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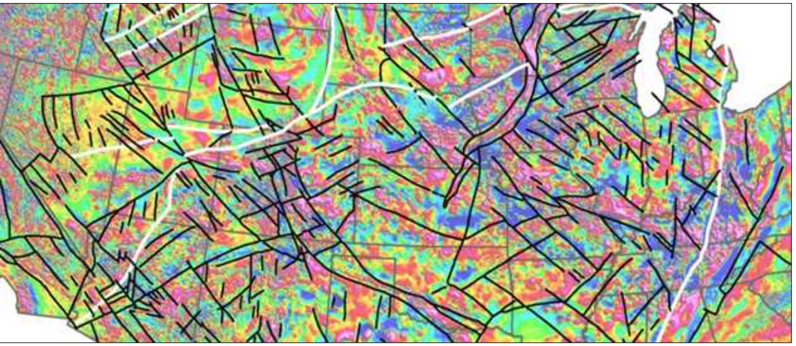

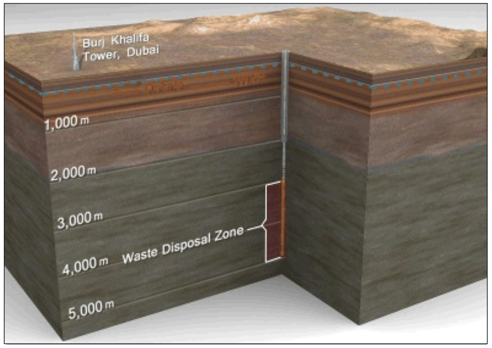

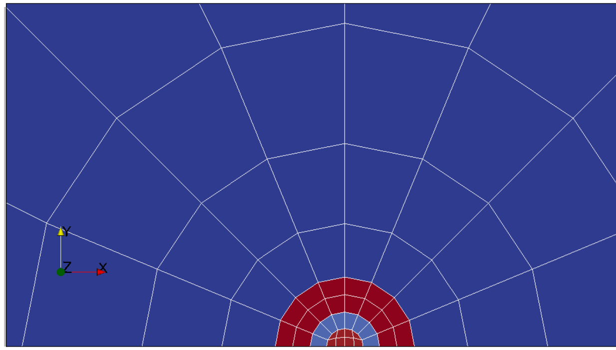

Drilling And Testing in the Deep Borehole Field Test

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Sandia National Laboratories

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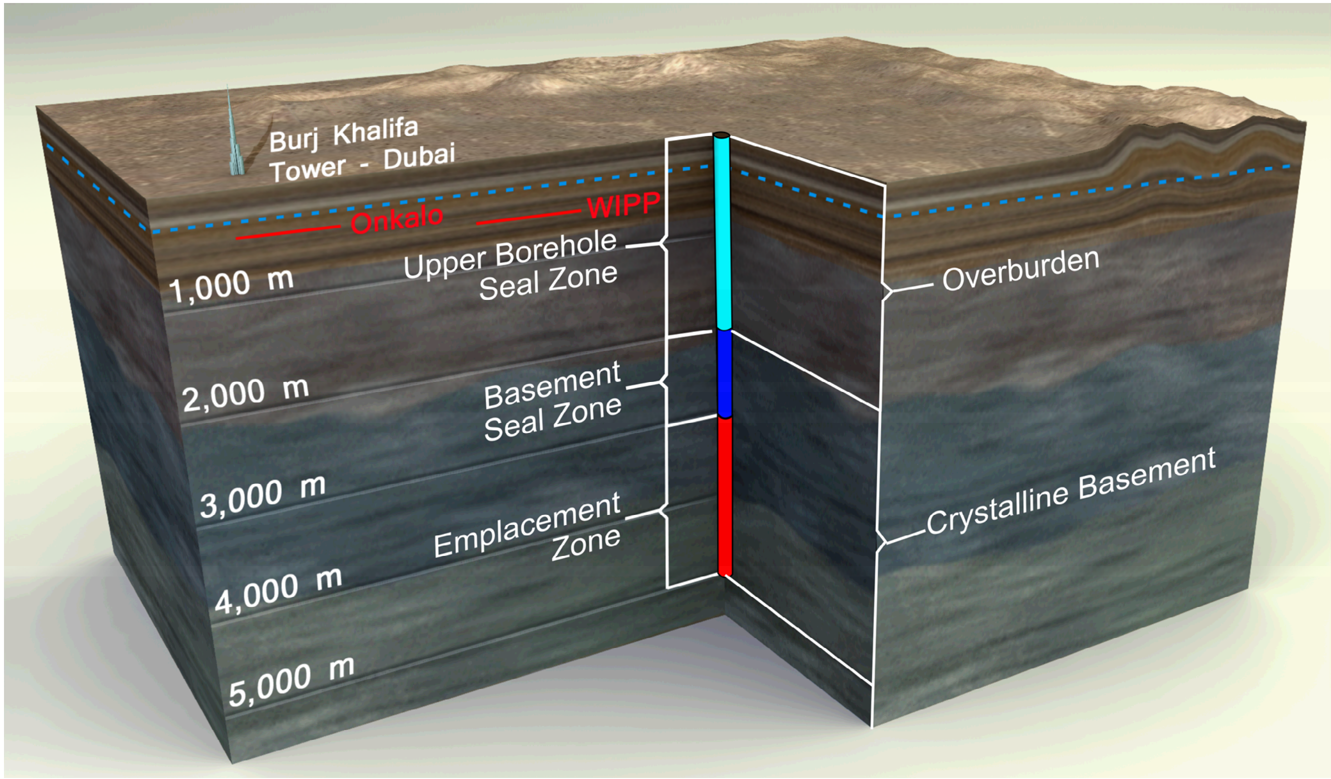
Deep Borehole Disposal Concept

