SAND2016-11157PE

Exceptional service in the national interest

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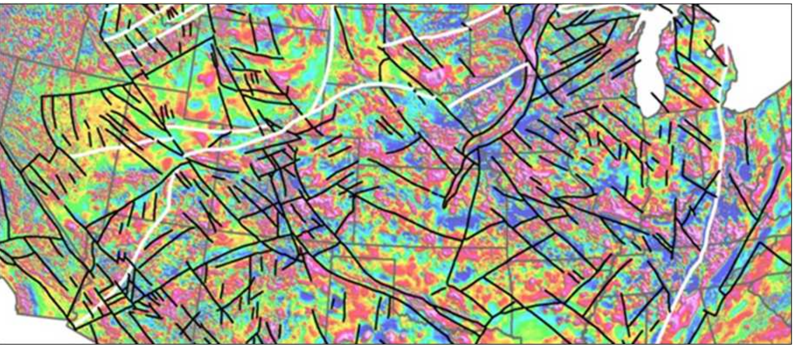

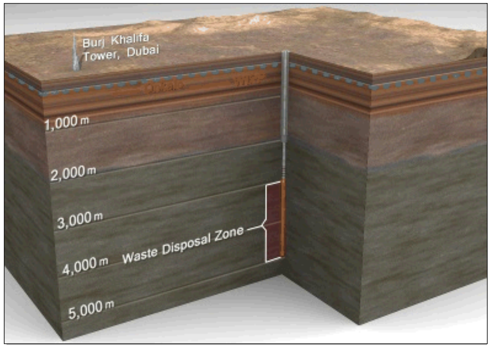

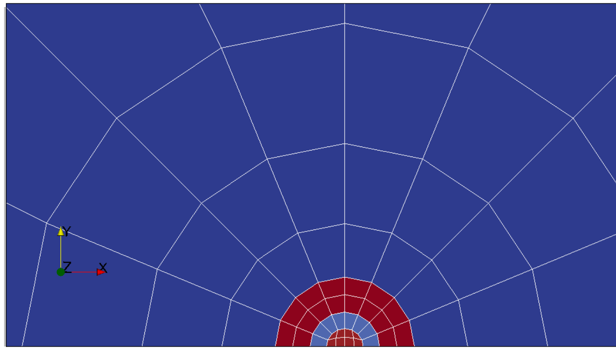

Deep Borehole: from Disposal Concept to Field Test

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Sandia National Laboratories

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

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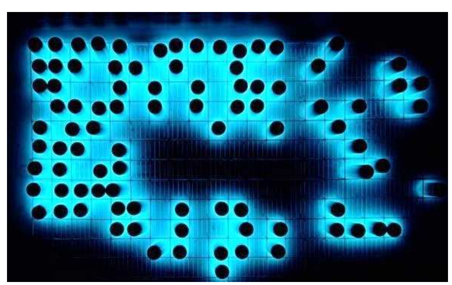
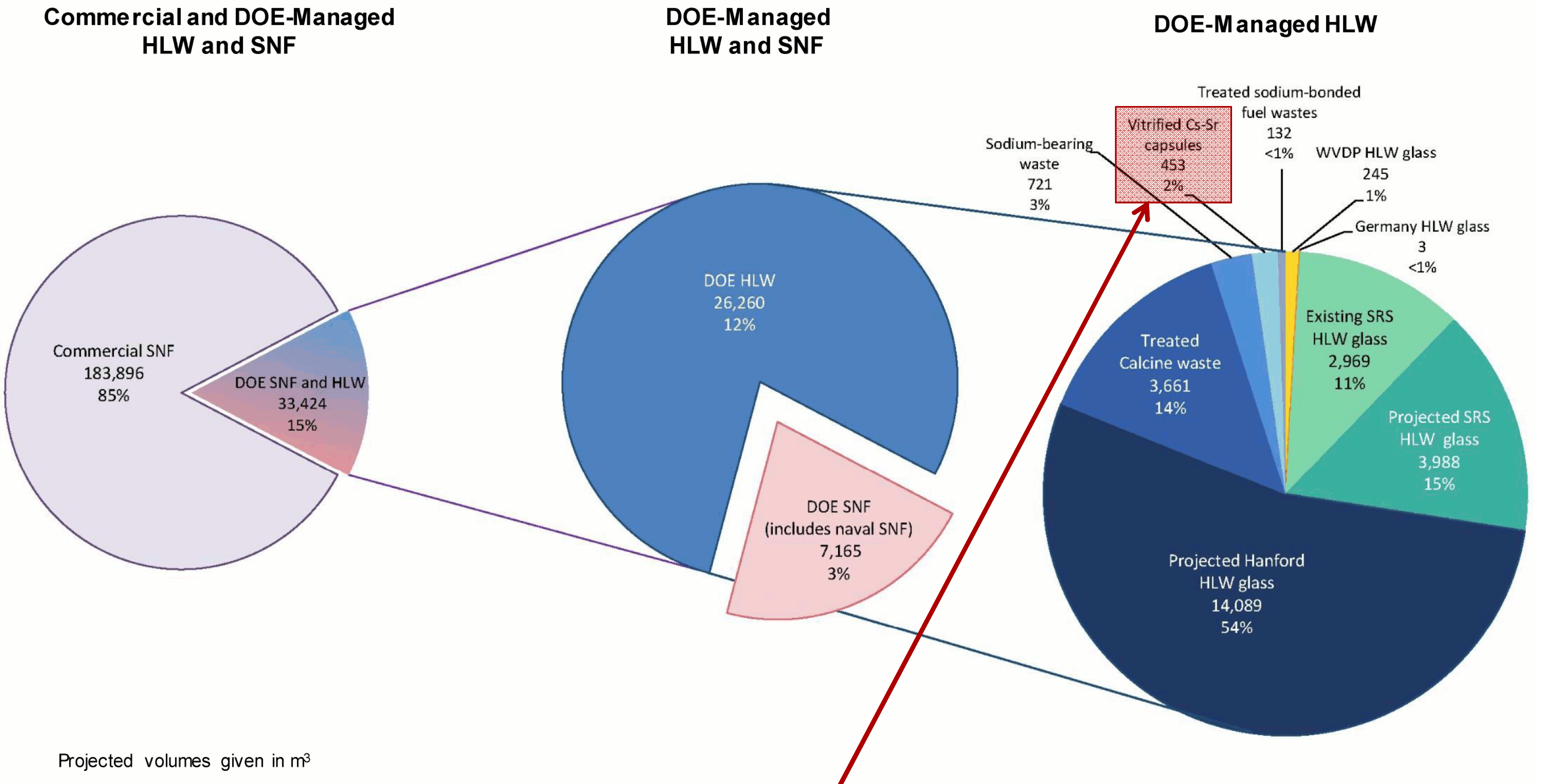
- **Waste Properties**
  - **Thermal output**
  - **Physical size**
  - **Waste total volume**
- **Primary Waste Forms**
  - **DOE-managed high-level waste**
    - **Liquid reprocessing wastes:**
      - **Borosilicate glass logs**
      - **Cs-137/Sr-90 capsules**
      - **Calcine powder**

Hanford tank farm



2,000 Cs/Sr Capsules [≈3” diam.]

Radioactive Waste Volumes



HLW = High-Level Waste
SNF = Spent Nuclear Fuel

≈ 30% total curies of radioactivity at Hanford

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 → select up to 5 teams**

History

Deep Crystalline Drilling

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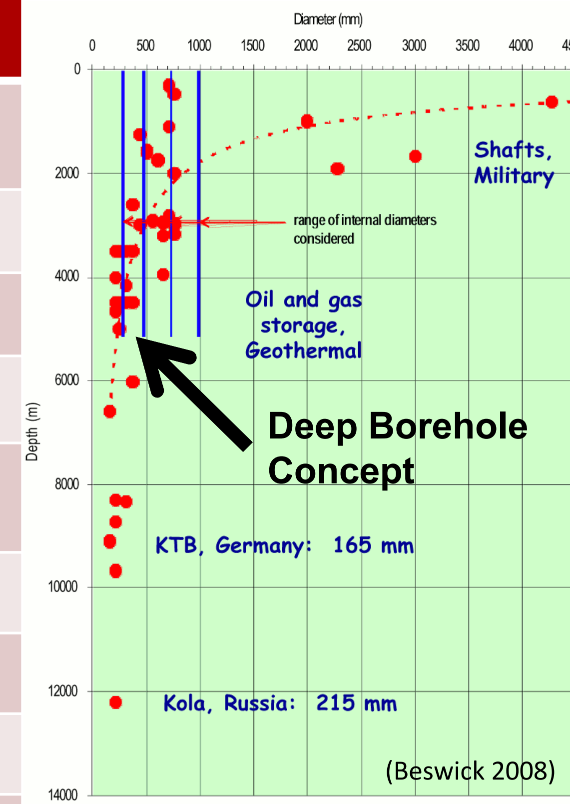
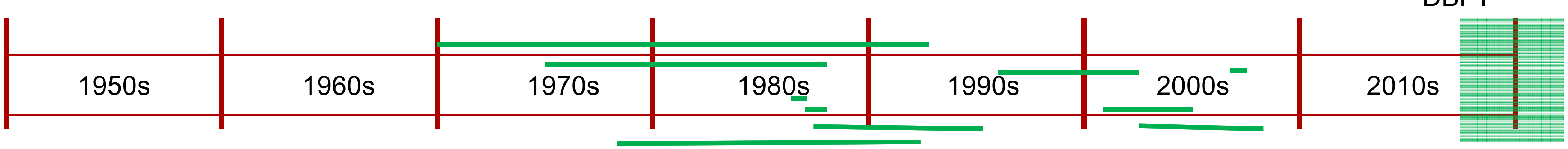
Site	Location	Years	Depth to Crystalline [km]	Total Depth [km]	Diam* [inch]
Kola	NW USSR	1970-1992	0	12.2	8½
Fenton Hill	New Mexico	1975-1987	0.7	2.9, 3.1, 4.0, 4.4	8¾, 9⅞
Urach	SW Germany	1978-1992	1.6	4.4	5½
Gravberg	Central Sweden	1986-1987	0	6.6	6½
Cajon Pass	Southern California	1987-1988	0.5	3.5	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



Deep Borehole Disposal

- **Hess et al. (1957) NAS Publication 519**

  The Disposal of Radioactive Waste on Land. Appendix C: Committee on Deep Disposal

- **Obrien et al. (1979) LBL-7089**

  The Very Deep Hole Concept: Evaluation of an Alternative for Nuclear Waste disposal

- **Woodward-Clyde (1983) ONWI-226**

  Very Deep Hole Systems Engineering Studies

- **Juhlin & Sandstedt (1989) SKB 89-39**

  Storage of Nuclear Waste in Very Deep Boreholes

- **Ferguson (1994) SRNL WSRC-TR-94-0266**

  Excess Plutonium Disposition: The Deep Borehole Option

- **Heiken et al. (1996) LANL LA-13168-MS**

  Disposition of Excess Weapon Plutonium in Deep Borehole: Site Selection Handbook

- **Harrison (2000) SKB-R-00-35**

  Very Deep Borehole – Deutag's Opinion on Boring, Canister Emplacement and Retreivability

