# Technical Challenges for Deep Borehole Disposal

Presented to:

**Geological Society of America Annual Meeting**

Presented By:

**Mary Lou Zoback, Stanford University & Board Member**

**Bret Leslie, Board Senior Professional Staff**

**Jean M. Bahr, UW-Madison and Board Member (presenter)**

**Sept. 26, 2016, Denver Colorado**

# About the Board

- Created by 1987 Nuclear Waste Policy Act
- 11 Board members appointed by the President -- technical and scientific experts nominated by the National Academy of Sciences;
- Board members serve on a part-time basis for four-year terms.
- The Board evaluates the technical and scientific validity of DOE activities, including
  - Transportation and packaging of spent nuclear fuel and high-level radioactive wastes
  - Site characterization, design, and development of facilities for disposing of such wastes.
- Congress gave the Board access to draft DOE documents to ensure Board's recommendations could be made during the decision-making process, not after the fact.
- Required by law to report findings, conclusions, and recommendations at least twice each year to Congress and the Secretary of Energy.

# Board Members

# Board Members

- Rodney Ewing (Chairman) – Geochemistry/Actinides (Stanford)
- Jean Bahr – Hydrogeology/reactive solute transport (UW-Madison)
- Steven Becker - Emergency resp./risk communication (Old Dominion)
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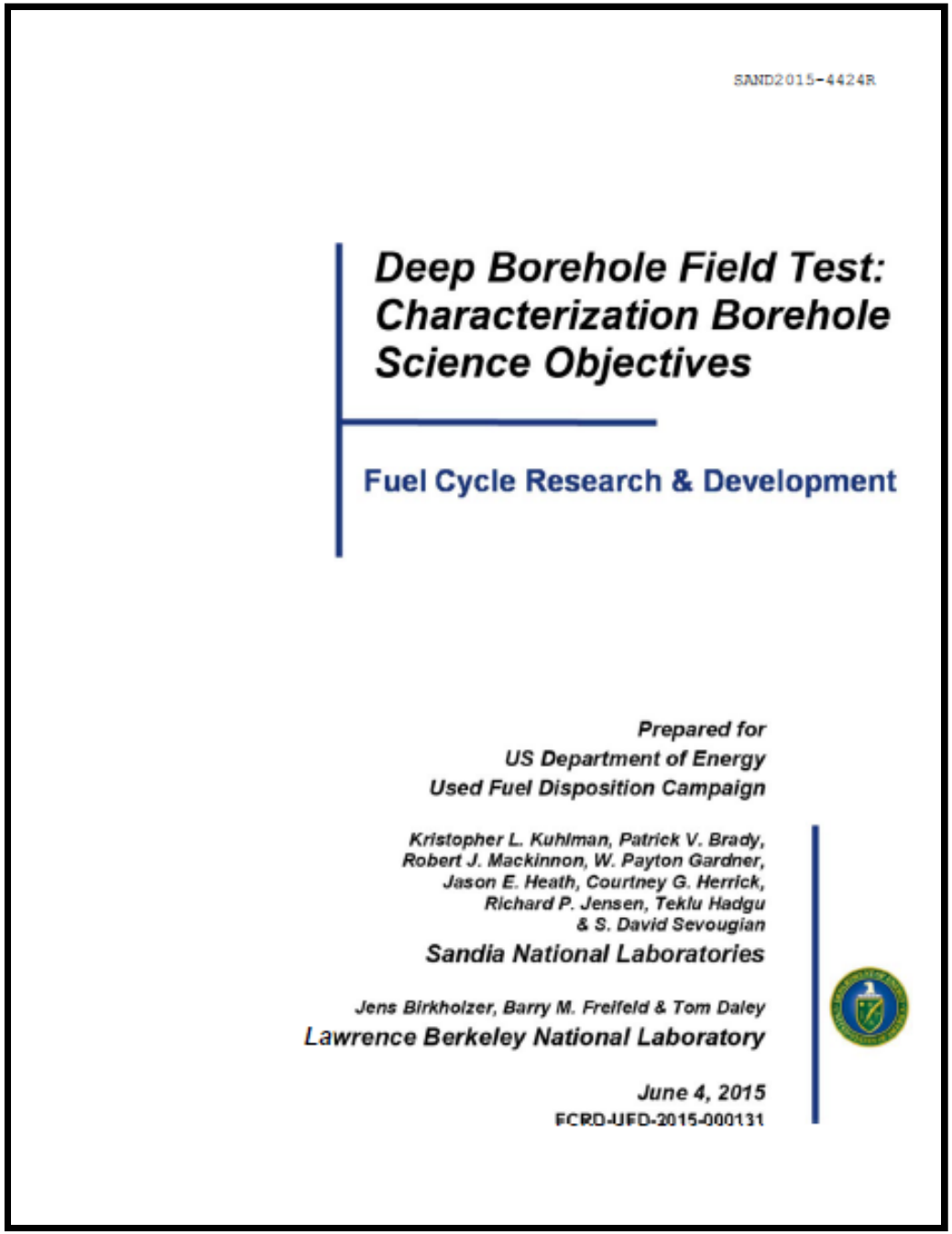
- Gerald Frankel - Materials Science and Eng. (Ohio State)
- Linda Nozick – Systems Eng./Transportation & Logistics (Cornell)
- Kenneth (Lee) Peddicord - Nuclear Eng./Adv. Nuc. Fuels (Texas A&M)
- Paul Turinsky - Nuclear Eng./Large Nuc. Systems (N. Carolina State U.)
- Mary Lou Zoback - Geophysics/risk assessment (Stanford)

- 20-21 October, 2015 International Workshop on Deep Borehole Disposal of Radioactive Waste, Washington, DC

- Panels of independent experts to discuss the scientific, technical, and regulatory aspects of deep drilling and nuclear safety



SAND2015-4424R

**Deep Borehole Field Test: Characterization Borehole Science Objectives**

**Fuel Cycle Research & Development**

*Prepared for*
*US Department of Energy*
*Used Fuel Disposition Campaign*

*Kristopher L. Kuhlman, Patrick V. Brady, Robert J. Mackinnon, W. Payton Gardner, Jason E. Heath, Courtney G. Herrick, Richard P. Jensen, Teklu Hadgu & S. David Sevougian*
*Sandia National Laboratories*

