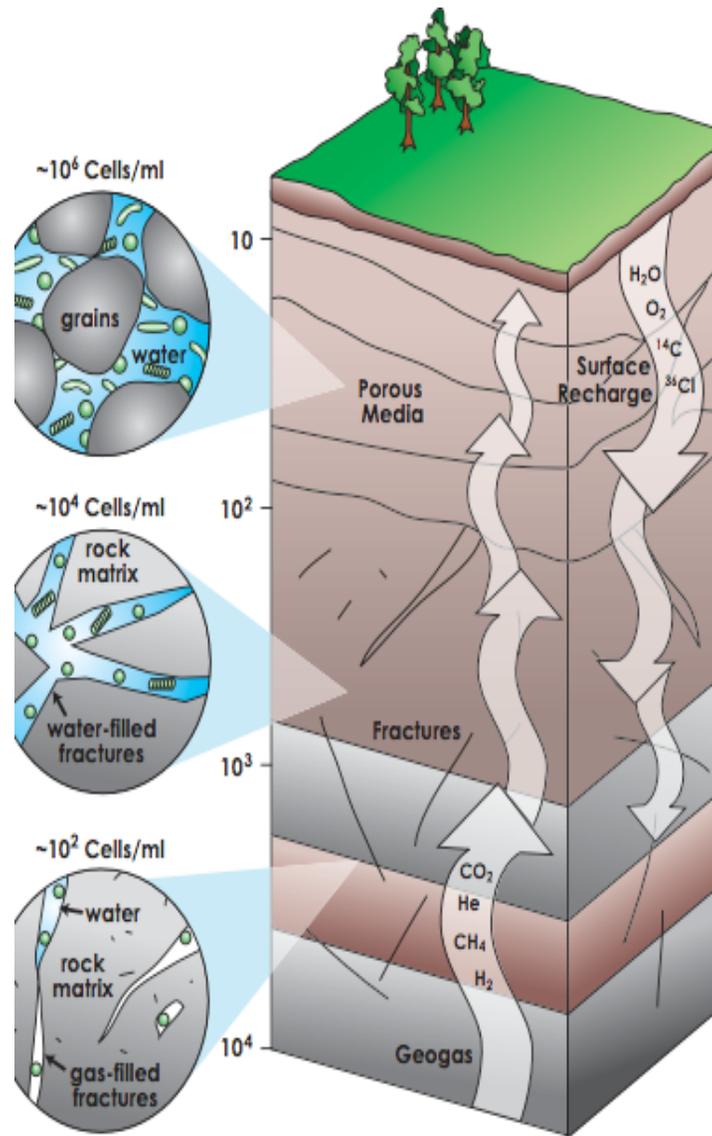


Despite challenges the Bio-Geo community has been highly successful

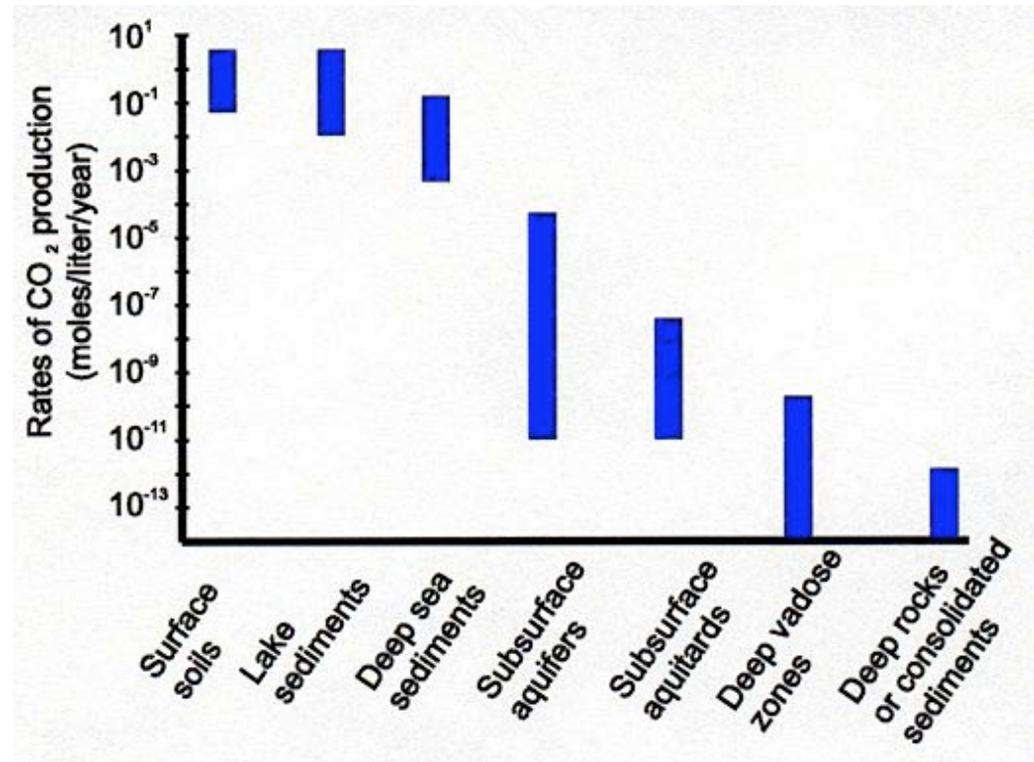


- Old water accessed at depths 1-3 km, temperature $> 55^{\circ}\text{C}$,
pH > 9 , gushing at $> 10,000$ L/hr
- Glimpse of ancient life and energy sources

What have we learned? Advancements in Subsurface Microbiology



- Drilling, tracer and QA/QC methodologies developed
- Extended known biosphere to 3 km
- Revealed biomass, biodiversity, unusual traits & microbes
- Linked microbial activity with geological interfaces
- Slow rates of deep subsurface microbial activity
- Indications of autotrophic ecosystems
- Insights into evolution and ecological genomics

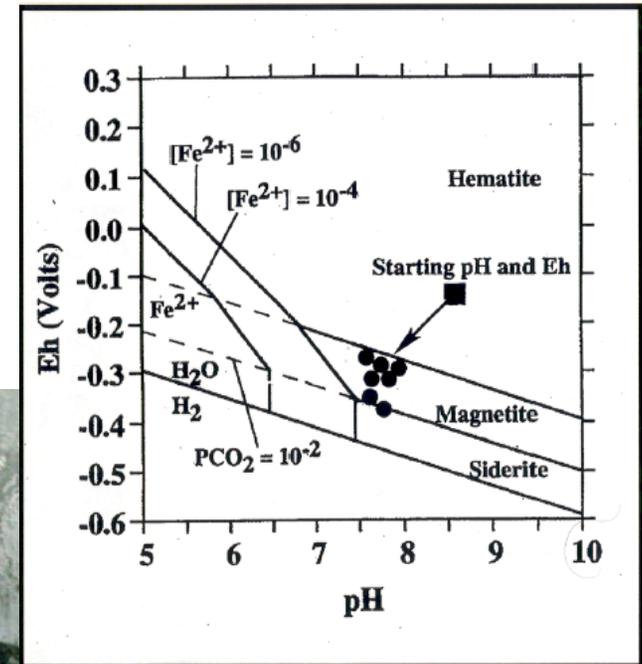


What have we learned?