- **Nirex (2004) N/108**

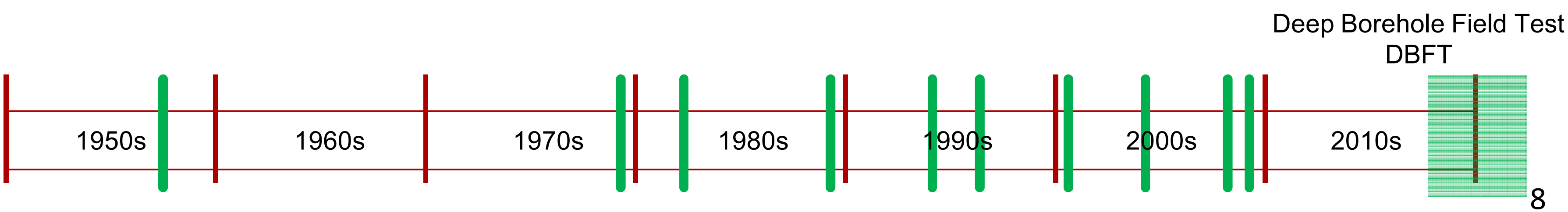
  A Review of the Deep Borehole Disposal Concept

- **Beswick (2008)**

  Status of Technology for Deep Borehole Disposal

- **Brady et al. (2009) SNL SAND2009-4401**

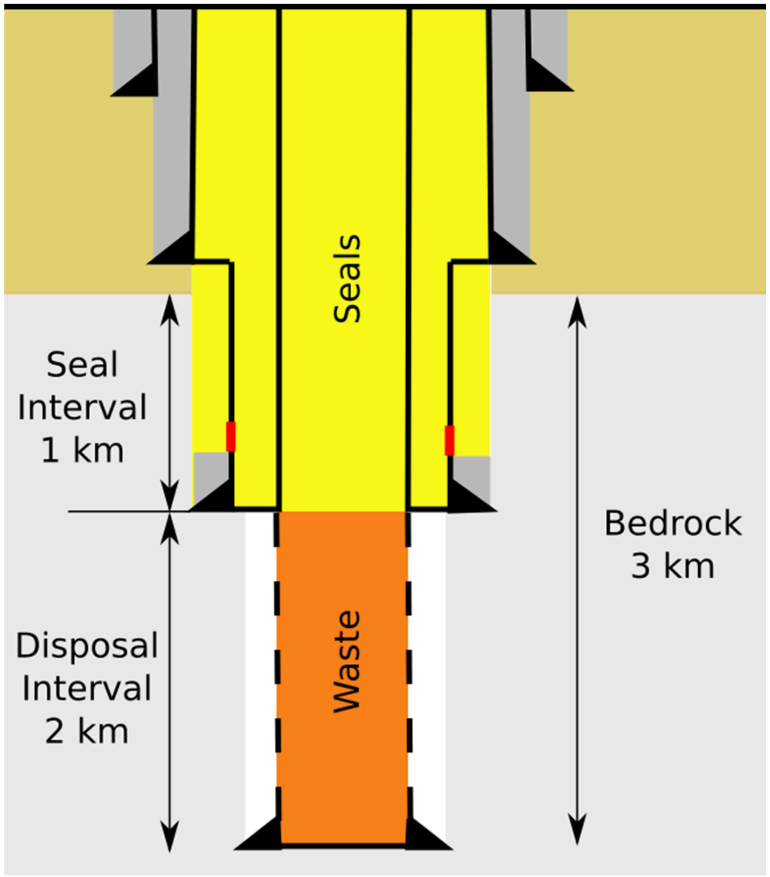
  Deep Borehole Disposal of High-Level Radioactive Waste



Deep Borehole Disposal Concept

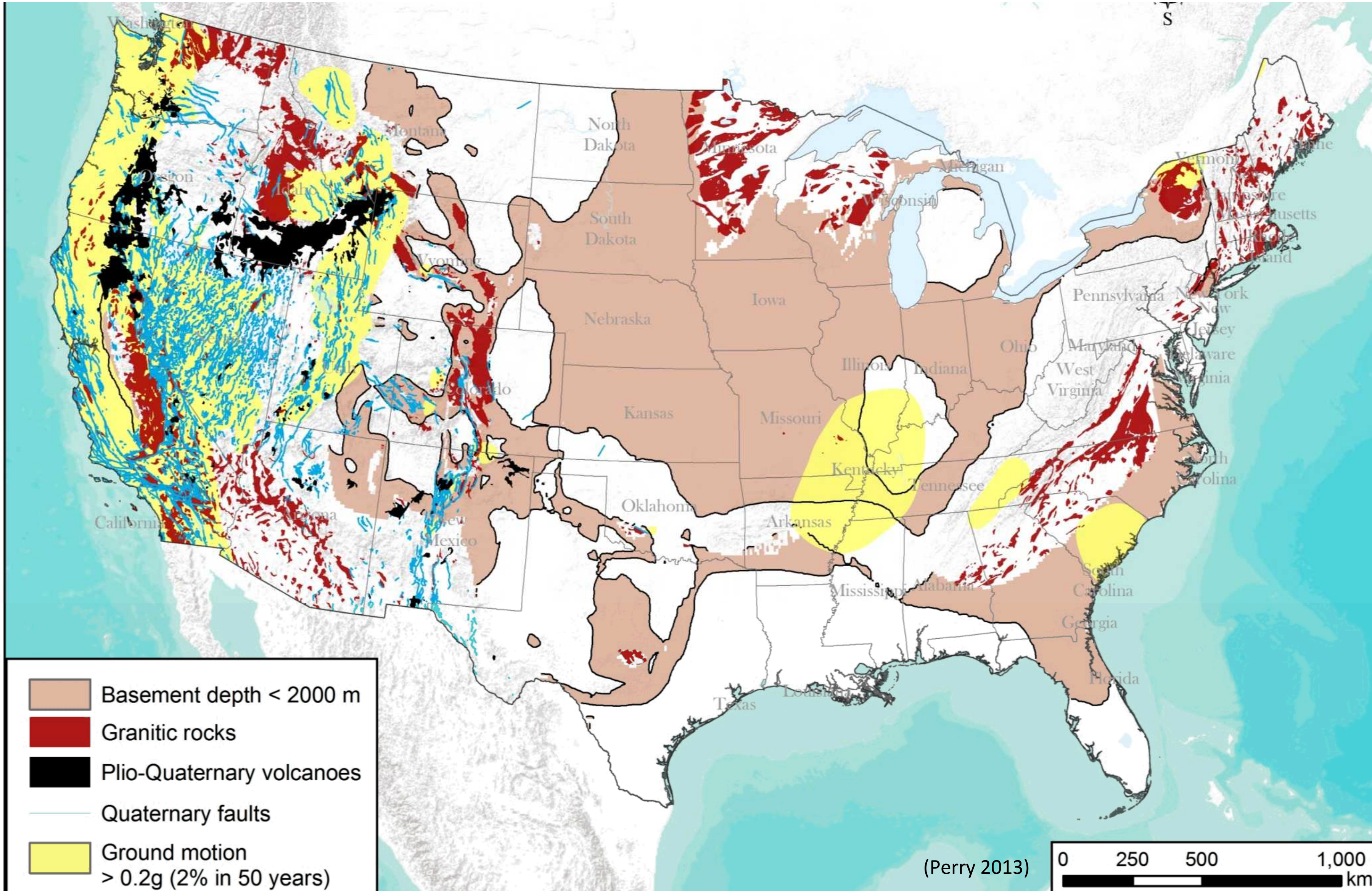
Deep Borehole Concept vs. Field Test

- **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



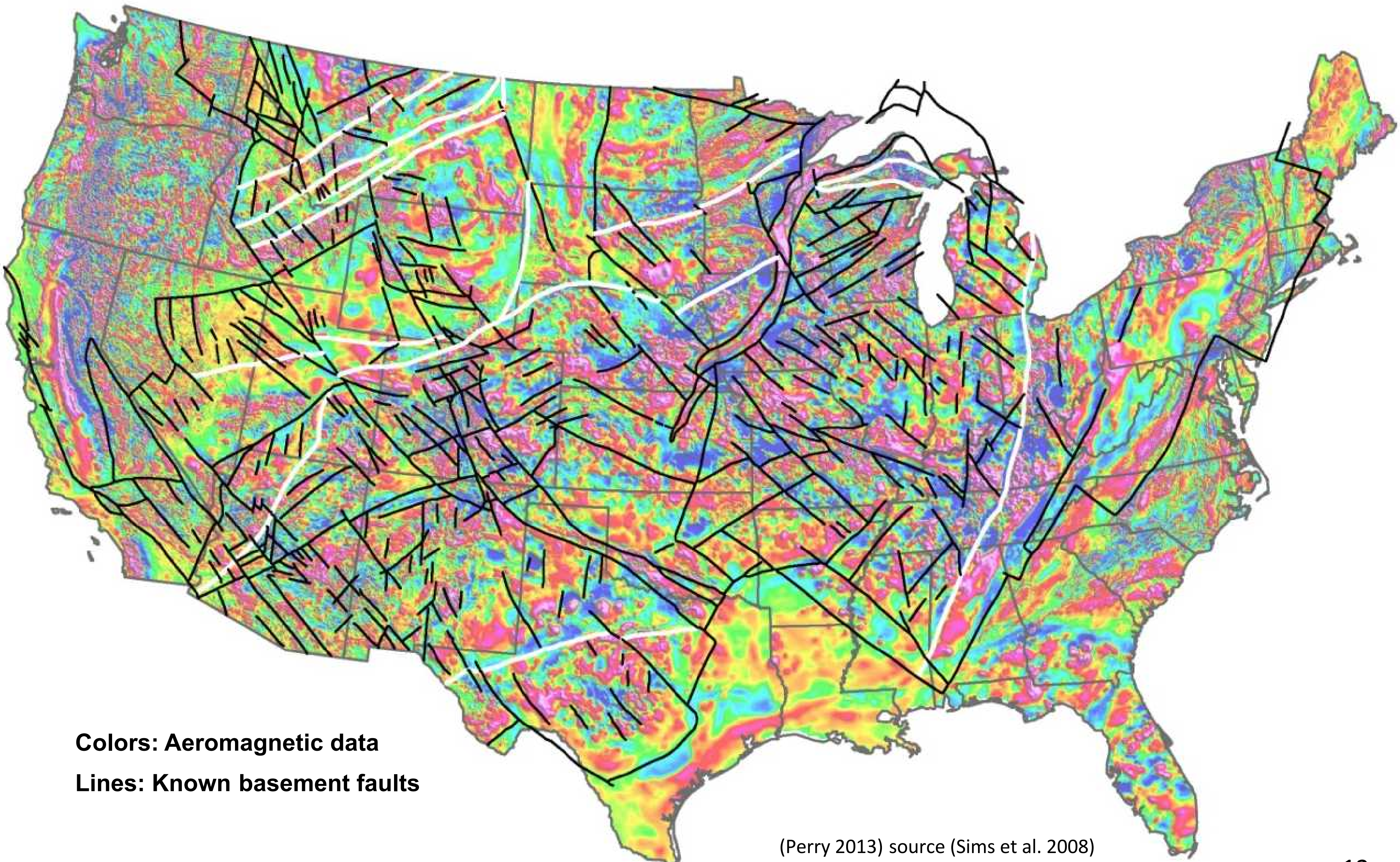
- **Deep Borehole Field Test (DBFT)**
  - Department of Energy – Office of Nuclear Energy (DOE-NE)
  - FY 2017-2021 project
  - Two boreholes to 5 km TD
  - Science and engineering demonstration

Siting: Depth to Basement + Hazards



(Perry 2013)

