SAND2016-11798PE

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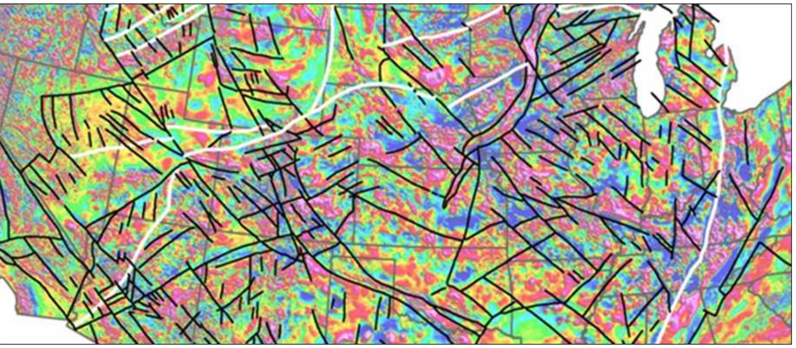

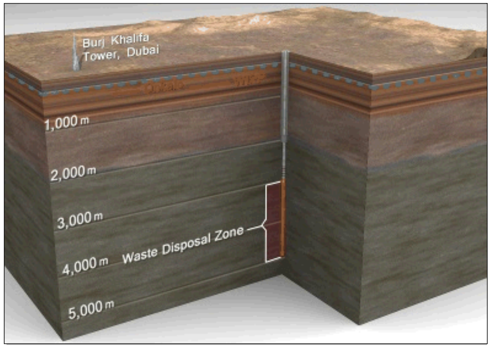

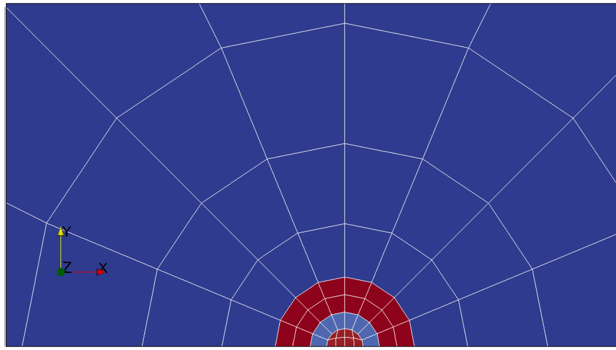

Deep Borehole: Disposal Concept and Field Test

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Applied System Analysis & Research Department

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

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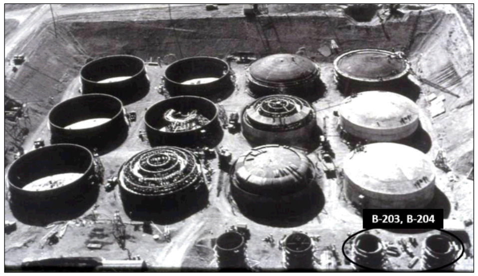
Deep Borehole Disposal Concept

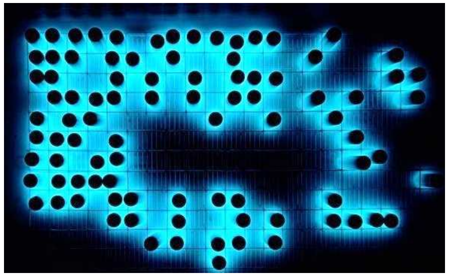
- **≤17” hole to 5 km**
- **Straightforward Construction**
- **Robust Isolation from Biosphere**
- **Conditions at Depth**
  - Low permeability
  - Stable fluid density gradient
  - Reducing fluid chemistry
  - Old groundwater

Radioactive Waste Forms

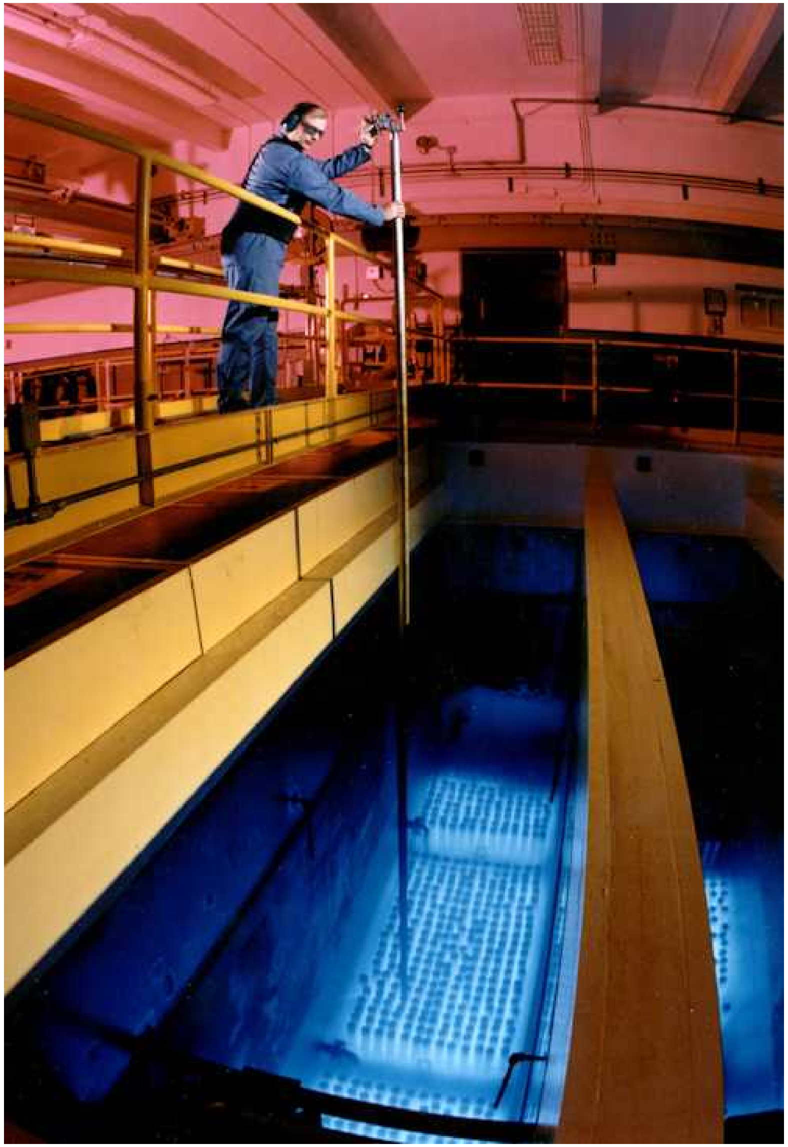
- **Waste Properties**
  - Thermal output
  - Physical size
  - Waste total volume
- **Primary Waste Forms**
  - DOE-managed high-level waste
    - Liquid reprocessing wastes:
      - Borosilicate glass logs
      - Cs-137/Sr-90 capsules
      - Calcine powder



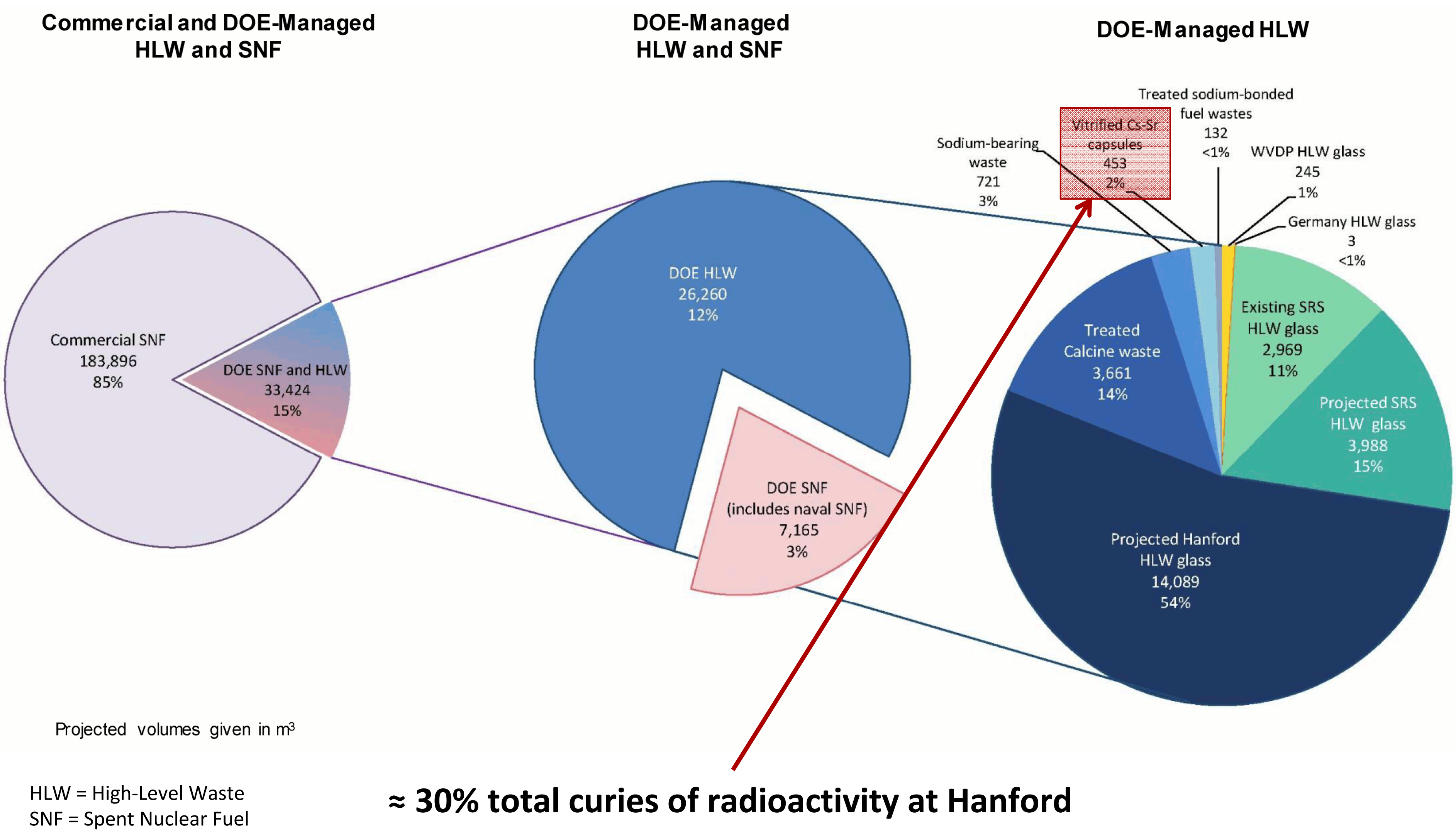
Hanford tank farm



2,000 Cs/Sr Capsules [≈3" diam.]



