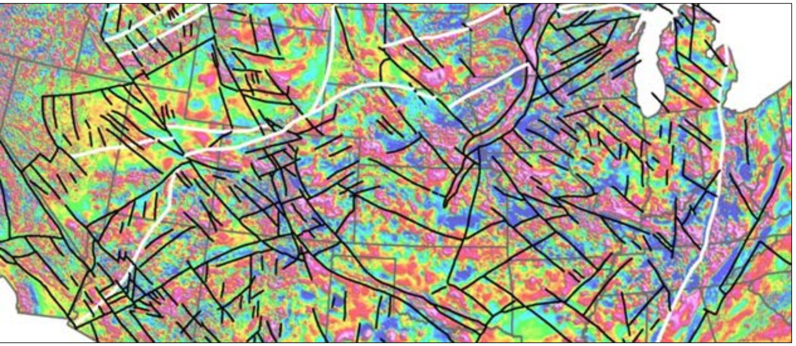
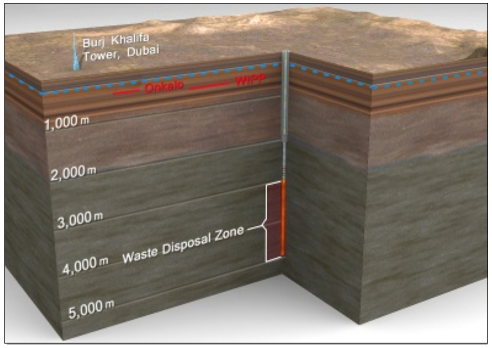
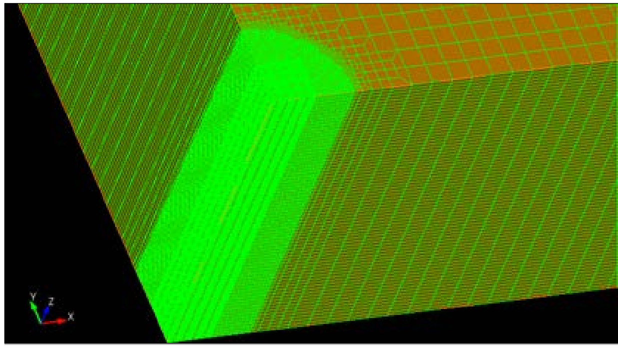
Exceptional service in the national interest







Deep Borehole: from Disposal Concept to Field Test

Kristopher L. Kuhlman

Sandia National Laboratories

Applied System Analysis & Research Department

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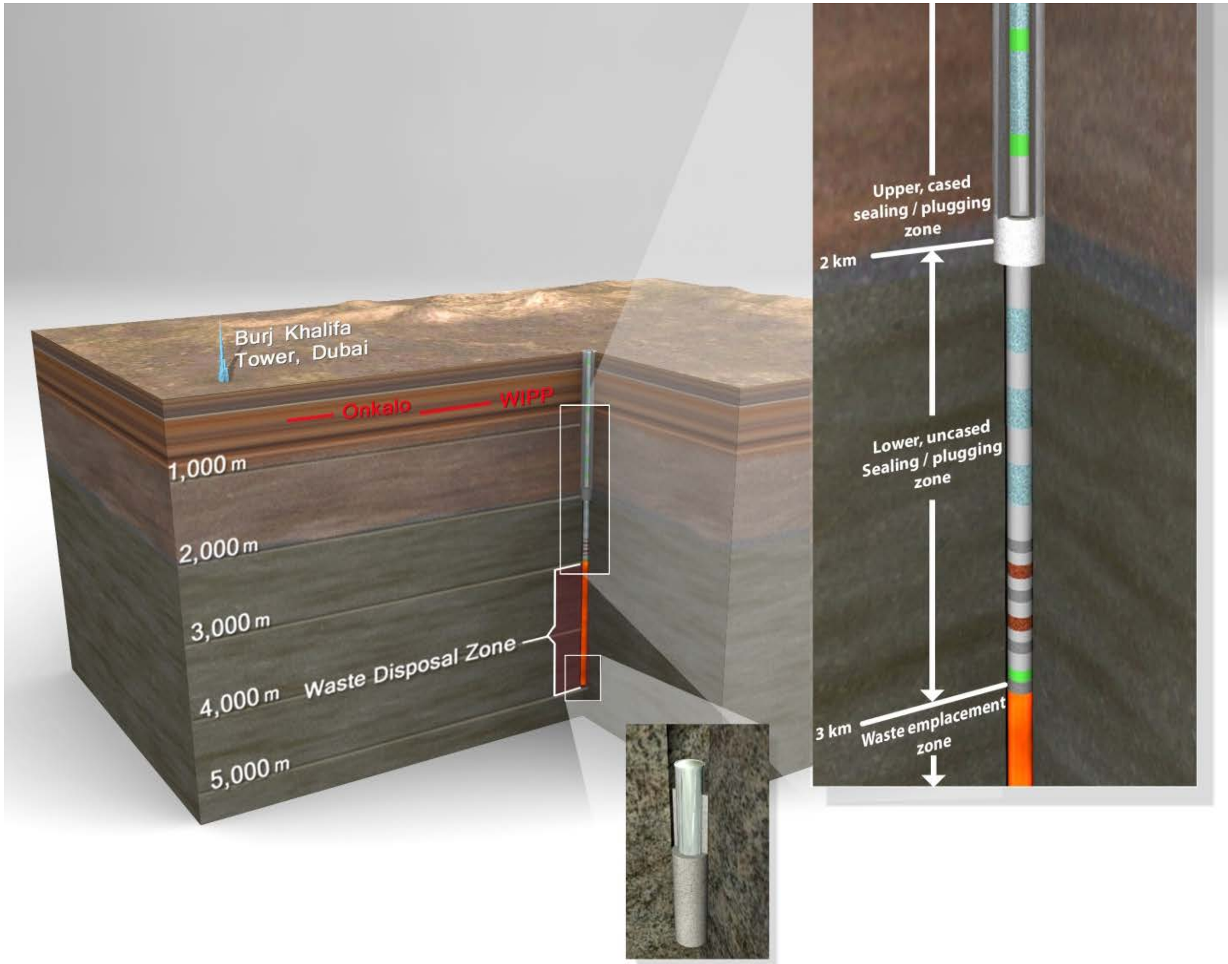
Deep Borehole Disposal Concept

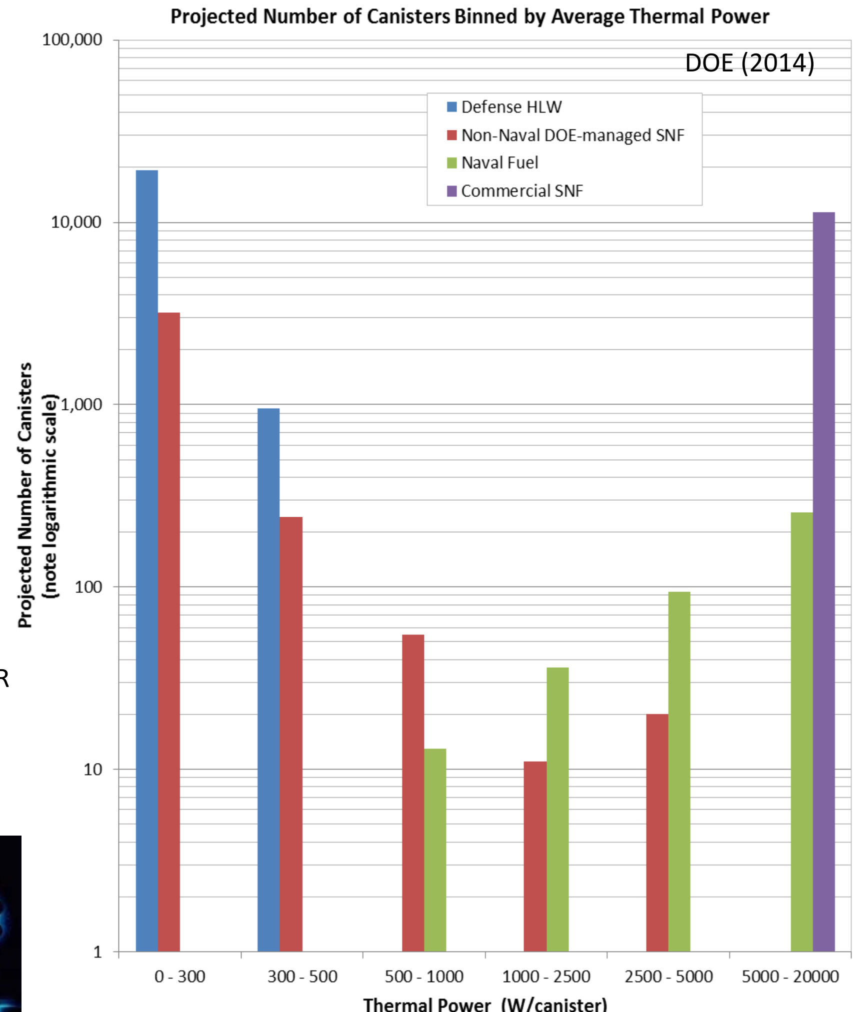
- ≤17" hole to 5 km
- Straightforward Construction
- 10× Geologic Isolation of Mined Repository
- Conditions at Depth
  - Low permeability
  - Stable density gradient
  - Reducing fluid chemistry



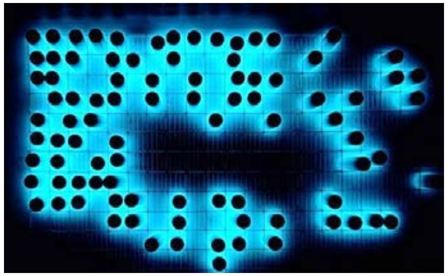
Radioactive Waste Forms

- **Waste Properties**
  - **Thermal output**
  - **Physical size**
  - **Waste total volume**
- **Primary Waste Forms**
  - **Commercial spent nuclear fuel**
  - **DOE-managed high-level waste**
    - **Tank waste converted to:**
      - **Borosilicate glass logs**
      - **Cs-137/Sr-90 capsules**

>200,000 PWR Assemblies [≈12” diam.]