Siting: Basement Structure

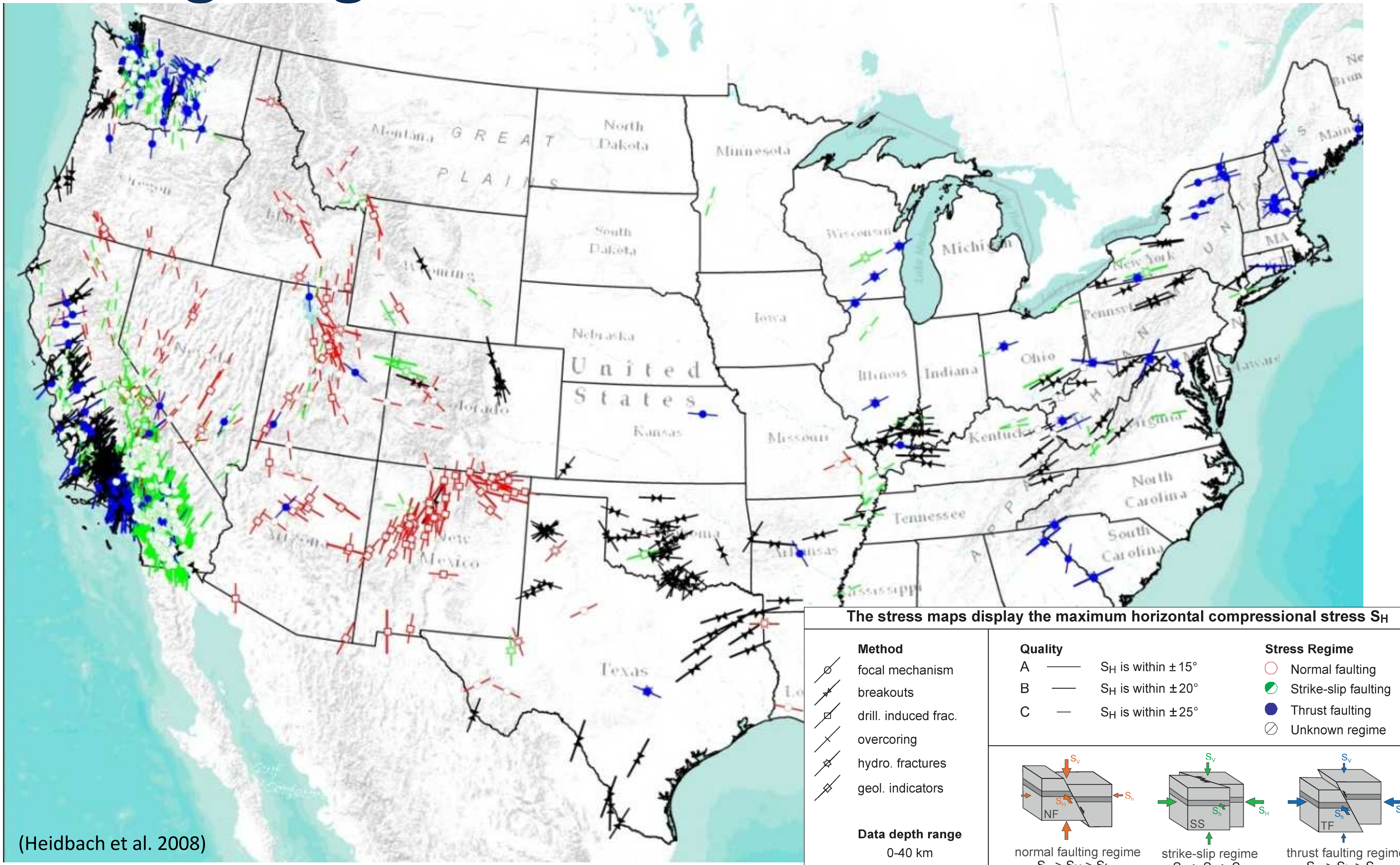


Colors: Aeromagnetic data

Lines: Known basement faults

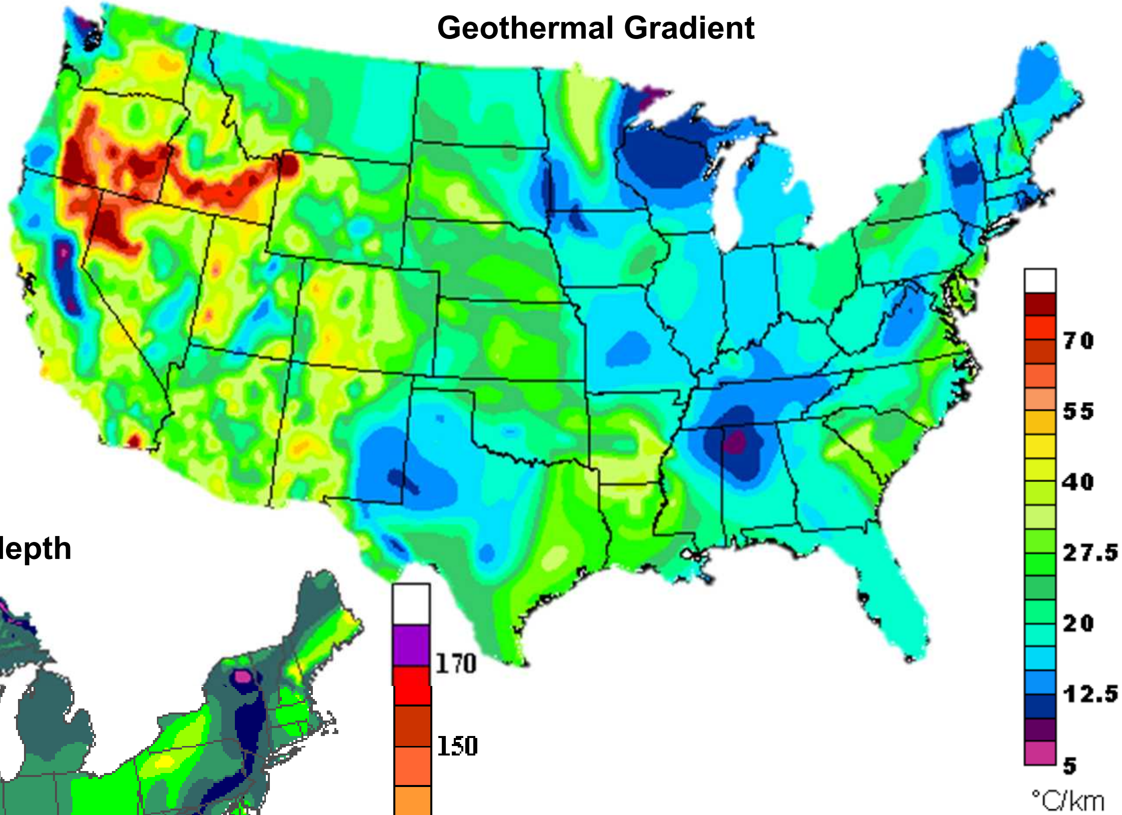
(Perry 2013) source (Sims et al. 2008)

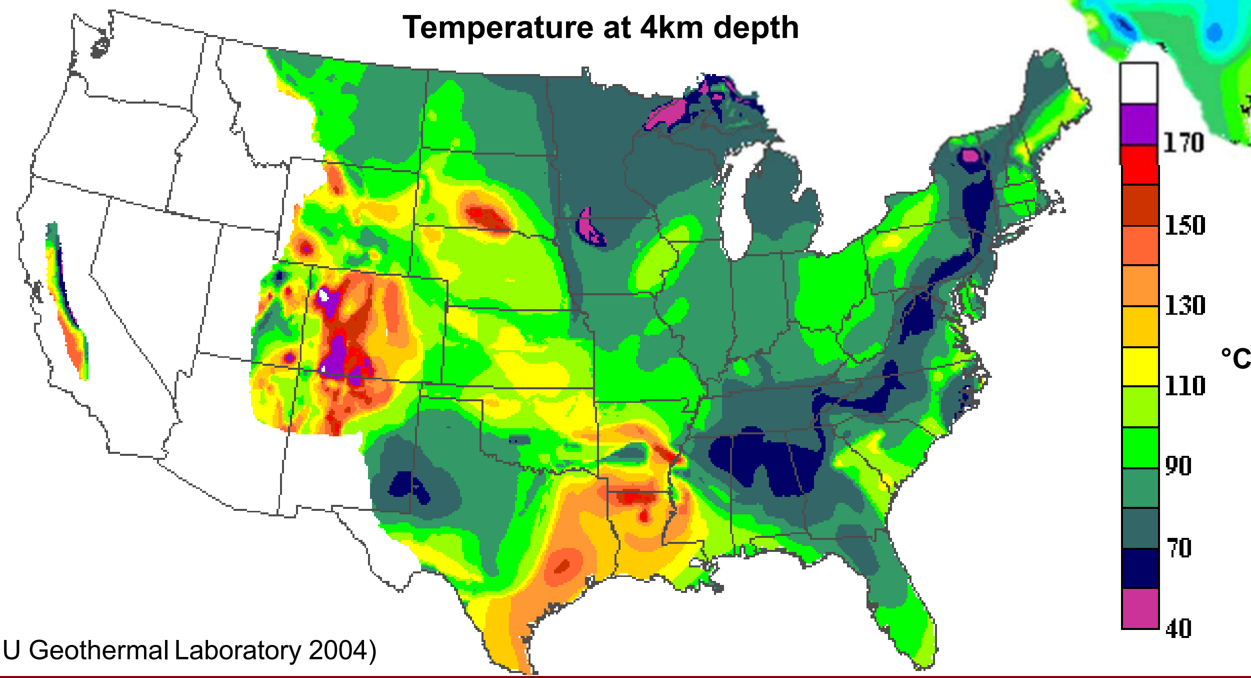
Siting: Regional Stress State



(Heidbach et al. 2008)

Siting: Geothermal



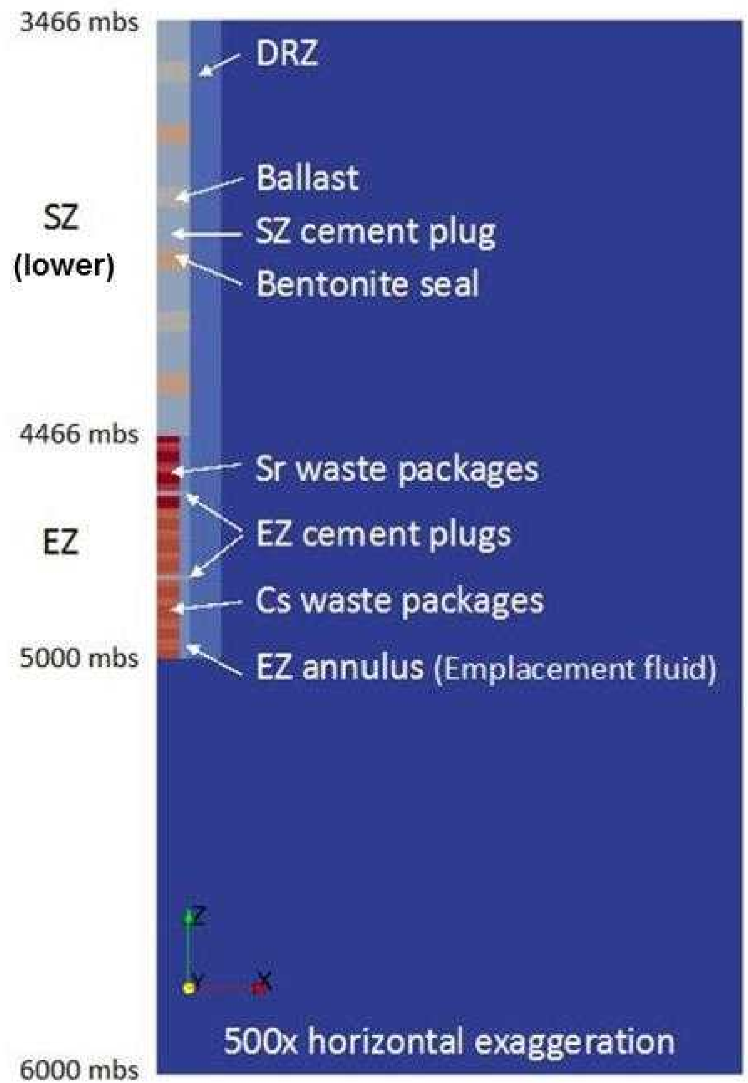


(SMU Geothermal Laboratory 2004)

