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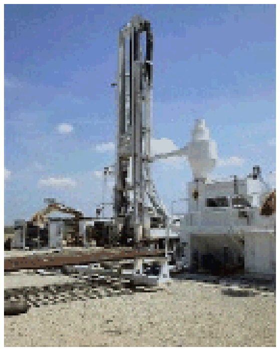

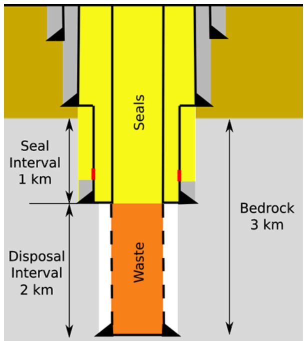

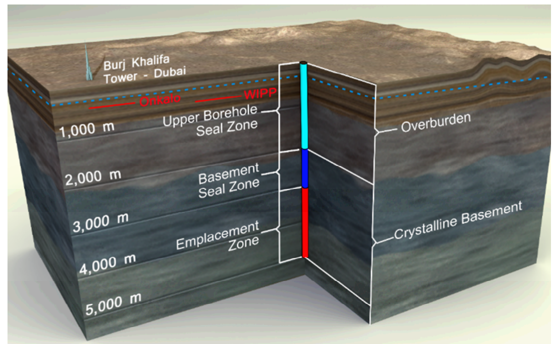

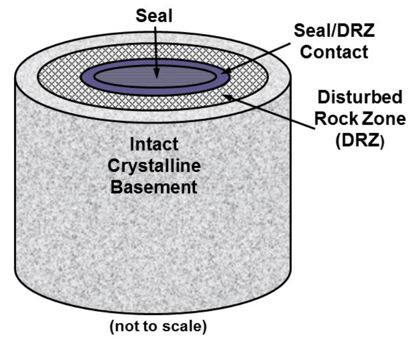

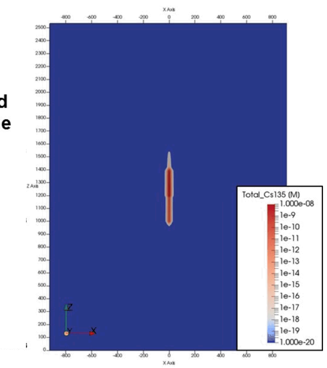

Deep Borehole Disposal: Overview of U.S. Research

Geoff Freeze (SNL), Robert MacKinnon (SNL), and Frank Perry (LANL)

NNSA/IAEC Topic Area V Workshop: Waste Management and Subsurface Science

Sde Boqer, Israel

December 6, 2017

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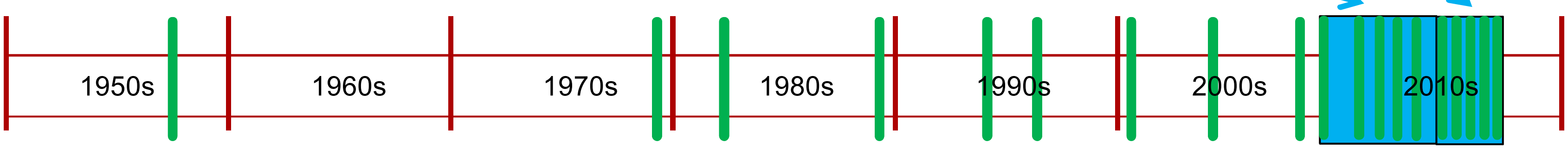
Outline

- Deep Borehole Disposal (DBD) Overview
  - History and Concept
  - DBD Research at Sandia National Laboratories (SNL)
- Deep Borehole Field Test (DBFT)
  - Objectives
  - Accomplishments
- DBD Safety Case
  - Pre-Closure Safety Analysis (PCSA)
  - Post-Closure Performance Assessment (PA)
    - Nominal Scenario
    - Disturbed Scenario
- DBD Siting Guidelines
  - Applicability to Israel

Deep Borehole Disposal (DBD) Overview

DBD of spent nuclear fuel (SNF) and high-level radioactive waste (HLW) has been considered in the U.S. and elsewhere since the 1950s and has been periodically studied since the 1970s