Radioactive Waste Volumes



HLW = High-Level Waste
SNF = Spent Nuclear Fuel

Recent Events

- **Jan. 2012: Blue Ribbon Commission Report**
- **Oct. 2014: DOE Disposal Options**

  Assessment of Disposal Options for DOE-Managed High-Level Radioactive Waste and Spent Nuclear Fuel

  1. Dispose all HLW & SNF in common repository
  2. Dispose some DOE-managed HLW and SNF in separate mined repository
  3. Dispose of smaller waste forms in deep boreholes

- **March 24, 2015: Obama Memo**

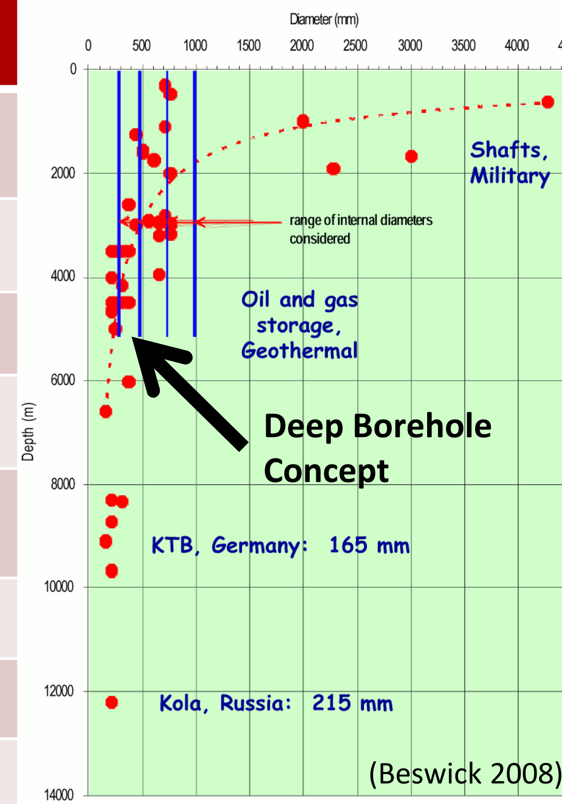
  "In accordance with the [Nuclear Waste Policy] Act, I find the development of a repository for the disposal of high-level radioactive waste resulting from atomic energy defense activities only is required"

- **Jan 2016: Request for Proposals (RFP) → DOE selects 1 team**
  - Battelle, Schlumberger, SolExperts in North Dakota
- **Jan 2017: Second RFP, DOE selecting up to 5 teams**

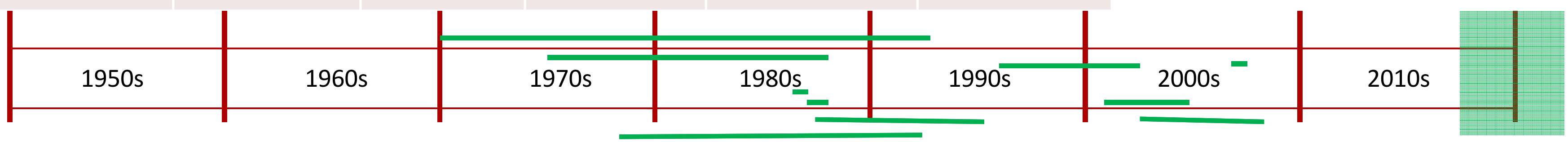
Deep Borehole Disposal Concept

Deep Crystalline Drilling

Site	Location	Years	Depth to Crystalline [km]	Total Depth [km]	Diam. at TD [inch]
Kola	NW USSR	1970-1992	0	12.2	8½
Fenton Hill	New Mexico	1975-1987	0.7	2.9, 3.1, 4.0, 4.4	8¾, 9⅞
Urach	SW Germany	1978-1992	1.6	4.4	5½
Gravberg	Central Sweden	1986-1987	0	6.6	6½
Cajon Pass	Southern California	1987-1988	0.5	3.5	6¼
KTB	SE Germany	1987-1994	0	4, 9.1	6, 6½
Soultz	NE France	1995-2003	1.4	5.1, 5.1, 5.3	9⅝
CCSD	E China	2001-2005	0	2, 5.2	6
SAFOD	Central California	2002-2007	0.8	2.2, 4	8½, 8¾
Basel	Switzerland	2006	2.4	5	8½



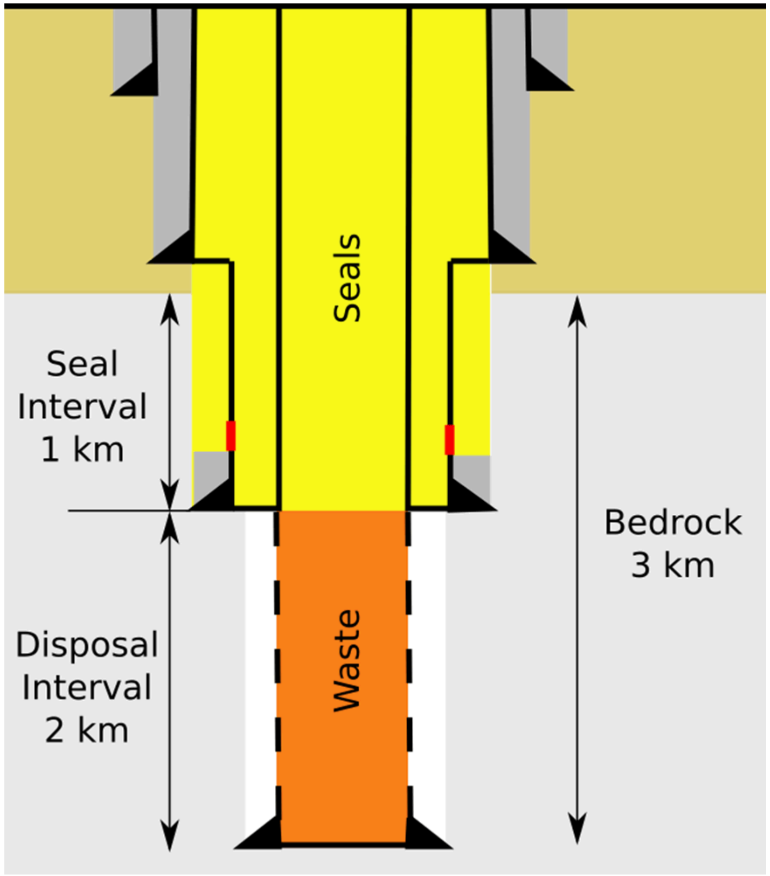
Deep Borehole Field Test
DBFT



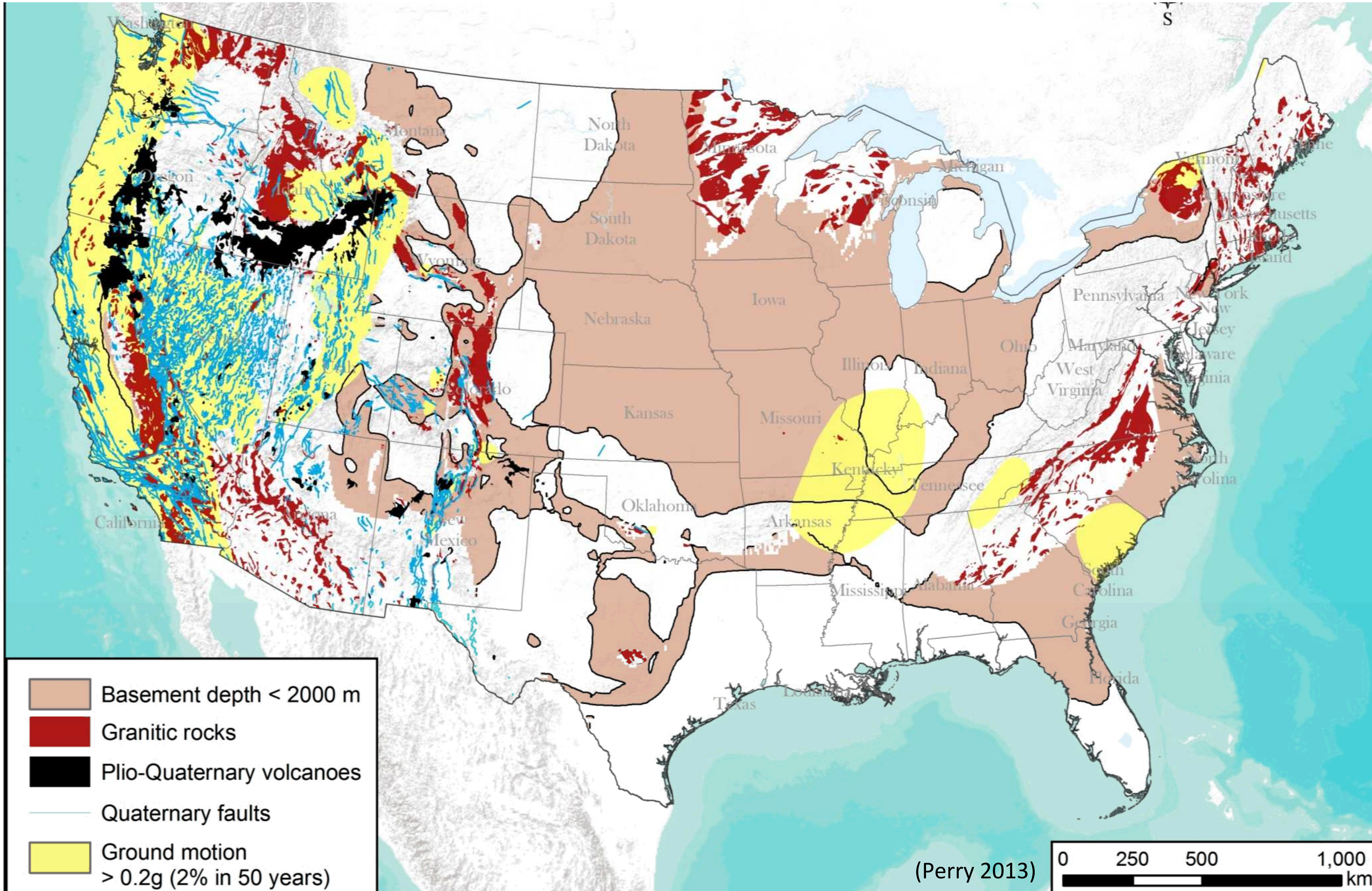
Disposal Concept vs. Field Test

- **Deep Borehole Disposal (DBD)**
  - Boreholes in crystalline rock to 5 km TD
  - 3 km basement / 2 km overburden
  - 1 km basement seal
  - 2 km disposal zone
  - Single borehole or grid