Deep Borehole Performance Assessment Modeling

Deep Borehole PA Models

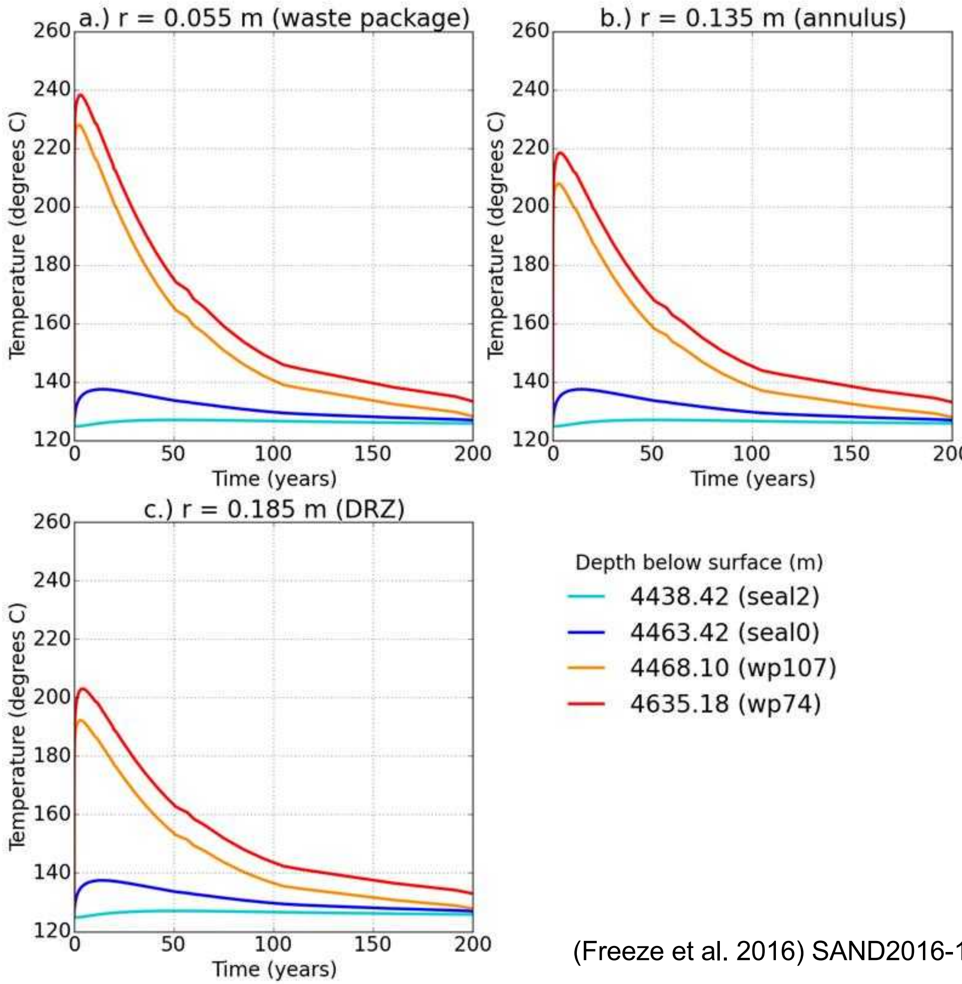
- **Performance Assessment (PA) Modeling**
  - **Reference geology and borehole design**
  - **Assume single boreholes Cs/Sr**
  - **Assess post-closure safety**
  - **Thermal-hydrological-chemical processes simulated via PFLOTRAN**