- All observations are consistent with the laws of physics
- Transformations mechanisms include:
 - Thermogenic, geochemical, biological, and biogeochemical



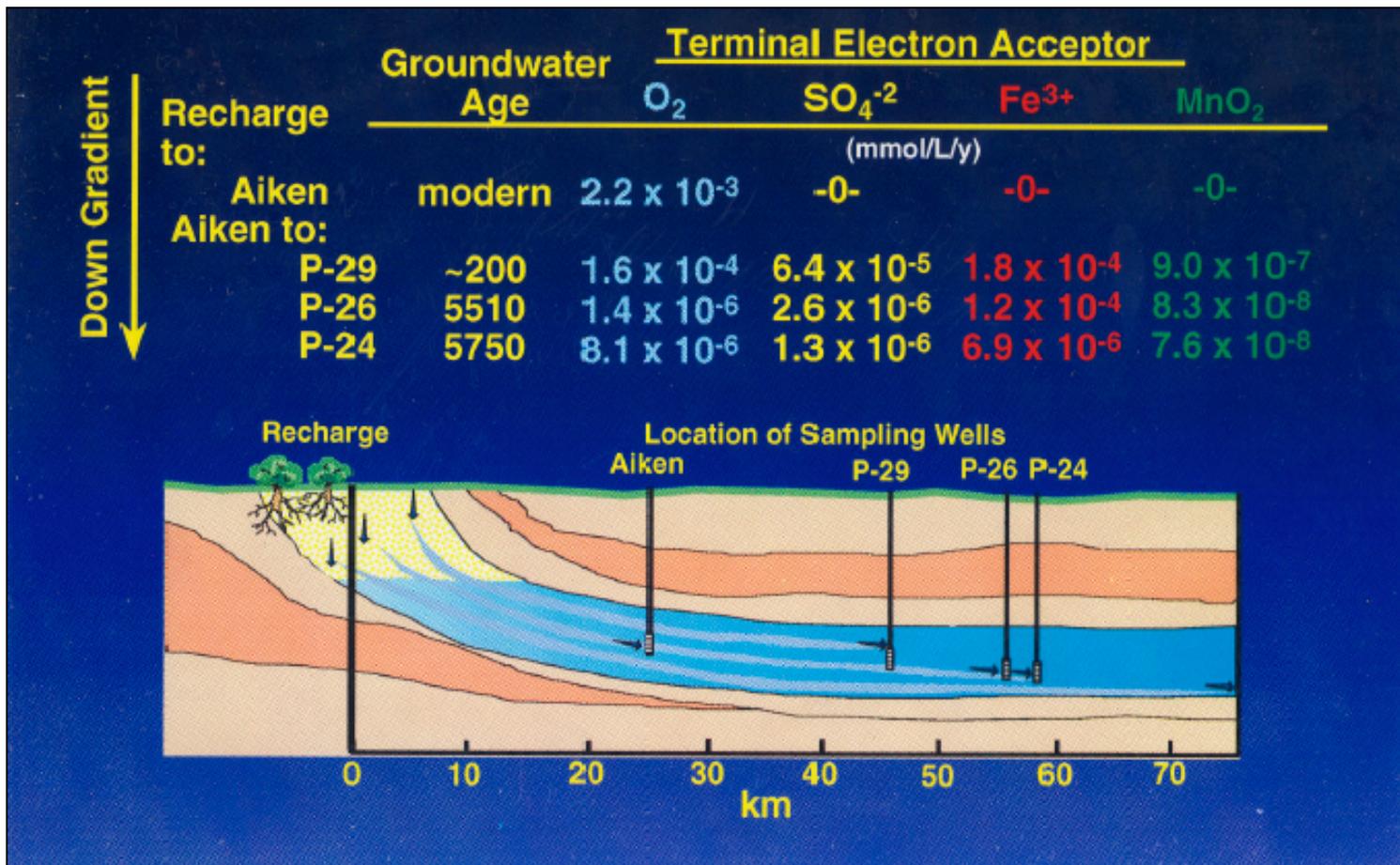
Core Processing



Eh/pH Diagram

What have we learned?

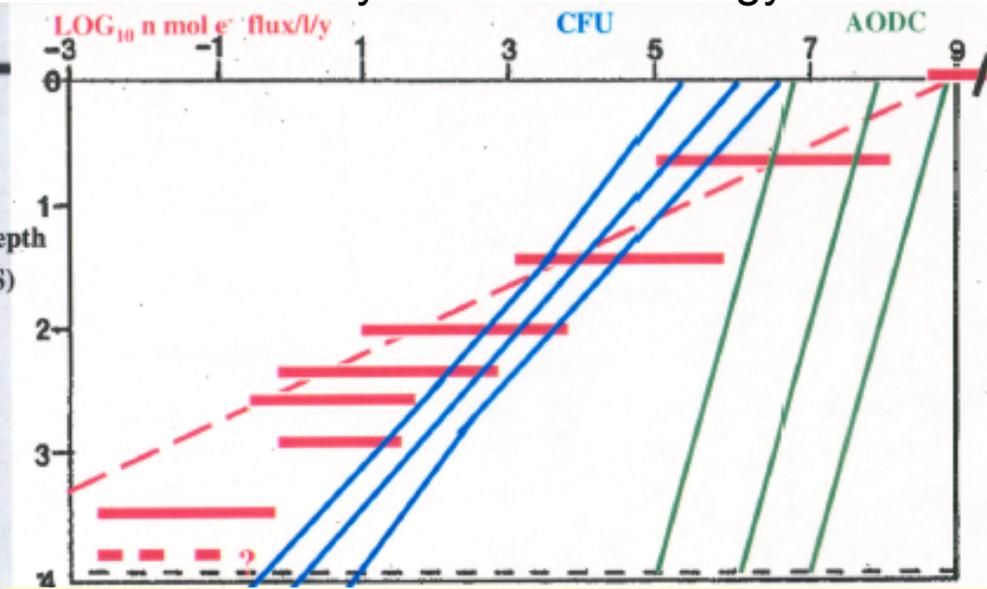
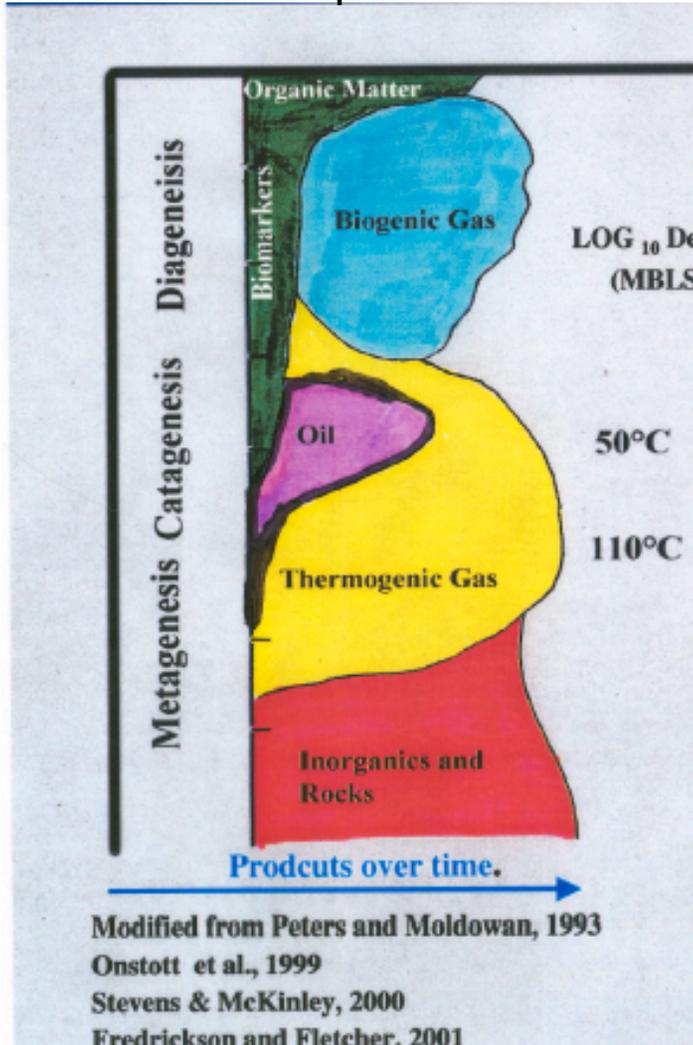
- Subsurface biomass was considered insignificant but is now recognized as a major fraction of planetary biomass (likely greater than surface biomass?)
- Subsurface microbial populations are: diverse, active, unusual, possess novel traits, represent an exploitable resource