- 17” @ 5 km TD
- Straightforward Construction
- Robust Isolation from Biosphere

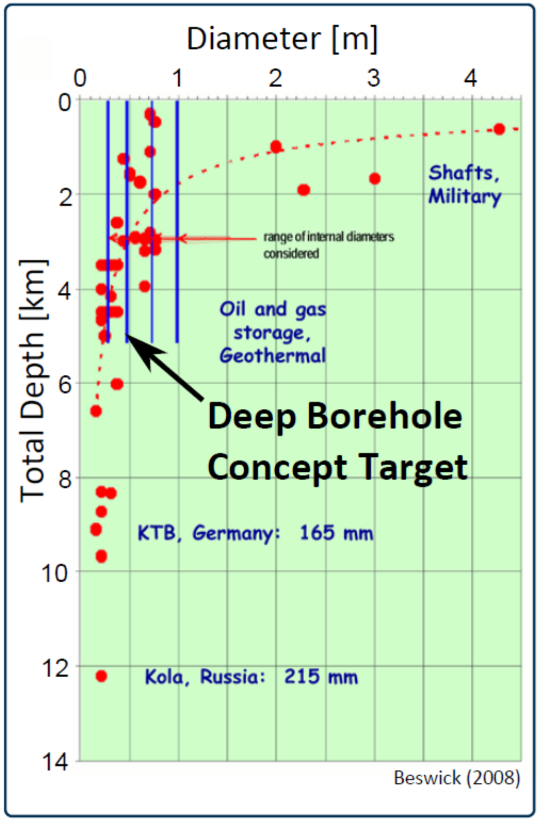


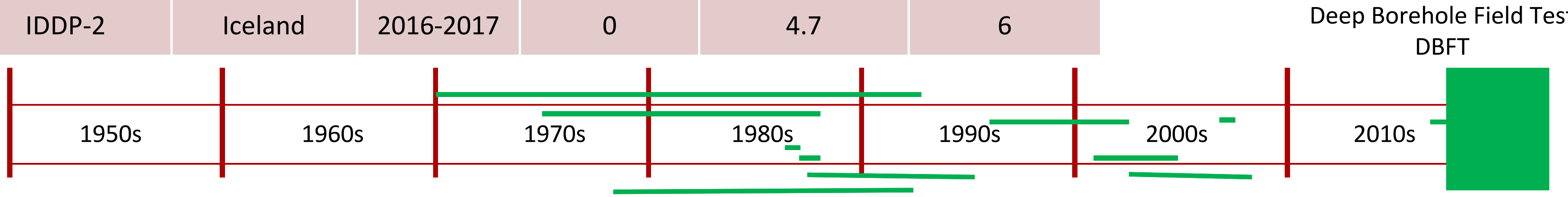
Conditions at Depth

- Low permeability
- Stable fluid density gradient
- Reducing systemchemistry
- Old groundwater

Deep Crystalline Drilling

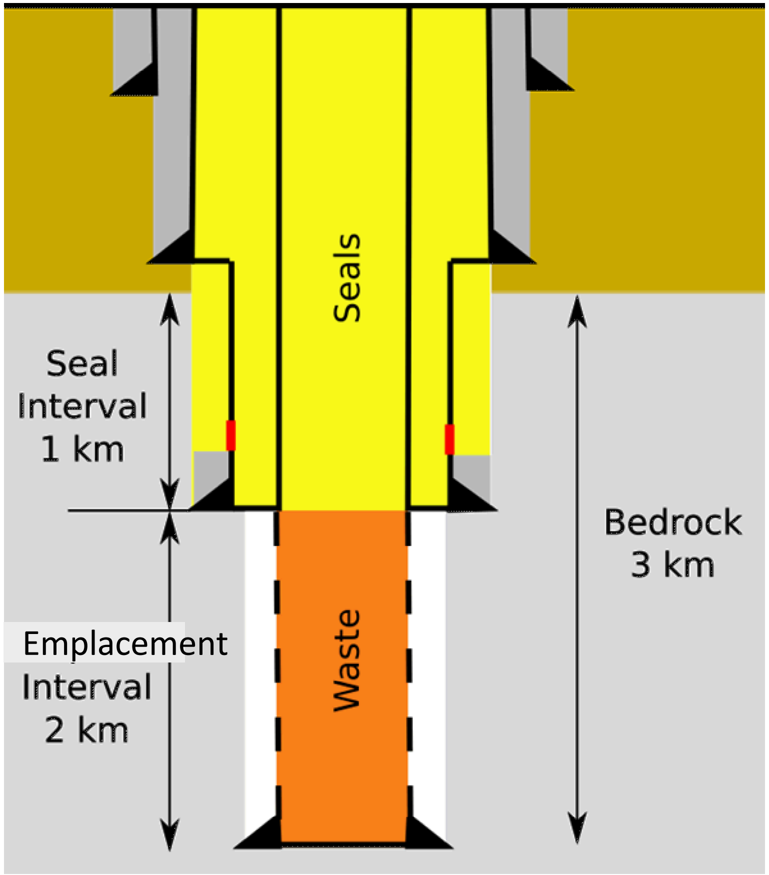
Site	Location	Years	Depth to Crystalline [km]	Total Depth [km]	Diam. at TD [inch]
Kola	NW USSR	1970-1992	0	12.2	8½
Fenton Hill	New Mexico	1975-1987	0.7	2.9, 3.1, 4.0, 4.4	8¾, 9⅞
Urach	SW Germany	1978-1992	1.6	4.4	5½
Gravberg	Central Sweden	1986-1987	0	6.6	6½
Cajon Pass	Southern California	1987-1988	0.5	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
IDDP-2	Iceland	2016-2017	0	4.7	6