- **National Academy of Sciences (1957)**
  Publication 519: The Disposal of Radioactive Waste on Land
- **O'Brien 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 and 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
- **Sandia National Laboratories (SNL) (2009-17)**
  Multiple Reports; Deep Borehole Field Test (DBFT)



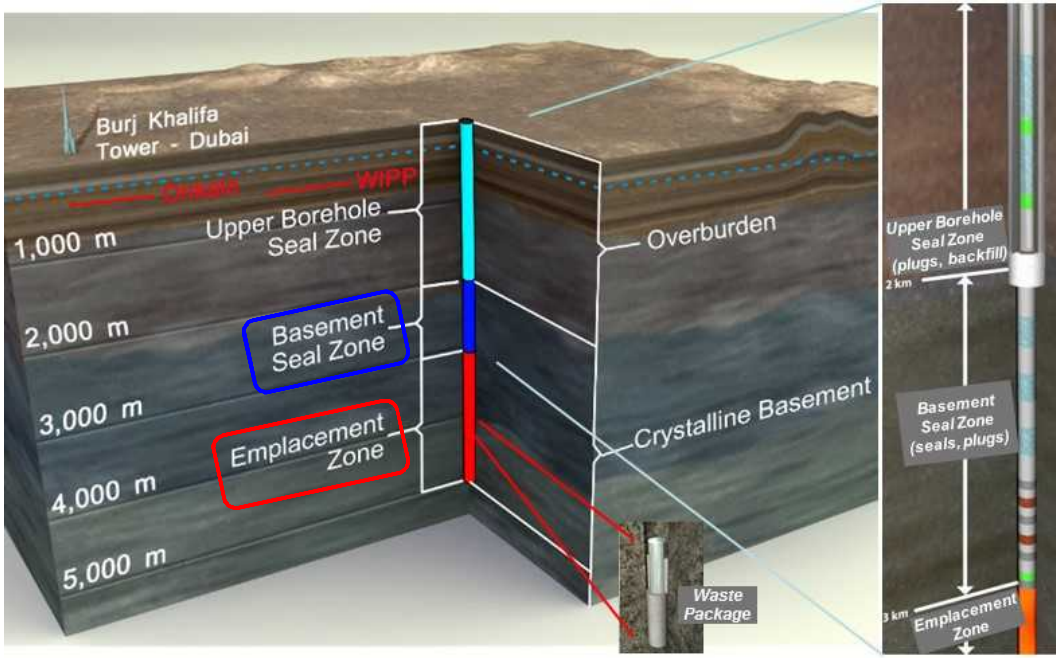
Deep Borehole Disposal (DBD) Overview

DBD research by country

Country / Region	References
Canada	Brunskill 2006; Jackson and Dormuth 2008; Brunskill and Wilson 2011
China	Brady 2016
East Asia	von Hippel and Hayes 2010; Chapman 2013
Japan	Tokunaga 2013
Germany	Bracke 2015; Schilling and Müller 2015
Netherlands	Hart et al. 2015, Section 4.2.2
South Korea	Lee 2015
Sweden	Juhlin and Sandstedt 1989; Harrison 2000; Grundfelt 2013
Ukraine	Shestopalov et al. 2004
U.K.	Gibb 1999; Nirex 2004; Baldwin et al. 2008; Beswick 2008; Beswick et al. 2014
U.S. (SNF/HLW)	O'Brien et al. 1979; Woodward-Clyde Consultants 1983; Sapiie and Driscoll 2009; Brady et al. 2009; Arnold et al. 2011; Vaughn et al. 2012; Arnold et al. 2012; Arnold et al. 2013; Arnold et al. 2014; Bates 2015
U.S. (Excess Pu)	Ferguson 1994; Heiken et al. 1996; DOE 2014b, Section 5.2.5
U.S. (DBFT)	SNL 2014a; Kuhlman et al. 2015; SNL 2015; Sassani et al. 2016; SNL 2016a; SNL 2016b; Freeze et al. 2016; Hardin et al. 2017a