What have we

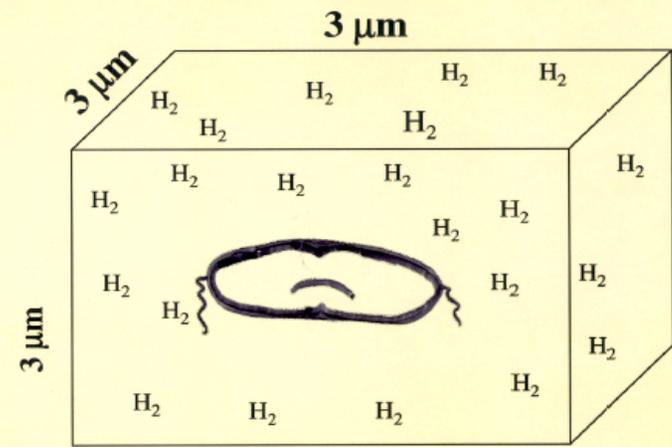
learned?

- Energy does not appear to be limiting the deep subsurface
- Deep subsurface biosphere not linked to the terrestrial subsurface (?)
- Deep anaerobic communities fueled by subsurface energy sources (?)



Daily energy supply for a cell supplied ~ 1 μM e⁻/y

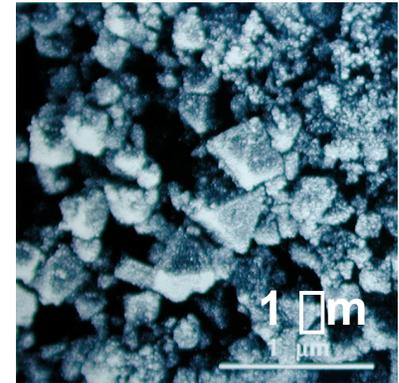
- 1 M/y = 6×10^{23} e⁻/L/y
- 1 μM/y = 6×10^{17} e⁻/L/y
- 1 μM/y ~ 600 e⁻/μm³/y
- 1 μM/y = 0.8 H₂/μm³/y
- 1 μM/y ≅ 22 H₂/box/d



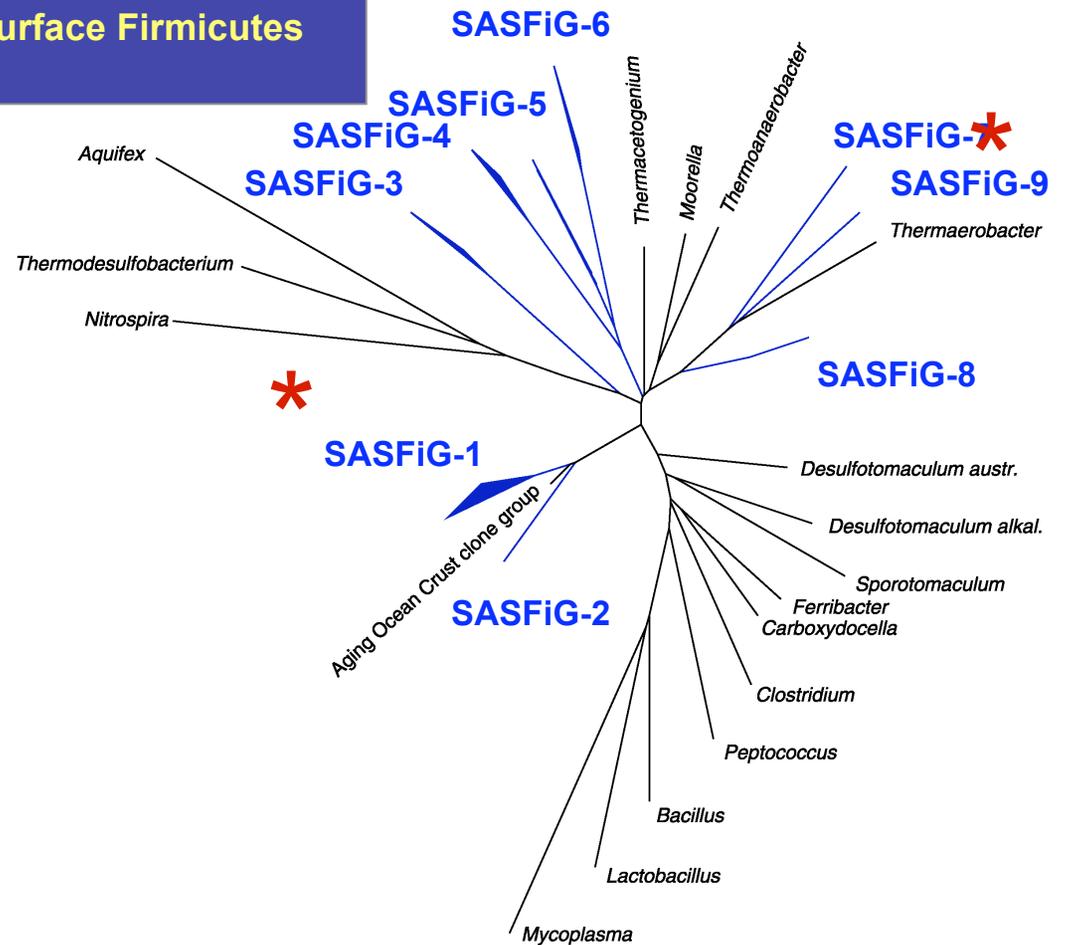
•Enough energy to make a couple of amino acid molecules each day

What have we learned?

Novel indigenous microbes and communities
 Novel and unusual deeply branched sequences may be indicative of ancestral linkages, (early life?),
 Novel products for biomed and biotech applications