- **Deep Borehole Field Test (DBFT)**
  - Department of Energy – Office of Nuclear Energy (DOE-NE)
  - FY 2017-2021 project
  - Two boreholes to 5 km TD
  - Science and engineering demonstration

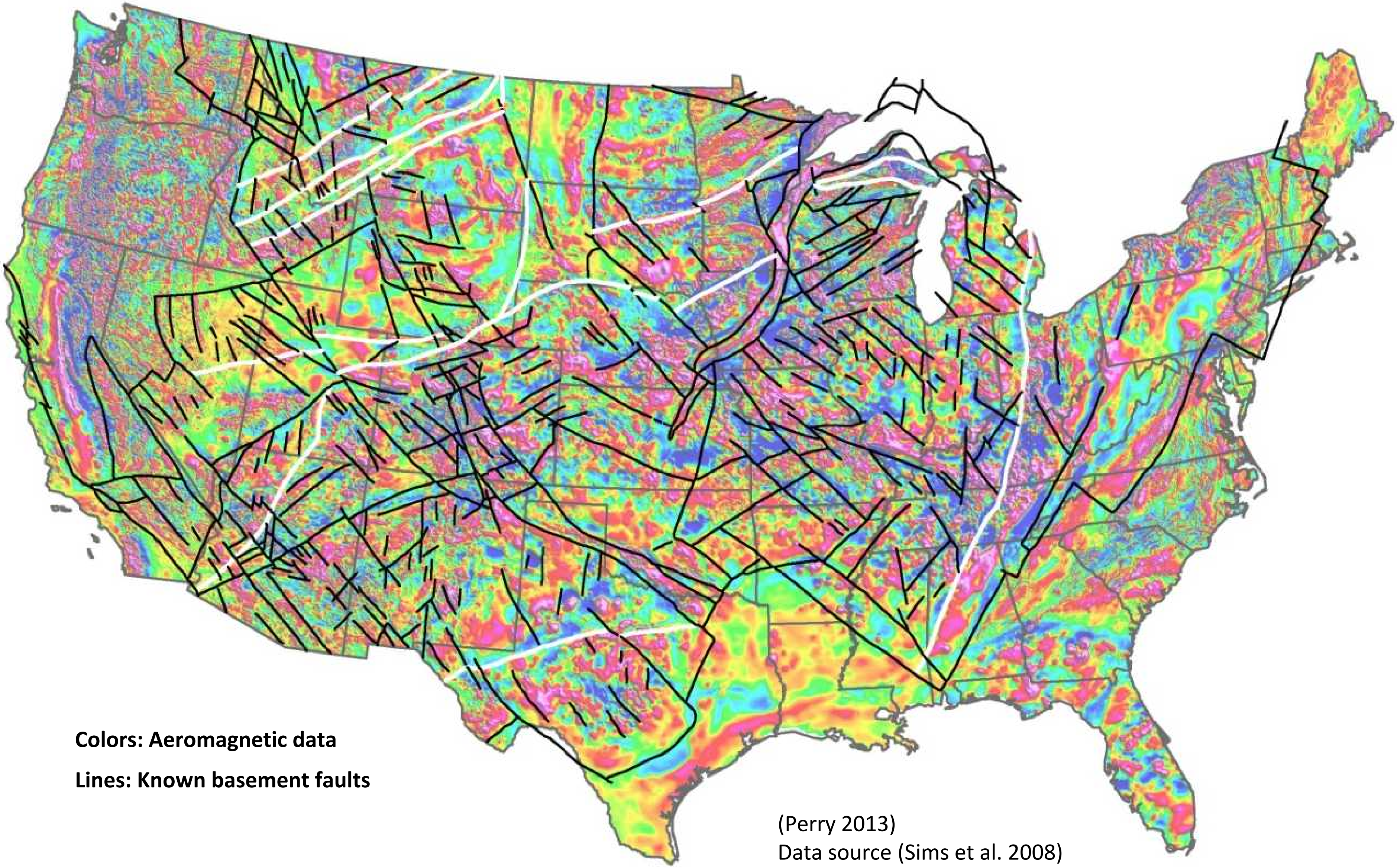


Siting: Depth to Basement + Hazards



(Perry 2013)