Deep Borehole Disposal Concept

- Drill a borehole or array of boreholes into deep, competent rock (e.g., crystalline basement)
  - ~ 5,000 m total depth (TD)
  - ≤ 17” diam. at TD
    - 17” for SNF (1 PWR assembly)
    - ≥ 8.5” for some HLW
- Emplacement Zone (EZ)
  - Waste in the lower 2,000 m
- Seal Zone (SZ)
  - Engineered seals and plugs in upper borehole
    - 1,000 m seal in competent basement rock



Robust Isolation from Biosphere

Natural Barriers – deep, low permeability host rock
Engineered Barriers – redundant seals, possibility of long-lived waste forms and waste packages

DBD Concept – Safety and Feasibility

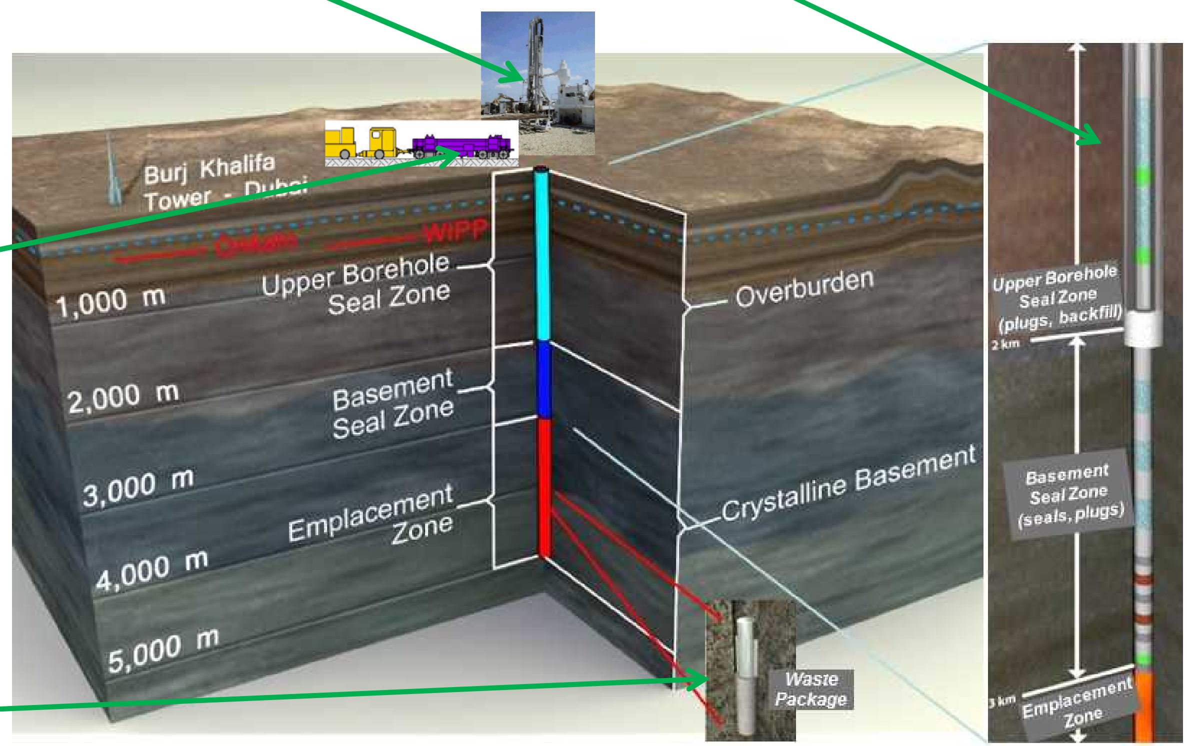
(Pre-Closure Design, Engineering, and Operations)

Drilling Technology exists to drill and case larger-diameter boreholes to 5,000 m depth in basement rock at acceptable cost

Borehole and Casing Design maintains borehole integrity (against borehole breakout) and minimizes probability of waste packages becoming stuck during emplacement

Emplacement System Design provides assurance the waste packages can be safely surface-handled and emplaced at depth

Waste Package Design maintains structural integrity and prevents leakage of radioactive materials during operations