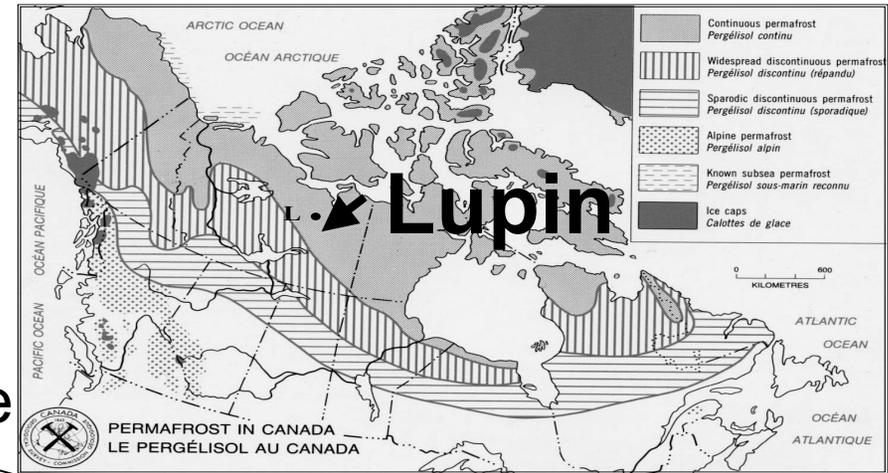


**Novel Bacterial lineages unique to the SA deep-subsurface:
 South Africa Subsurface Firmicutes Groups (SASFiG)**

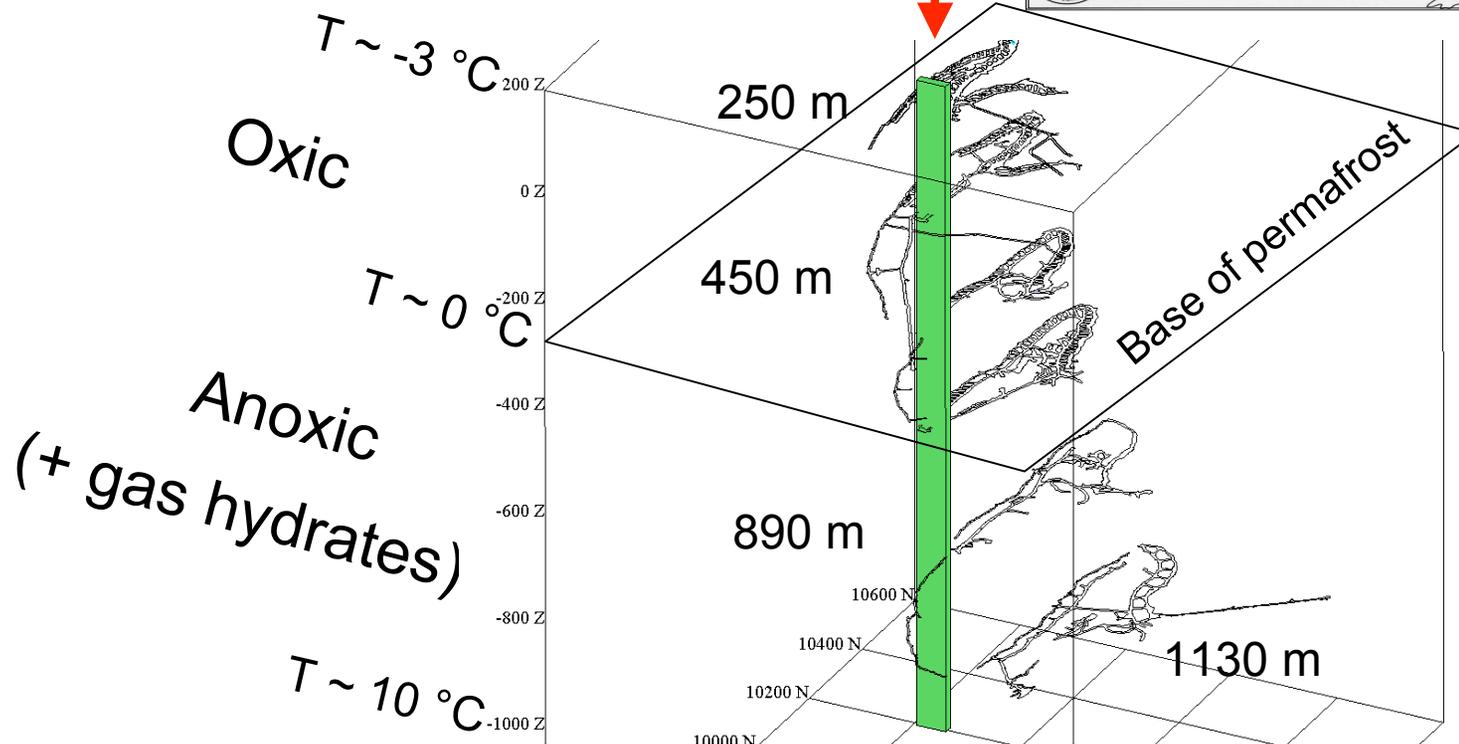


***SASFiG-9 (isolated)**
 Detected within a water-bearing dyke/fracture at 3.2 Km depth.
 strictly anaerobic; iron-reducer
 optimal growth temperature = 60 °C
 virgin rock temp = ~ 45 °C

Near Future: One Example of Planned Deep Subsurface Activities



Ore Zone

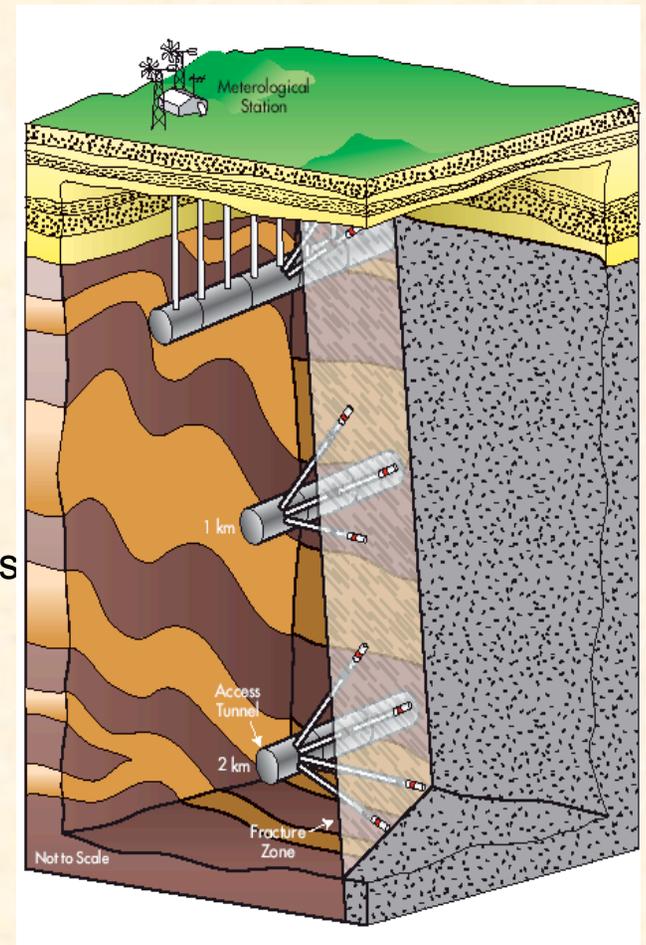


~50°C
cooler than
S. Africa

- Old water, saline, deep
- Close proximity, controlled access, infrastructure, safer

What kind of experiments would we like to do?

- Deep biosphere and biogeochemistry
- Limits of life and survival/tolerance/adaptation
- Evolutionary gradients, eco-genomics, and primitive life
- Fluid, energy, and organismal transport
- Impact of geological formations on life/preservation
- Test for an absence of life
- Impacts of human intervention on subsurface ecology
- Relationships to energy generation and carbon sequestration
- Study ore and vein forming/disassociation and mining processes
- Geo/bio/chemical study of a fabricated petroleum reservoir
- Carbon management in geological/hydrological repositories
- Role of faults on regional fluid (energy) migration
- Engineering, imaging, robotic, and in-situ mining sciences
- Others



Scientific Case for DUSEL

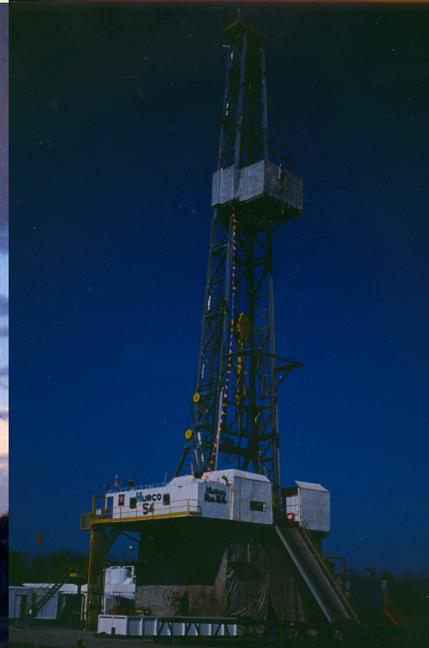
Overriding Themes: Access, Isolation and Scale

- **Dedicated Site for Quality Cores and Ground Waters**
- **Complex Coupled Processes (therm-chem-geo-hydro-bio-)**
- **Microbial Life at Depth and Deep Biosphere** (*Essence of life*)
- **U.S. Source for Biodiversity/Technology Transfer**
- **Hydrologic Cycling, Deep Energy Flow**
- **Fractures (induced), Water/Rock/Bio-Chemical Interactions**
- **Deep Seismic and Geophysical Examinations**
- **Deep Transport of Solids, Gases, Liquids and Organisms**
- **Multiple Cubic Km Perturbation Experiments**
- **Fundamental Science and Engineering Innovations**
- **Education, Mentoring, and Public Outreach**