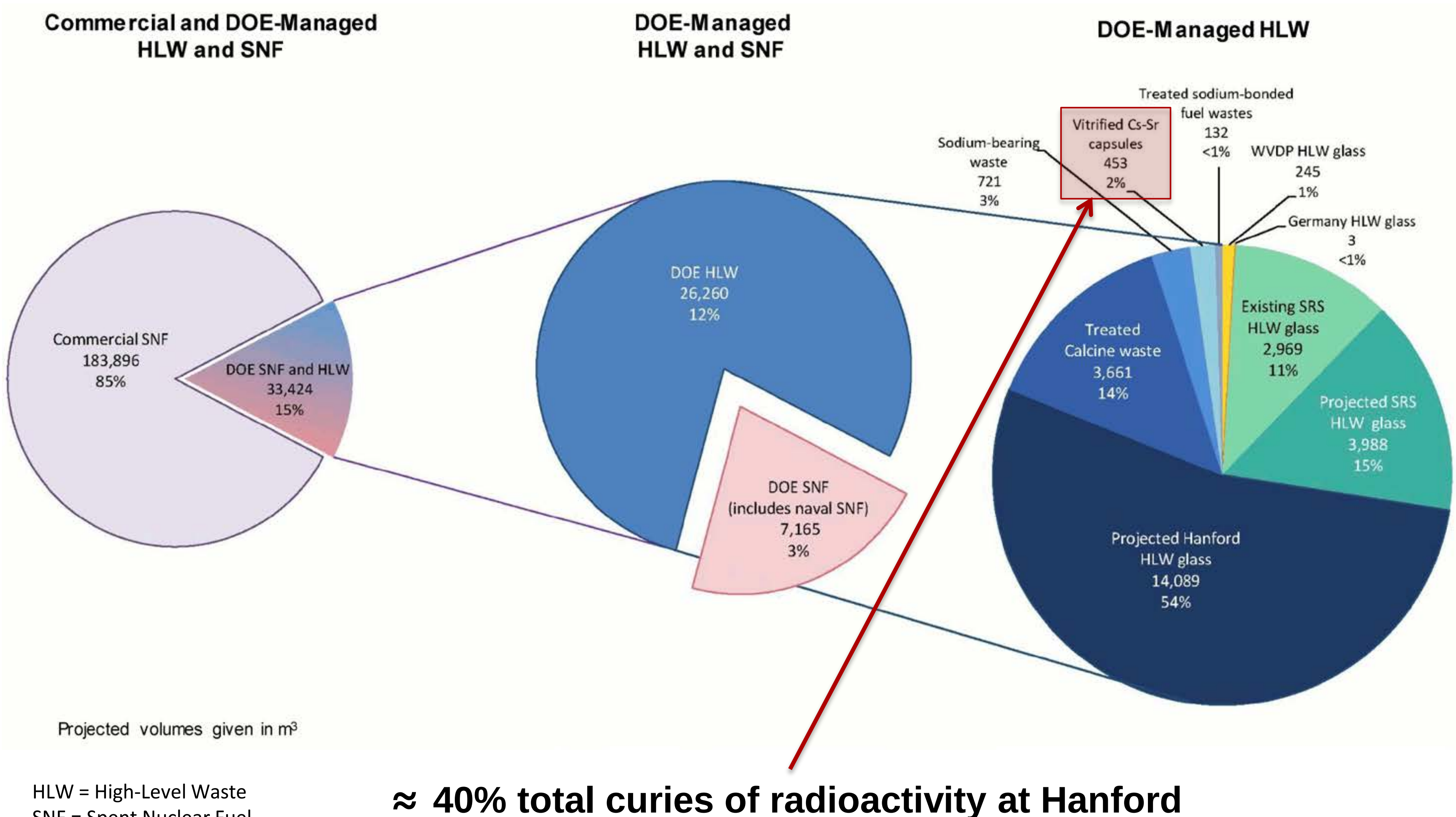


Hanford tank farm



2,000 Cs/Sr Capsules [≈3” diam.]

Radioactive Waste Volumes



HLW = High-Level Waste
SNF = Spent Nuclear Fuel

Recent Motivating Events

- **Jan. 2012: Blue Ribbon Commission Report**
- **Jan. 2013: US Department of Energy (DOE) Strategy**

  Strategy for Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste
- **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**
- **Oct. 2014: Deep Borehole Request for Information (RFI)**

  Seeking Interest in siting a Deep Borehole Field Test
- **March 24, 2015: Obama Memo**

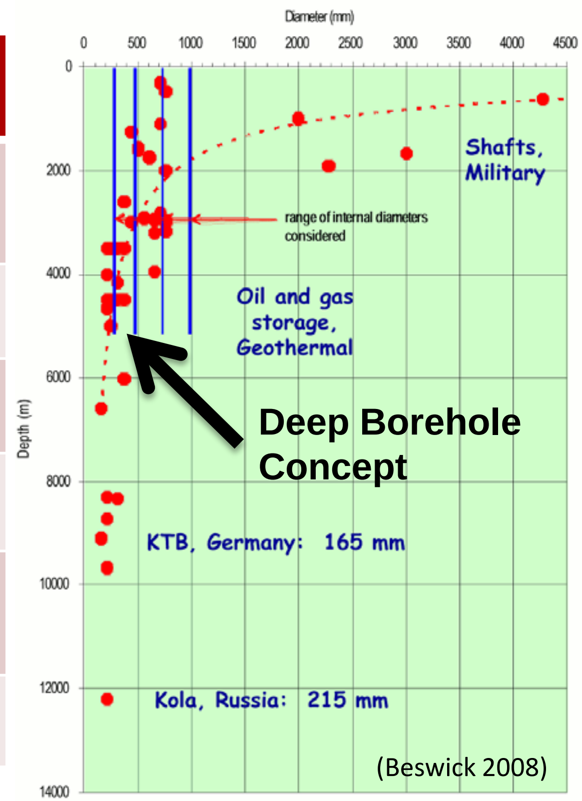
  "In accordance with the [Nuclear Waste Policy] Act, I find the development of a repository for the disposal of high-level radioactive waste resulting from atomic energy defense activities only is required"
- **March 2015: Deep Borehole Draft Request for Proposals (RFP)**

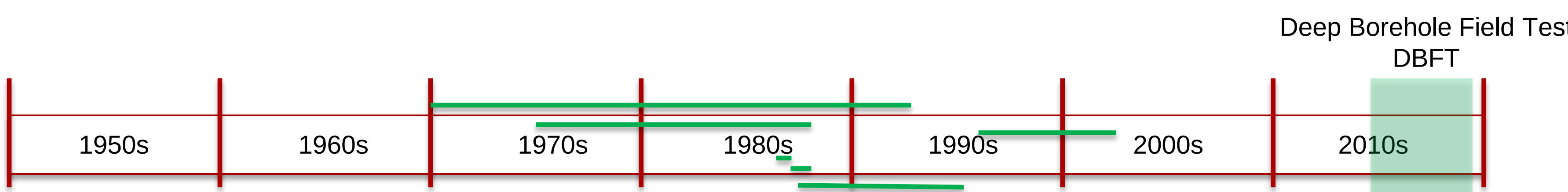
  Seeking Site, Drilling & Management Proposals for Deep Borehole Field Test

History

Deep Continental Drilling

Name	Location	Years	Depth [km]	Diam. [in]	Purpose
Kola SG-3	NW USSR	1970-1992	12.2	8½	Geologic Exploration + Technology Development
Fenton Hill (3)	New Mexico	1975-1987	3, 4.2, 4.6	8¾, 9⅞	Enhanced Geothermal
Gravberg	Central Sweden	1986-1987	6.6	6½	Gas Wildcat in Siljan Impact Structure
Cajon Pass	California	1987-1988	3.5	6¼	Geomechanics near San Andreas Fault
KTB (2)	SE Germany	1987-1994	4, 9.1	6, 6½	Geologic Exploration + Technology Development
Soultz-sous-Forêts GPK (3)	NE France	1995-2003	5.1, 5.1, 5.3	9⅝	Enhanced Geothermal





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**

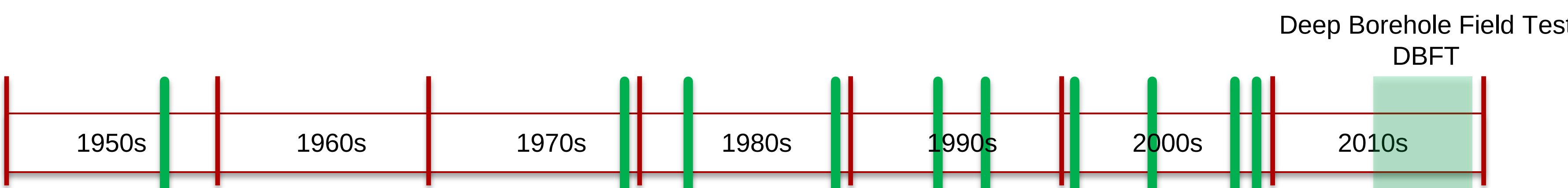
  A Review of the Deep Borehole Disposal Concept

- **Beswick (2008)**

  Status of Technology for Deep Borehole Disposal

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

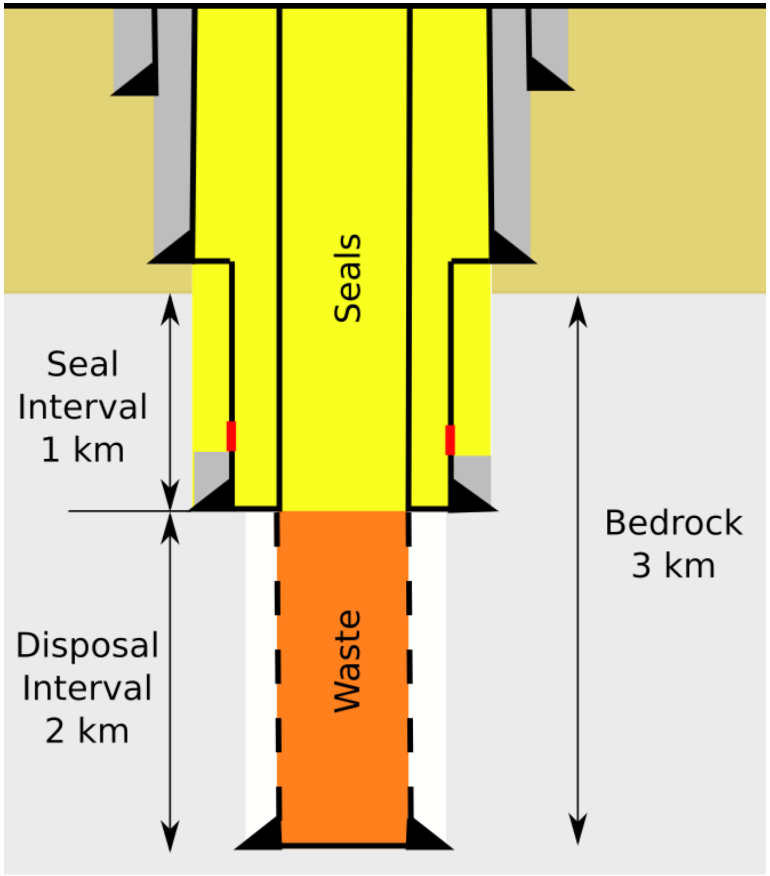
  Deep Borehole Disposal of High-Level Radioactive Waste