DBD Concept – Safety and Feasibility

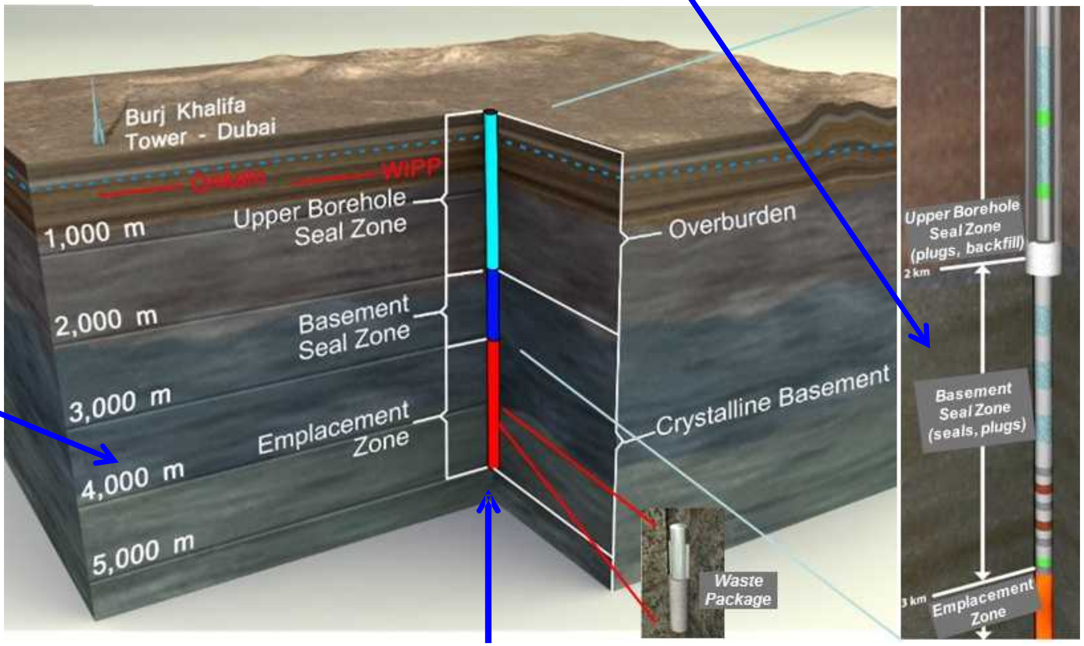
(Post-Closure Hydrogeochemical Waste Isolation)

Zenifim Formation arkose may exhibit adequate host rock properties with sufficient depth and thickness

Borehole Seals and Disturbed Rock Zone (DRZ) can be engineered/evolve to maintain a low-permeability barrier, at least over the time scale of thermally-induced upward flow

Deep basement rocks

- hydrologically isolated from shallow groundwater (low permeability and long groundwater residence time)
- deep groundwater typically exhibits density stratification (saline water underlying fresh water) that opposes upward flow
- geochemically reducing conditions at depth limit the solubility and enhance the sorption of many radionuclides



Waste is deep in basement rock

- well below typical depth of fresh groundwater ------
- with at least 1,000 m of basement rock (Seal Zone) overlying the Emplacement Zone

DBD Research and Development (R&D) at Sandia National Laboratories (SNL)

- 2009 – 2012 (SNL internally funded)
  - DBD Consortium with Mass. Inst. of Tech. (MIT), U. of Sheffield, Industry
  - SNF disposal (Brady et al. 2009, Arnold et al. 2011)
- 2012 – 2014 (DOE funded R&D)
  - Preliminary siting, design, and post-closure performance assessment (PA) focused on SNF disposal
  - DOE (2014a) recommended consideration of DBD of smaller DOE-managed waste forms, such as Cs and Sr capsules
- 2014-2017 (DOE funded DBFT)
  - Lead Lab for a planned 5-year Deep Borehole Field Test (DBFT) to evaluate the feasibility of siting and operating a DBD facility
    - Supported by other National Labs: LANL, LBL, ORNL, PNNL, INL
    - DBFT will use surrogate waste packages (no radioactive waste)