Scientific Case for DUSEL: Access



- Drive
- Drill
- Shaft

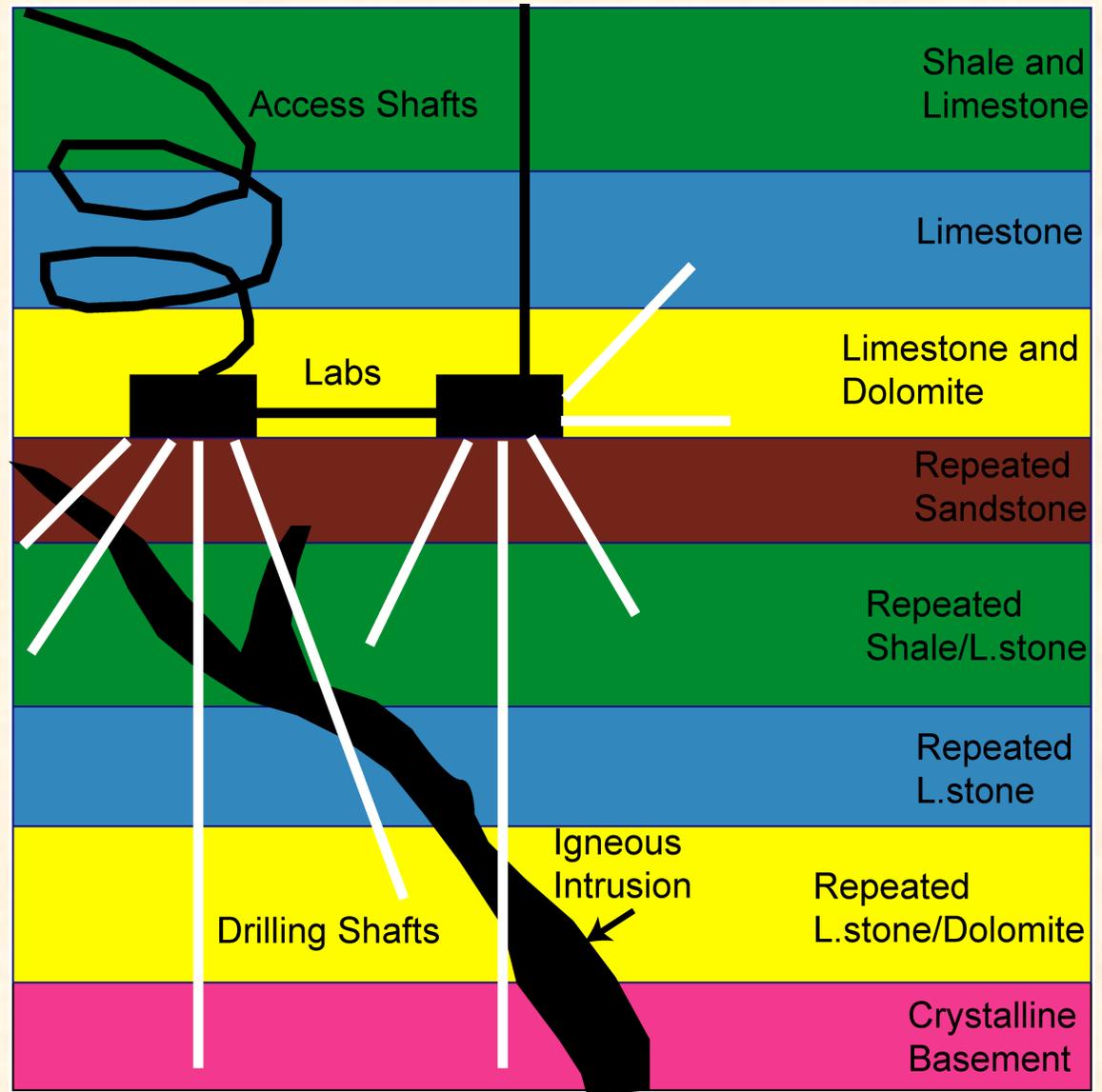


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Scientific Case for DUSEL: Isolation

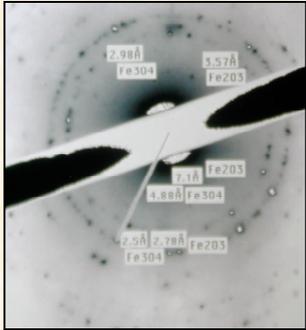
- Longtime sequestered
- Old water
- Old sediments/rocks
- Multiple interfaces
- Access to varied lithologies
- Access to Faults/Intrusions
- Varied T, P, structure, stress
- Multiple cubic km test blocks



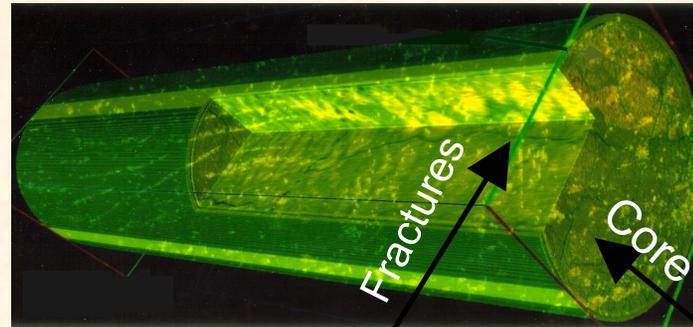
Scientific Case for DUSEL: Scale

Multidisciplinary examination of biogeochemical processes from nm to km scales

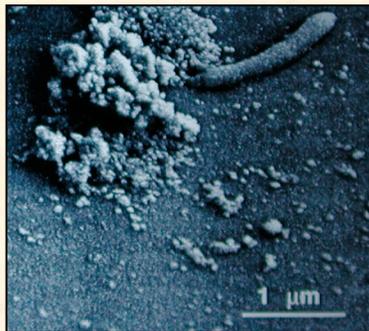
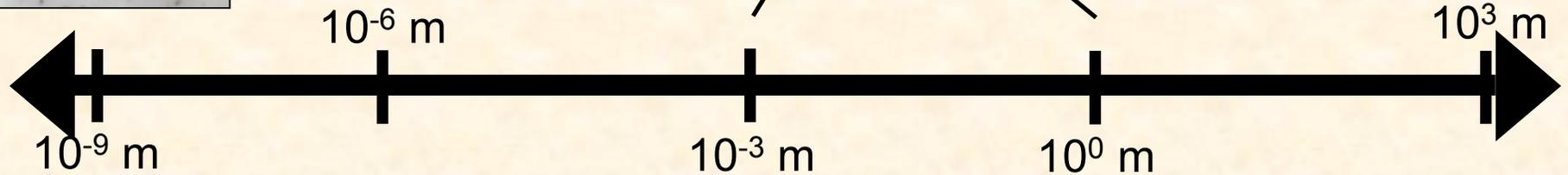
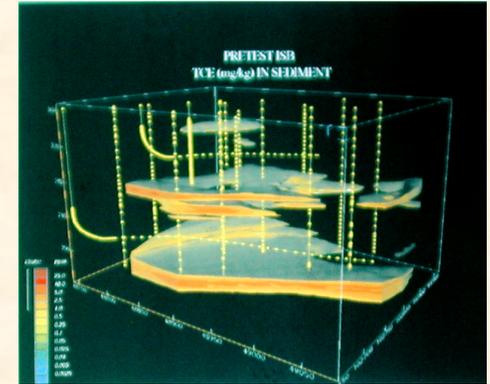
Electron diffraction of magnetic particles