Deep Borehole Disposal Concept

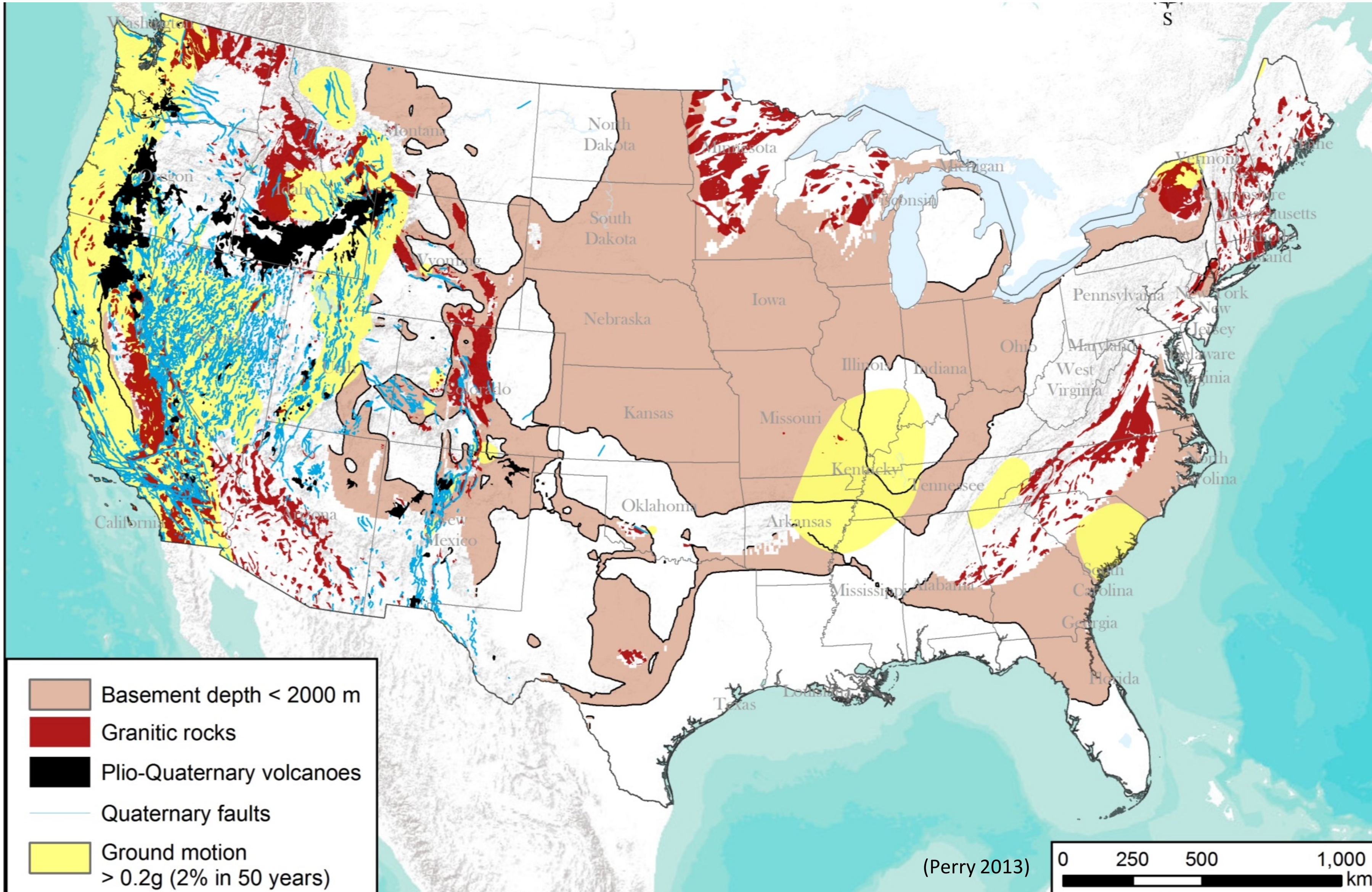
Deep Borehole Concept & Field Test

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

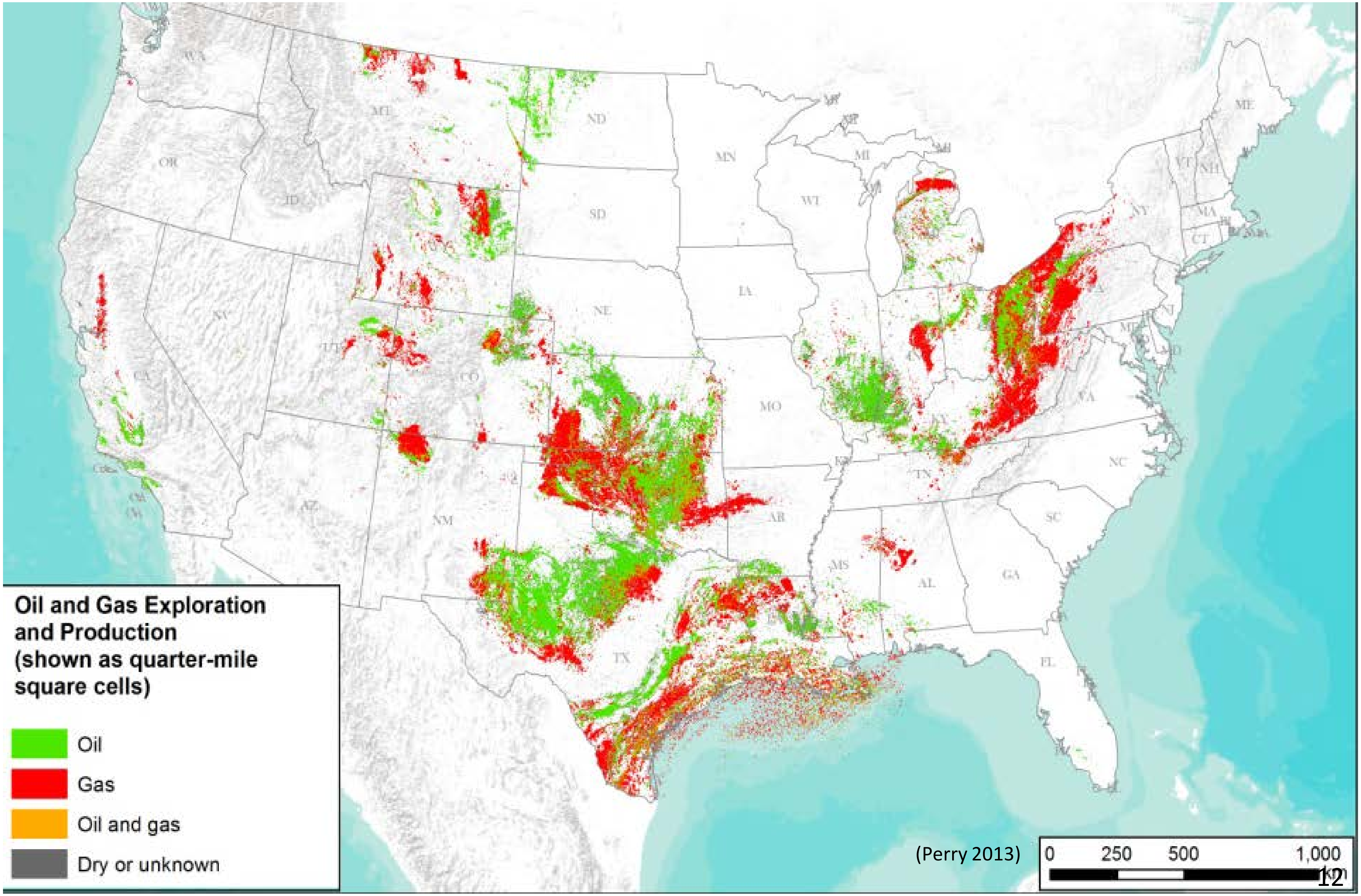


- **Deep Borehole Field Test (DBFT)**
  - **Department of Energy – Office of Nuclear Energy (DOE-NE)**
  - **FY 2015-2019 project**
  - **Two boreholes to 5 km TD**
  - **Science and engineering demonstration**