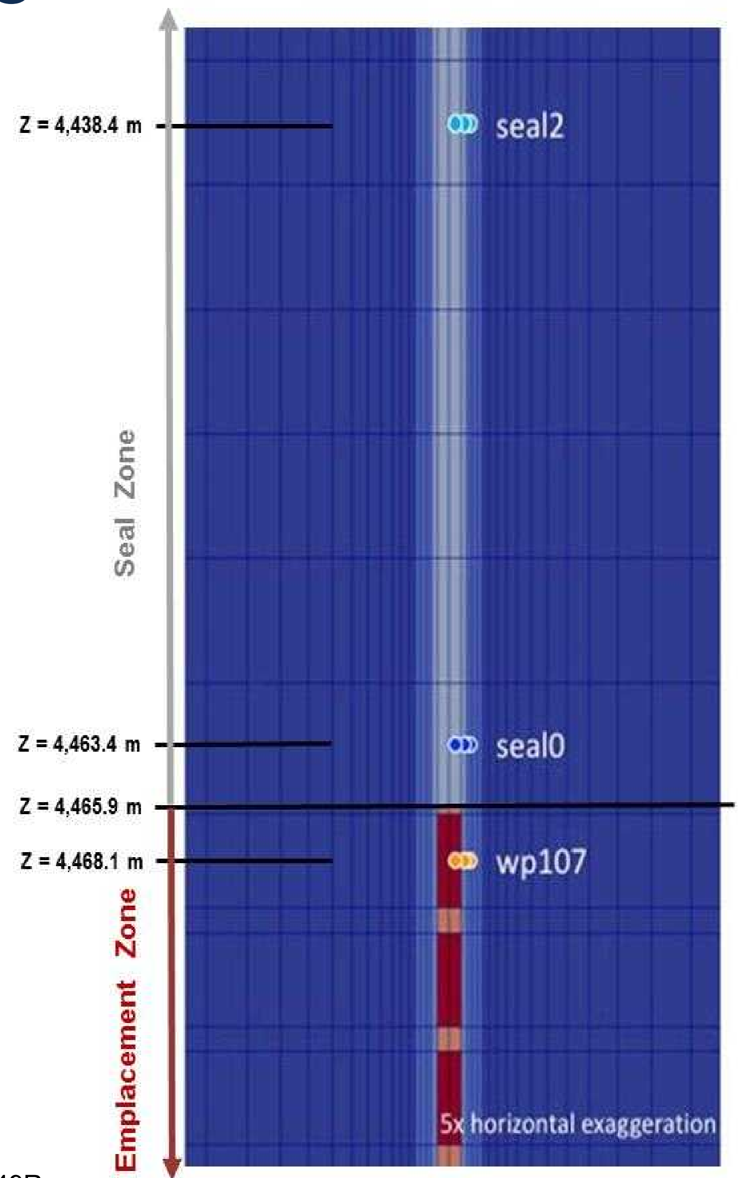


(Freeze et al. 2016) SAND2016-10949R

Deep Borehole PA Models

- **Short Thermal Perturbation**
- **Minimal Resulting Free Convection**





(Freeze et al. 2016) SAND2016-10949R

Deep Borehole PA Models

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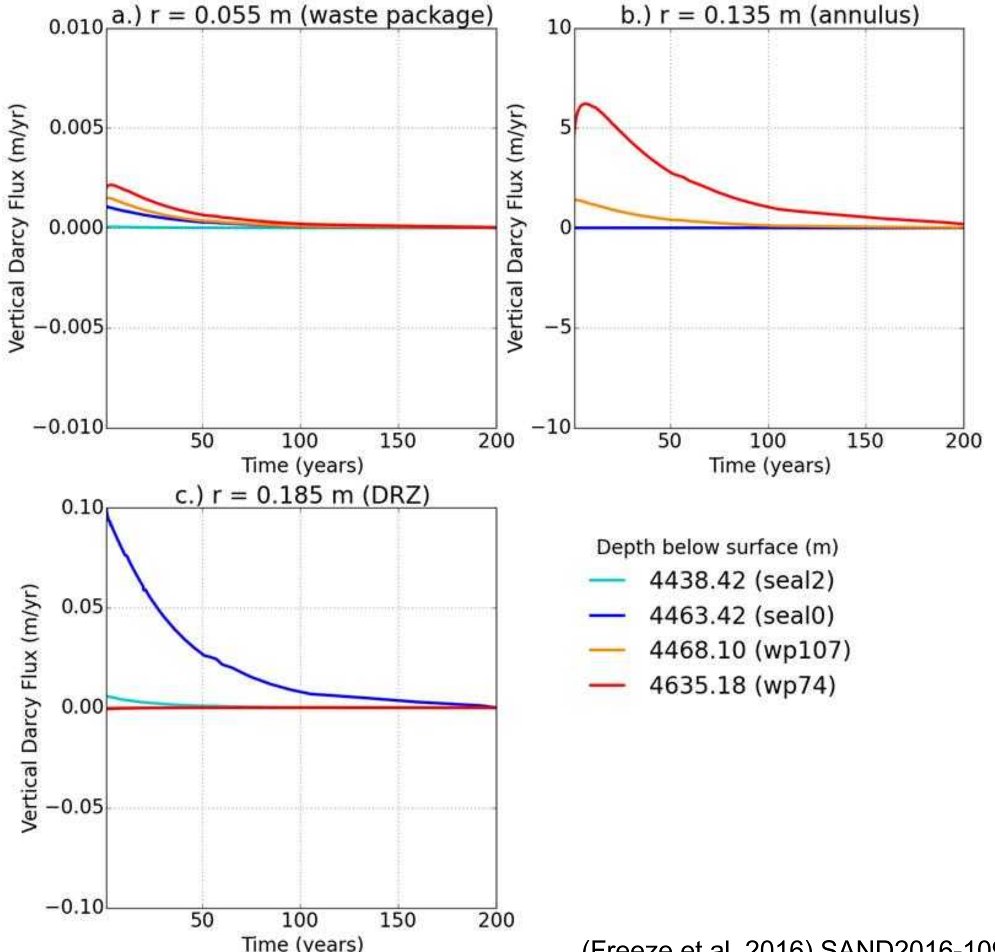
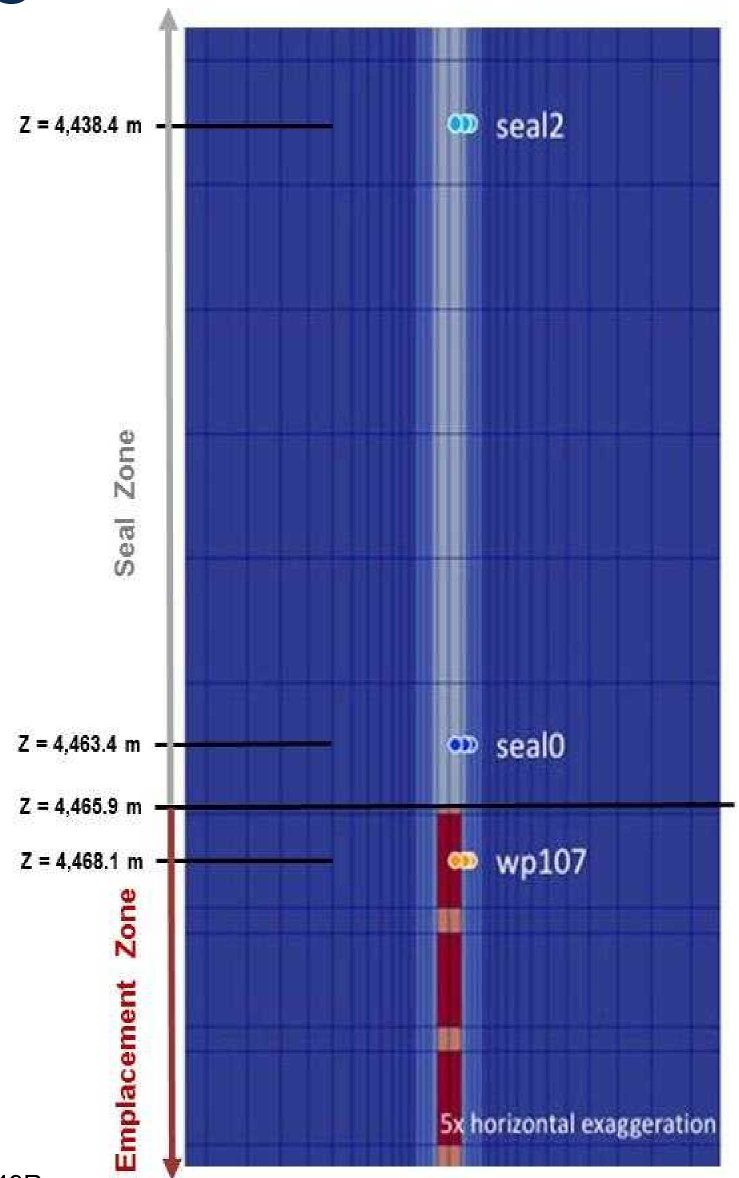
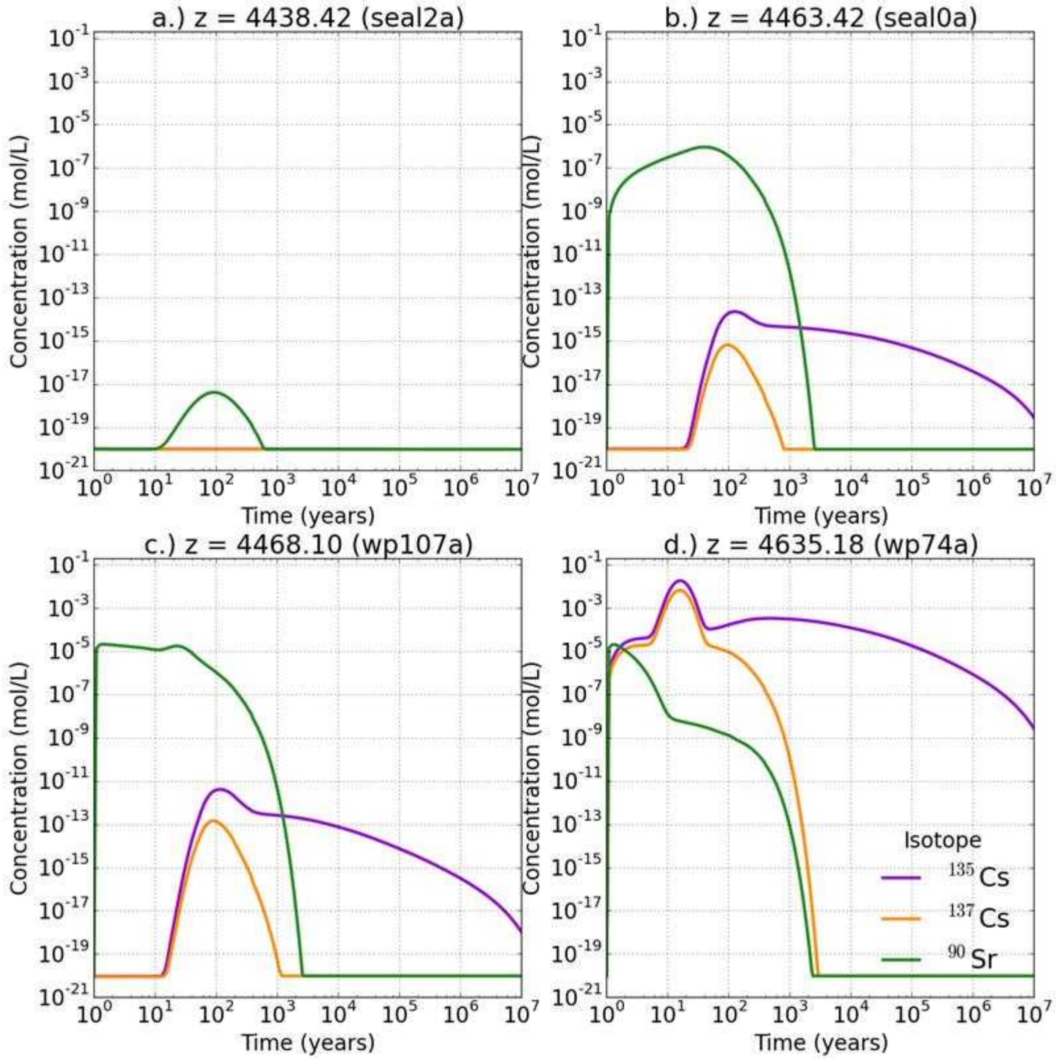