*Jens Birkholzer, Barry M. Freifeld & Tom Daley*
*Lawrence Berkeley National Laboratory*

*June 4, 2015*
FCRD-UFD-2015-000131

Final report, all presentations, webcast, and full transcript available at: www.nwtrb.gov/meetings

**International Technical Workshop on Deep Borehole Disposal of Radioactive Waste**

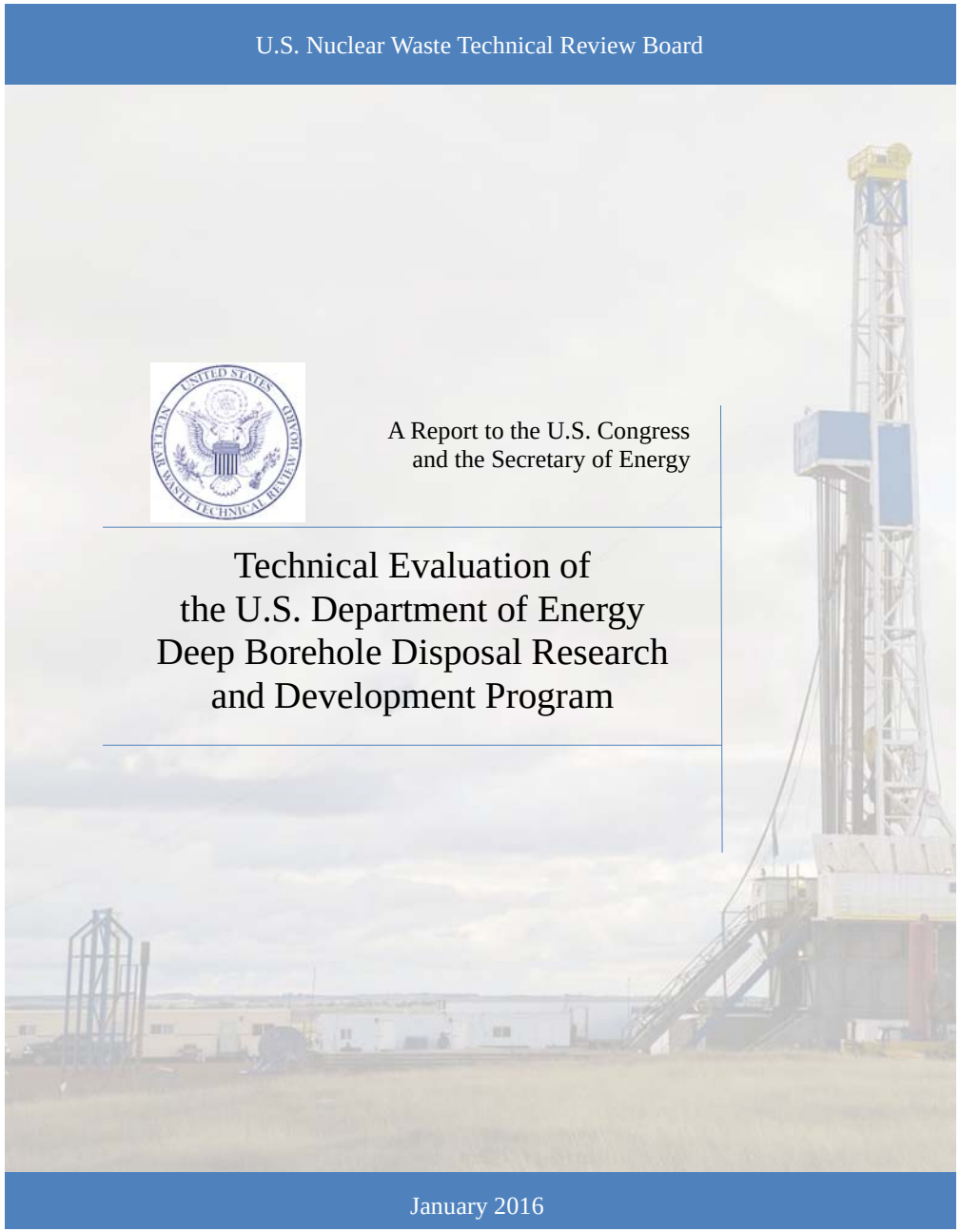
**AGENDA PAGE**

To view the webcast click on the date of the webcast you would like to view below:

Tuesday, October 20, 2015
8:00 AM Eastern Time

Wednesday, October 21, 2015
8:00 AM Eastern Time

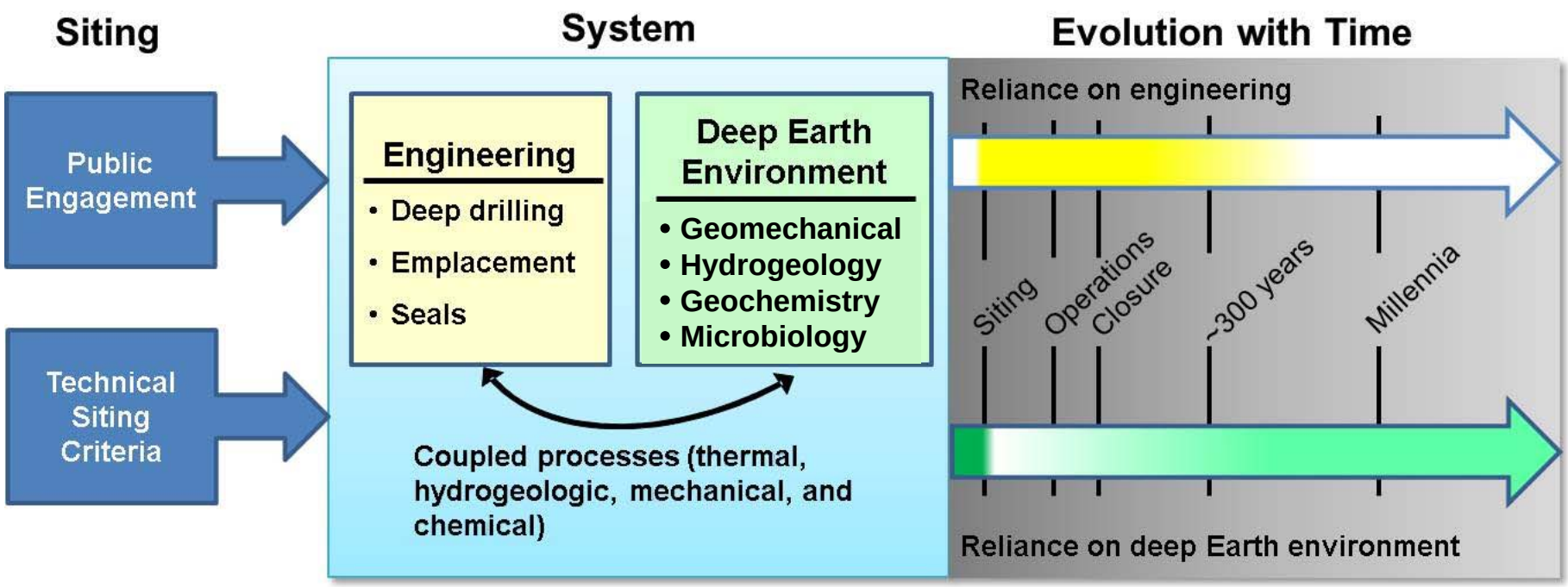
**U.S. Nuclear Waste Technical Review Board**