Siting: Bedrock + Hazards

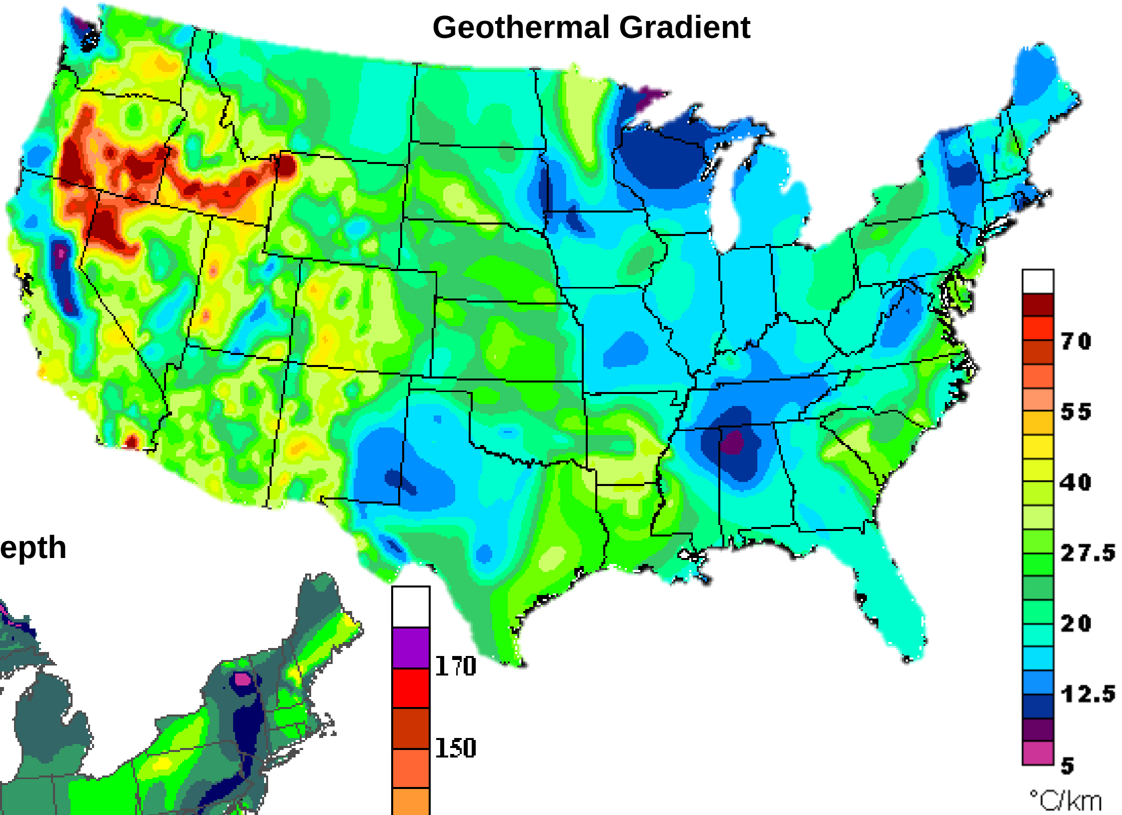


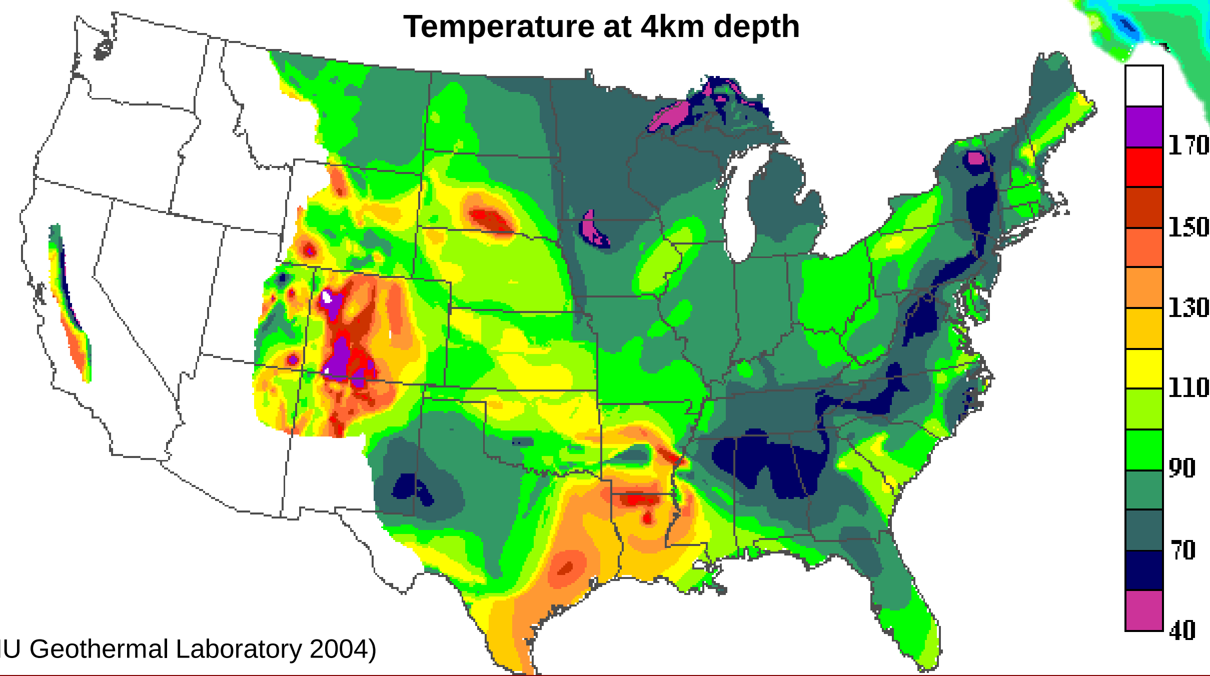
Siting: Oil/Gas Activity



(Perry 2013)

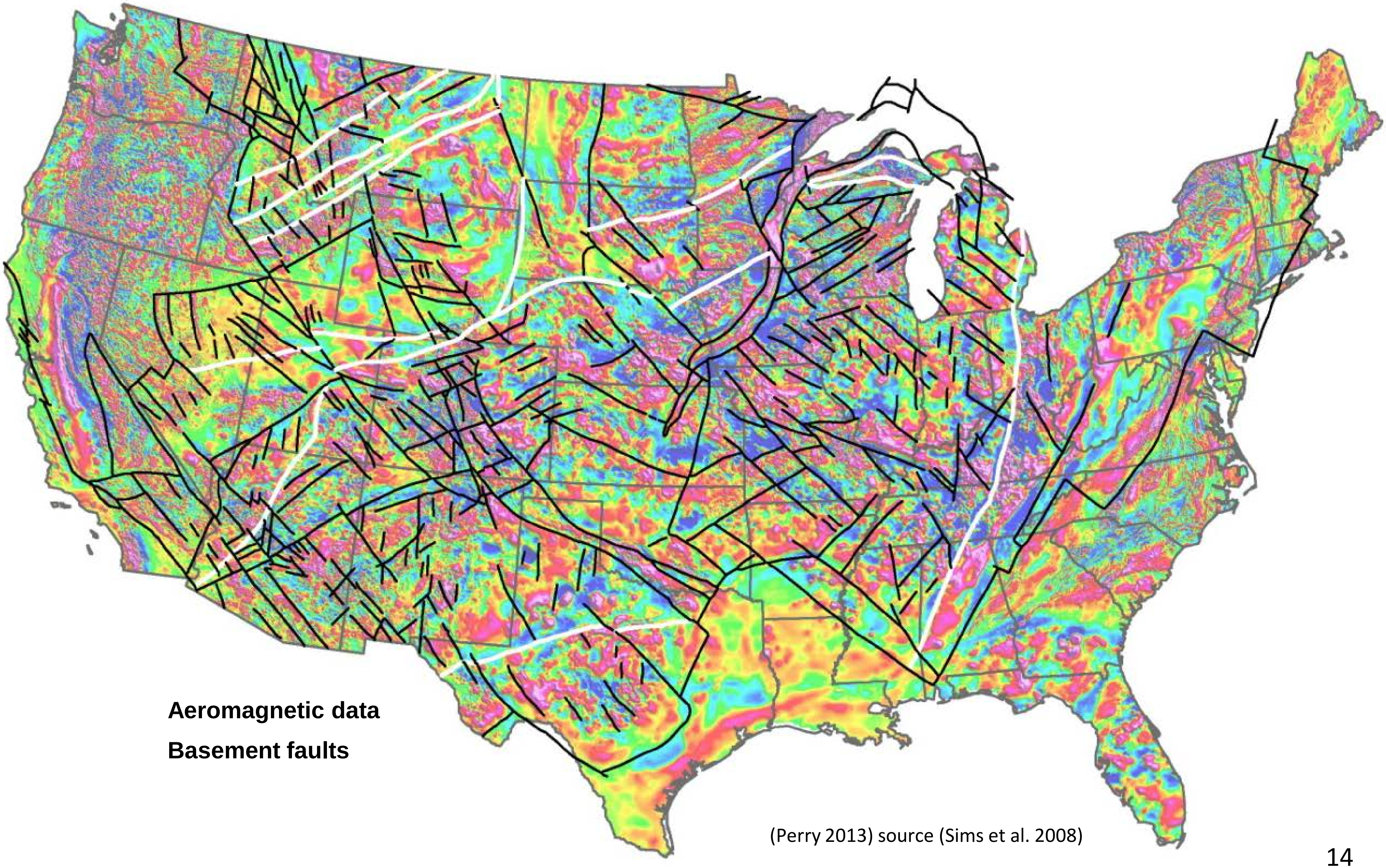
Siting: Geothermal





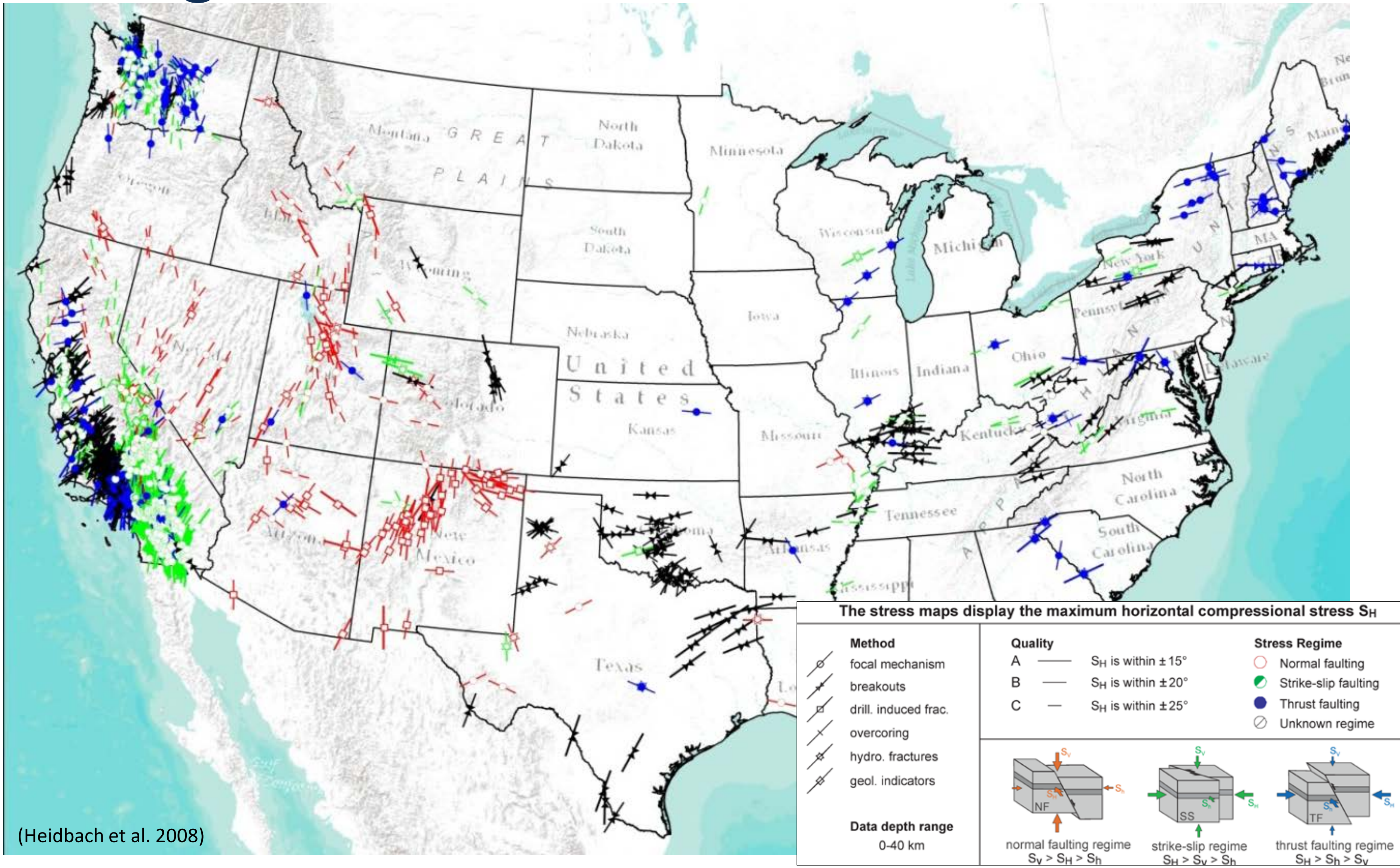
(SMU Geothermal Laboratory 2004)