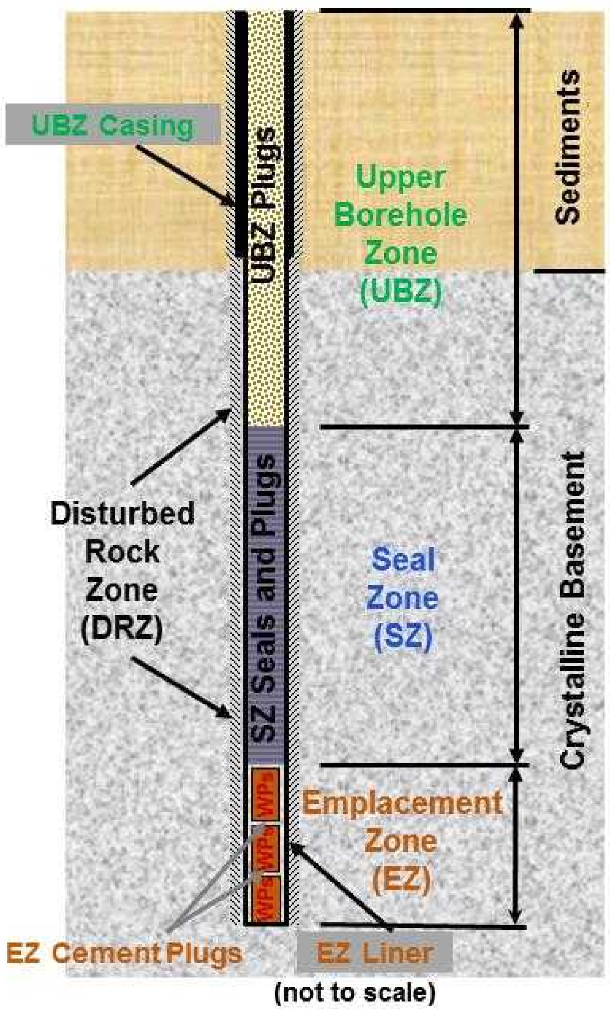


(Freeze et al. 2016) SAND2016-10949R

Deep Borehole PA Models

- **No Radionuclide Release in 10^7 Years**

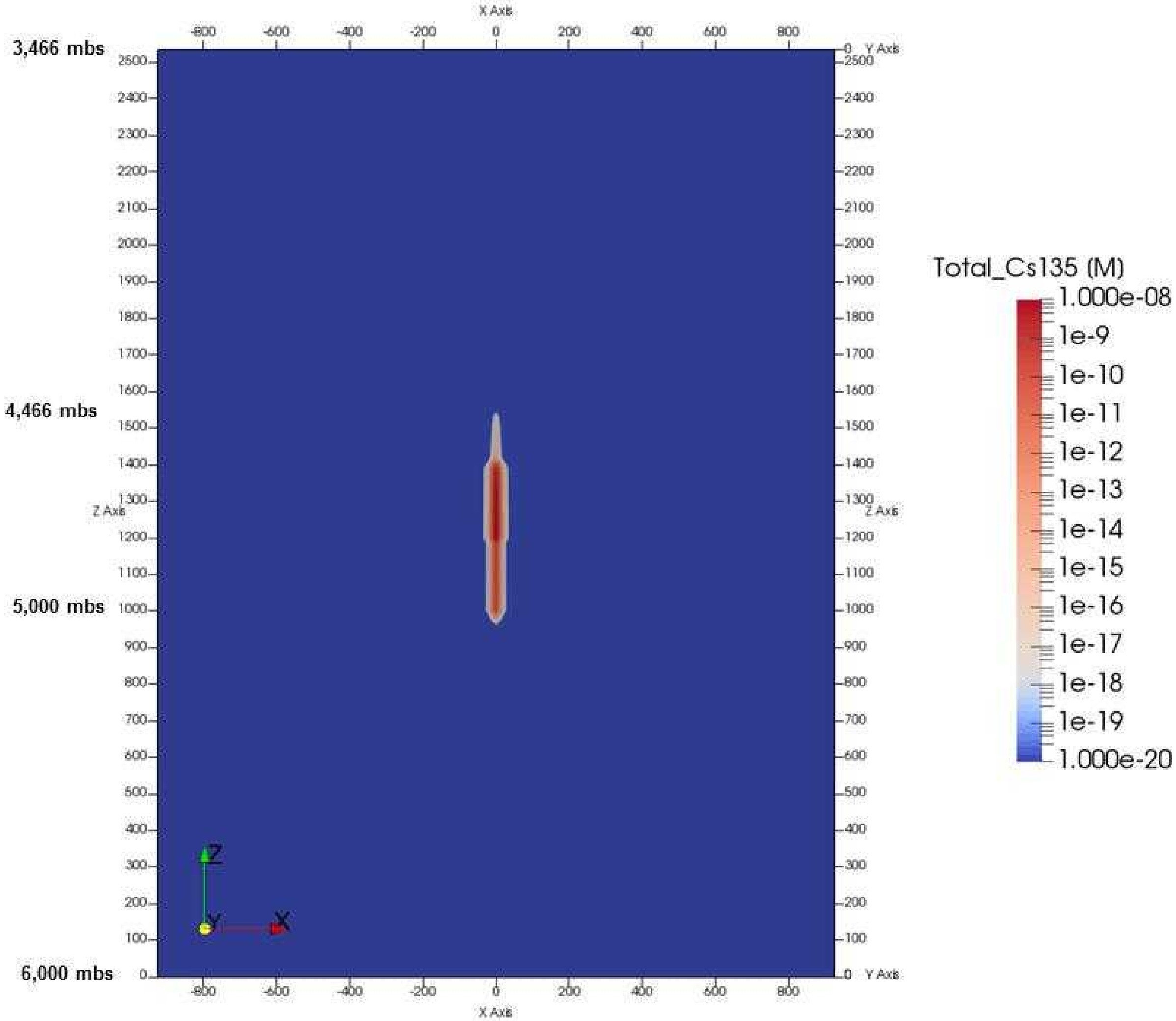


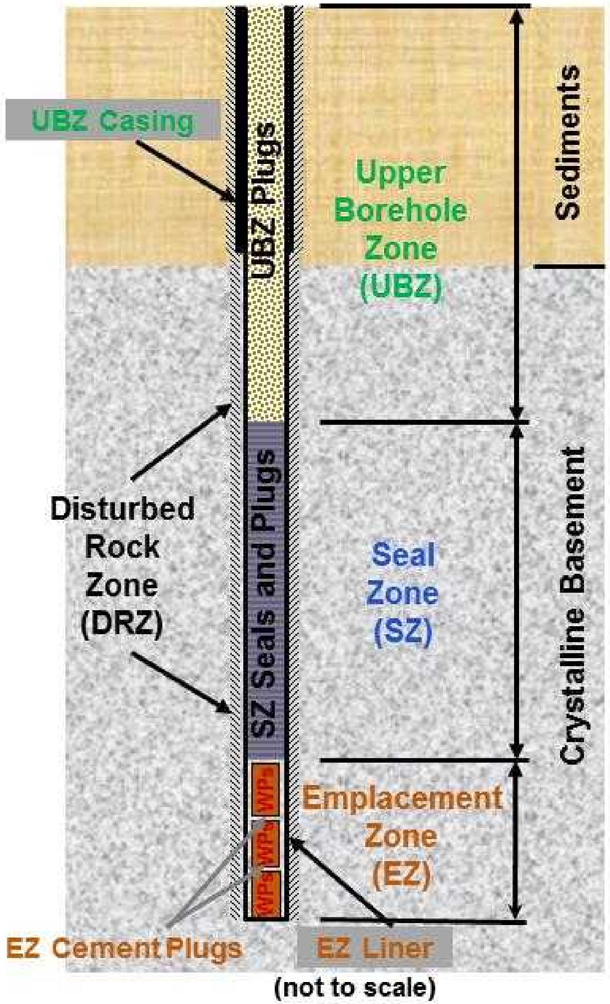


(Freeze et al. 2016) SAND2016-10949R

Deep Borehole PA Models

- **Cs distribution at 10^7 Years**





(Freeze et al. 2016) SAND2016-10949R

Deep Borehole Field Test

Deep Borehole Field Test (DBFT)

Sandia National Laboratories

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

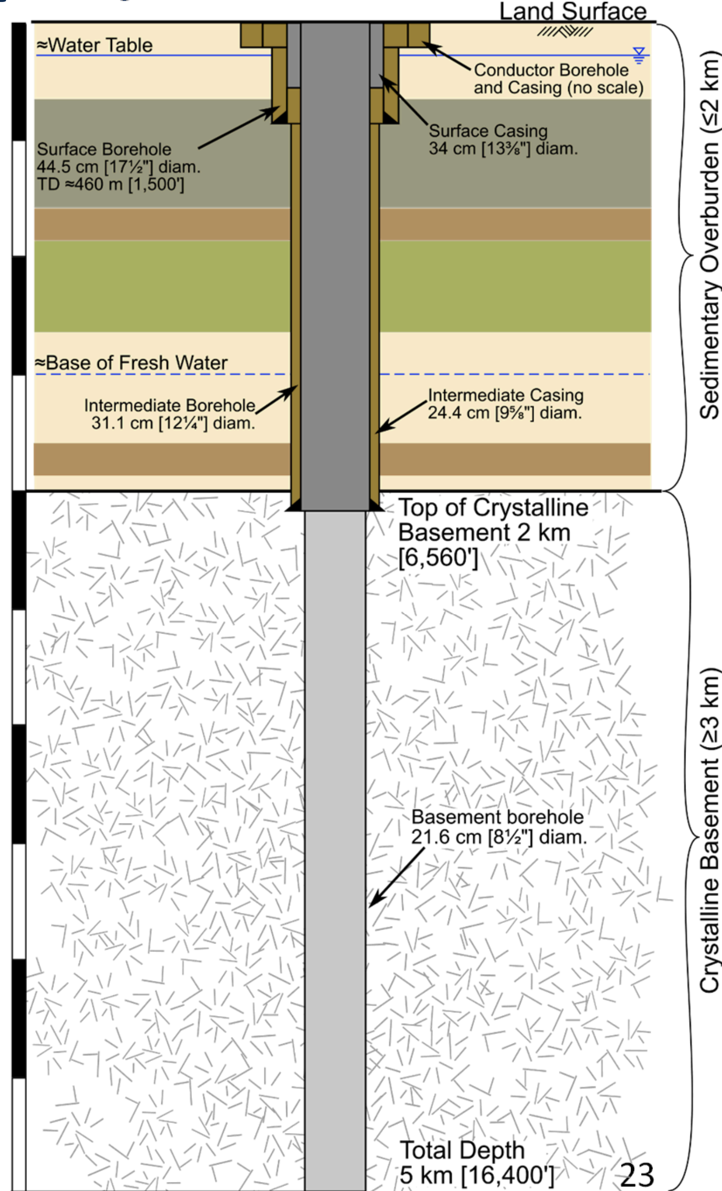
- **Prove Ability to:**
  - **Drill deep, wide, straight borehole safely (CB + FTB)**
  - **Characterize basement (CB)**
  - **Test formations in situ (CB)**
  - **Collect geochemical profiles (CB)**
  - **Emplace/retrieve test packages (FTB)**

Characterization Borehole (CB)

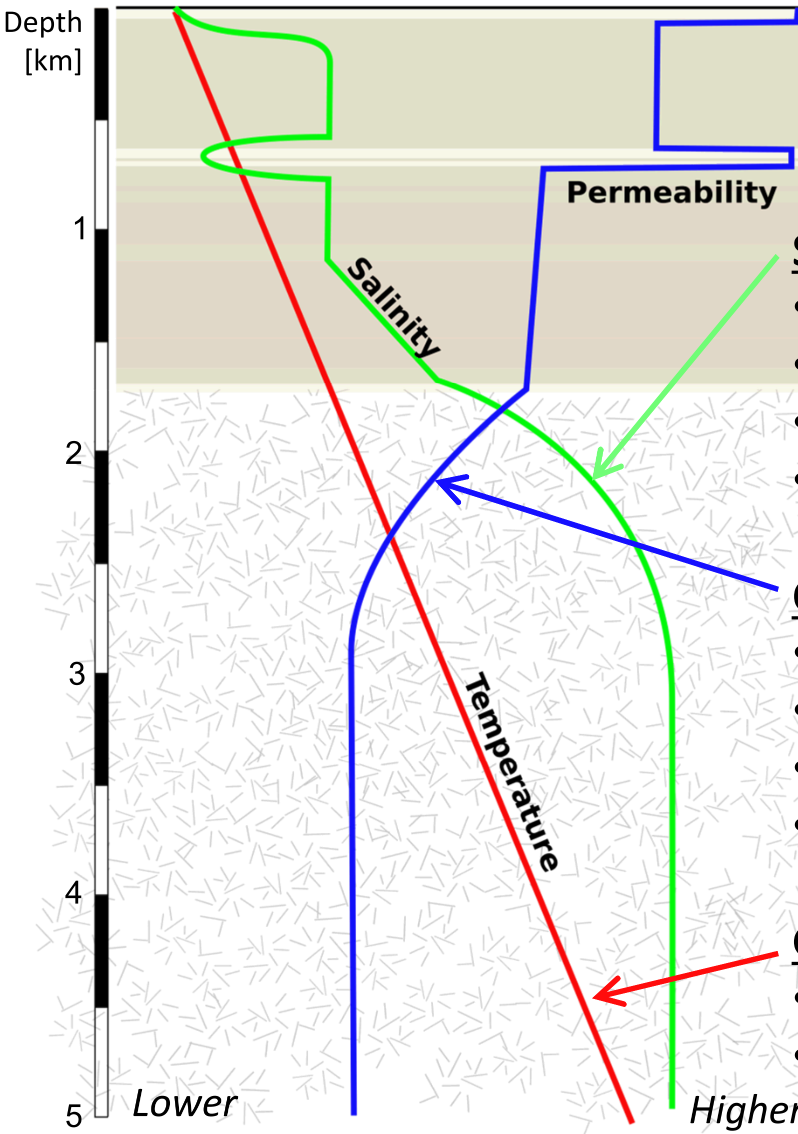
- **Medium-Diameter Borehole**
  - **Within current drilling experience**
- **Drill/Case Sedimentary Section**
  - **Minimal testing (not DBFT focus)**
- **Drill Bedrock Section**
  - **Core (5%) and sample bedrock**
- **Testing/Sampling After Completion**
  - **Packer tool via work-over rig**
  - **At limits of current technology**

Borehole designed to maximize likelihood of good samples

(SNL 2016) SAND2016-9235R



Deep Borehole Conceptual Profiles



Sources of Salinity
- Evaporite dissolution
- H_2O-rock interactions
- Ancient seawater
- Fluid inclusions

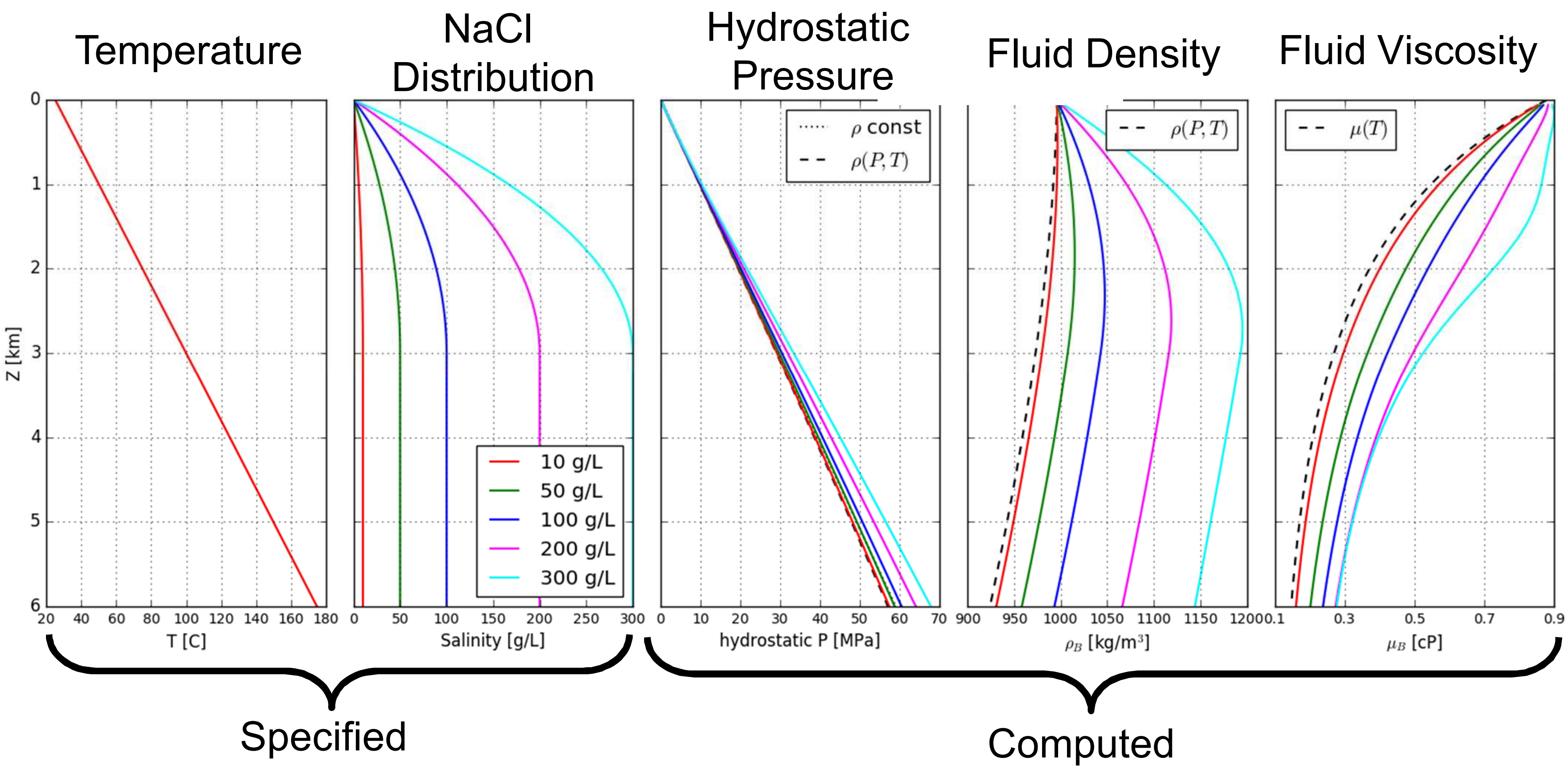
Controls on Permeability
- Increasing confining stress
- Fracture zones
- Mineral precipitation
- Overpressure → hydrofracture