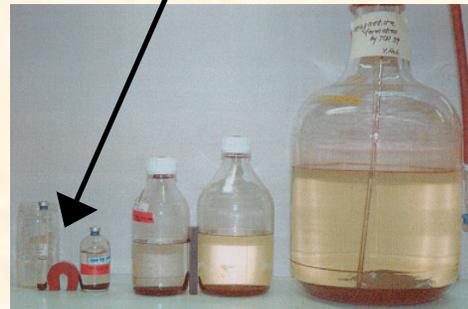
Core with fractures



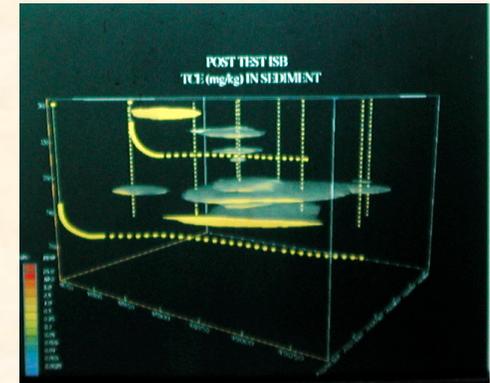
Pre-test TCE Plume



Bacteria



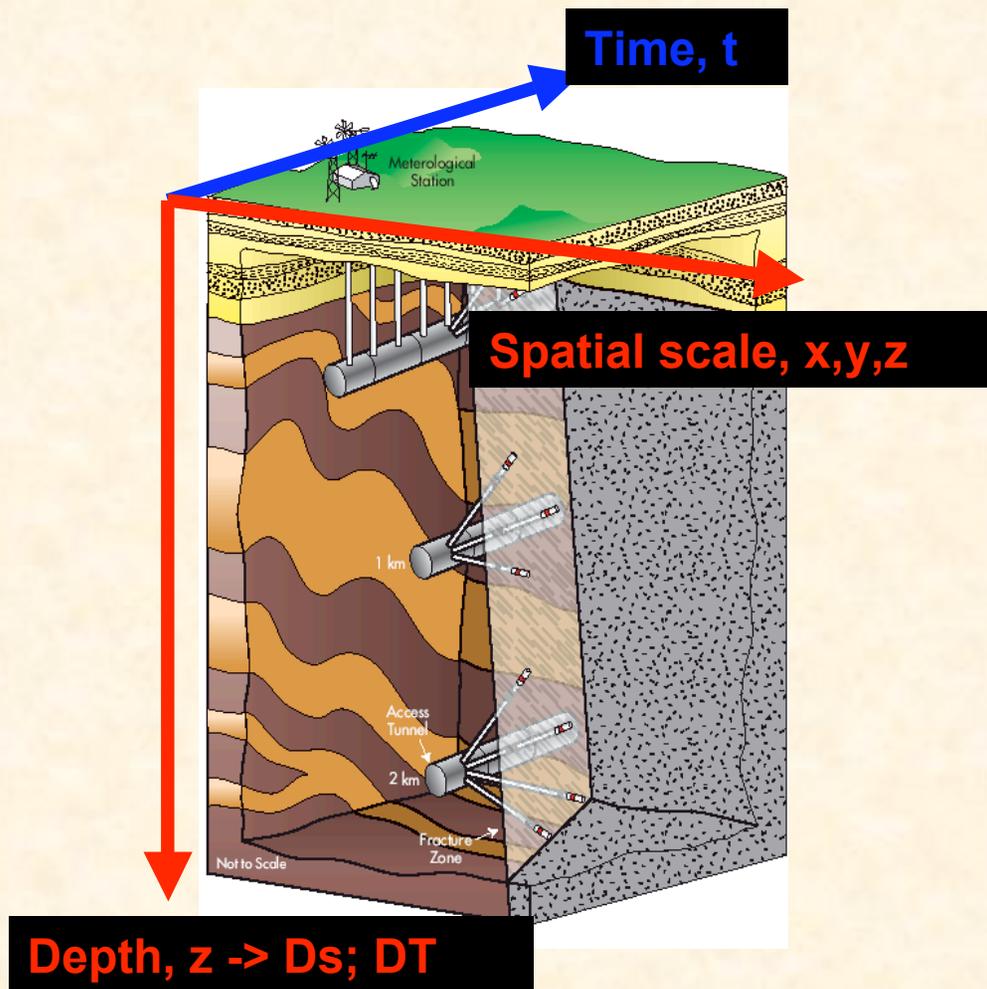
Microbial formation of magnetite



Post-test TCE Plume

How DUSEL Fits Scientific Needs?

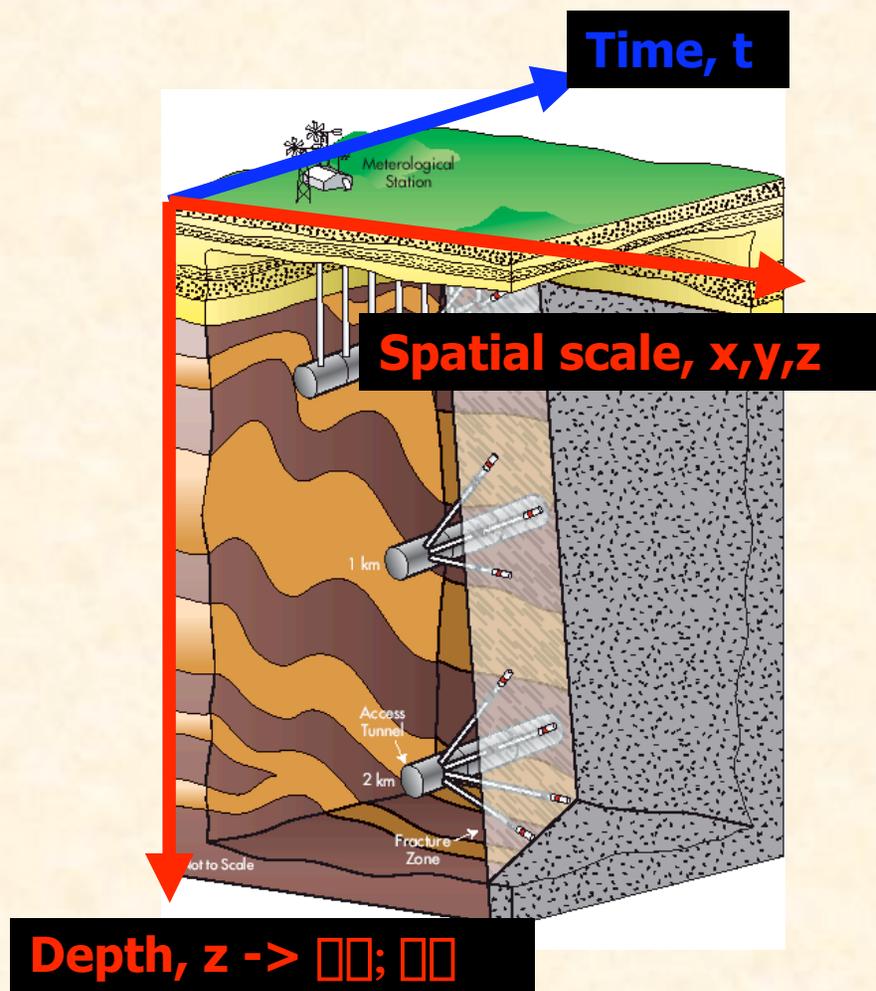
What's special about DUSEL?