Siting: Basement Structure



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

Siting: Stress State



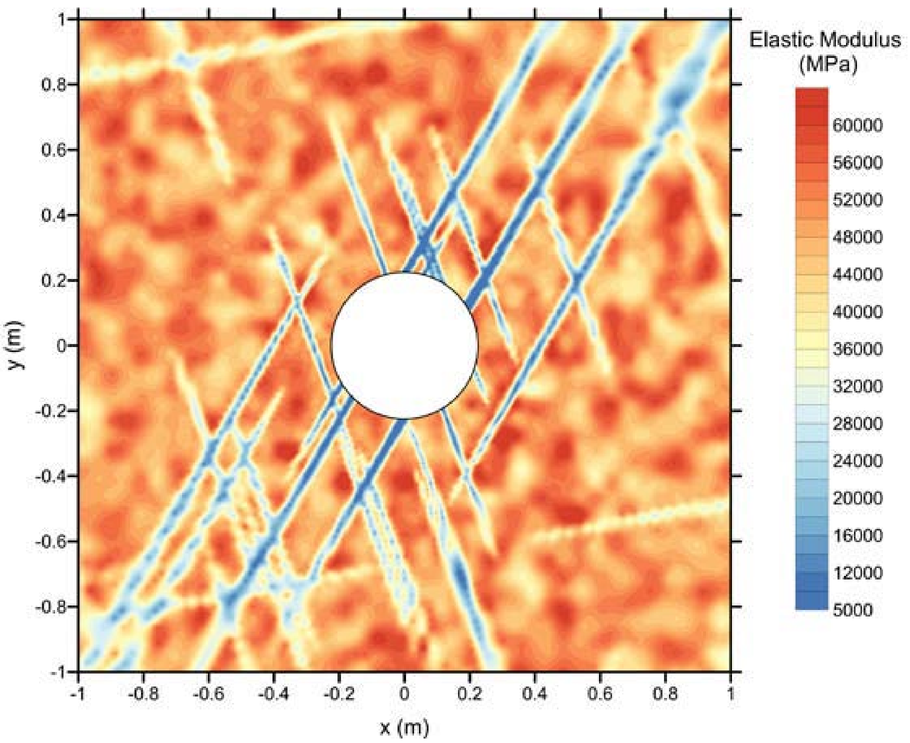
(Heidbach et al. 2008)

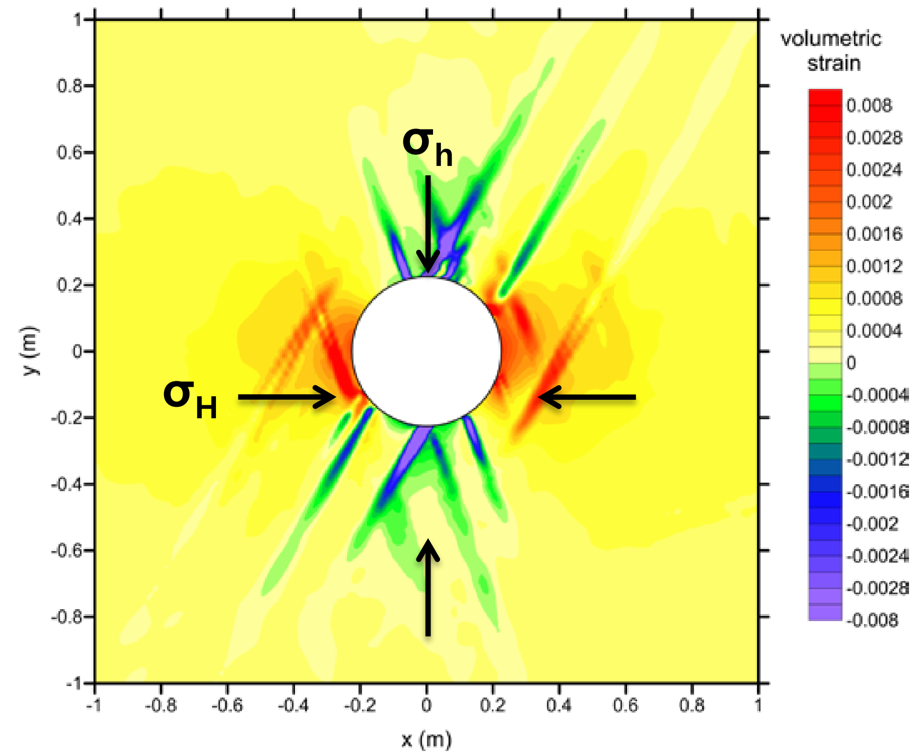
Deep Borehole Preliminary Modeling

Deep Borehole TM Model

- Thermal-Mechanical Model of Borehole Response @ 5 years
- Borehole Heating + Stress → Host Rock in Compression Along σ_H
- Fractures in σ_h Direction Still Extensional

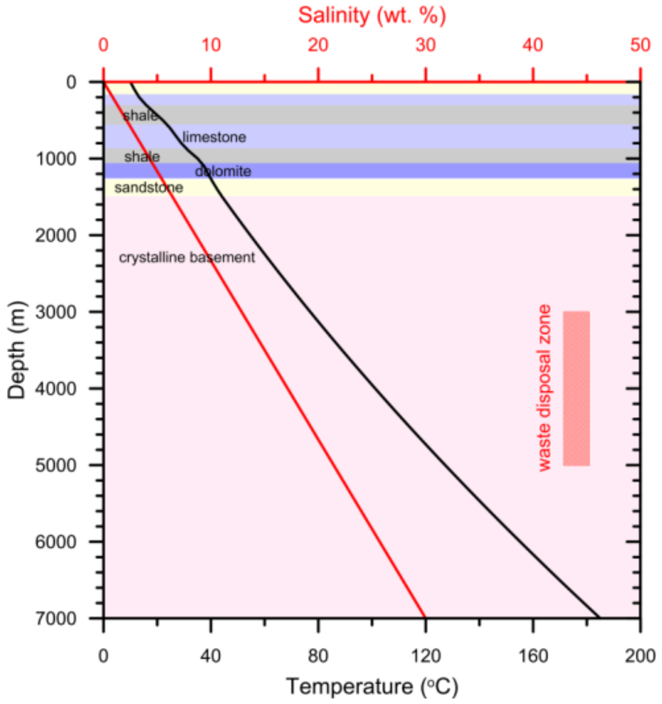
(Arnold 2011) SAND2011-6517C

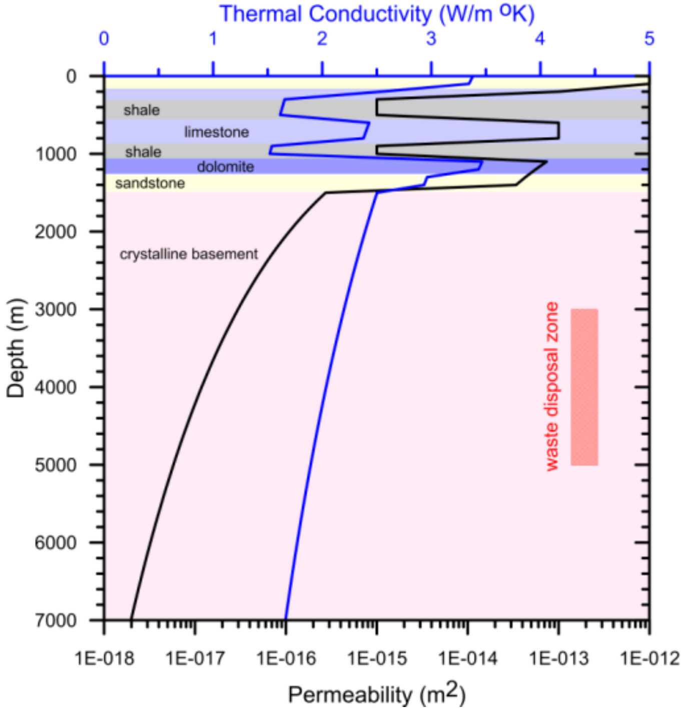


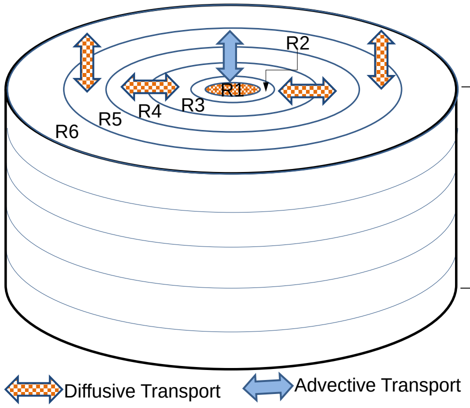


Deep Borehole PA Models

- **Performance Assessment (PA) Modeling**
  - **Reference geology and borehole design**
  - **Assume grid of boreholes for used nuclear fuel**
  - **Assess post-closure safety**
  - **Thermal-hydrological-chemical processes simulated with FEHM**