Deep Borehole Field Test (DBFT)

- Planned to improve scientific understanding of the DBD concept
  - Drill two boreholes to a depth of 5 km in a suitable location
    - Characterization Borehole (CB): 8.5 in. @ TD
    - Field Test Borehole (FTB): 17 in. @ TD
- DBFT Objectives:
  - Demonstrate technology to drill deep, wide, straight boreholes (CB + FTB)
  - Evaluate the feasibility of characterizing deep boreholes (CB)
    - Testing deep formations in situ
    - Sampling for deep geochemical profiles
  - Demonstrate safe operations for downhole package emplacement and retrieval (FTB)
    - Without emplacement of radioactive wastes
  - Investigate seal design and performance
    - Laboratory studies of methodologies, designs, and material behaviors
  - Perform modeling and analyses to support a preliminary DBD safety case

DBFT – Planned Activities

Sandia National Laboratories

Design, drill, and construct FTB

Develop systems for handling, emplacing, and retrieving packages

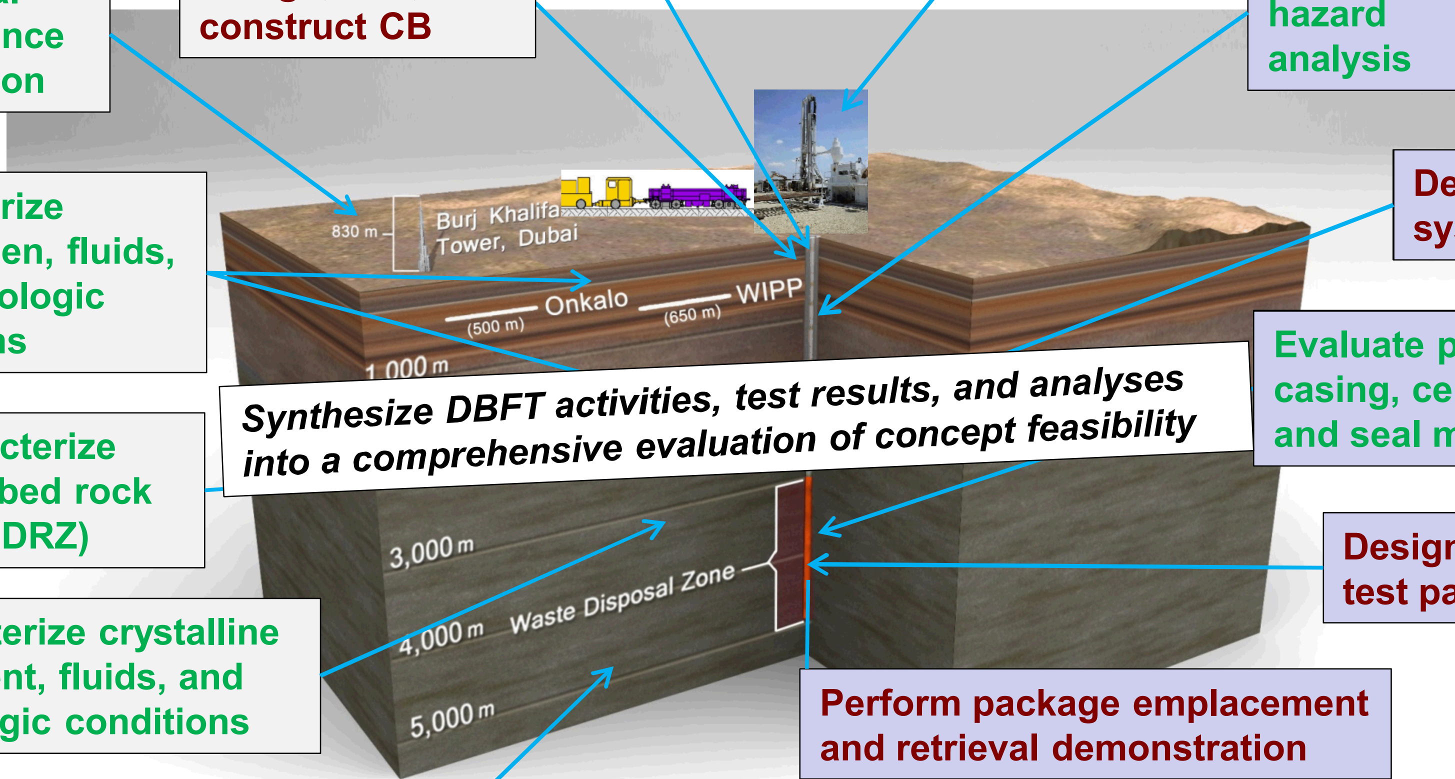
Regional geoscience evaluation

Design, drill, and construct CB

Emplacement hazard analysis

Characterize overburden, fluids, and hydrologic conditions

Design seal system



Synthesize DBFT activities, test results, and analyses into a comprehensive evaluation of concept feasibility

Evaluate package, casing, cement, and seal materials

Characterize disturbed rock zone (DRZ)

Design and test packages

Characterize crystalline basement, fluids, and hydrologic conditions

Perform package emplacement and retrieval demonstration

Develop site-specific geologic framework model

Assess post-closure safety

Assess pre-closure safety

DBFT – Chronology

- September 2014: DBFT Project Plan Rev. 0 issued (SNL 2014a)
- July 2015: DOE Request for Proposal (DOE 2015) for a suitable site and management team to conduct drilling and testing