Disposal Concept vs. Field Test

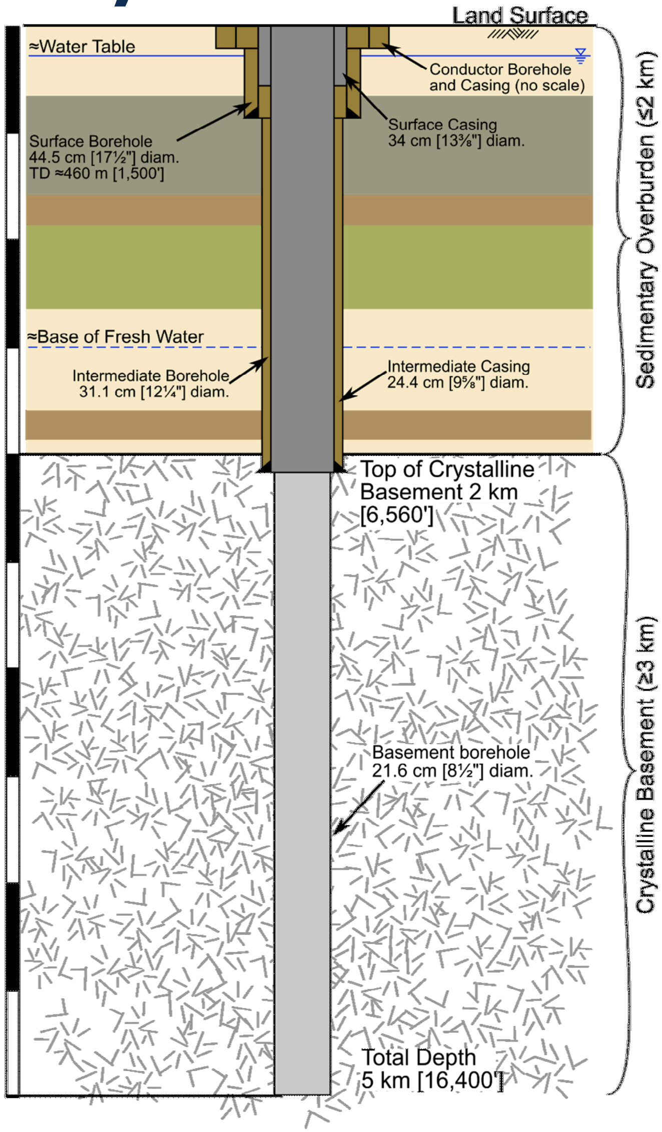
- **Deep Borehole Disposal (DBD)**
  - Crystalline rock borehole to 5 km TD
  - 3 km basement / 2 km overburden
  - 1 km basement seal
  - 2 km disposal zone
- **Deep Borehole Field Test (DBFT)**
  - Department of Energy – Office of Nuclear Energy (DOE-NE) Project
  - FY 2017-2021
  - Two boreholes to 5 km TD (8½” & 17”)
  - Science and engineering demonstration
  - 4 teams and sites seeking public support
  - *No nuclear waste in field test*