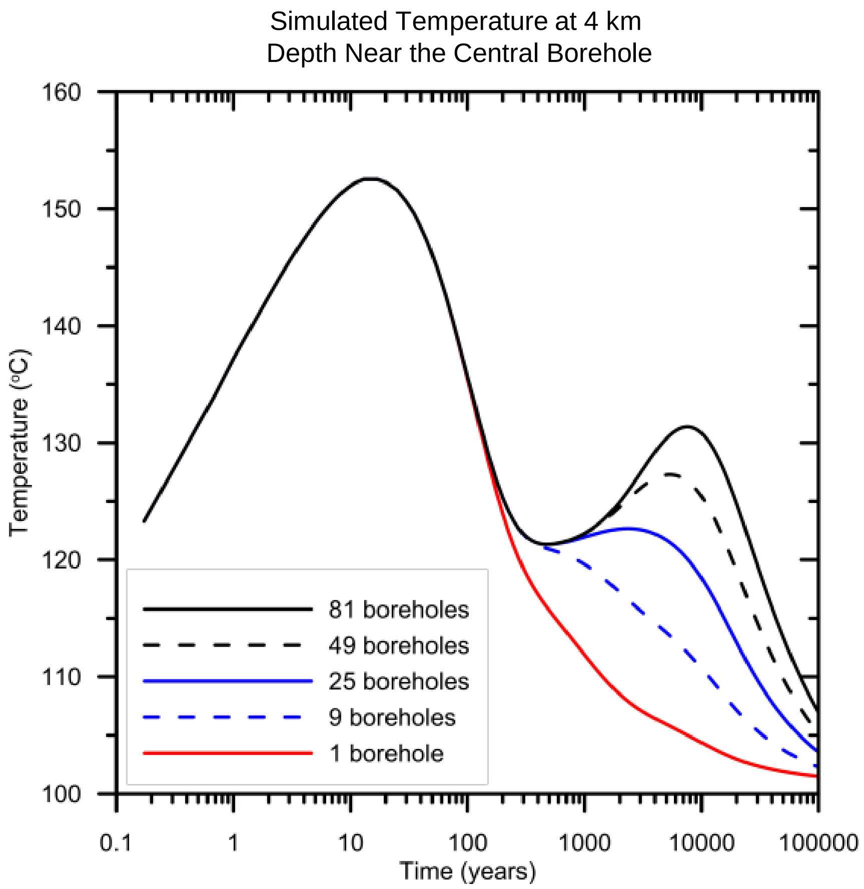


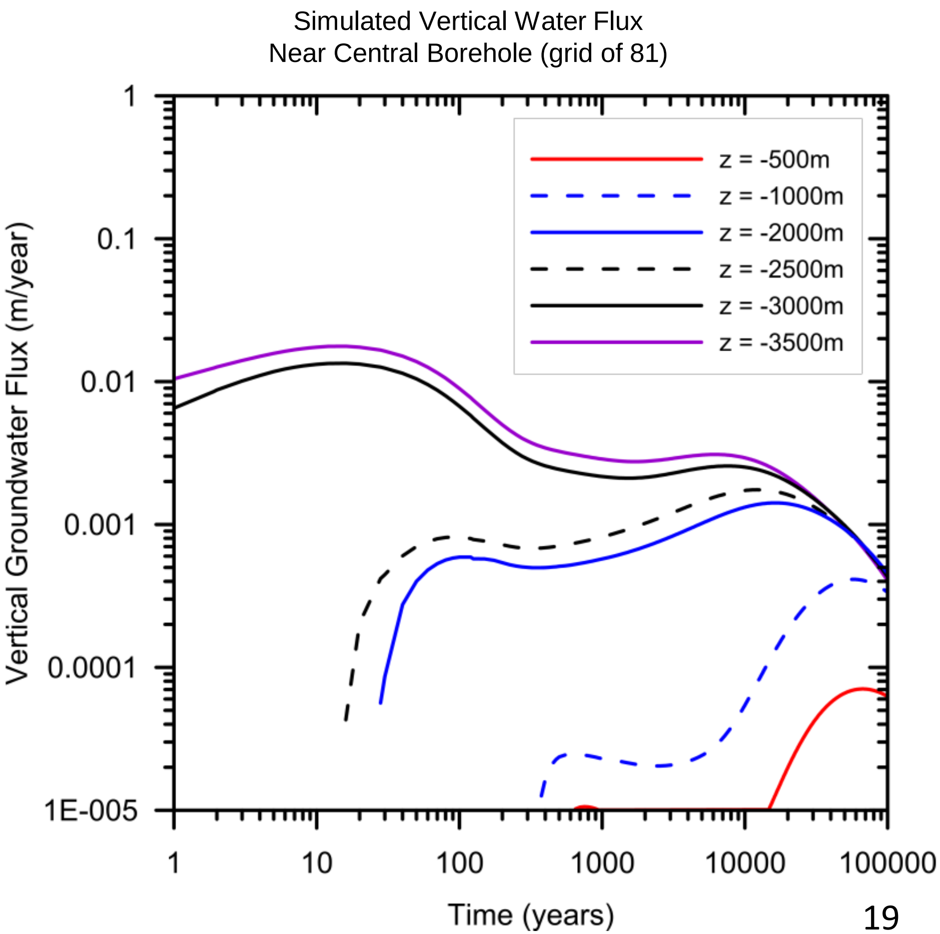


(Arnold et al. 2013) SAND2013-9490P

Deep Borehole PA Models

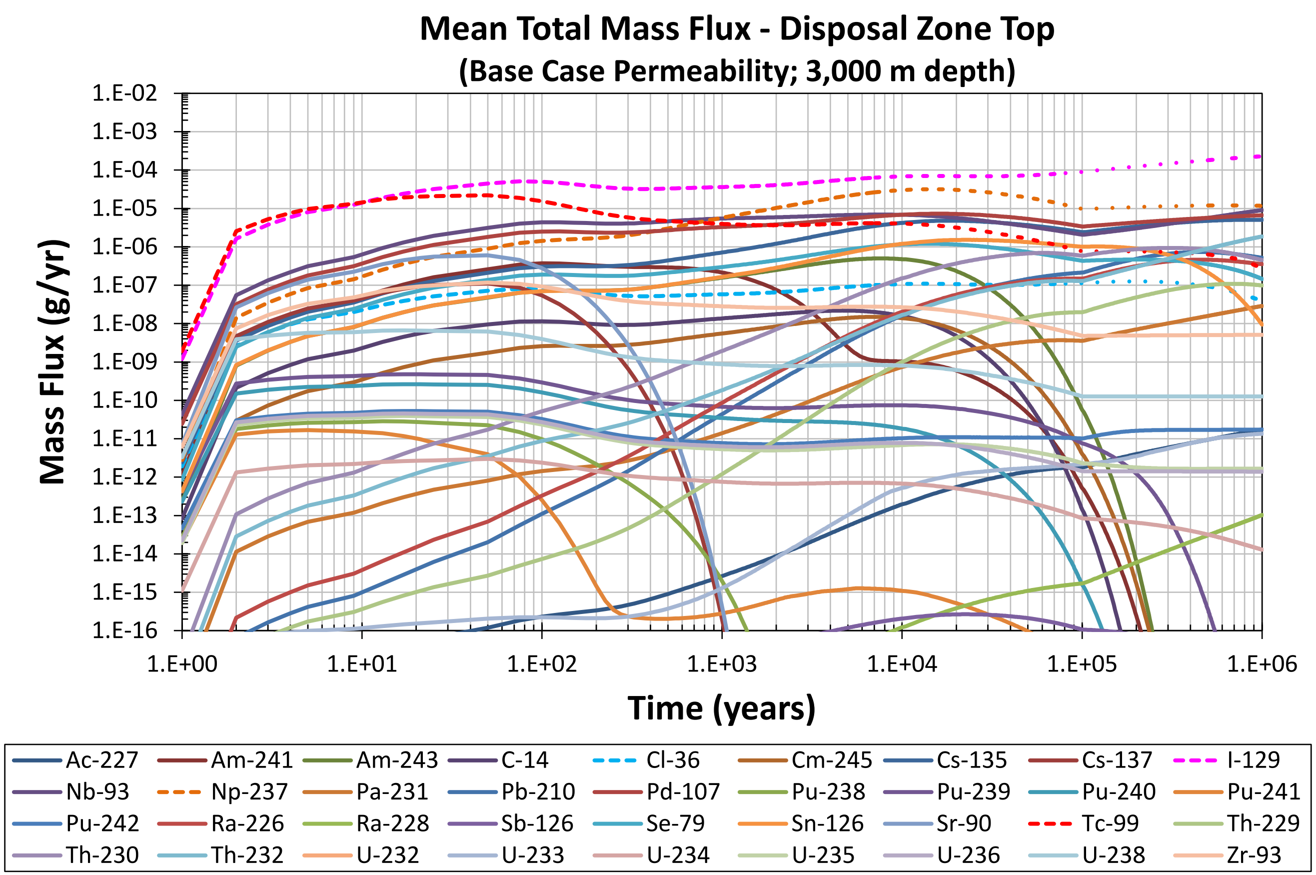
- **Short Thermal Perturbation**
- **Minimal Resulting Free Convection**

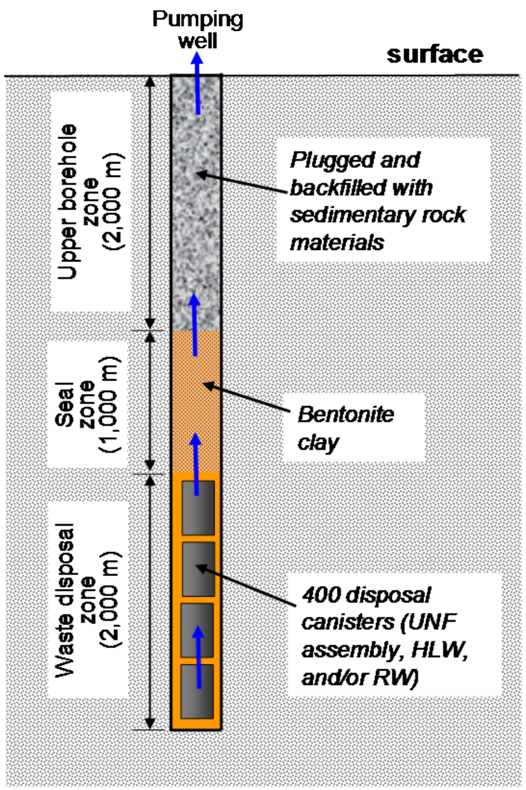




Deep Borehole PA Models

- **No Radionuclide Release in 10^6 Years**





(Arnold et al. 2013) SAND2013-9490P

Deep Borehole Field Test

Deep Borehole Field Test (DBFT)