Siting: Basement Structure

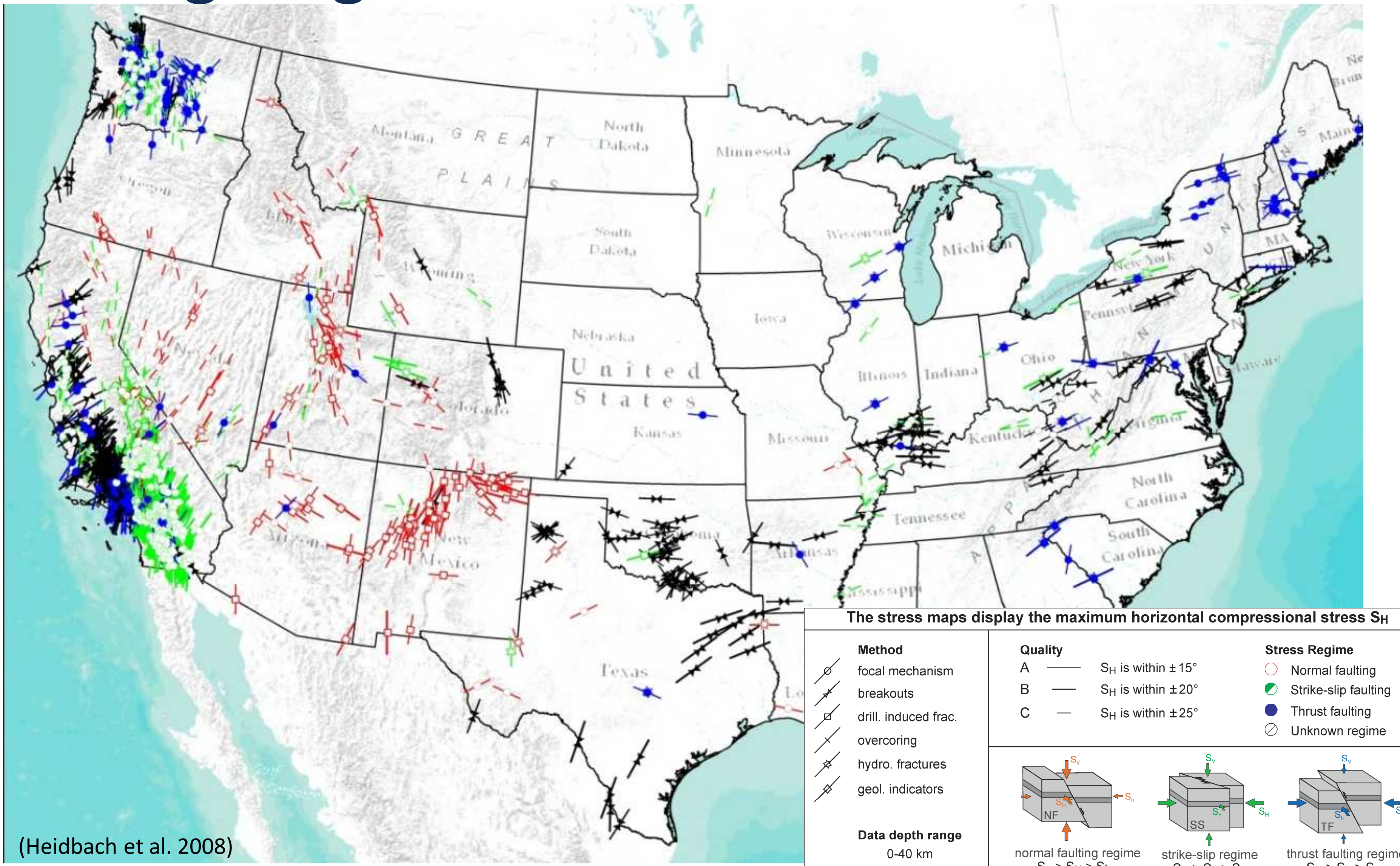


Colors: Aeromagnetic data

Lines: Known basement faults

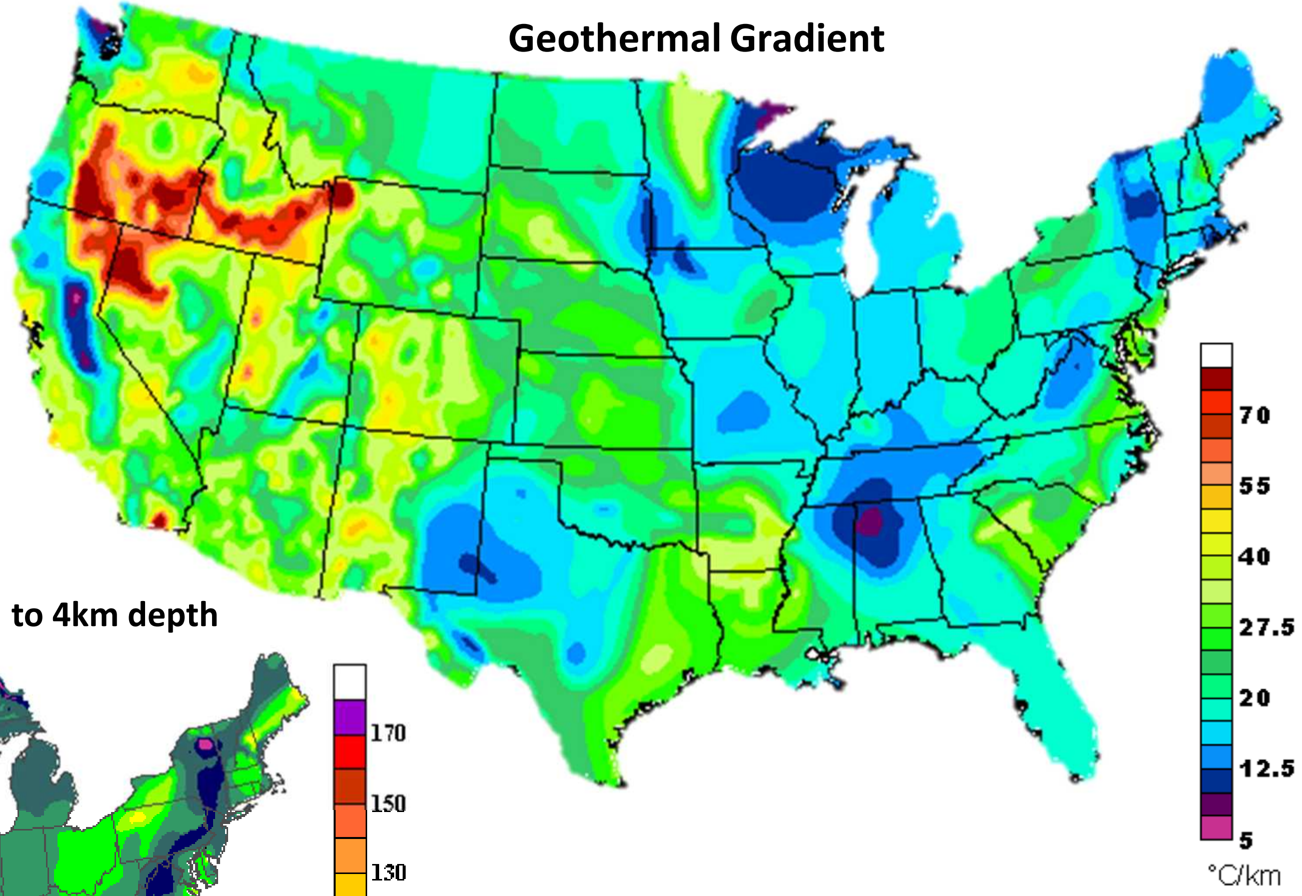
(Perry 2013)
Data source (Sims et al. 2008)

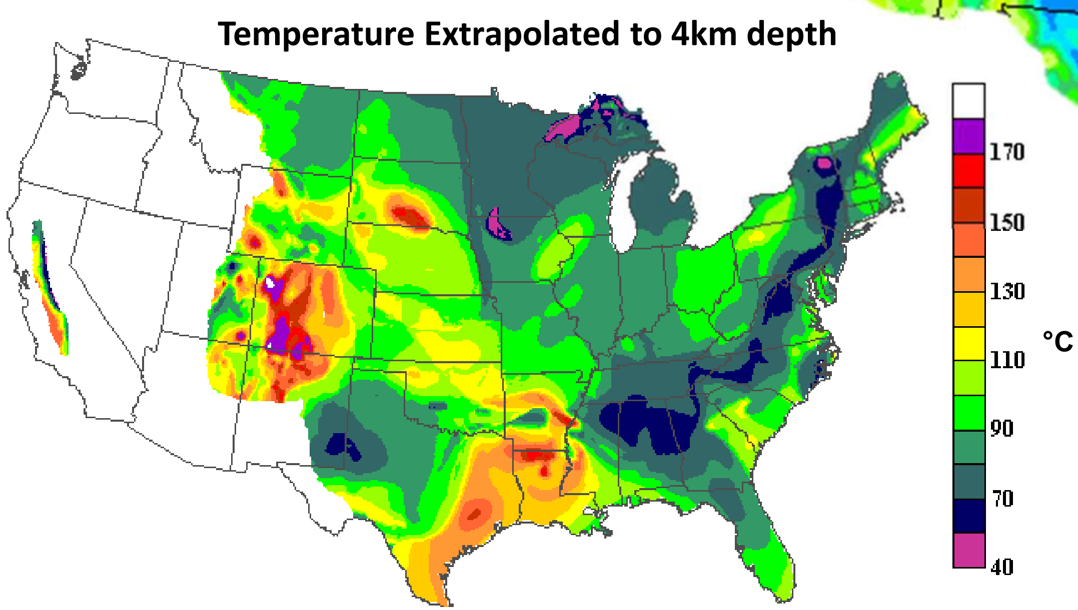
Siting: Regional Stress State



(Heidbach et al. 2008)

Siting: Geothermal





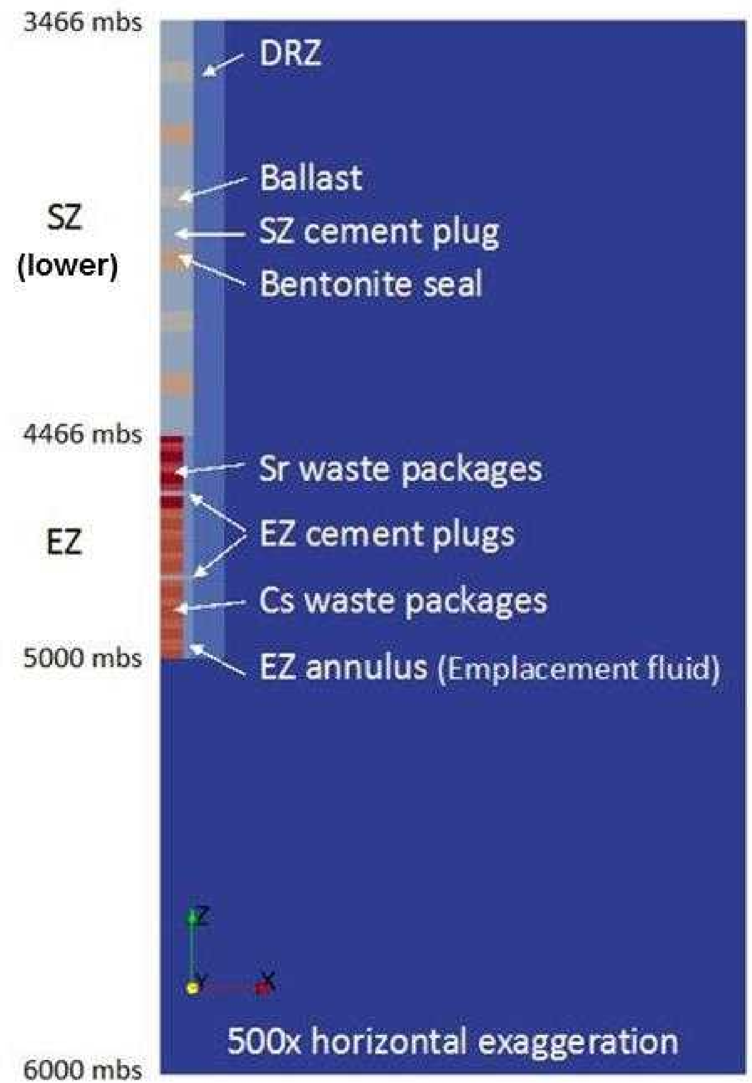
(SMU Geothermal Laboratory 2004)

Deep Borehole Disposal Performance Assessment Modeling

Deep Borehole PA Models

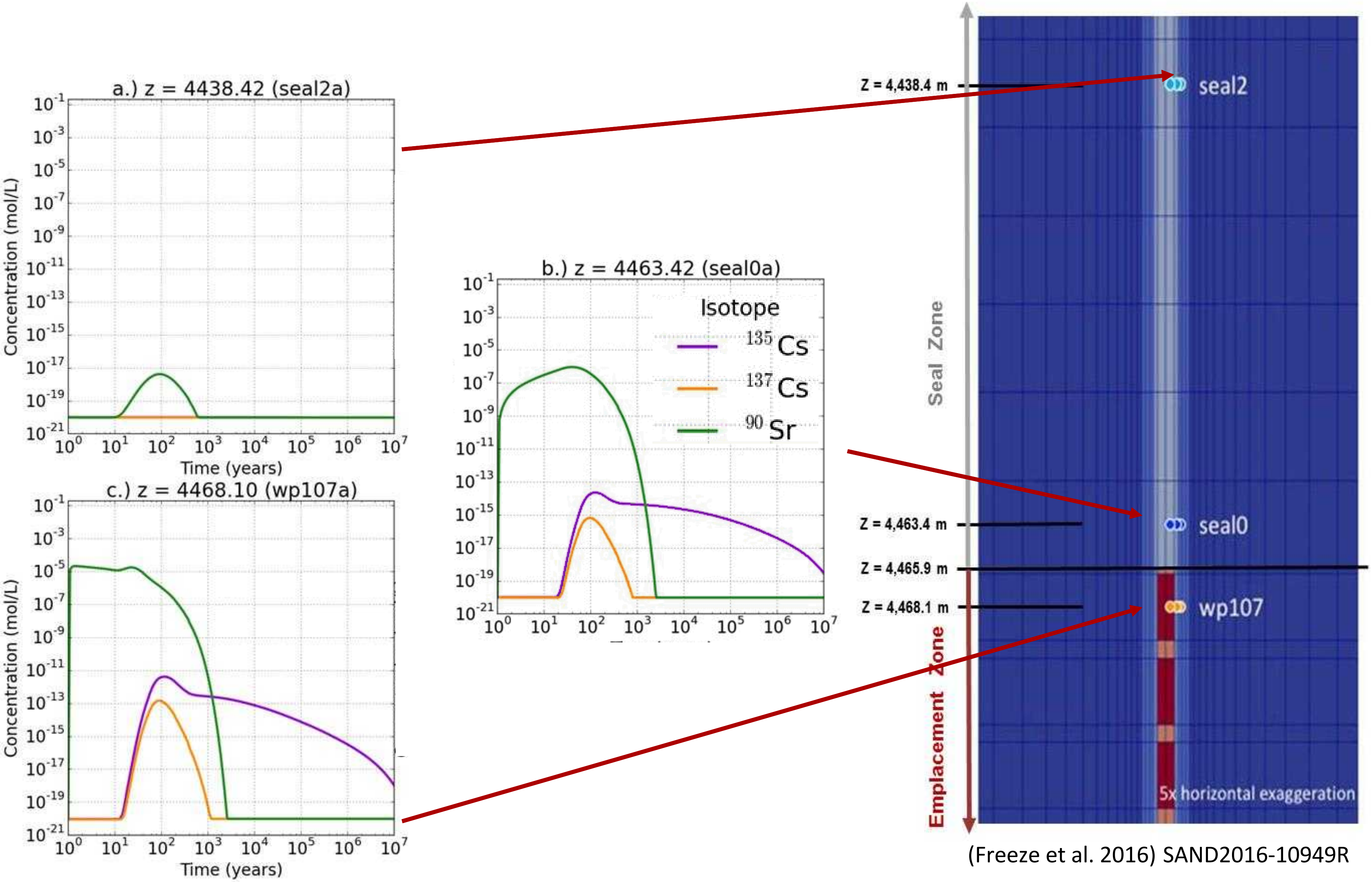
- **Performance Assessment (PA) Modeling**
  - Use standard reference:
    - geology
    - borehole design
  - Assume single boreholes Cs/Sr
  - Assess long-term post-closure safety
  - Thermal-hydrological-chemical processes simulated via PFLOTRAN