# Report Principal Findings

- Even if disposal of some radioactive waste in deep boreholes is determined to be feasible, **need for a mined, geologic repository is not eliminated.**
- Establishing a regulatory framework, identifying an acceptable site, and characterizing a deep borehole at depths down to 5 km (3.1 mi) are challenging and time consuming activities--suggesting **that time required for completing a deep borehole disposal facility might be comparable to that of a mined, geologic repository.**
- DOE's Deep Borehole Field Test will provide only **limited information on which to base an evaluation of the feasibility of the deep borehole disposal concept** and the selection of a deep borehole disposal site.
- The operational implications and limitations of handling and emplacing highly radioactive waste at depth are very different from those for operations involving non-radioactive material; however, **evaluating and understanding those implications and limitations are of utmost importance for the design of a deep borehole disposal facility** and for the feasibility assessment of the deep borehole disposal concept.

# Board's view: DBD System




- Two subsystems: 1) Engineering 2) Deep Earth Environment
- Subsystems interact continuously over a range of temporal and spatial scales, and involve a range of coupled processes

# Recommendations

- **REGULATORY**
  - Develop an operational safety strategy
    - Must integrate conventional borehole operations and remote handling of highly radioactive materials
    - Emphasize engineering controls over administrative controls
  - Engage regulators to define requirements, including retrievability

- "If you're going to treat this as a demonstration of a nuclear disposal system, you really need to try and ensure that you have demonstrated all of the key elements of a nuclear disposal system." *Doug Minnema U.S. Defense Nuclear Facilities Safety Board*

# Recommendations

- **MANAGEMENT**
  - Independent expert review (drilling and downhole operations)
  - Chief scientist to lead Deep Borehole Field Test program
    - Integrate science and engineering objectives and assure the drilling and scientific sampling and testing program are fully coordinated and collecting key data to develop safety case for deep borehole disposal
  - Transparent pathway from the Deep Borehole Field Test to siting needed
    - Missed opportunity to obtain experience on consent-based siting

"Integrated approach is needed for the whole lifetime of the project, for the drilling, for the completion, and the emplacement phase. ….project leaders need to own entire process…you can subcontract services, but you cannot subcontract responsibilities." *Claus Chur, Chief Drilling Engineer, German KTB Scientific Deep Drilling Project*

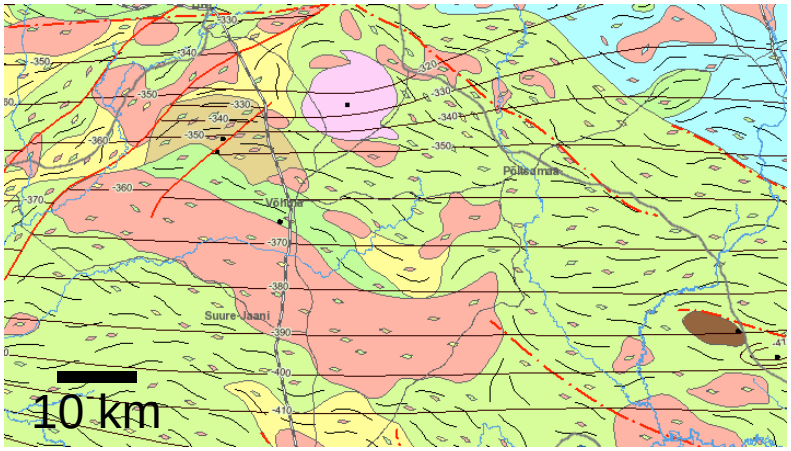
# Some key scientific and technical issues

- Coupled geomechanical-geohydrologic-geochemical-geomicrobiological processes and feedbacks
  - Basement permeability may be higher than assumed, difficult to measure, and may vary over time with natural or induced seismicity
  - Breakouts, drilling induced fractures, natural fractures, implications for seals/damage zone
  - Corrosion, hydrogen gas generation, microbial activity, implications for seals and possible migration
- Limited time for adequate characterization in the proposed project schedule of the field test
- Emplacement risks
- Seal design and implementation

# Technical Challenge: Site characterization

Complexity of site characterization

- Implicit assumptions:
  - less characterization would be needed because conditions likely more homogeneous at depth?
  - potentially advantageous conditions are found everywhere?