Geothermal Gradient
- Radioactive decay
- Regional heat flux

Sedimentary Overburden ≤ 2 km

Crystalline Basement ≥ 3 km

Modeled Profiles

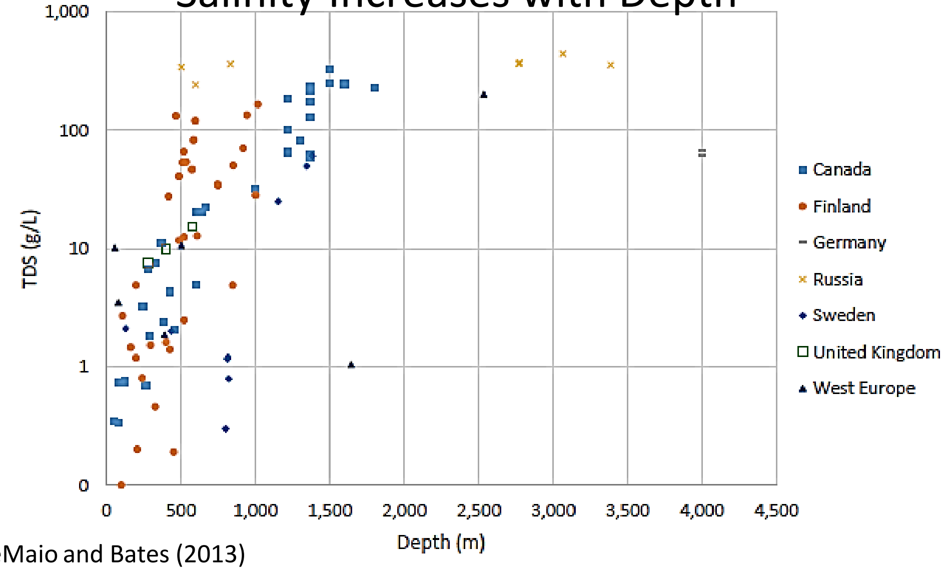


No-flow steady-state profiles

Density equation of state: Batzle and Wang (1992)

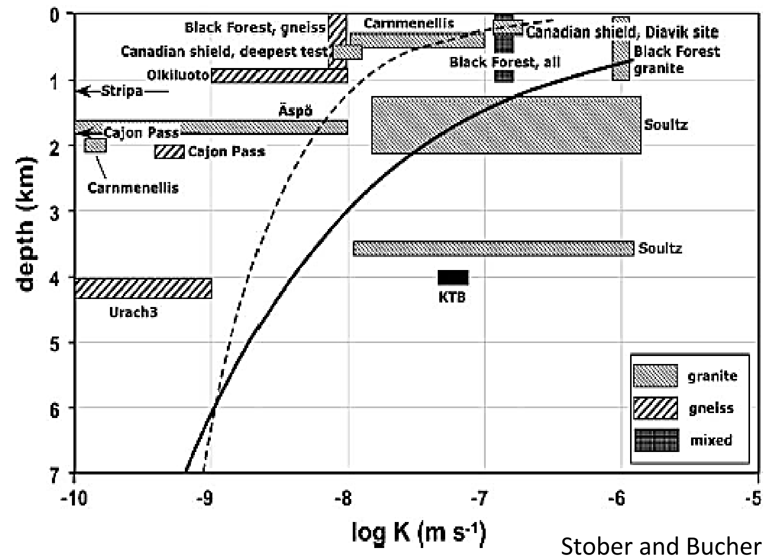
Observed Profiles

Salinity Increases with Depth

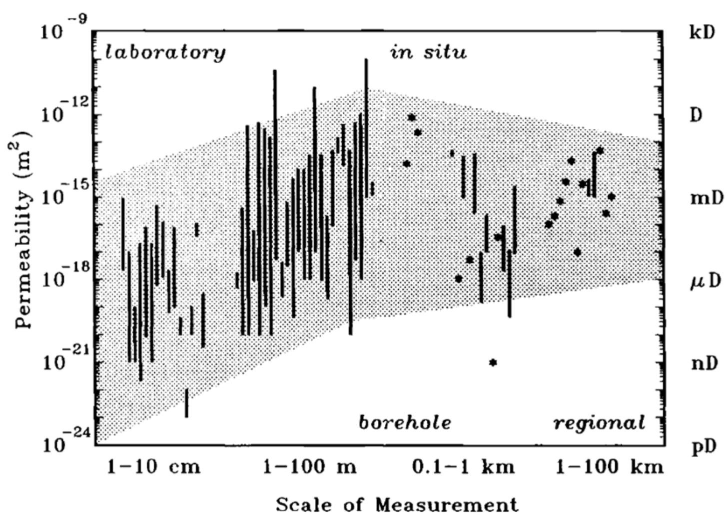


DeMaio and Bates (2013)

Bulk Permeability Decreases with Depth



Stober and Bucher (2007)

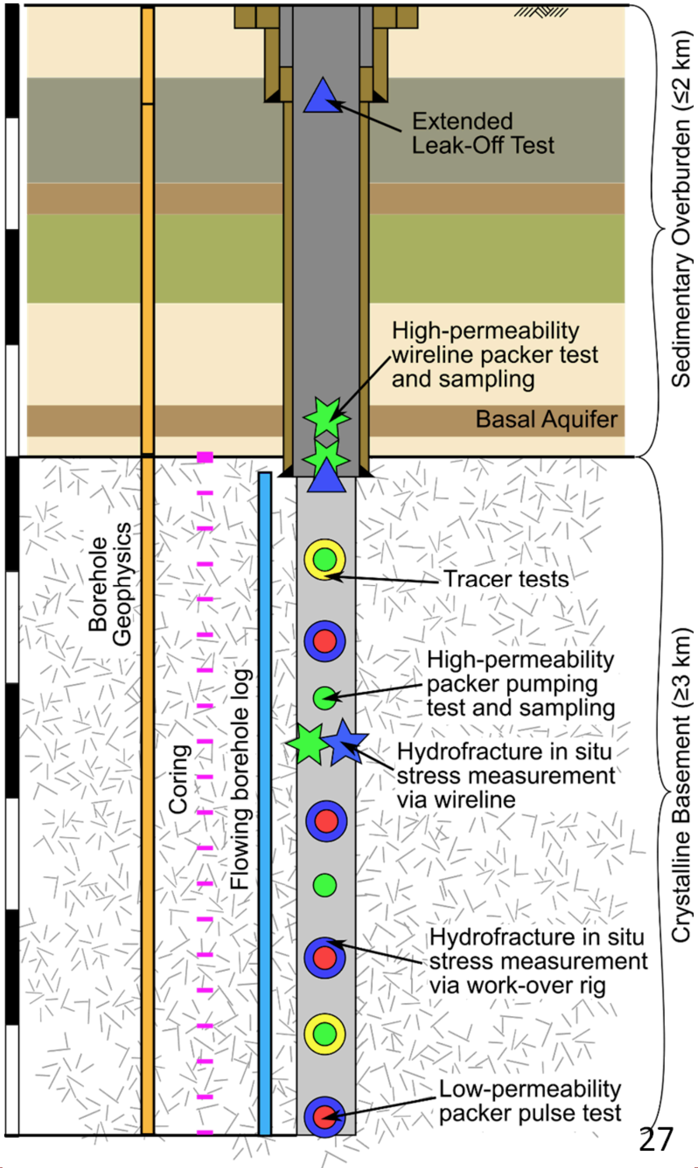


Bulk Permeability Increases with Scale

Clauser (1992)

Characterization Borehole (CB)

- **Borehole Geophysics**
- **Coring/Cuttings/Rock Flour**
  - **Mineralogy/petrology**
  - **Fluid samples from cores**
    - **Bulk composition (salinity; water/rock rxn)**
- **Sample-based Profiles**
  - **Fluid density/temperature/major ions**
  - **Pumped samples from high-*k* regions**
  - **Samples from cores in low-*k* regions**
- **Testing-Based Profiles**
  - **Static formation pressure**
  - **Formation hydraulic/transport properties**
  - ***In situ* stress (hydrofrac + breakouts)**

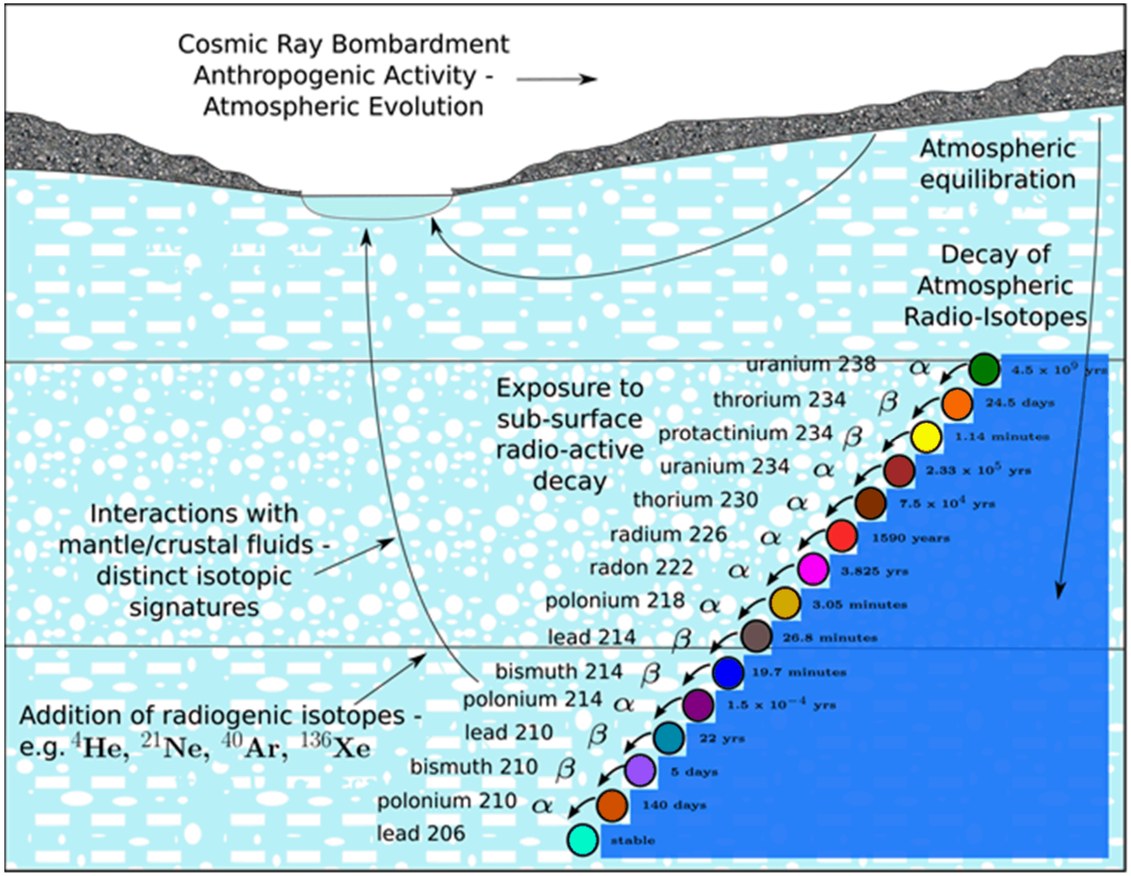


(SNL 2016) SAND2016-9235R

Environmental Tracers

- **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**
- **Long-Term Data**
  - **Water provenance**
  - **Flow mechanisms/isolation**