PFLOTRAN



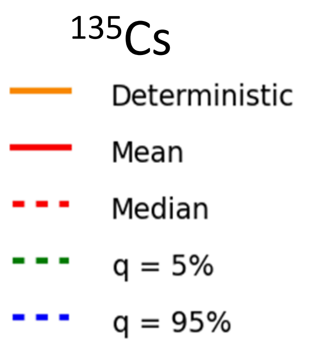
(Freeze et al. 2016) SAND2016-10949R
Deep Borehole Disposal Safety Analysis

Deep Borehole PA Models

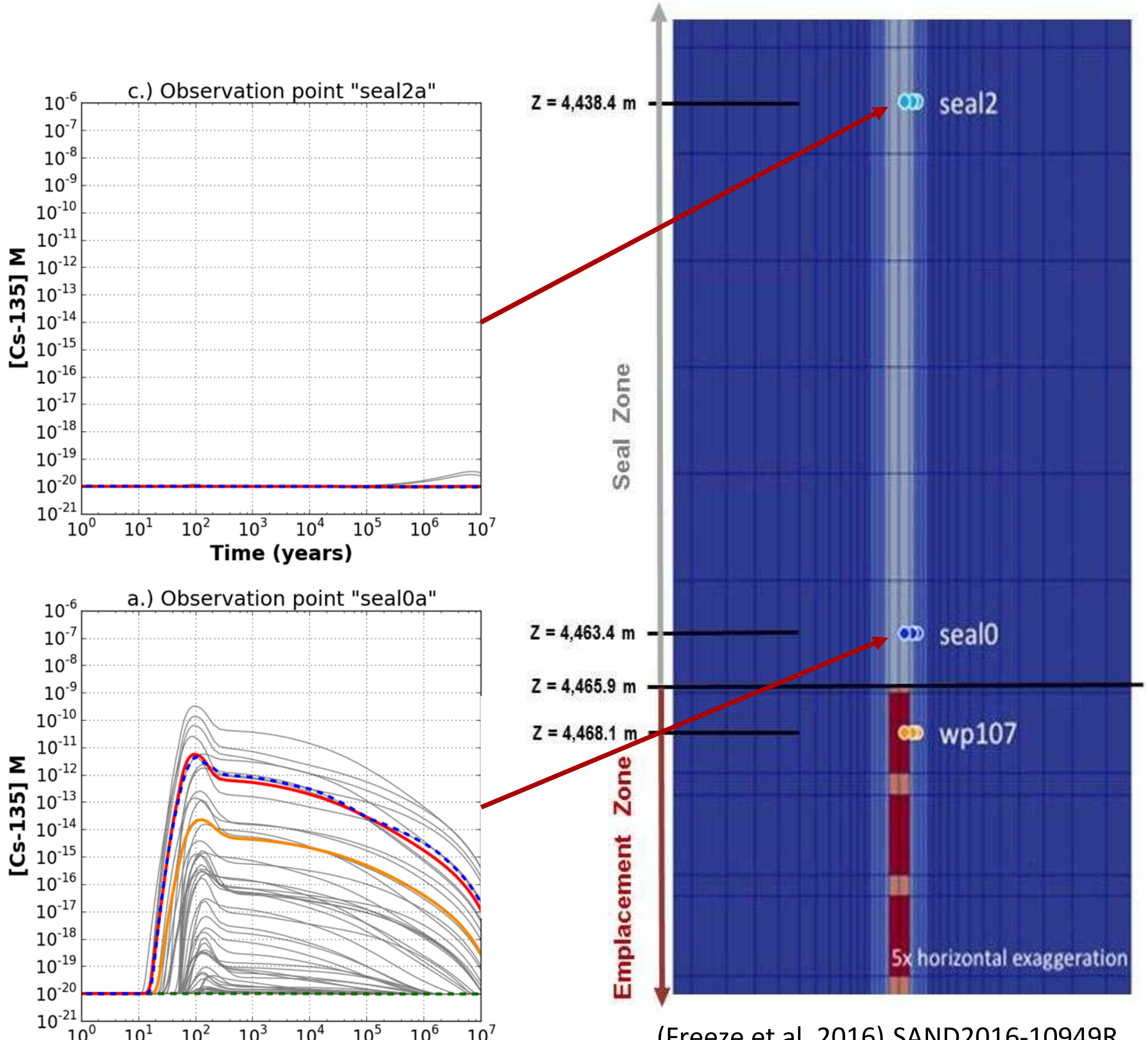


(Freeze et al. 2016) SAND2016-10949R

Deep Borehole PA Models



Parameter	Range	Units
Bentonite *k*	$10^{-20} - 10^{-16}$	m^2
Cement *k*	$10^{-20} - 10^{-16}$	m^2
DRZ *k*	$10^{-18} - 10^{-15}$	m^2
WP τ	0.01 – 1.0	--
Bentonite ϕ	0.40 – 0.50	--
Cement ϕ	0.15 – 0.20	--
WP Breach Time	1 – 100	yr
Cs K_d bentonite	120 – 1000	L/kg
Sr K_d bentonite	50 – 3000	L/kg
Cs K_d crystalline	5 – 40	L/kg
Sr K_d crystalline	0.4 – 3	L/kg
Cs K_d DRZ	5 – 40	L/kg
Sr K_d DRZ	0.4 – 3	L/kg



(Freeze et al. 2016) SAND2016-10949R

Deep Borehole Field Test: 2017-2021

Deep Borehole Field Test (DBFT)

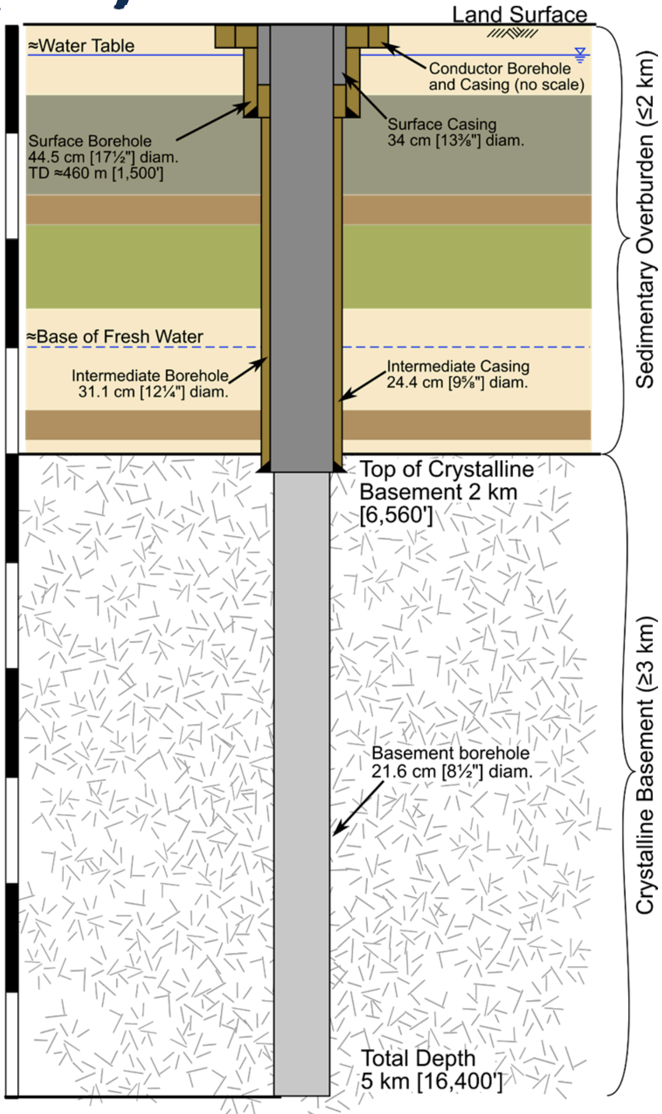
- **Drill Two 5-km Boreholes**
  - Characterization Borehole (CB): **21.6 cm [8.5”] @ TD**
  - Field Test Borehole (FTB): **43.2 cm [17”] @ TD**

- **Demonstrate Ability to:**
  - Drill deep, wide, straight borehole safely (CB + FTB)
  - Characterize basement (CB)
  - Test formations in situ (CB)
  - Collect geochemical profiles (CB)
  - Emplace/retrieve test packages (FTB)

Characterization Borehole (CB)

- **Medium-Diameter Borehole**
  - Within current drilling experience
- **Testing/Sampling During Drilling**
  - Drilling mud logging (gas, liquid & solid)
  - Core in crystalline section
- **Testing/Sampling After Completion**
  - Packer tool via work-over rig
  - At limits of current technology
- **Demonstrate Ability to**
  - Perform in situ testing at high P & T
  - Build evidence for old groundwater