- January 2016: Initial contract awarded to a Battelle-led team for a proposed test site in Pierce County, North Dakota
  - Efforts to secure the test site in North Dakota were later suspended
  - Attempts to acquire an alternative test site in Spink County, South Dakota were also unsuccessful
- July 2016: Activities suspended

DBFT – Chronology (cont.)

- August 2016: New Request for Proposal (DOE 2016) issued based on lessons learned in the Dakotas
  - Phased approach with initial emphasis on obtaining public support
  - Option to award to multiple contractors
  - Down-selection to one contractor team for executing the drilling and testing
- December 2016: Four contract awards announced
  - AECOM team for a proposed site in Pecos County, Texas
  - ENERCON team for a proposed site in Quay County, New Mexico
  - RESPEC team for a proposed site in Haakon County, South Dakota
  - TerranearPMC team for a proposed site in Otero County, New Mexico
- May 2017: Project discontinued
  - "Due to changes in DOE budget priorities, the [DOE] … has initiated a process to effectively end the project immediately." (DOE 2017)

DBFT – Accomplishments

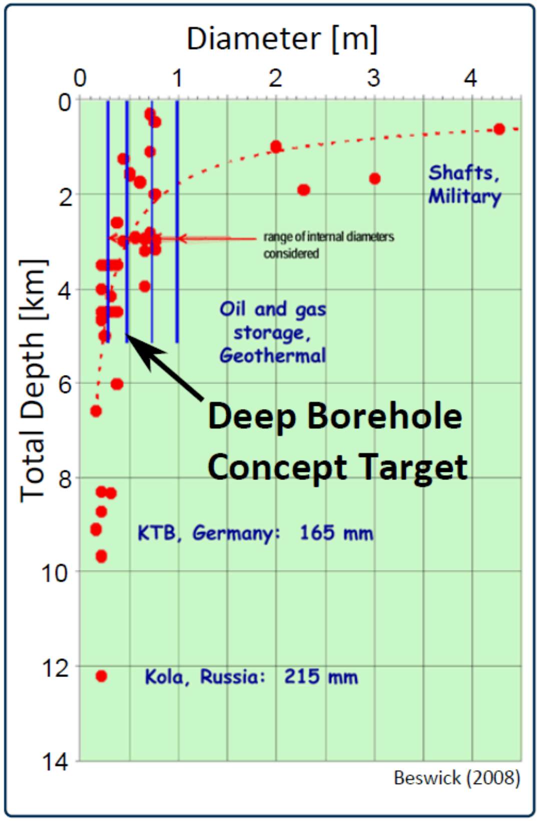
- The DBFT objectives and scope specifically addressed key technologies and data necessary to evaluate the feasibility of the DBD concept, particularly unproven or especially critical components
  - e.g., collecting diagnostic geochemical signatures from deep low-permeability crystalline rocks at possibly elevated temperatures
- This is a lesser scope than is needed to site and fully characterize an actual DBD facility
  - some activities required for DBD have a high technology readiness level (TRL) and therefore did not require explicit demonstration in the DBFT