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



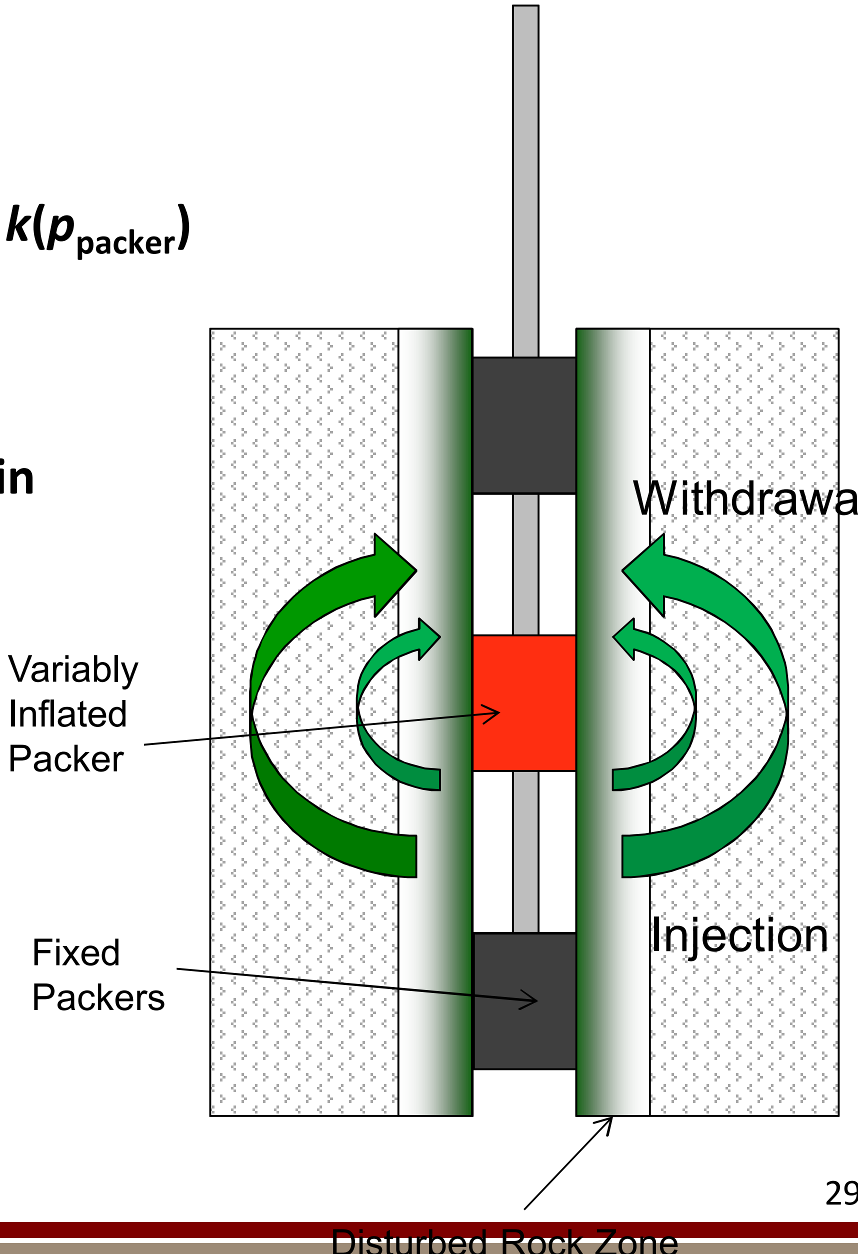
(After Kuhlman, 2015)

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

Repeatability between drill-stem testing, *packer & core samples?*

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**
  - **σh magnitude**
  - **Estimate stress tensor via**
  - **existing fractures**



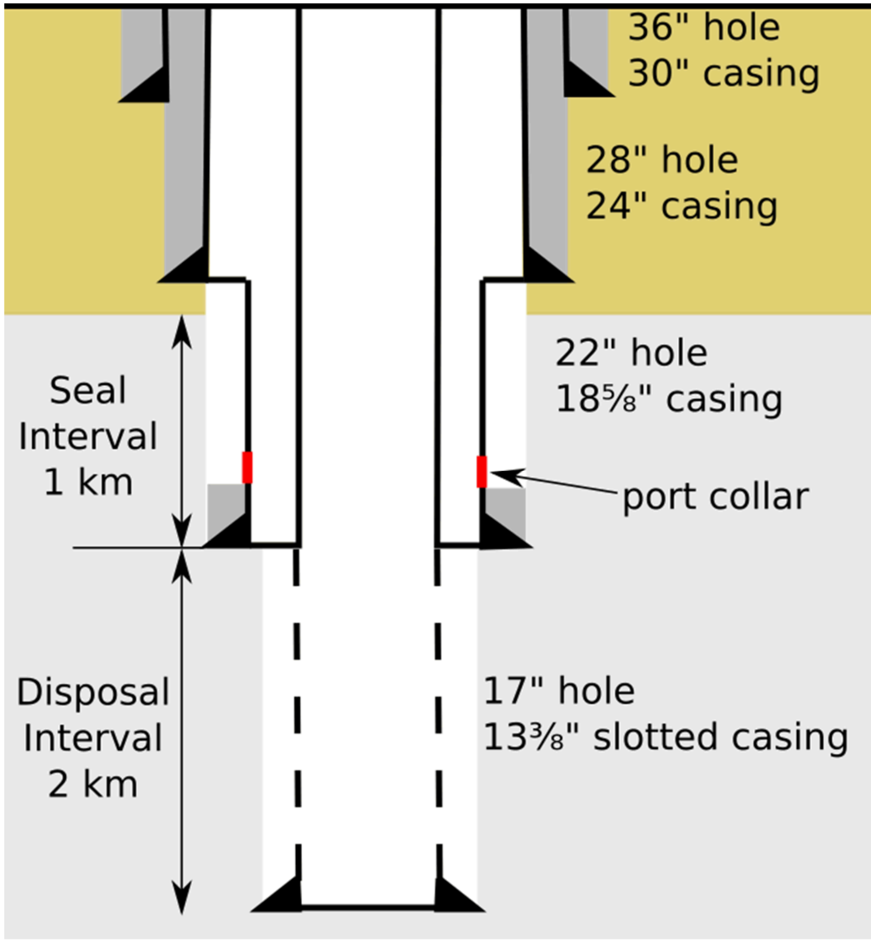
Characterization Differences

- **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

DBFT: 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**
  - Emplacing canisters
  - Removing canisters
  - Surface handling operations

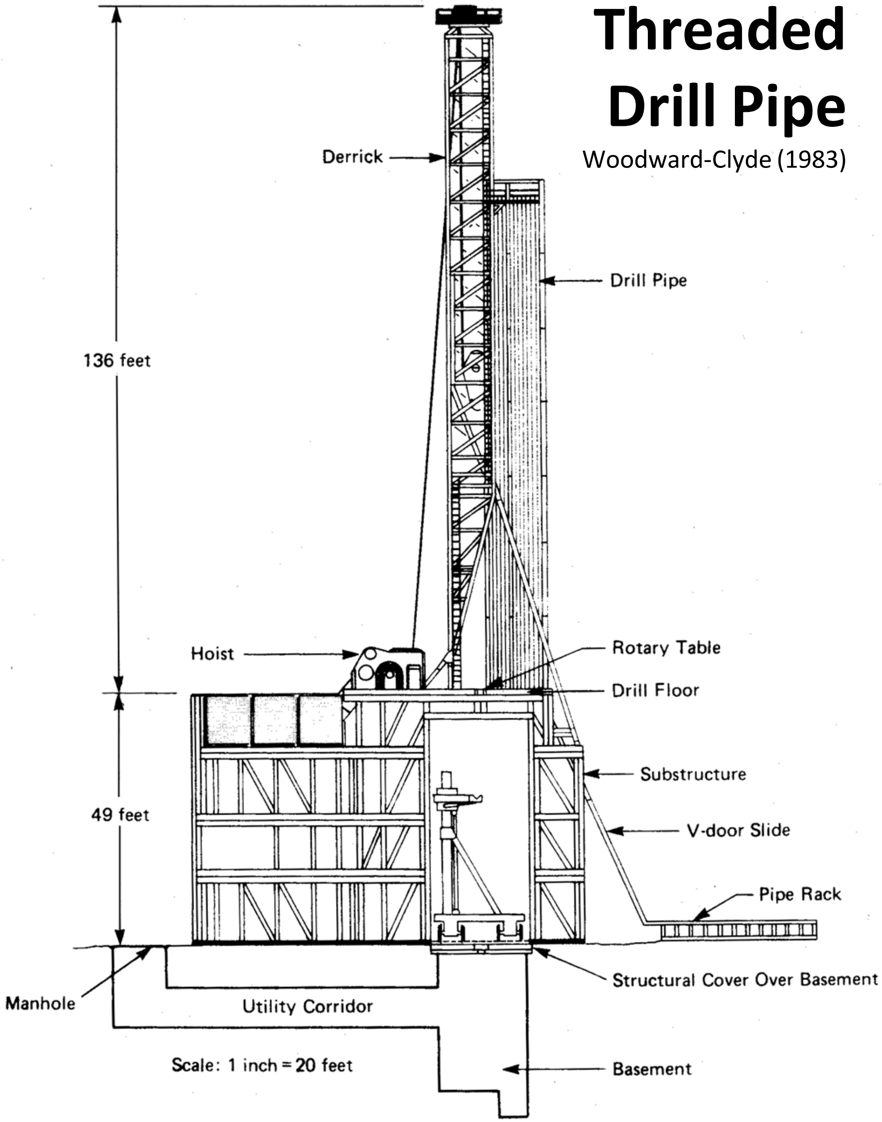


Borehole designed to maximize emplacement safety

FTB: Emplacement Methods

Threaded Drill Pipe

Woodward-Clyde (1983)



Coiled Tubing

Wireline

Summary

- **Deep Borehole Disposal Concept**
  - **Robust isolation from biosphere**
  - **Seals 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 system (CB)**
    - **Emplace/retrieve test packages (FTB)**

SAND2010-6048