Borehole designed to maximize likelihood of good samples

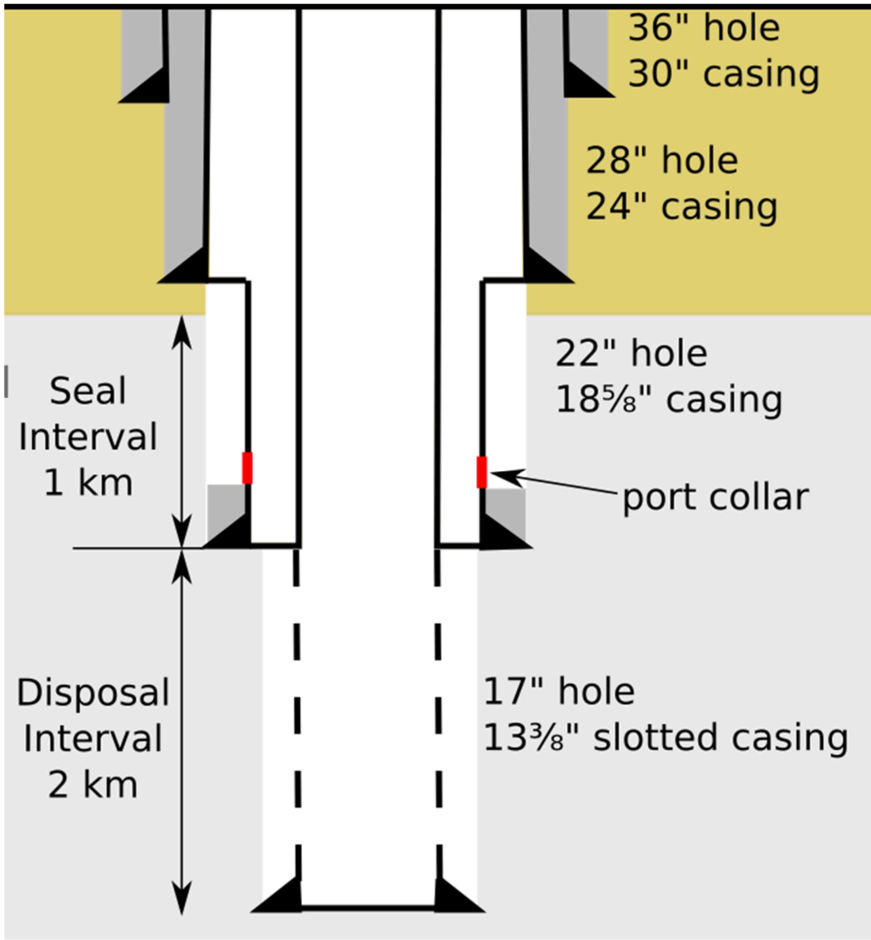


(SNL 2016) SAND2016-9235R
DBFT Laboratory and Borehole Testing Strategy

Field Test Borehole (FTB)

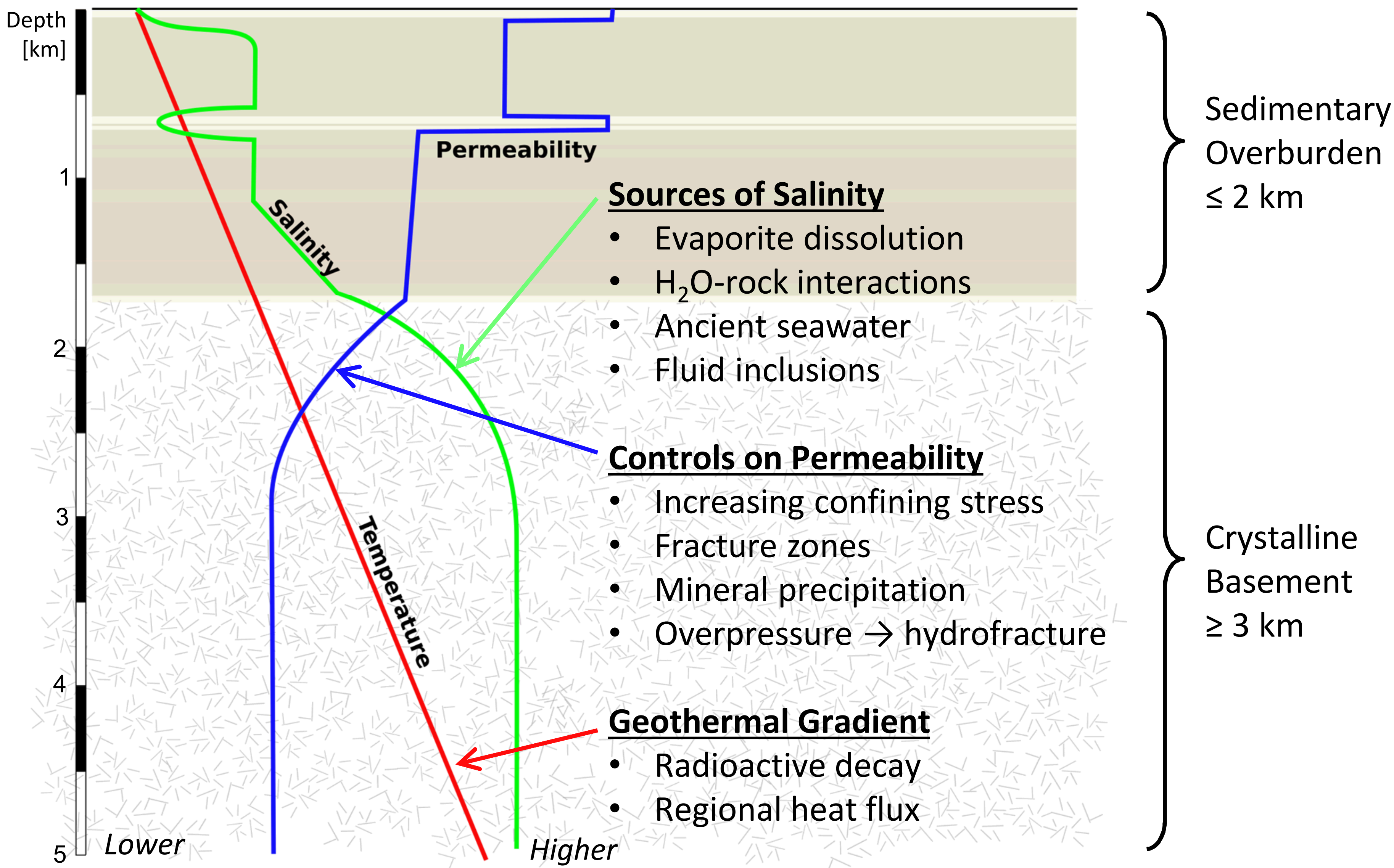
- **Large-Diameter Borehole**
  - Push envelope of drilling tech
- **Casing Schedule**
  - Continuous 13 ⅜” pathway to TD
    - Slotted & permanent in disposal interval
    - Removable in seal and overburden intervals
- **Demonstrate Ability to**
  - Emplace canisters
  - Remove canisters
  - Surface handling operations

Borehole designed to maximize emplacement safety



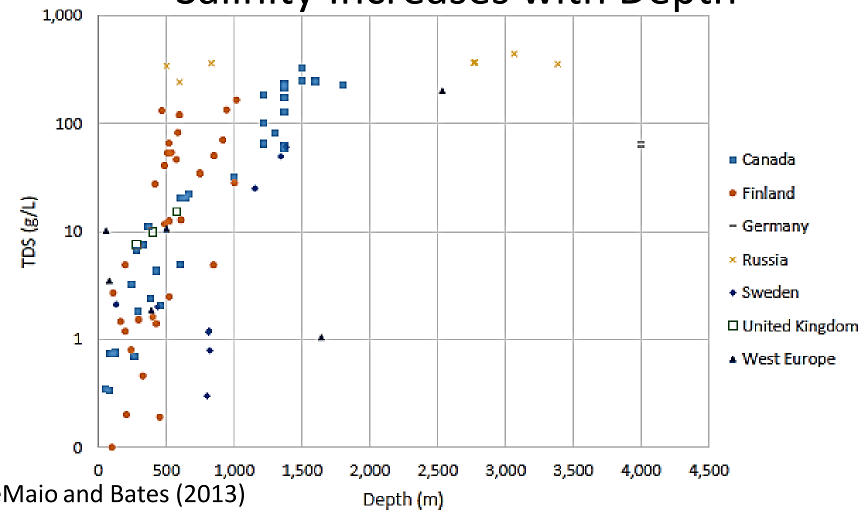
(SNL 2016) SAND2016-10246 R
Deep Borehole Field Test Conceptual Design Report

Basement Conceptual Profiles



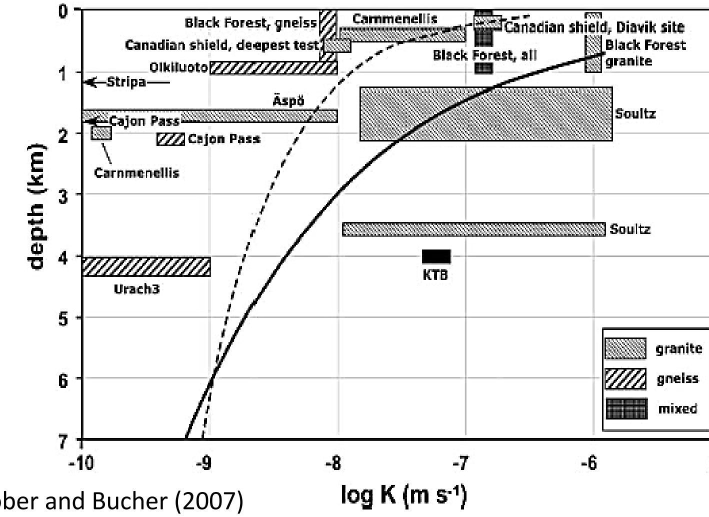
Observed Profiles

Salinity Increases with Depth



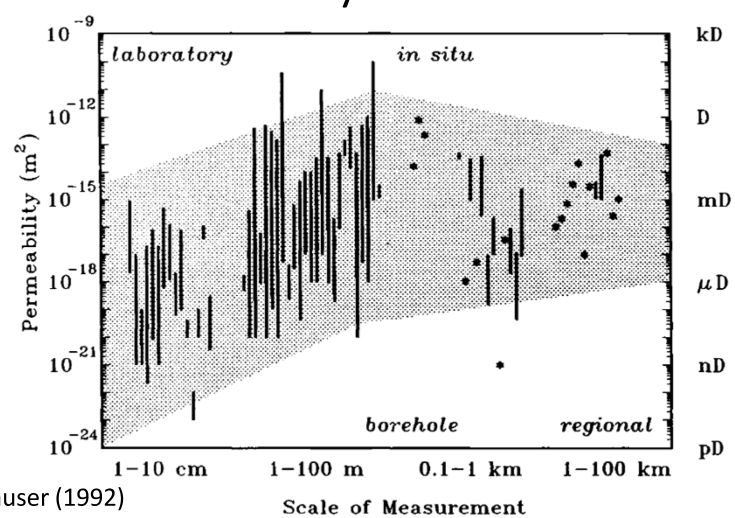
DeMaio and Bates (2013)