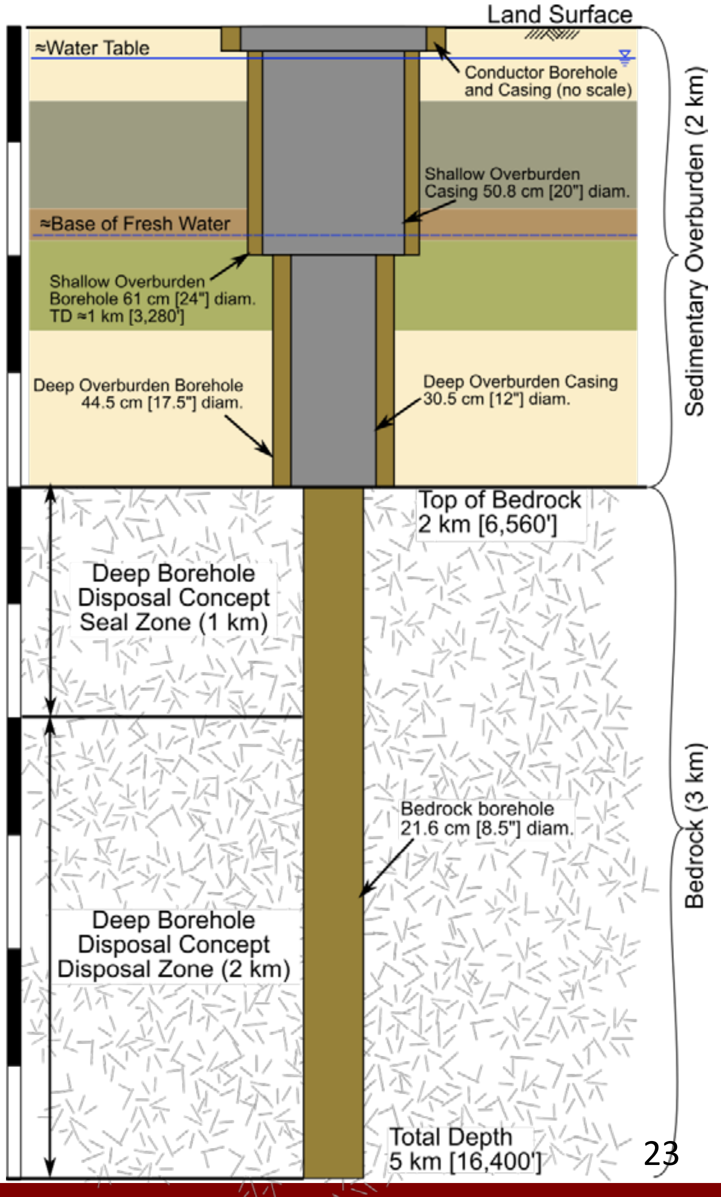
- **Drill Two 5-km Boreholes**
  - **Characterization Borehole (CB): 21.6 cm [8.5”] @ TD**
  - **Field Test Borehole (FTB): 43.2 cm [17”] @ TD**

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

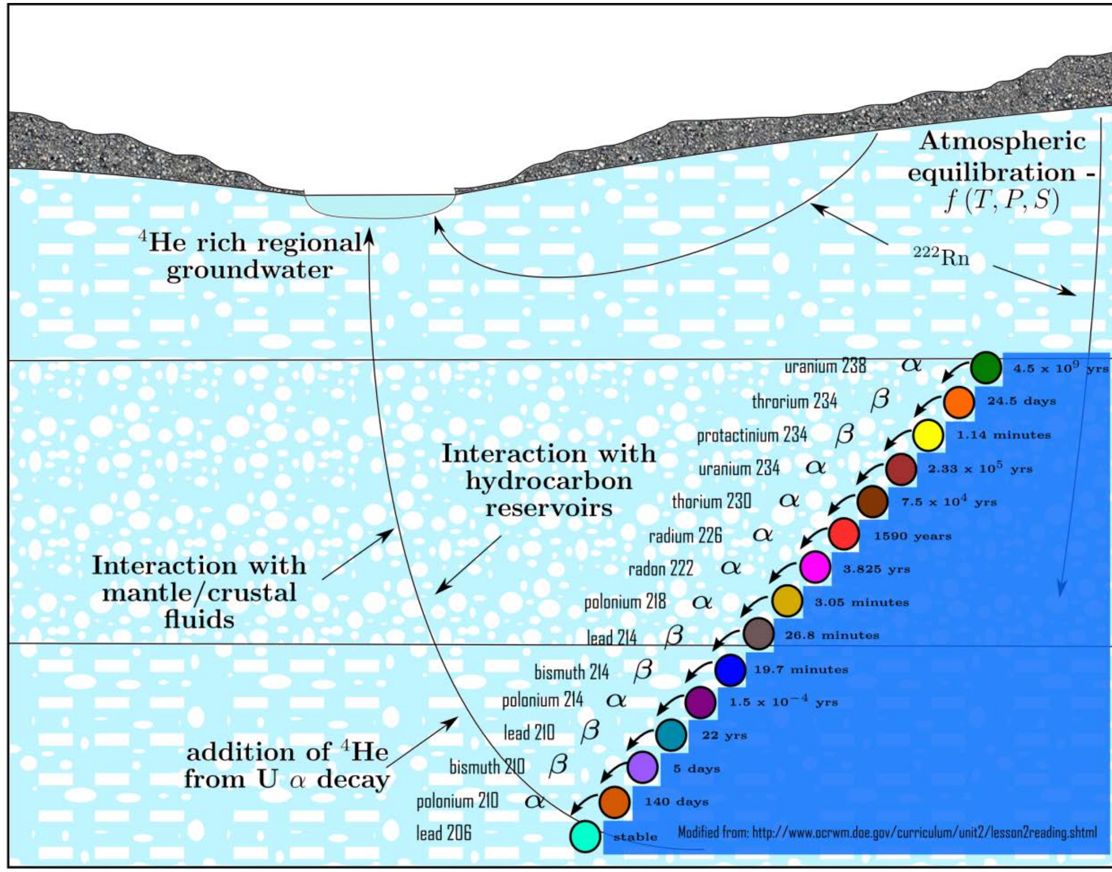
Borehole designed to maximize likelihood of good samples



CB: Environmental Tracer Profiles

- **Vertical Profiles**
  - **Fluid density**
  - **Temperature**
  - **Noble gases**
  - **Stable water isotopes**
  - **Atmospheric radioisotope tracers (e.g., Xe)**
- **Long-Term Data**
  - **Water provenance**
  - **Flow mechanisms**

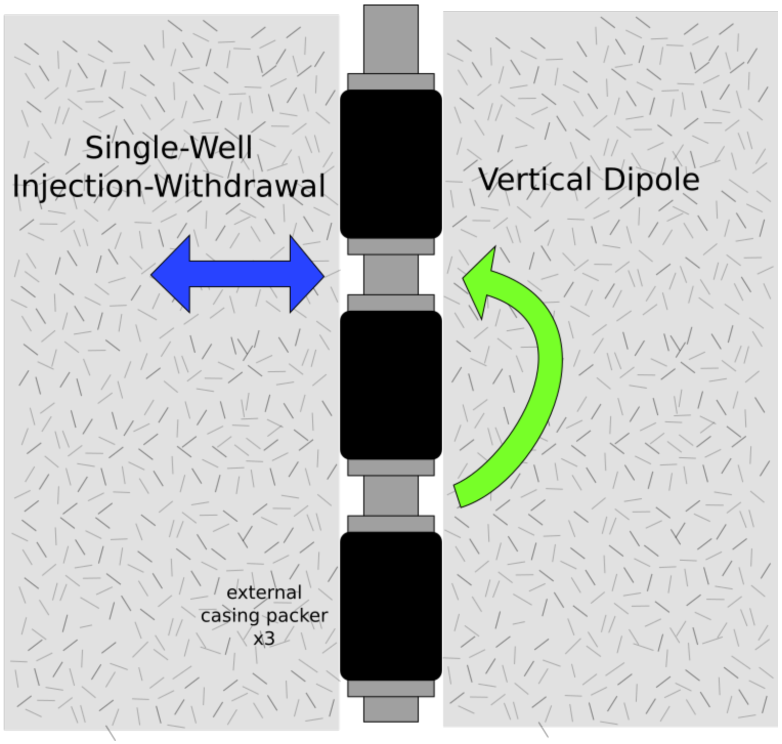
Minerals → pores → fractures



Fluid Sample Quality + Quantity *Very Important!*

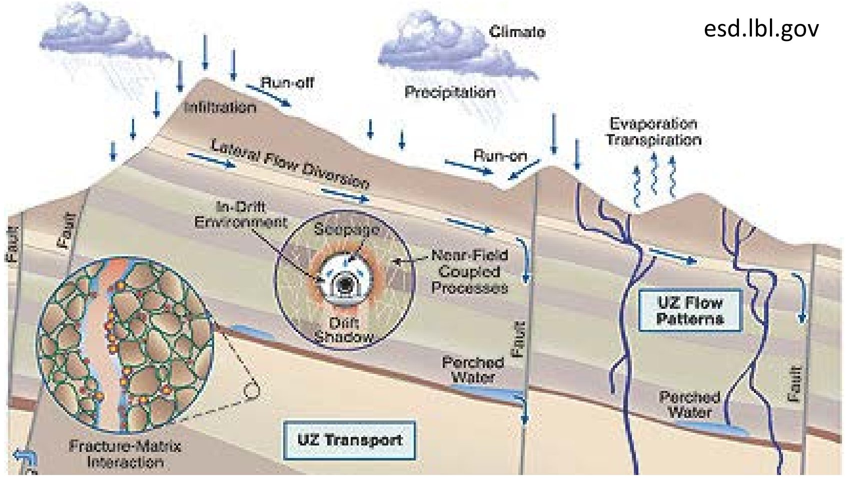
CB: Hydrogeologic Testing

- Hydrologic Property Profiles
  - Static formation pressure
  - Permeability / compressibility
    - Pumping/sampling in high K
    - Pulse testing in low K
- Borehole Tracer Tests
  - Single-well injection-withdrawal
  - Vertical dipole
  - Understand transport pathways
- Hydraulic Fracturing Tests
  - σ_h magnitude
- Borehole Heater Test
  - Surrogate canister with heater