Principal Attributes:

1. Long-term well characterized (3-D) dedicated site with controlled access and appropriate infrastructure
2. Isolation from surface environment with highly varied: lithologies, structure, geochemical, flow, thermal and stress regimes
3. Appropriate for nm scale investigations of electron transfer reactions at interfaces to multiple independent (manipulated) reservoir scale experiments of cubic km's

Experiments Concurrent with Construction



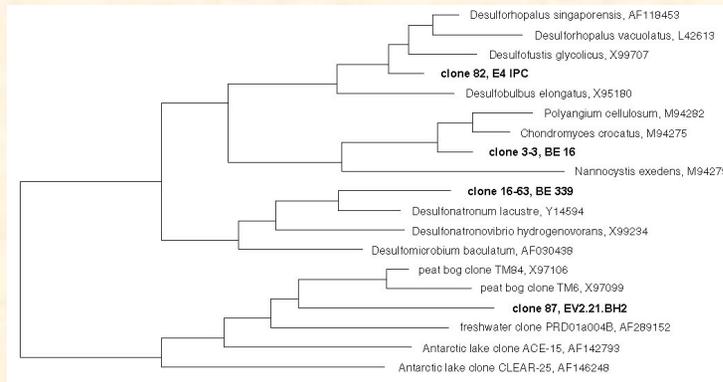
Characterization

- Corehole biogeochemistry
- Groundwater biogeochemistry
- Effects of formational changes
- Scale effects on biogeochemistry
- Scale effects on heterogeneity
- Effects of stress, temperature, gas and fluid flow
- Complex coupled processes
- Deep biosphere
- Carbon and energy fluxes
- Others

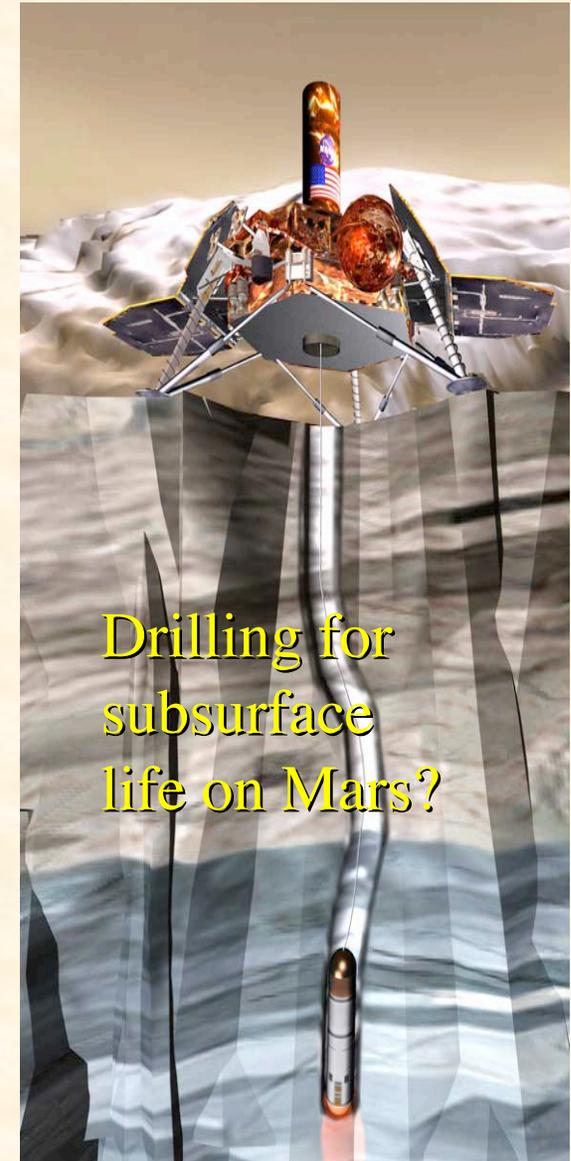
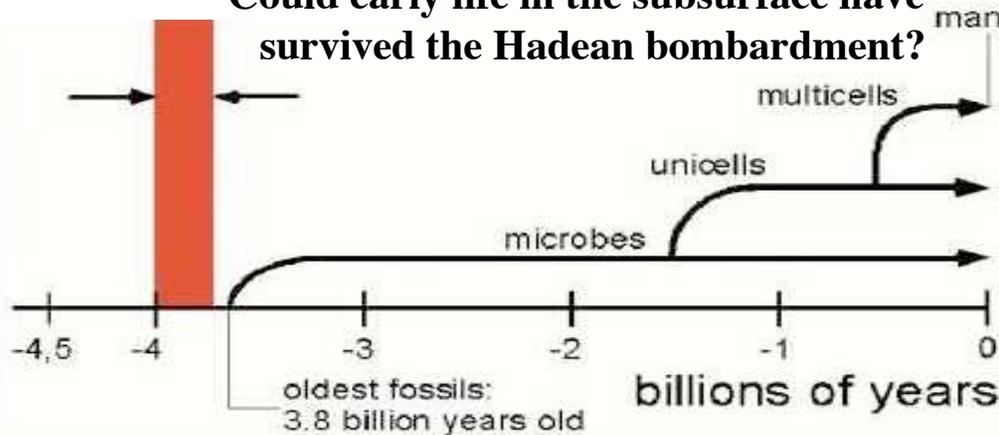
Key Experiments: Culture-Independent Evidence for Deep Life

Genomic advancements

- Sequencing of a microbe required ~18 months in mid 90's
- Currently >150 microbes have been sequenced
- In 2004 TIGR discovers 1.2 million new bacteria/archaea genes in the Sargasso Sea
- By 2005 JGI could sequence 400 microbes per year

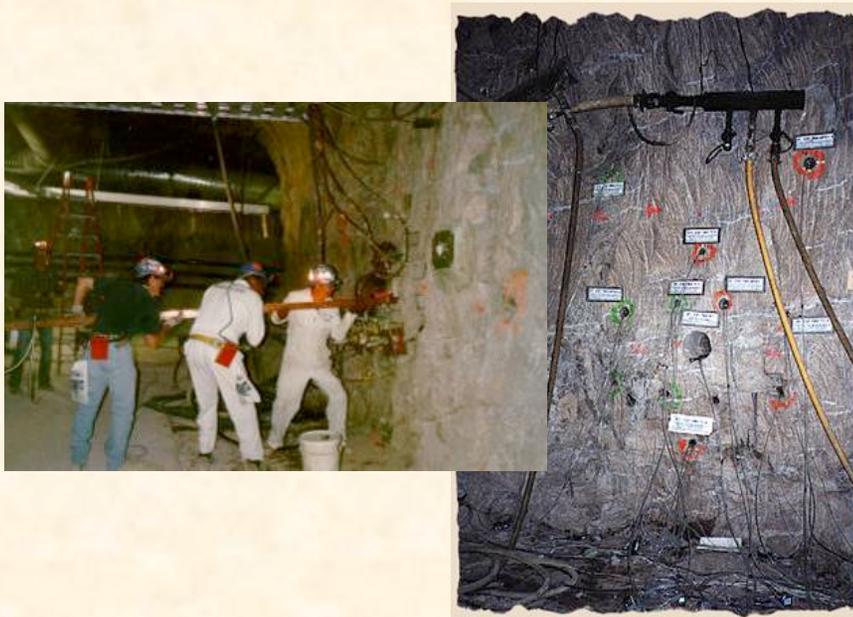


Could early life in the subsurface have survived the Hadean bombardment?