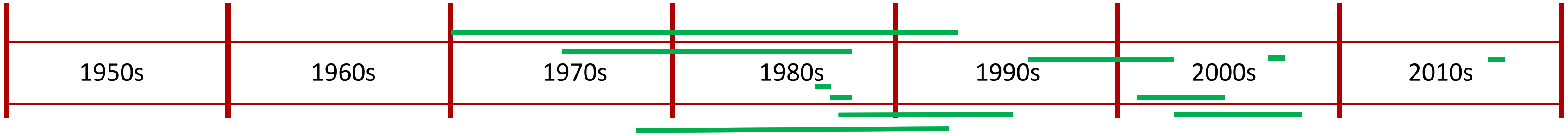
DBFT – Accomplishments

- Despite the premature termination of the DBFT project, significant R&D relevant to the DBFT objectives and to DBD feasibility was performed
  - Recent DBFT Technical Reports
    - DBFT Site Geoscience Guidelines and Data Evaluation
      - Sassani et al. 2016; Perry and Kelley 2017
    - DBFT Conceptual Design
      - SNL 2016a; Hardin et al. 2017a
    - DBFT Laboratory and Borehole Testing Strategy
      - SNL 2016b
    - DBD Safety Case and Safety Assessment
      - Freeze et al. 2016; Freeze et al. 2017

DBFT Objective - Deep Crystalline Drilling

Site	Location	Years	Total Depth [km]	Diam. at TD [in]
Kola	NW USSR	1970-1992	12.2	8½
Fenton Hill	New Mexico	1975-1987	2.9, 3.1, 4.0, 4.4	8¾, 9⅞
Urach	SW Germany	1978-1992	4.4	5½
Gravberg	Central Sweden	1986-1987	6.6	6½
Cajon Pass	Southern California	1987-1988	3.5	6¼
KTB	SE Germany	1987-1994	4, 9.1	6, 6½
Soultz	NE France	1995-2003	5.1, 5.1, 5.3	9⅝
CCSD	E China	2001-2005	2, 5.2	6
SAFOD	Central California	2002-2007	2.2, 4	8½, 8¾
Basel	Switzerland	2006	5	8½
IDDP-2	Iceland	2016-2017	4.7	6