Characterization Difference

- **Borehole Characterization & Siting vs.**
  - **Mined waste repositories**
    - **Less “site mapping”**
    - **Go/no go decision point**
    - **Single-phase fluid flow**
    - **Less steep pressure gradients**
  - **Oil/gas or mineral exploration**
    - **Crystalline basement vs sedimentary rocks**
    - **Low-permeability**
    - **Minimal mineralization**
    - **Avoid overpressure**
  - **Geothermal exploration**
    - **Low geothermal gradient**



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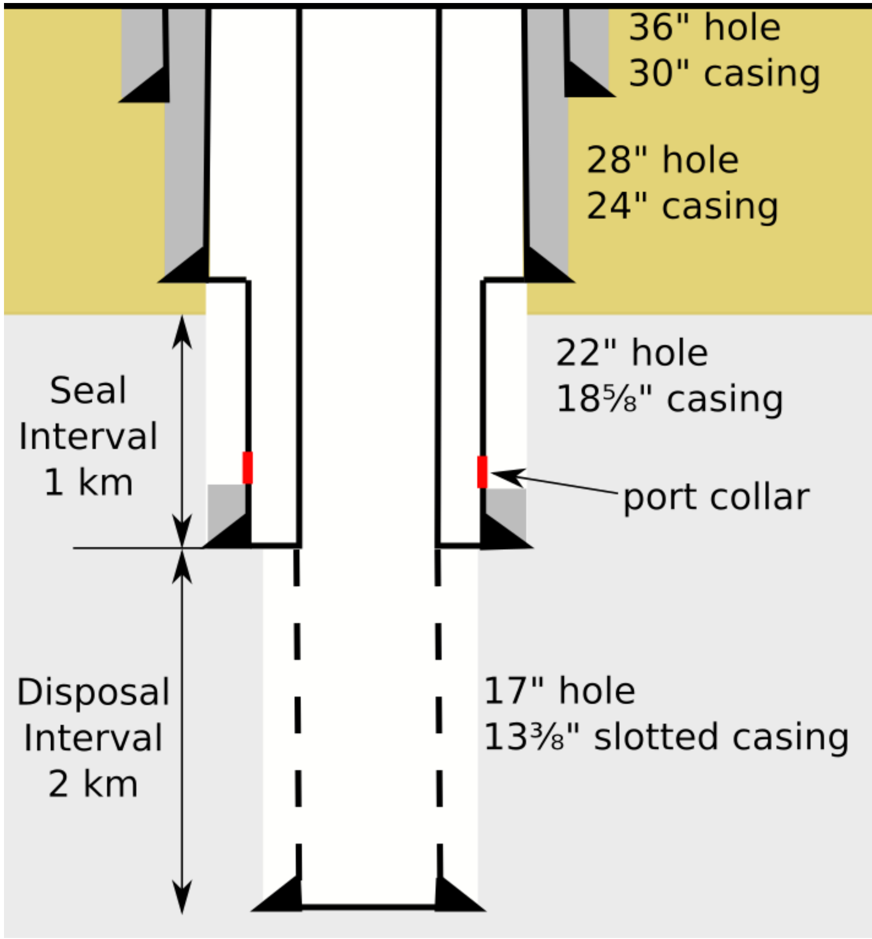
DBFT: Field Test Borehole (FTB)

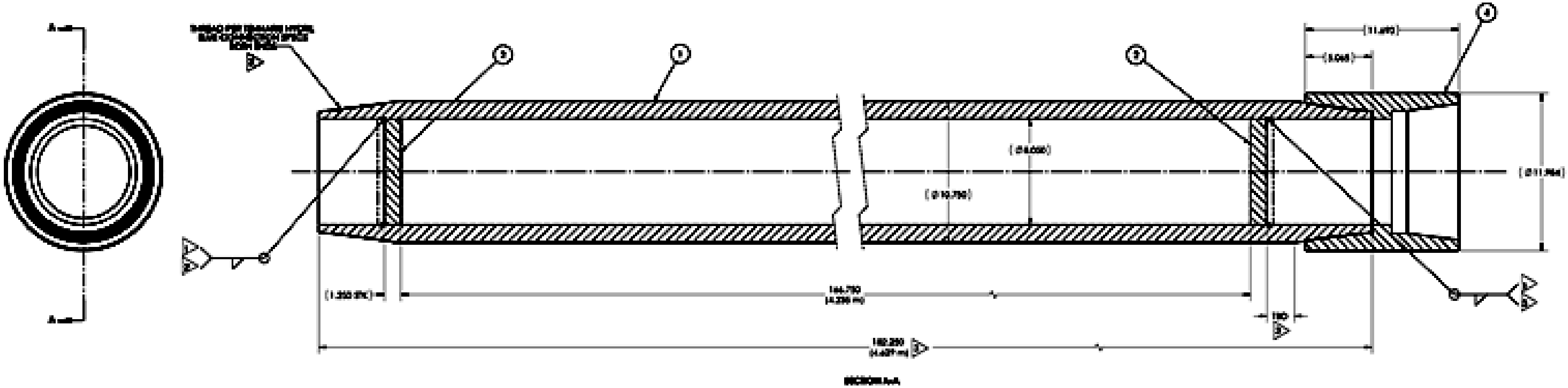
- **Large-Diameter Borehole**
  - Push envelope of drilling tech
- **Casing Schedule**
  - Continuous 13 ⅜" pathway to TD
    - Slotted & permanent in disposal interval
    - Removable in seal and overburden intervals
- **Demonstrate**
  - Emplacing canisters
  - Removing canisters
  - Surface handling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



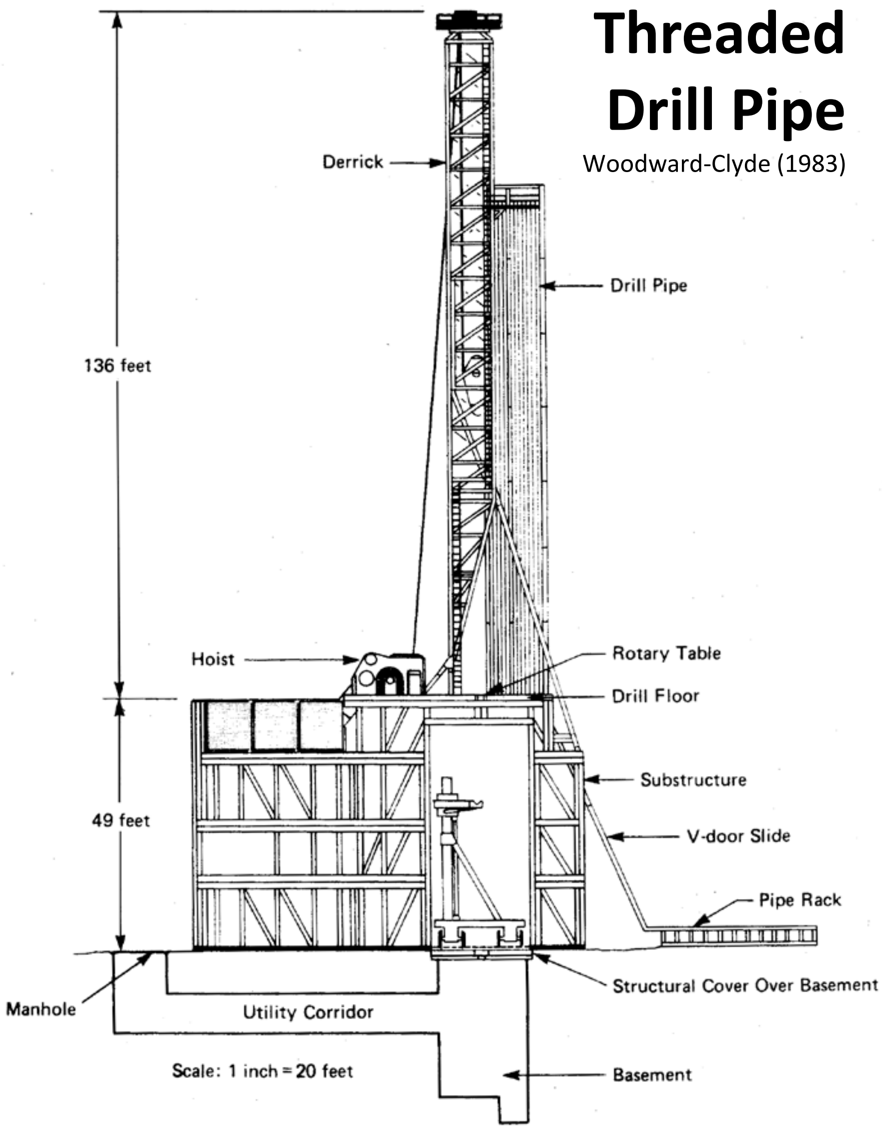
Borehole designed to maximize emplacement safety

Waste Package Design

- **Structural Integrity**
  - **Hydrostatic pressure and canister string load**
  - **Integrity through emplacement, sealing, and closure**
- **Waste Loading**
  - **Transport and dispose in same canister**
  - **Transfer from shipping casks onsite**



FTB: Emplacement Methods



FTB: Operational Safety

- **Zero Radiological Risk**
- **Focus on Downhole Safety**
- **Downhole Failure Modes**
  - **Pipe string + canister(s) drop in borehole**
  - **Pipe string drop onto canister(s)**
  - **Single canister drop in borehole (consequence?)**
  - **Canister leak/crush**
  - **Fishing operations**
  - **Seismic events**

NTS Climax Spent Fuel Test (1978-1983)

Summary

- **Deep Borehole Disposal Concept**
  - **10 × geologic isolation of mined repository**
  - **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 (FY15-19)**
  - **Drill two 5-km large-diameter boreholes**
  - **Demonstrate ability to**
    - **Characterize bedrock system (CB)**
    - **Emplace/retrieve surrogate canisters (FTB)**

SAND2010-6048