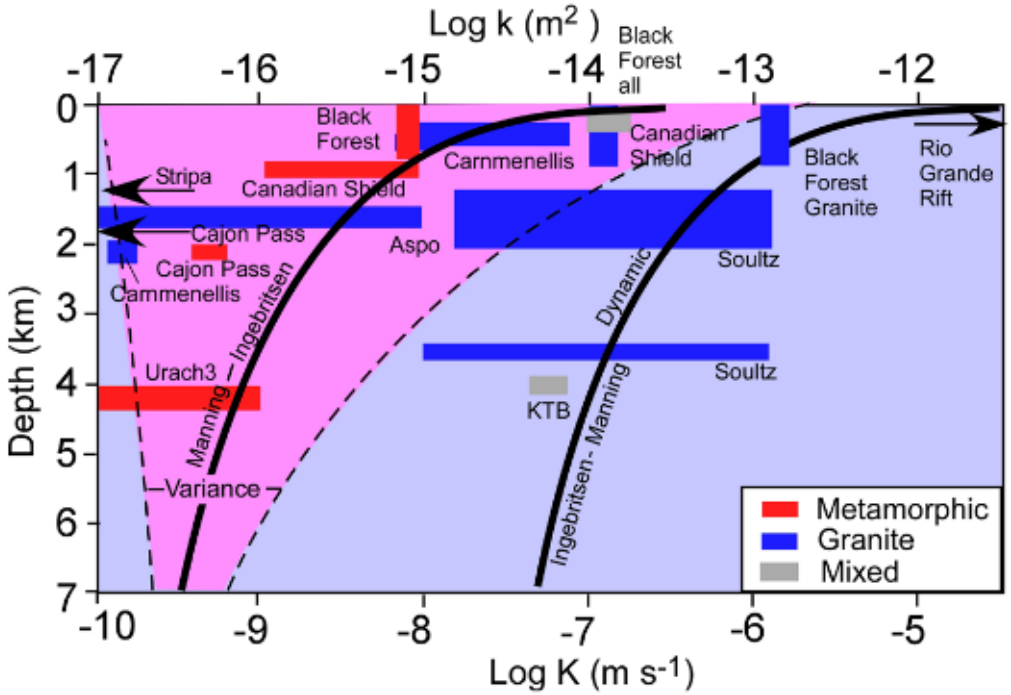



Crystalline basement,
Geological Survey of Estonia

# Crystalline Basement Permeability
## *(Mark Person, New Mexico Tech, 2015)*

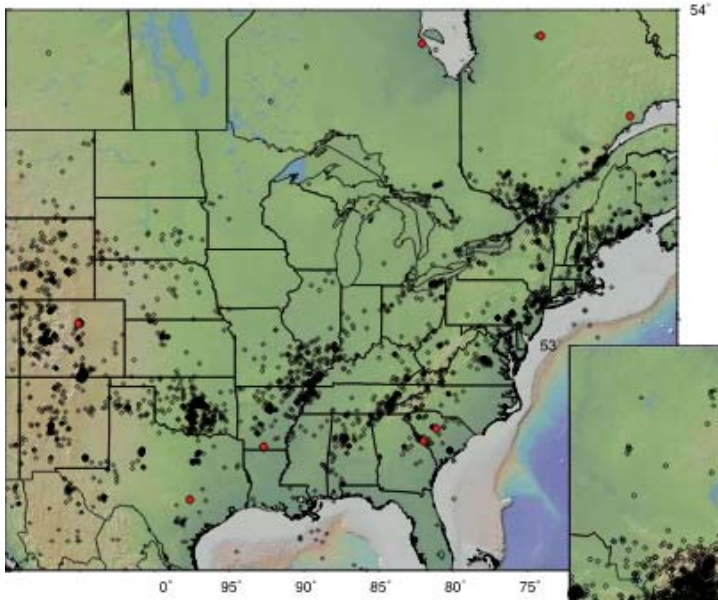
- Permeability Mean & Variance decays with depth
- Dynamic (based on Heat Flow Geophysics & Petrology data)
- Permeability Around Well Bore Annulus 8 Times Greater than Far Field Conditions
- Estimated Permeability @ 4km ~ $10^{-16}$ $m^2$

Inferred Permeability Below Deepest Borehole

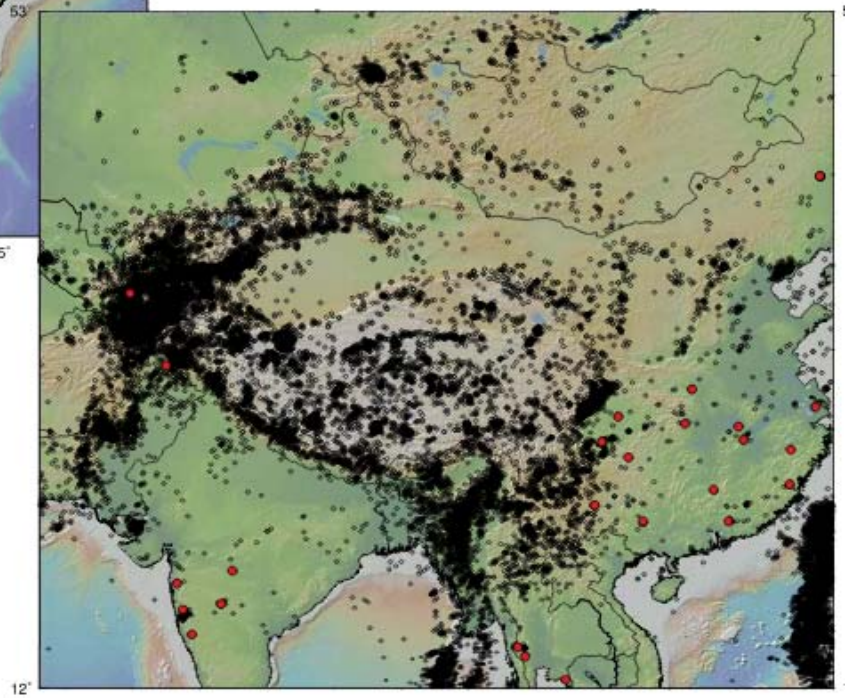



*Stober & Bucher (2007) Hydrogeology Journal v 15: p. 213–224*
*Stober & Bucher* (2015) Geofluids v. 15, p. 161–178
*Ingebritsen & Gleason (2015) Geofluids Editorial on Crustal Permeability Thematic Issue*