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

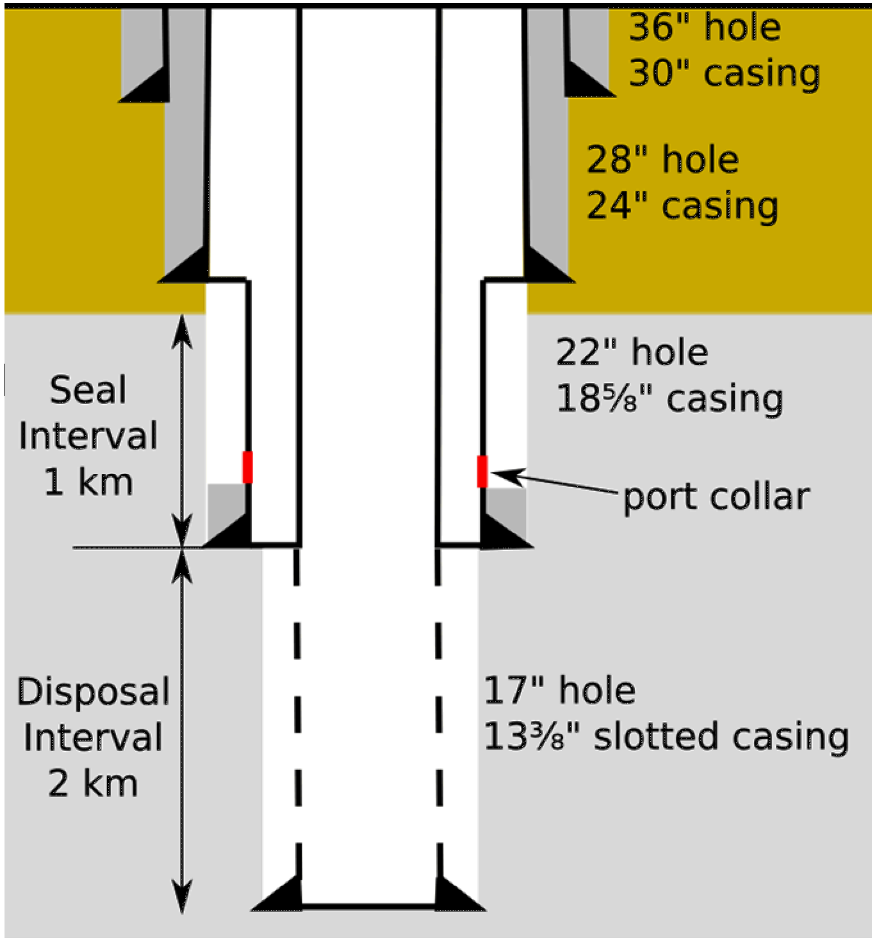


(SNL 2016) SAND2016-9235R
DBFT Laboratory and Borehole Testing Strategy

Field Test Borehole (FTB)

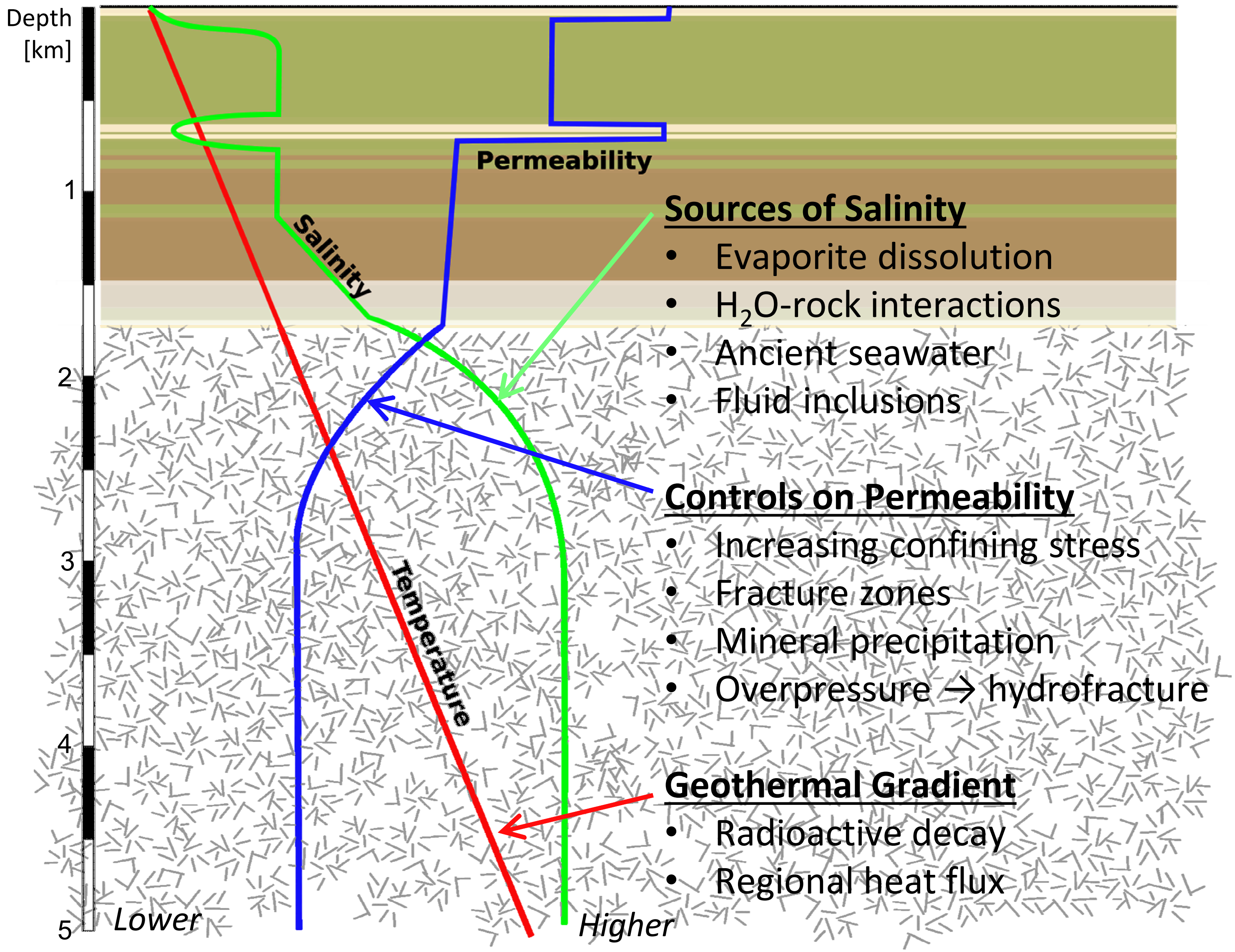
- **Large-Diameter Borehole**
  - Push envelope of drilling tech
- **Casing Schedule**
  - Continuous 13 ⅜” pathway to TD
    - Slotted & permanent in disposal interval
    - Removable in seal and overburden intervals
- **Demonstrate Ability to**
  - Emplace test packages
  - Remove test packages
  -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