Bulk Permeability Decreases with Depth



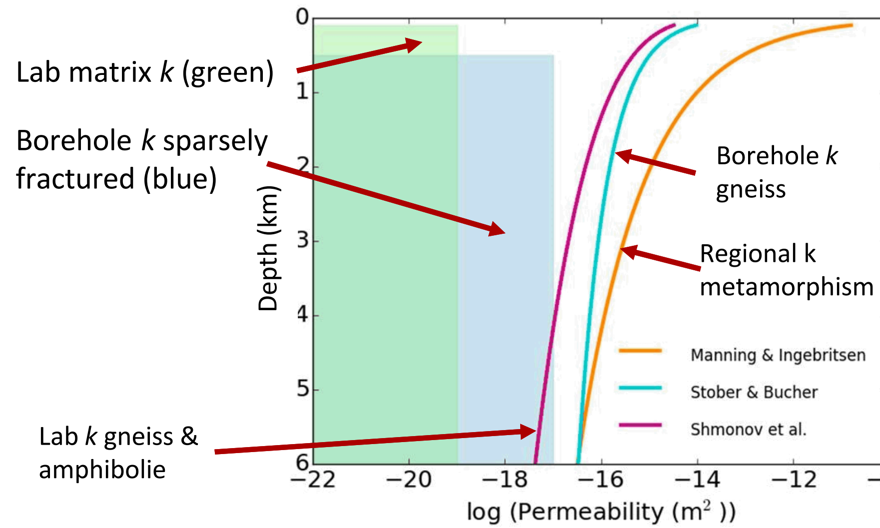
Stober and Bucher (2007)

Bulk Permeability Increases with Scale



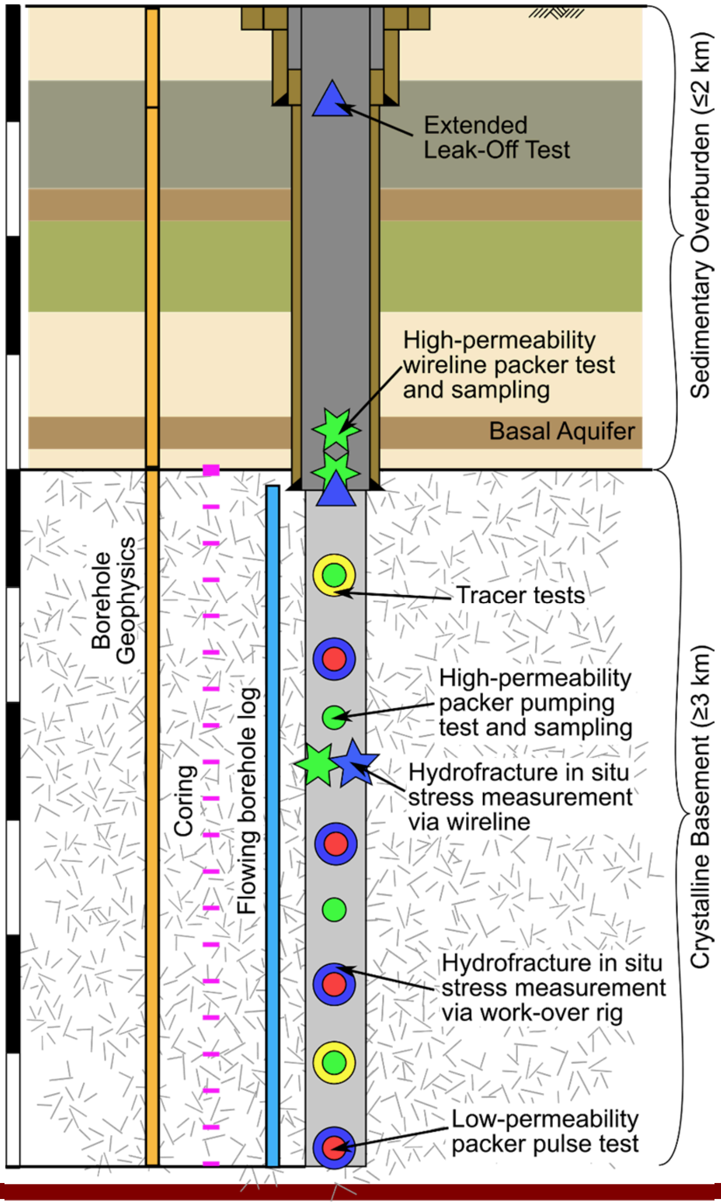
Clauser (1992)

(Freeze et al. 2016) SAND2016-10949R



Characterization Borehole (CB)

- **Sampling During Driling**
- **Borehole Geophysics**
- **Flowing Borehole Salinity Log**
- **Sample-based Profiles**
  - Fluid density/temperature/major ions
  - Pumped samples from high-*k* regions
  - Samples from cores in low-*k* regions
- **In Situ Testing-based Profiles**
  - Static formation pressure
  - Formation hydraulic/transport properties
  - *In situ* stress (hydrofrac + breakouts)



(SNL 2016) SAND2016-9235R

CB Characterization *During* Drilling

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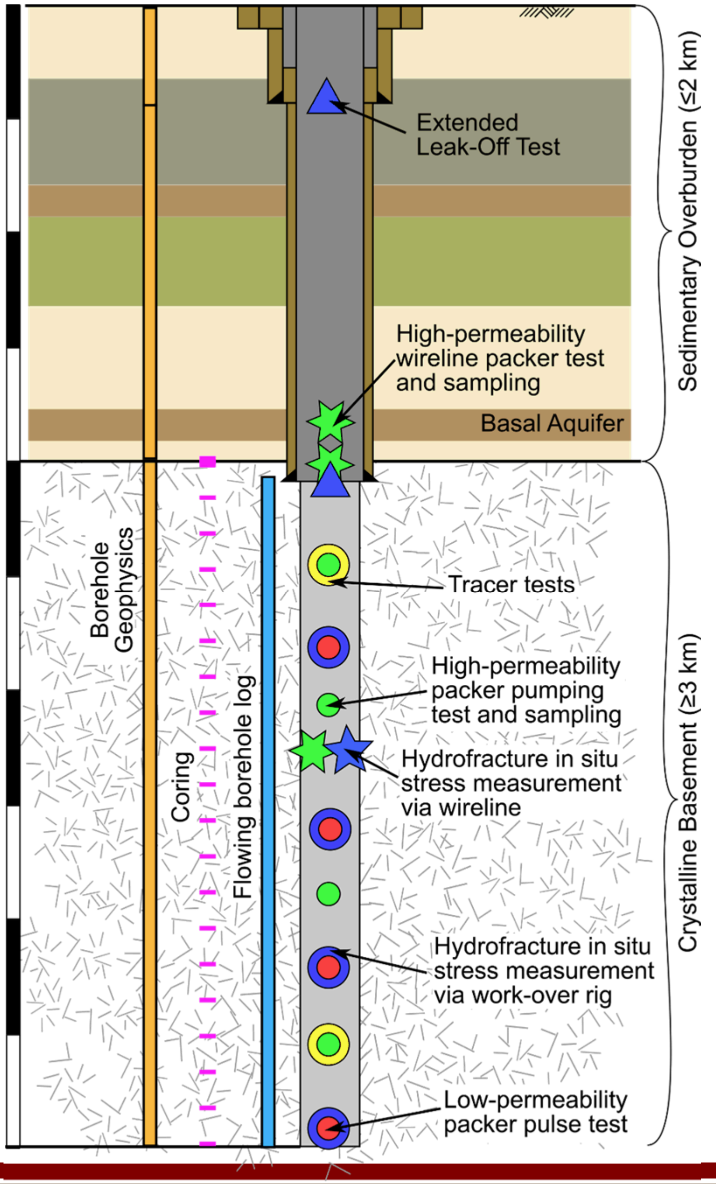
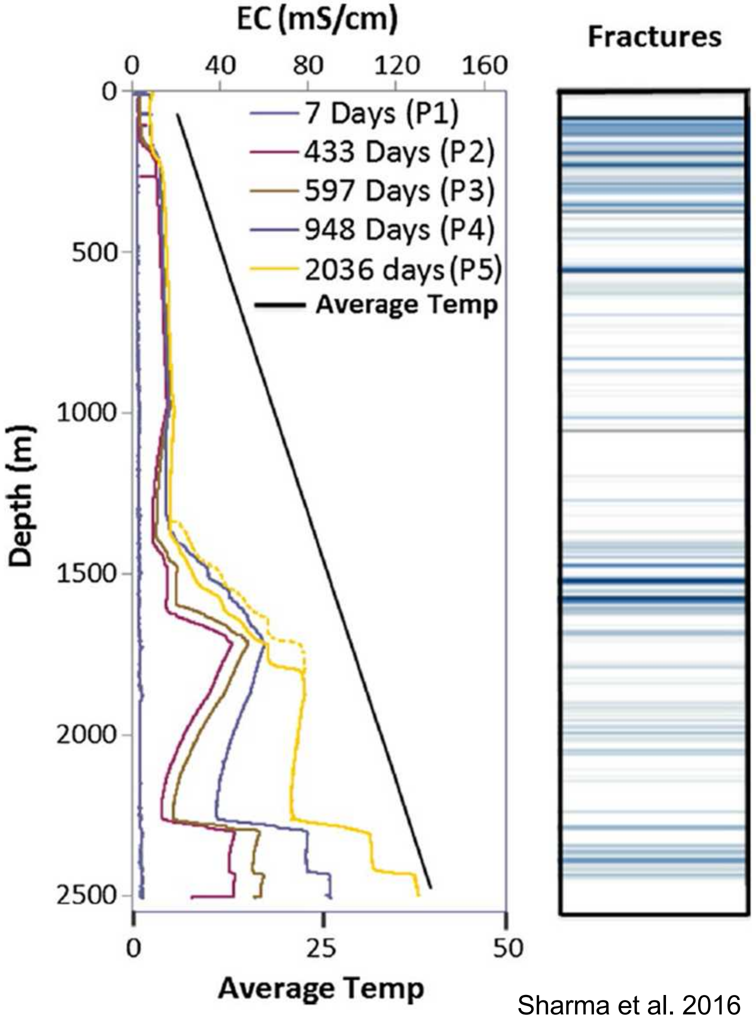
- **Mud logging (~continuous)**
  - Ion chromatograph (liquid)
  - Gas chromatograph (gas)
  - XRD/XRF rock flour (solids)
- **Fluid sampling (each ~30 m)**
  - Mud before & after circulation
  - Analytes
    - Drilling mud tracer (iodine, fluorescein)
    - C, S, N & stable water isotopes
    - Drilling mud additive
- **Advance Coring (5% → 150 m)**
- **Drilling parameters:**
  - rate, WOB, rotation speed, drilling specific energy, etc.