# Causes of high crustal permeability
## *(Mark Zoback, Stanford, 2015)*



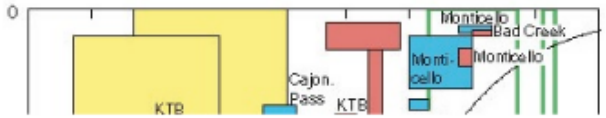

I-We Live on a
Critically-Stressed Crust




- Earthquakes Occur Nearly Everywhere in Intraplate Areas
- Stress is Near-Critical Everywhere - Earthquake Rate Reflects Intraplate Strain Rate

# Causes of high crustal permeability
## *(Mark Zoback, Stanford, 2015)*

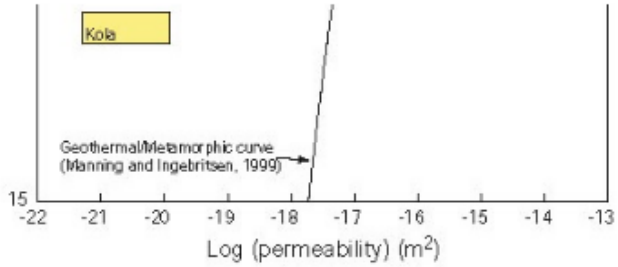
### III. Faulting Keeps The Crust Permeable




### High Permeability Maintains Near-Hydrostatic Pore Pressure

| Well location | Regime | Depth (km) | Observation | Source | Evidence for critical stress |
|---|---|---|---|---|---|
| Cornwall HDR, England | SS | 2.5 | DST | Pine et al. (1983) | Stress magnitudes; induced seismicity |
| Fenton Hill HDR, New Mexico | N, SS | 3.0 | SWC | Barton et al. (1988) | Stress magnitudes |
| Dixie Valley, Nevada | N | 2–3, 5–7 | DST, SG | Hickman et al. (1997) | Stress magnitudes; prehistoric fault offsets |
| Cajon Pass, California | SS | 3.5 | DST | Coyle and Zoback (1988) | Stress magnitudes; breakout rotations |
| Soultz HDR, France | N, SS | 5.0 | DST | Baumgärtner et al. (1998) | Stress magnitudes; induced seismicity |
| Siljan, Sweden | SS | 7.0 | DST | Lund and Zoback (1999) | Stress magnitudes |
| KTB, Germany | SS | 9.1 | DST, SWC | Huenges et al. (1997)<br>Zoback and Harjes (1997) | Stress magnitudes; induced seismicity |
| Kola, Russia | ?R | 12.2 | SWC | Borevsky et al. (1987) | N.A. |

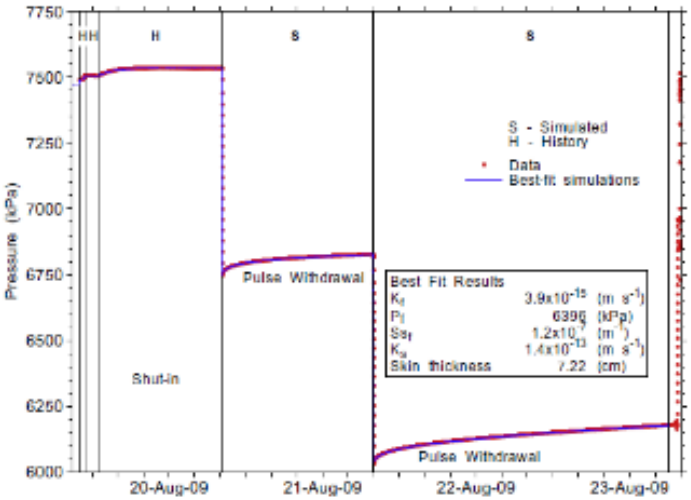
*Note*: HDR—hot dry rock; KTB—Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland (German Continental Deep Drilling Program); SS—strike-slip faulting regime; N—normal faulting regime; R—reverse faulting regime; DST—drill stem test; SWC—static water column; SG—silica geothermometry; N.A.—not available.




Townend and Zoback (2000)

# Challenges in k Measurement
## *(Kent Novakowski, Queens U. Canada, 2015)*

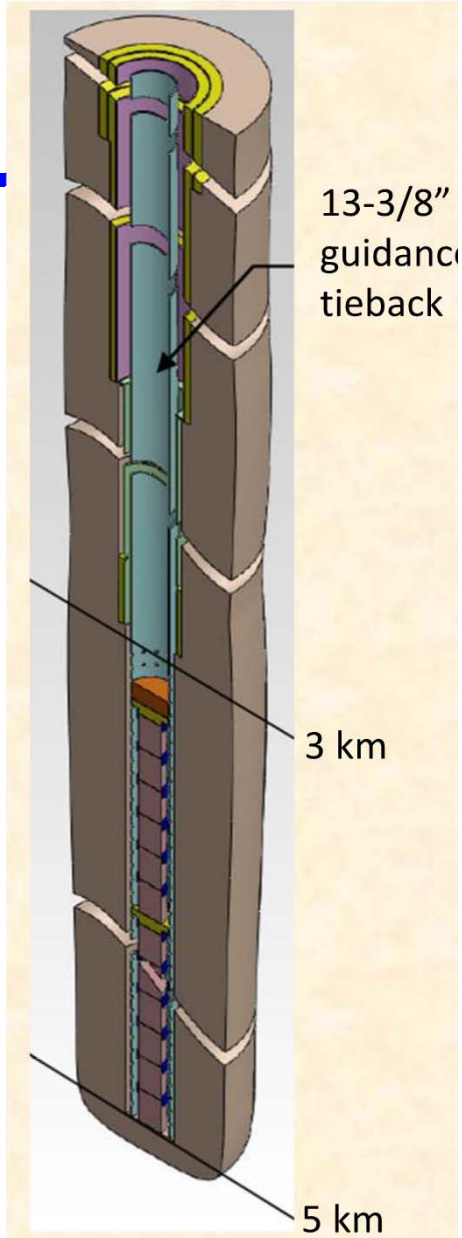
- Experience in North America and Europe measuring $k \geq 1\times10^{-22}$ m$^2$ at depths < 1 km in boreholes and mine access.
- Challenges specific to the Deep Borehole Disposal Program:
  - Depth – small-diameter tubing support may not work;
  - Hole quality – deformation may make testing difficult (ie artificially raise pressure in test section);
  - Large bottom hole size, particularly for Borehole Emplacement Test;
  - Time – there is a need for contiguous measurements;
  - Borehole should be inclined.