Purpose-Built Experiments

Large Block Tests



Confirm predictions and corroborate models by detailed characterization and or exhumation

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Scientific Observatories

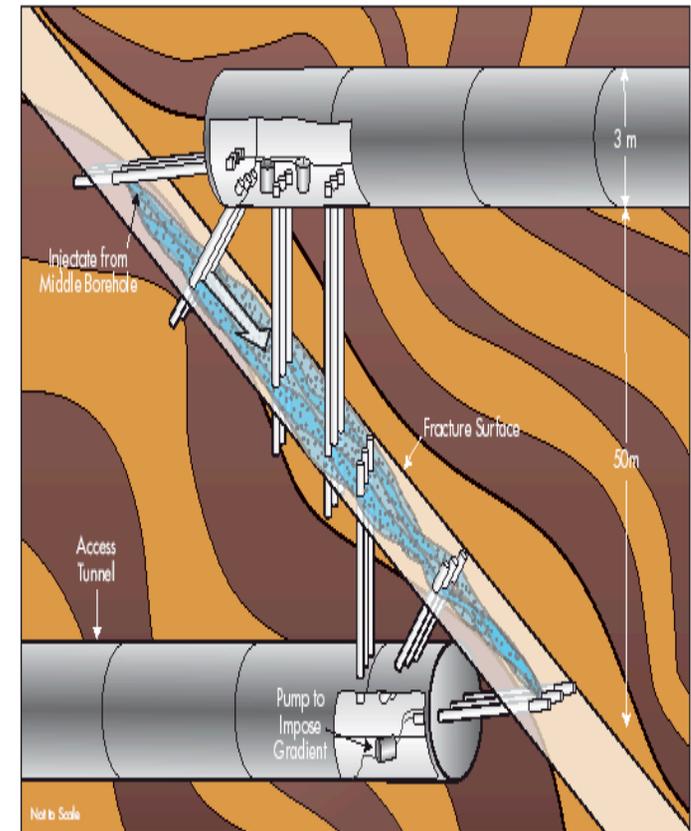
- Deep Biosphere/Deep Energy
- Adaptation, Survival, Colonization
- Bio-Geo-Hydro-Chem Characterization
- Scale effects on Coupled processes
- Reservoir experiments
- Mineral formation/dissolution
- Vein formation and mineral transport
- Biomining and engineering
- Geophysical, seismic and remote robotic characterization
- Induced fracture processes
- Deep flow and paleoclimate laboratory
- Education and outreach laboratory
- Others.....


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Example: Deep Coupled Processes Laboratory

Characterize coupled-processes that affect critical scales of environmental Bio-Geo-Hydro-Chem- and Engineering-Sciences, including:

- Gas, liquid, solid and bio-transport
 - Energy resource recovery
 - CO2 sequestration
 - Conservative tracer and geophysics
 - Heterogeneity (Chem-bio-geo-)
 - Waste isolation
 - In situ mining
 - Mineralization and ore body formation
 - Others
- Characterize coupled processes under ambient and manipulated conditions
 - Chemical fate and transport including dissolution/precipitation and modification of mechanical and transport parameters
 - Multiphase flow and transport
 - Microbial colonization, adaptation, survival
 - Evolutionary gradients/eco-genomics



What Questions Remain Unresolved?

(with comments from Derek Elsworth)

- Attributes of different geo-environments
 - One site versus multiple sites for DUSEL activities?
- Define incompatibilities
- Integrate site-characterization with project
- Coordination of activities
- Decades out?

DUSEL as a launch pad for new science, new understandings and new widgets

Unresolved Issues, Cont'd:
Attributes of Different Geo-Environments
(High Heterogeneity Enhances Scientific Value)

Sci/Eng Focus	Relevant Range of Attributes
Overall/Geo/Eng	Low-high stress Low-high thermal gradient Small-large site volume Homogeneous-heterogeneous Unfractured-fractured
Geo-biological	Sterile-teeming Low-high nutrient and water flux
Geo-chemical	Reactive-inert Low-high electrochemical flux
Geo-hydrological	Permeable-porous to non-porous/fractured
Geo-mechanical	Brittle-ductile Low-high stress
Geo-physical	Aseismic-Seismic

Unresolved Issues, Cont'd:

Define and Disengage Incompatibilities

- Explosions & impacts of blast mechanics?
- Radioactive minerals, or added isotopes?
- Time and space separation of large scale experiments?

- Appropriate care and QA/QC during site characterization
- Longterm recording and accessing of results
- Longterm organizational structure
- Identify Other constraints

Basic Technical Requirements:

****Integrated site-characterization with DUSEL Science Plan**

(Maximize info and minimize compromising future R&D)

- Longterm, dedicated, deep, isolated with infrastructure
- Coreholes and boreholes should be positioned and developed with appropriate QA/QC for Bio-Geo-Chemo-Hydro-characterization
- Access to several cubic km-sized pristine test cells
- Access to old subsurface media and ancient waters
- Integrated records and data access for future planning
- Boreholes coordinated for Geo-Bio-Chemo and geophysics
- Boreholes coordinated for segregated packered screened zones
- Integrated and redundant community participation for max science

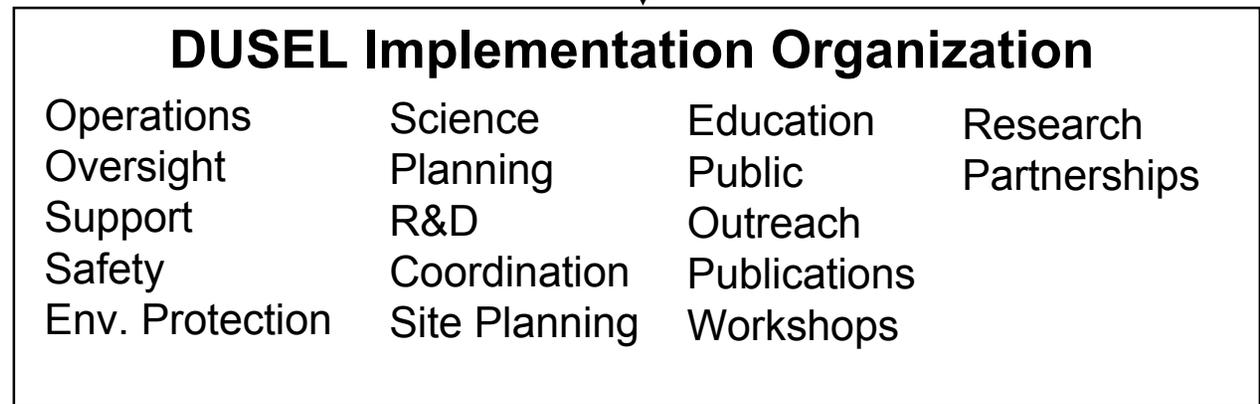
Coordination of Activities

Suggestions:

1. Cast a big net for attracting funds



2. Widespread community participation



3. Coordinated at T=0



4. Evolve

What Will be Done in 20 years?

(Best comments were liberated from Derek Elsworth)

Heavier than air flying machines are impossible..... *Lord Kelvin, President, Royal Society, 1890-95.*

- Digital characterization for Earth processes (**Faster, more reliable, cheaper, better**)
- Transparent prediction of processes, scaling and heterogeneities (**Faster, more reliable, less expensive, more accurate**)
- Predicting performance of engineered structures in space and time
- Understanding the essence of life, its origin, evolution and potential
- Future generation scientists with their superior ideas

Somewhat more predictable:

- Genetic materials, microorganisms with novel capabilities, biotech applications
- Instrumentation for monitoring/mapping (imaging/sensors)
- Widgets and technology transfer
- Applications in exobiology & underground in-situ mining
- Environmental remediation technologies
- CO2 sequestration field testing (leakage, impact)
- Drilling & excavation technology (rock engineering, structural support of rock masses)
- Advanced natural resource exploitation technologies
- T. J. Phelps will have retired

Summary

- Hundreds of subsurface biogeoscientists are poised for DUSEL (e.g. >300 co-authors of Phelps and of Onstott from > 100 institutions)
- DUSEL represents an exciting opportunity for collaborative interdisciplinary examination of: deep biosphere, evolution and genomics, hydrologic and fluid cycling, deep flux of energy, water/rock interactions, and geophysics
- DUSEL is unique: Dedicated, controlled access, isolated environment, multiple scales, many disciplines, education and outreach, and HERE!
- Appropriate tools have recently been developed for sample retrieval and interrogation, evolutionary genomics, detailed 3-D geophysics, and examination of coupled Bio-Geo-Hydro-Chemo-processes
- Biogeoscientists have prepared for two decades ground truthing hypotheses and procedures for this grand opportunity

We look forward to DUSEL collaborations