CB Testing After Drilling

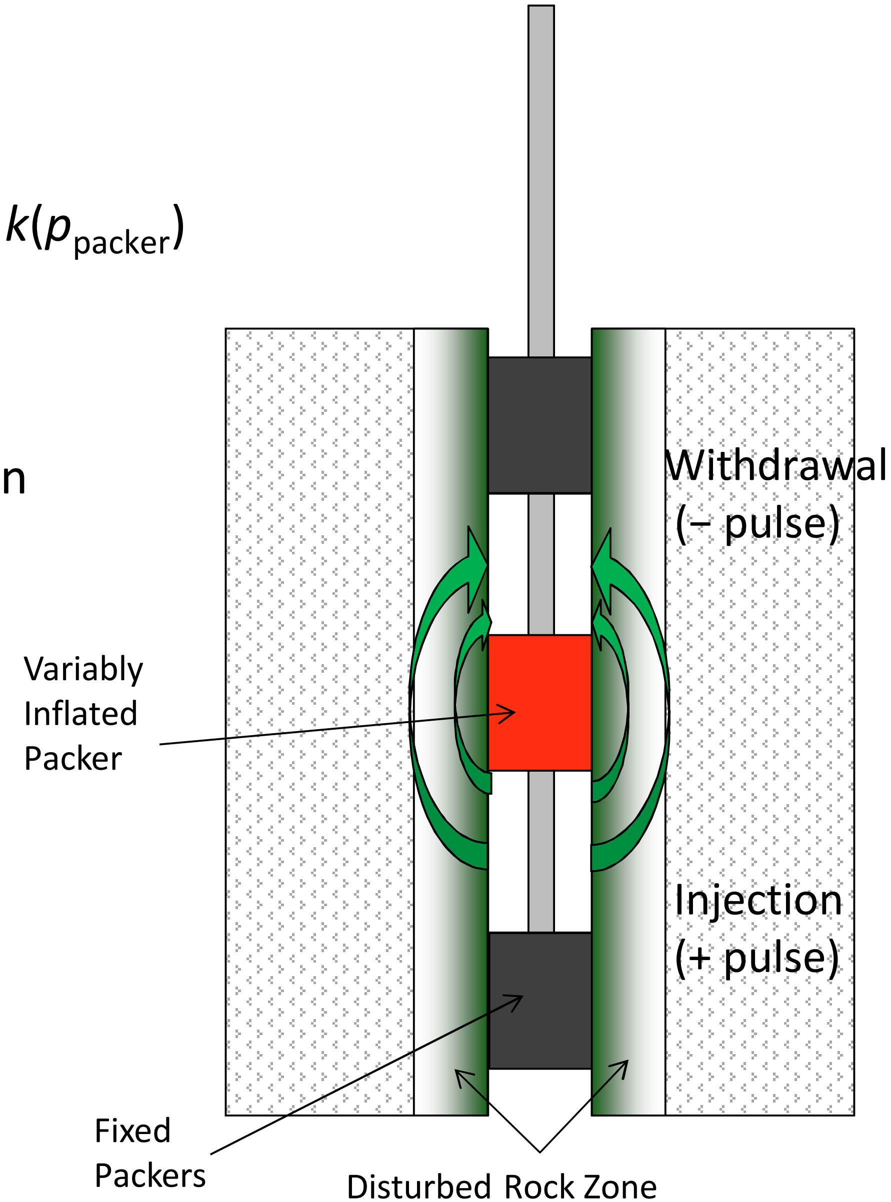
- **Flowing Fluid Electrical Conductivity (FFEC) log**
- **Determine location of:**
  - Permeable zones
  - Gaining zones
  - Losing zones
- **Focus in situ packer testing on:**
  - 5 permeable zones
    - Formation fluid samples collected at surface
    - Estimate hydraulic properties
  - 5 low-permeability zones
    - Estimate hydraulic properties



Sharma et al. 2016

In Situ Testing

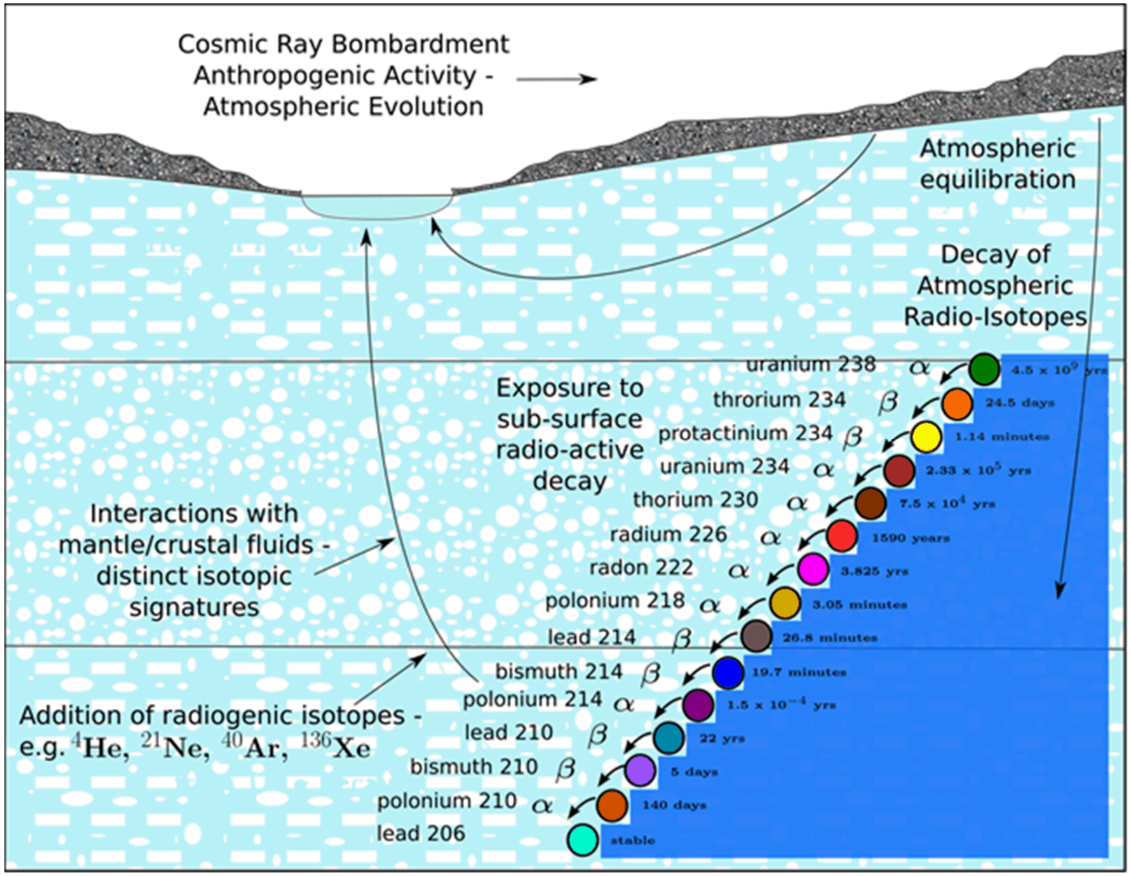
- **In Situ Packer Testing**
  - New hydromechanical dipole test: $k(p_{packer})$
- **Hydrologic Tests**
  - Static formation pressure
  - Permeability / compressibility / skin
  - Sampling in high k intervals
- **Tracer Tests**
  - Single-well injection-withdrawal
- **Hydraulic Fracturing Tests**
  - σ_h magnitude
  - Estimate stress tensor via existing fractures



Environmental Tracers in Samples

- **Vertical Profiles**
  - Noble gases (He, Ne, etc.)
  - Stable water isotopes
    - Oxygen; hydrogen
  - Atmospheric radioisotope tracers (e.g., ^{81}Kr, ^{129}I, ^{36}Cl)
  - $^{238}U/^{234}U$ ratios
  - $^{87}Sr/^{86}Sr$ ratios
- **Estimate**
  - Water provenance
  - Flow mechanisms/isolation

Minerals → pores → fractures (evaluate the "leakiness")



(After Kuhlman, 2015)

Fluid Sample Quality + Quantity *will be a Focus!*

Repeatability across driling, packer & core samples?

Characterization Differences

- **DBFT Likely Different From:**
  - Oil/gas or mineral exploration (low perm., low porosity rocks)
  - Geothermal exploration (low geothermal gradient)
  - Shallow drilling/testing (high *p*, high *σ*, deep, breakouts)
- **DBFT Characterization Approach**
  - Not exhaustive permeability characterization (scaling)
  - Seeking *geochemical* evidence of system isolation
  - Use “off-the-shelf” approaches when available
- **DBFT Goals**
  - Drill straight large-diameter boreholes to 5 km depth
  - Demonstrate sample collection (cores + formation fluid)
    - Enough samples
    - Low enough contamination level
  - Demonstrate *in situ* testing at depth (3 to 5 km)

SAND2010-6048

Summary

- **Deep Borehole Disposal Concept**
  - Robust isolation from biosphere
  - Seal/DRZ only pathway for release
  - Simple construction (for few boreholes)
  - Wide site availability
  - Single-phase, diffusion dominated
  - Geological issues?
    - Drill elsewhere vs. Engineer away

- **Deep Borehole Field Test (FY17-21)**
  - Drill two 5-km large-diameter boreholes
  - Demonstrate ability to
    - Characterize bedrock flow system (CB)
    - Emplace/retrieve test packages (FTB)

SAND2010-6048