(Beauheim et al., Journal of Hydrology 509 (2014) 163–178.)

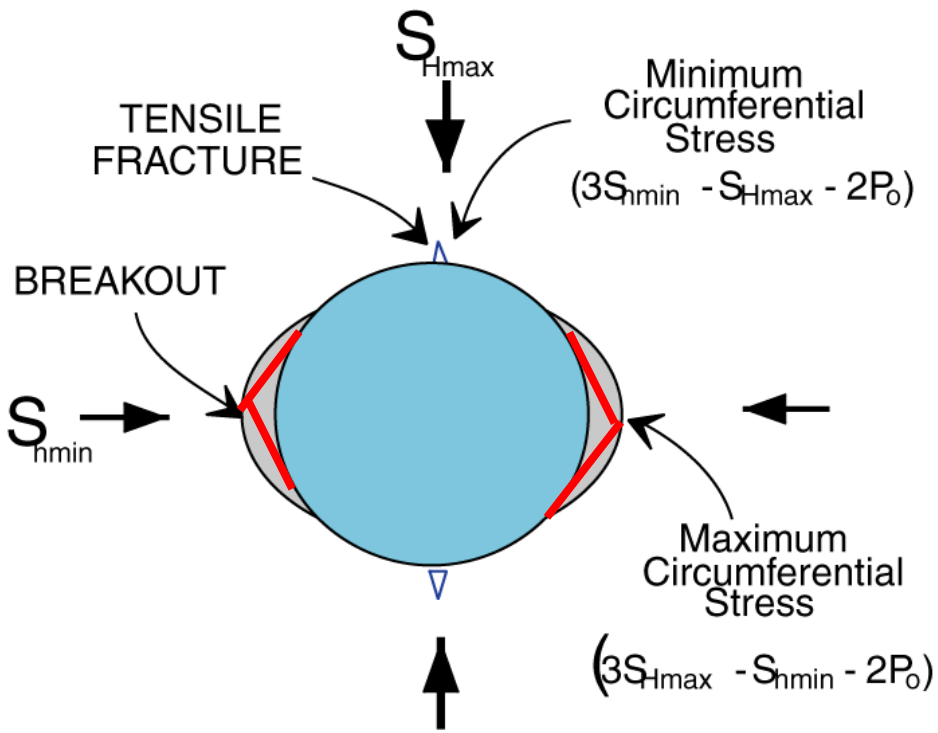
# Coupled Geochemistry-Hydrology

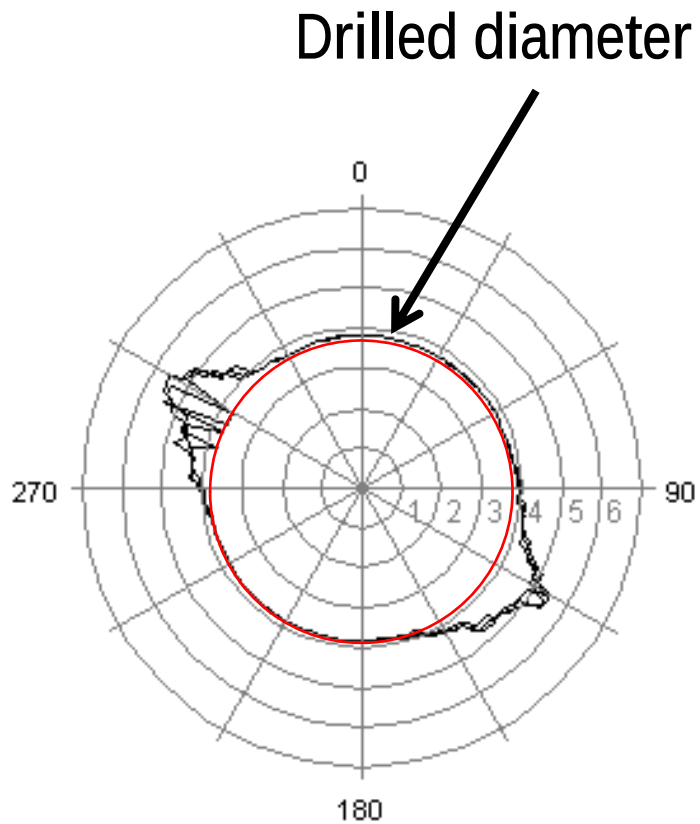
- Drilling and emplacement of waste packages changes conditions at depth, modeling difficult due to lack of thermodynamic and kinetic data for many chemical species in concentrated brines
- 2 km-long line source of heated brine corroding canisters and steel casing will generate hydrogen, either dissolved in brine or as free gas phase → implications for radioactive transport unknown
- Possibility of other gases ($CO_2$, $CH_4$) and other gaseous species as result of radiolysis
- Pressure buildup can cause brine to move, possibly with radioactive material, lack of knowledge of solubility controlling phases, limited understanding of interaction radionuclides and salts in solution
- Even under salinity stratification, potential exists for regional scale horizontal flow in basement



After waste in place, but before removing casing (Arnold et al., 2011)