Borehole designed to maximize emplacement safety



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

Basement 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

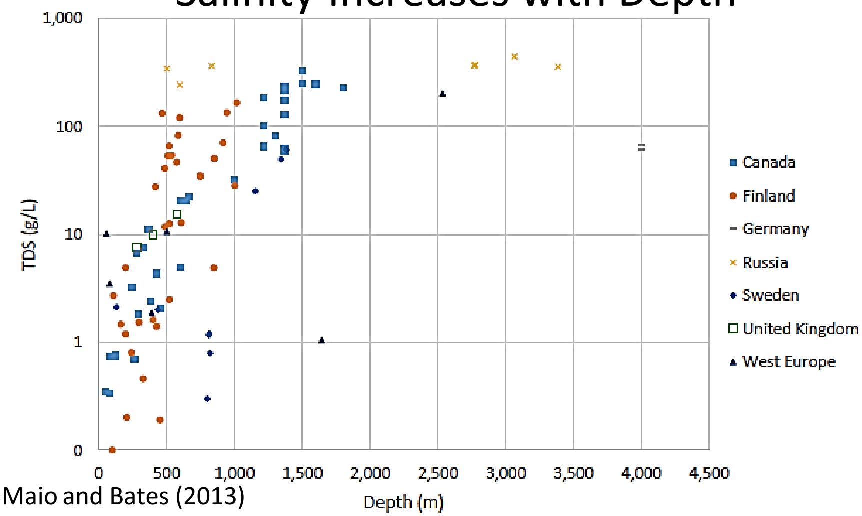
- Radioactive decay
- Regional heat flux

Sedimentary Overburden ≤ 2 km

Crystalline Basement ≥ 3 km

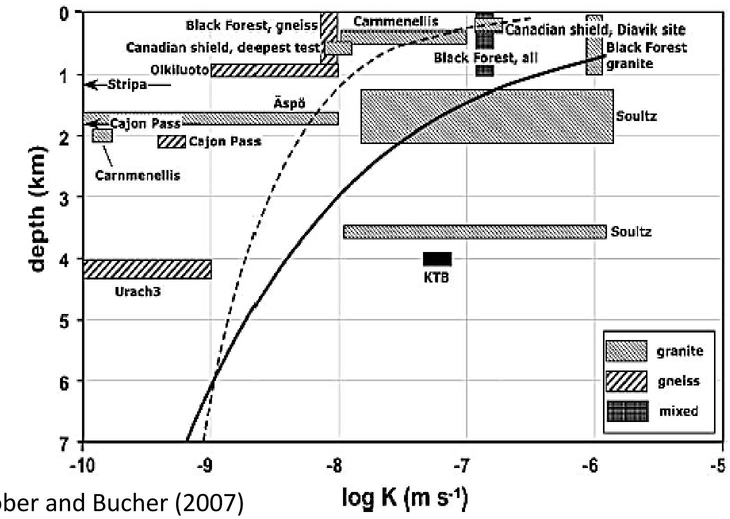
Observed Profiles

Salinity Increases with Depth



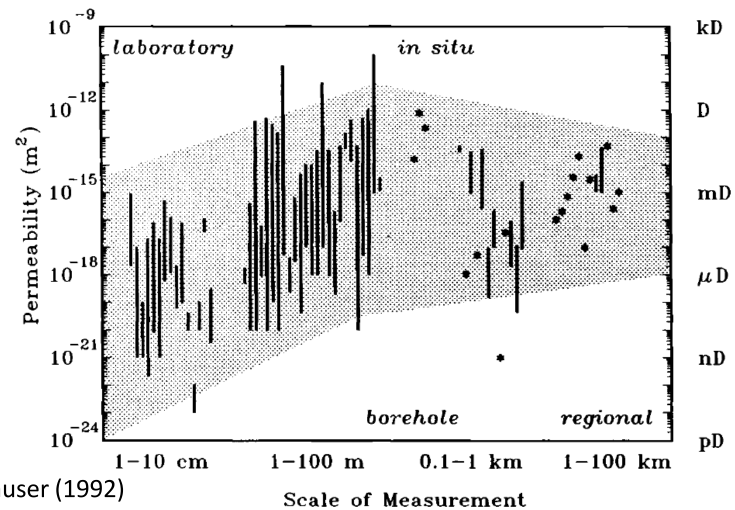
DeMaio and Bates (2013)

Bulk Permeability Decreases with Depth



Stober and Bucher (2007)