# Breakouts: Spontaneous borehole deformation




*M. D. Zoback (2007)*

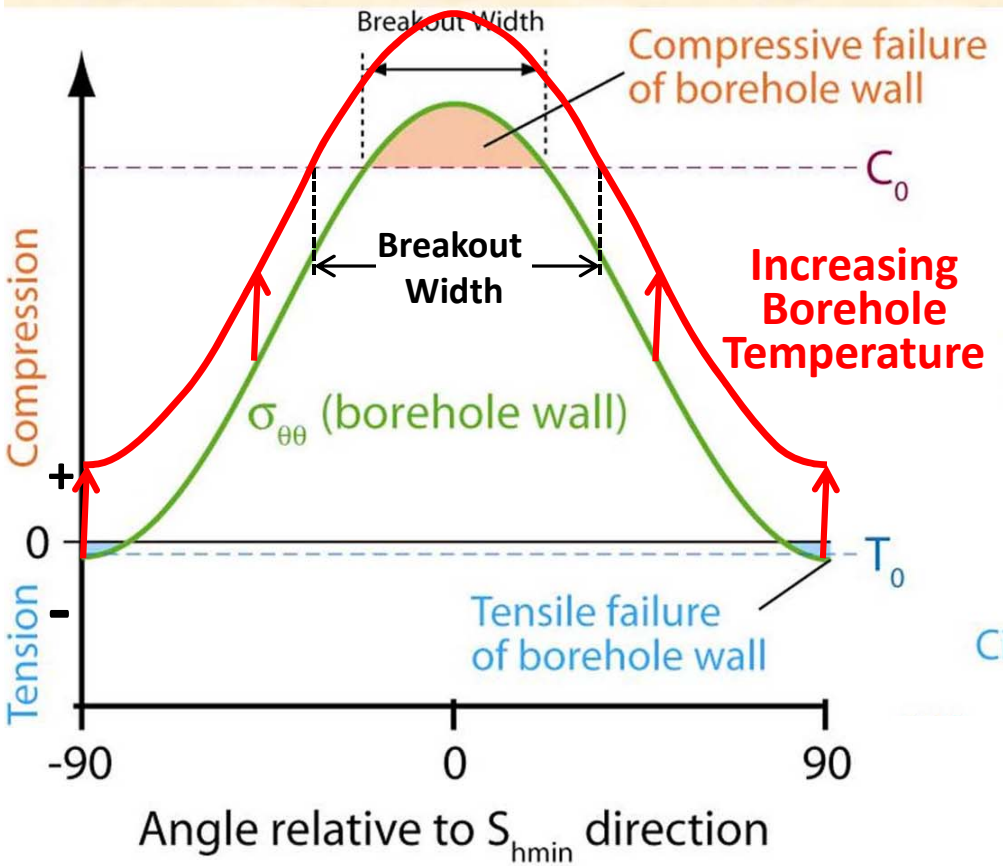
Elastic stress concentration produces borehole deformation

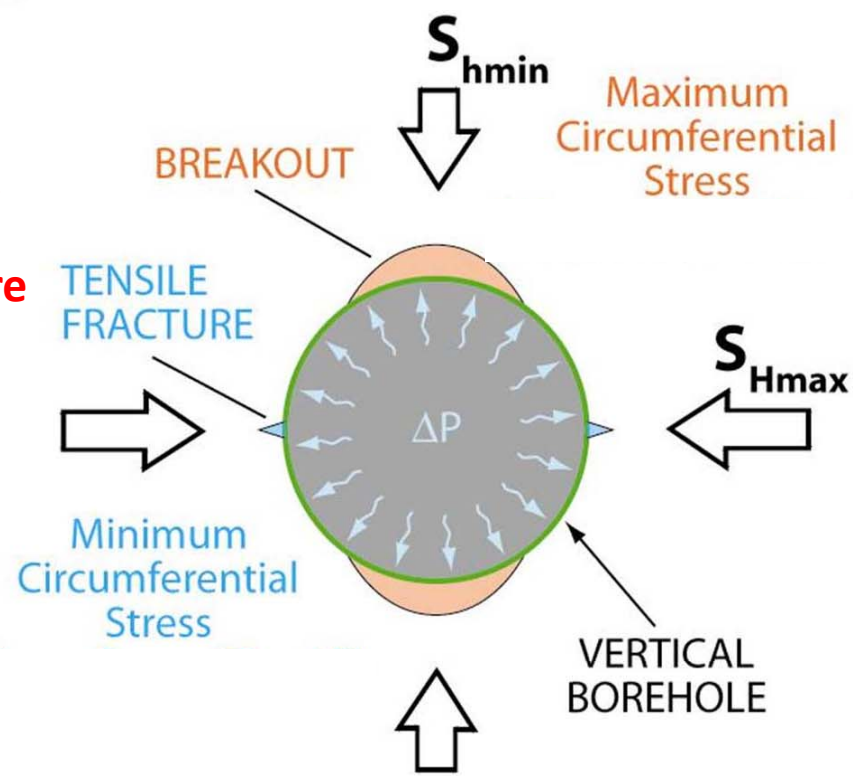
# Borehole Integrity Issues
## *(Steve Hickman, USGS, 2015)*

- Extensive wellbore failure will complicate drilling, completion and seal installation & could compromise ***long-term seal*** integrity:
  - Breakouts (BO) more severe with depth, BO growth continues with time (until rock deforms inelastically behind BO and absorbs some of the strain energy)
  - BO could pose operational challenges when cementing casing and setting multiple seals in long open-hole interval above canisters.
  - High-perm. damage zones produced by BO, drilling-induced tensile fractures and dilated natural fractures → "short-circuit" pathways around seals.
- Increasing temperature after canister emplacement could lead to:
  - Increase in compressive hoop stress, promoting continued BO growth and borehole enlargement/collapse.
  - Thermal pressurization of borehole fluids, reactivating nearby faults (esp. if slightly permeable) and significantly increasing fracture permeability.
  - Establishment of hydrothermal convection system, with unknown impact on permeability evolution and contaminant transport.
  - Microcracking due to differential thermal expansion (esp. quartz-rich rocks), increasing matrix permeability and decreasing rock strength.