Bulk Permeability Increases with Scale

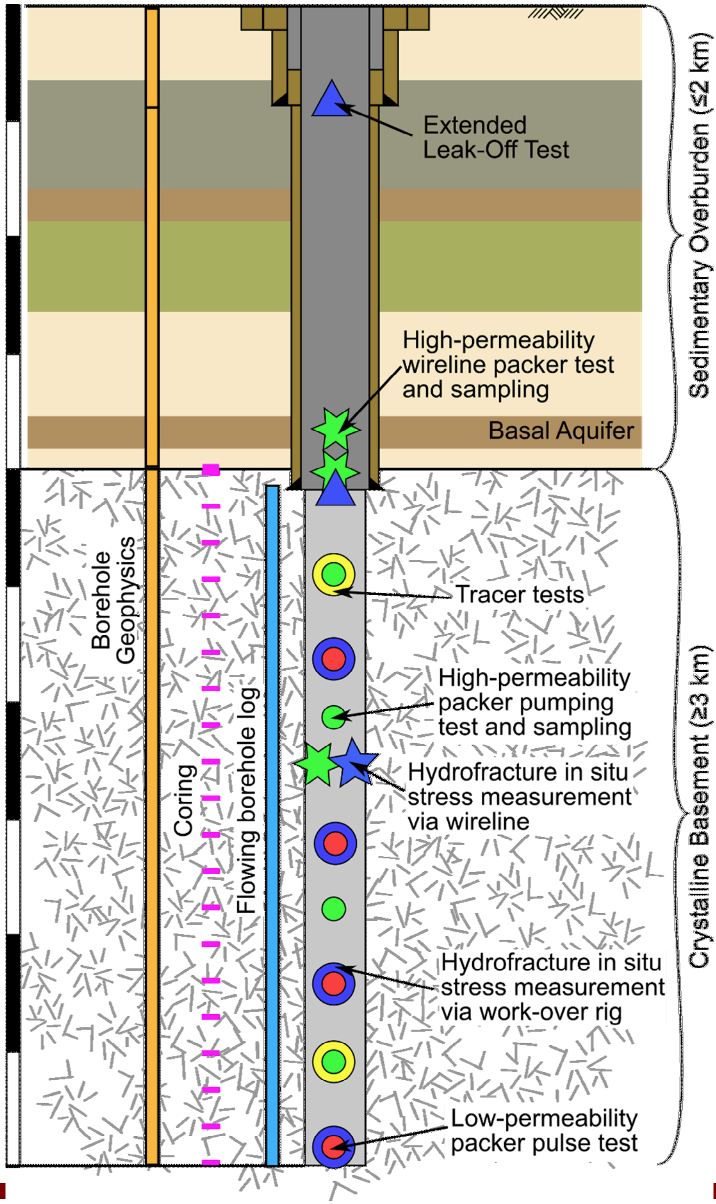


Clauser (1992)

Chemical evidence for isolation is less prone to scale-dependency than permeability

Characterization Borehole (CB)

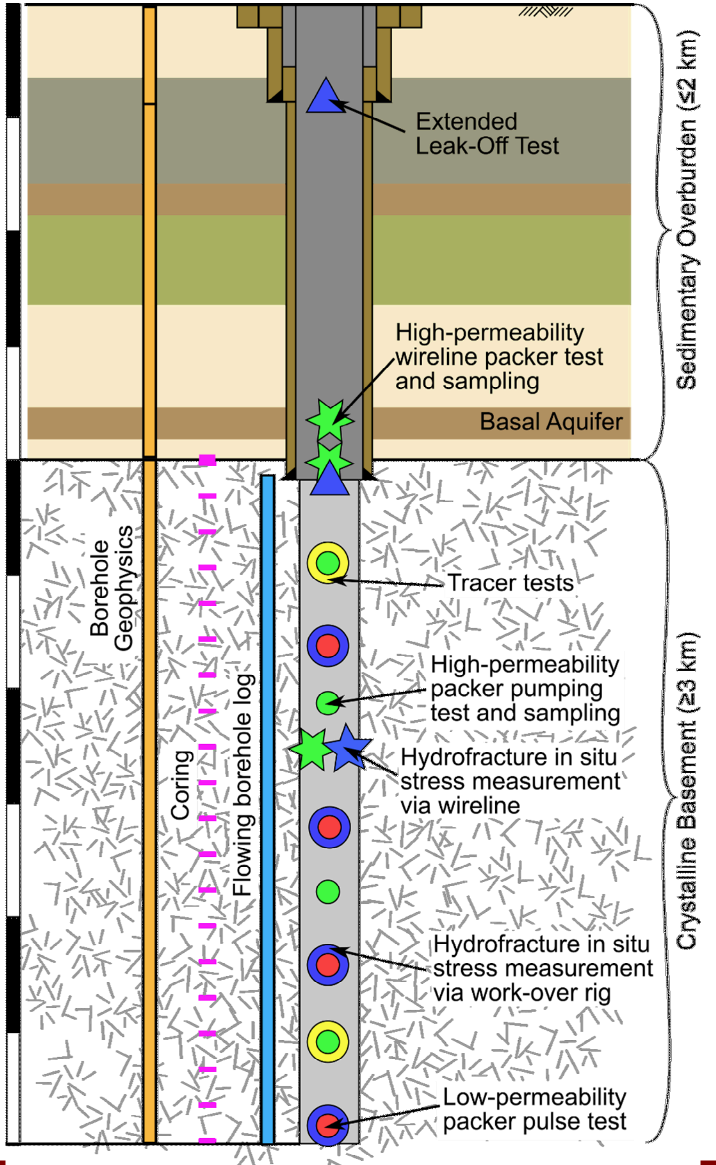
- **Sampling During Drilling**
- **Borehole Geophysics**
- **Flowing Borehole Salinity Log**
- **Sample-based Profiles**
  - Fluid density/temperature/major ions
  - Pumped samples from high-*k* regions
  - Samples from cores in low-*k* regions
- **In Situ Testing-based Profiles**
  - Formation hydraulic/transport properties
  - *In situ* stress (hydrofrac + breakouts)
- **Exploring TRL of Methods**
  - Not exhaustively testing a site for licensing
  - Workable at 50 Mpa / 150° C / 4 km tubing?
  - Compare methods under field conditions



(SNL 2016) SAND2016-9235R

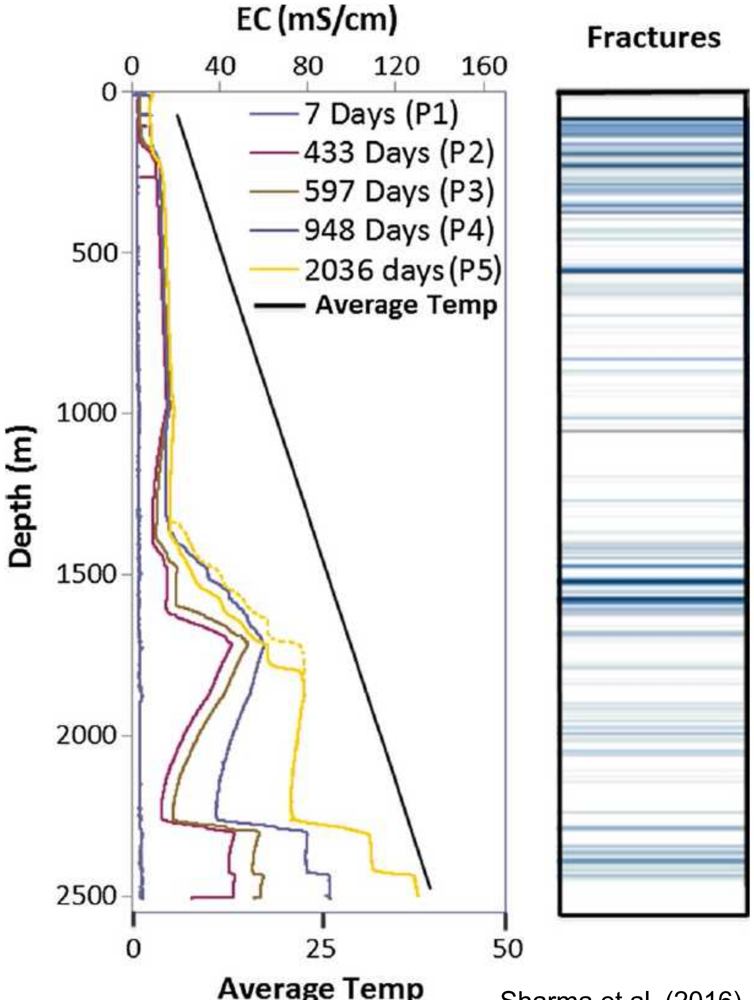
CB Characterization *During* Drilling

- **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, deviation, drilling specific energy, etc.



CB Testing After Drilling

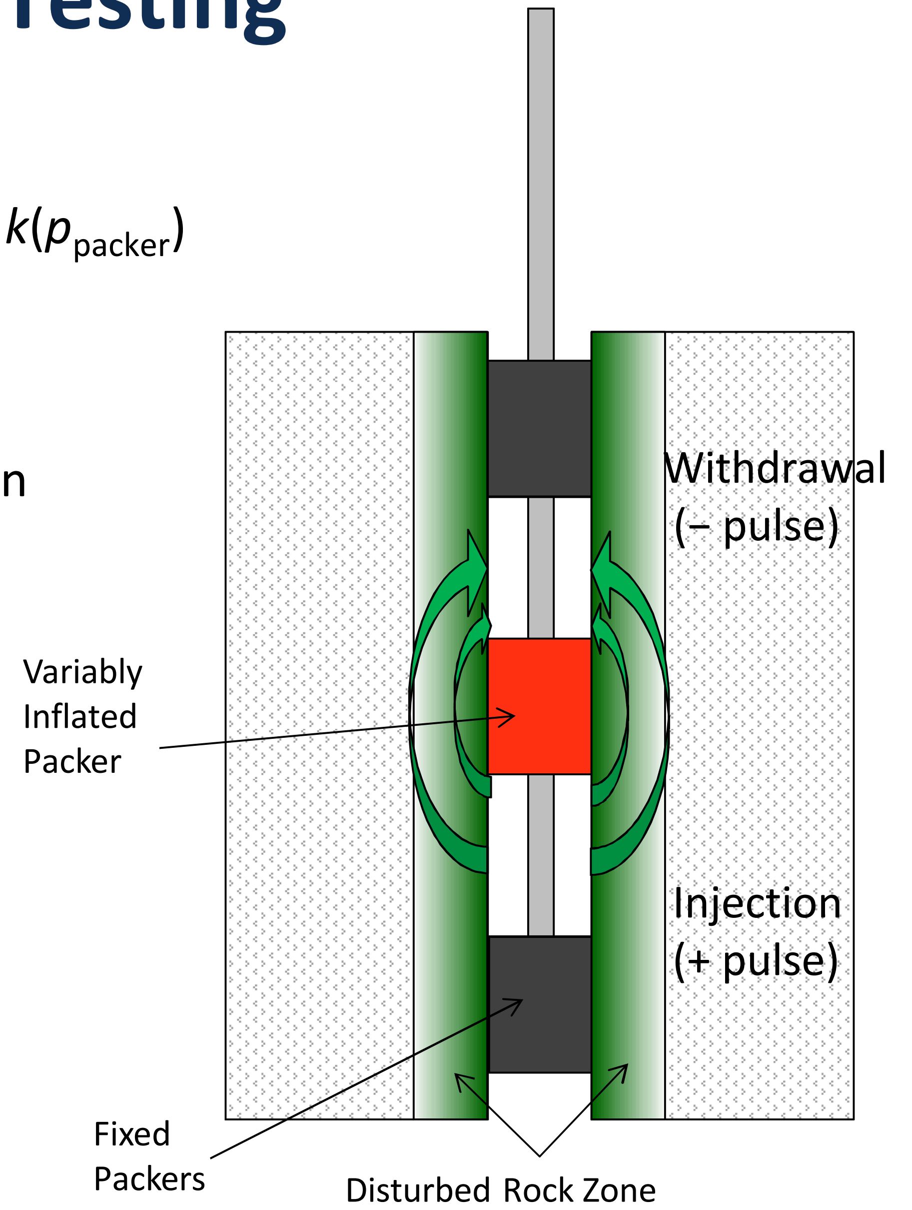
- **Flowing Fluid Electrical Conductivity (FFEC) log**
- **Find:**
  - Permeable zones
  - Gaining zones
  - Losing zones
- **in situ packer testing focused to:**
  - 5 permeable zones
    - Formation fluid samples collected at surface
    - Estimate hydraulic properties
  - 5 low-permeability zones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