# State of stress at depth

## Elastic Stress Concentration Around a Vertical Well



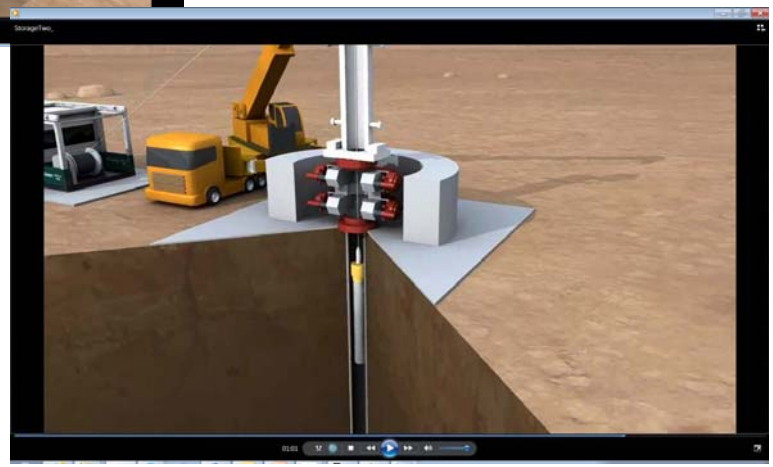

*Steve Hickman, USGS*

# Emplacement Risk

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

## *Wireline* Emplacement in Deep Borehole

Attach cable head to waste package

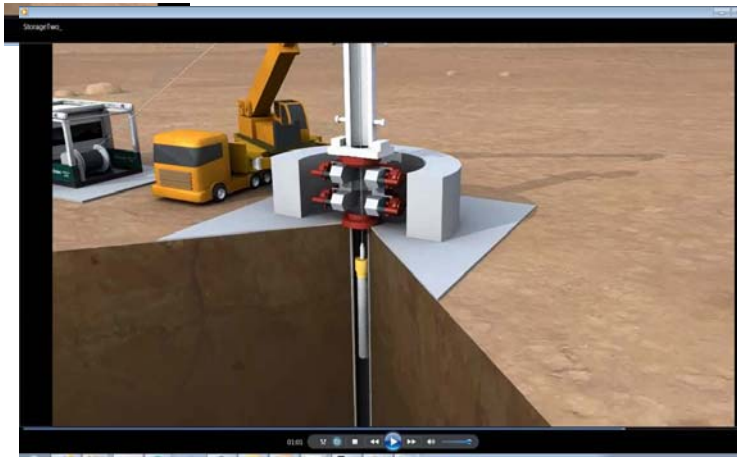


Lower waste package through blowout preventer and downhole le

*S. David Sevougian, Sandia*

# Risks with wireline emplacement

- You can't push, you can't pull and you can't rotate - all the things you need to do if you get stuck.

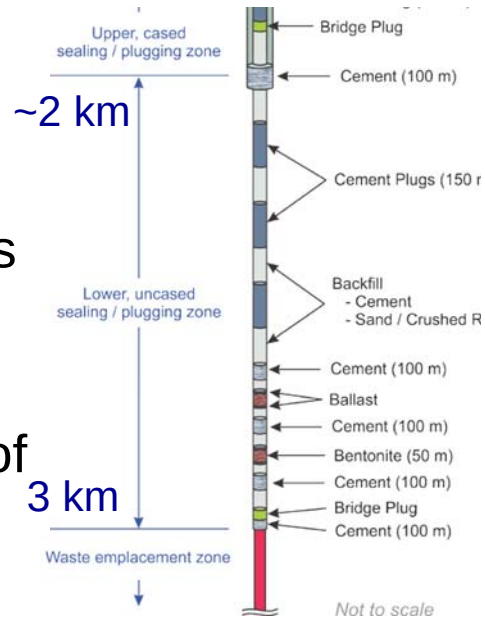


- Getting a tool hung up is potentially disastrous because the cable can get bundled up in the hole (you are unrolling the cable from the surface faster than the package is moving downhole) and can't be easily retrieved

- With logging tools, there are sensors in the tool, transmitting through the electrical cable, these sensors are very sensitive to changes in the weight of the tool, in case it gets hung up. The cable is then stopped very fast.

# Seal Design and Implementation

- Impact of breakouts and tensile fractures?
- Role of time-dependent failure and thermal stresses?
- How to test integrity of the seals over long time scales?
- Sensitivity of cement, and other sealing components in likely subsurface conditions?
- Seal performance under the real biaxial horizontal stress conditions likely at 2 - 5 kilometers depth?
- Microbial degradation of engineered barriers in the seal zone under enhanced heat energy and potentially a lot of available hydrogen, not well understood.
- Pat Brady, Sandia "…the Detroit sewer that collapsed in just a few years because of exactly that, the microbes breaking it down."
- *Grimsel underground Test Site in Switzerland working on sealing between steel casing, smectite and crystalline rock at depth*




*Arnold et al., 2011*

# Recommendations

- **SCIENCE AND ENGINEERING**
  - Heterogeneity and complexities of subsurface geology complicate transferability of data and results of analysis
  - Pre-drilling geophysical subsurface characterization essential
  - Consider robust waste forms, waste packages, and seals
  - Carry out comprehensive risk analysis
- "Available evidence indicates that …high stress levels, potentially active faults, and highly permeable fractures and faults persist to at 5+ kilometers depth. These features represent potential pathways for migration of gases and brines." *Mark Zoback, Stanford*
- "In geochemistry when we look to the subsurface, same thing. Wherever we go we found surprises." *Kirk Nordstrom, USGS*
- "Seal/liner/rock disturbed zone is a likely pathway for radionuclide migration… conceptually this is thought to be within engineering capability to manage, but this remains to be demonstrated." *Neil Hyatt, Sheffield*

# Some panelists' words of wisdom

- "Expect surprises", "Plan for contingencies", 'Plan for the unforseen"
- "Little things can turn into big things very quickly"
- 'Don't want a drilling engineer handling nuclear materials, don't want a nuclear engineer drilling'
- "Measure everything. Don't necessarily know beforehand what will be useful, so there's some betting that's involved."
- "Do not "assume away" things that could affect applicability or transferability of the results or conclusions of the test"

# Summary of Recommendations

- **SCIENCE AND ENGINEERING ISSUES**
  - Heterogeneity and complexities of subsurface geology complicate transferability of data and results of analysis
  - Pre-drilling geophysical subsurface characterization essential
  - Consider robust waste forms, waste packages, and seals
  - Carry out comprehensive risk analysis
- **REGULATORY**
  - Develop an operational safety strategy
  - Engage regulators to define requirements, including retrievability
- **MANAGEMENT**
  - Independent expert review
  - Transparent pathway from the Deep Borehole Field Test to siting needed
  - Chief scientist to lead Deep Borehole Field Test program