Sharma et al. (2016)

In Situ Packer-Based Testing

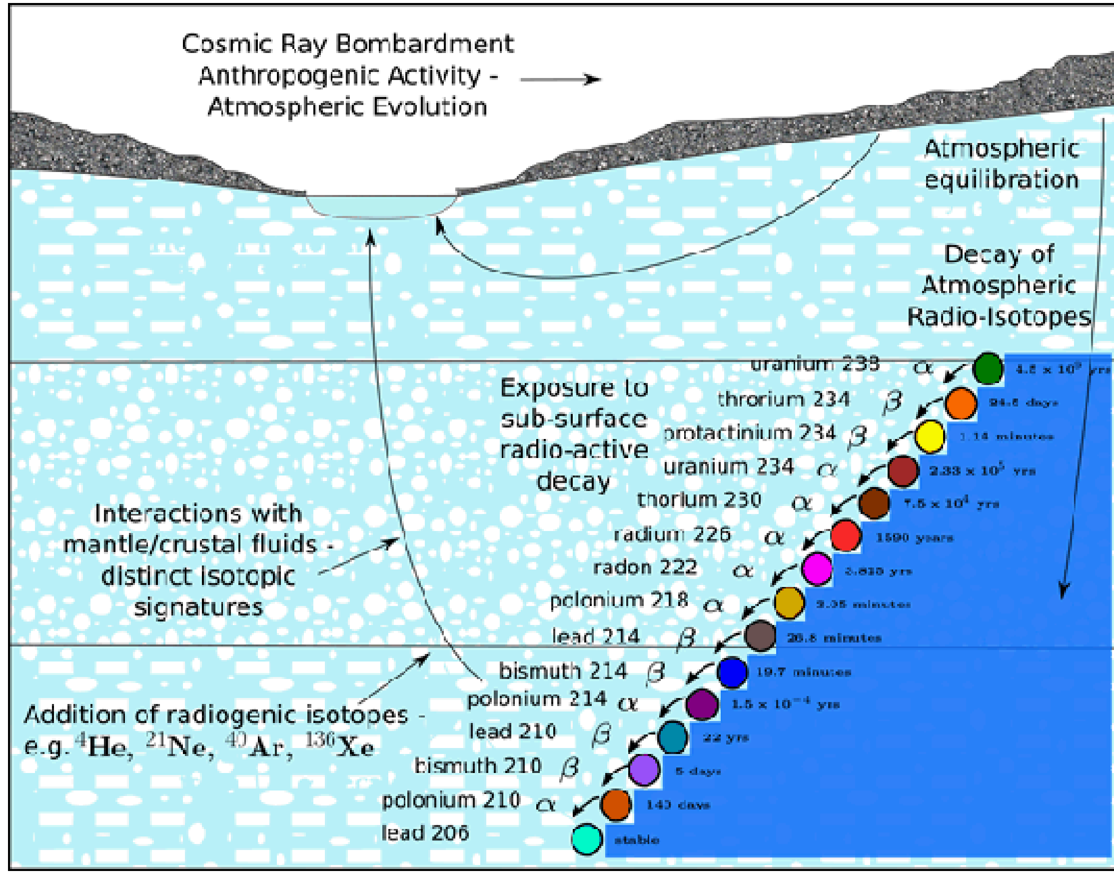
- **In Situ Packer Testing**
  - New hydromechanical dipole test: $k(p_{packer})$
- **Hydrologic Tests**
  - Static formation pressure
  - Permeability / compressibility / skin
  - Sampling in high *k* intervals
- **Tracer Tests**
  - Single-well injection-withdrawal
- **Hydraulic Fracturing Tests**
  - 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 drilling, packer & core samples?

Characterization Differences

- **DBFT Effort is 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
- **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)
  - FTB Engineering demonstration of package handling

SAND2010-6048