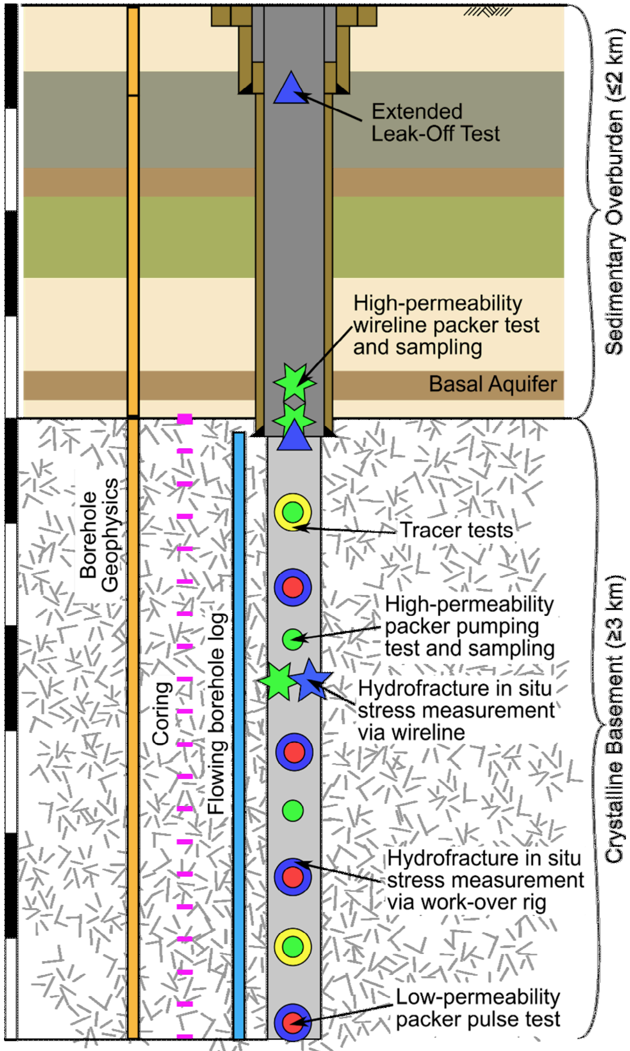


DBFT Objective – Testing and Sampling Plan

SNL (2016b)

- During Drilling (in CB)
  - Coring
  - Borehole Geophysics
  - Sampling
    - Fluid density/temperature/major ions
      - Samples pumped from high-k regions
      - Samples from cores in low-k regions
- After Drilling (in CB)
  - Flowing Fluid Electrical Conductivity (FFEC) Log
  - In Situ Packer Testing
    - Hydrologic and tracer tests
      - Formation hydraulic/transport properties
    - Hydraulic fracturing tests
      - In situ stress (breakouts)
  - Workable at 50 MPa / 150°C / 4 km tubing?

Characterization Borehole (CB)

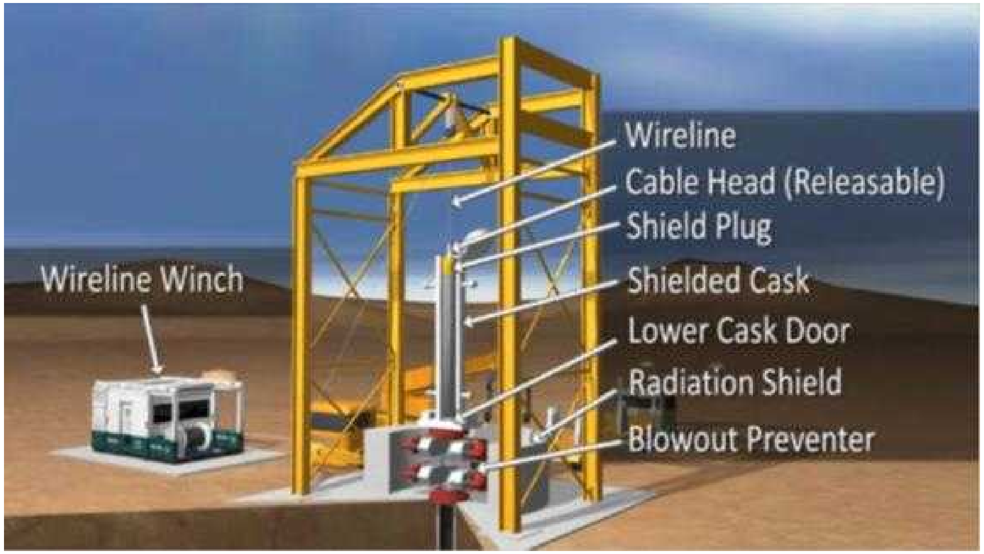


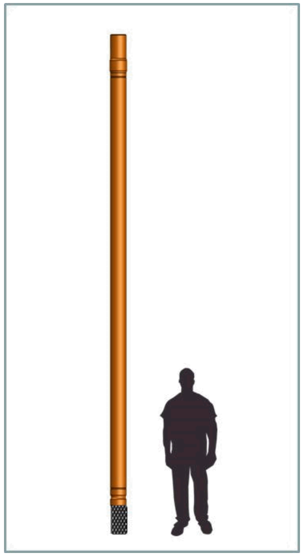
Source: SNL 2016b, Figure 3

DBFT Objective – Safe Package Emplacement

SNL (2015); SNL (2016a)

- Demonstrate downhole package emplacement and retrieval in FTB
  - Wireline Emplacement
    - Design and fabricate test packages
    - Design surface package handling components and facilities
  - Emplacement Demonstration
    - Demonstrate shielded surface operations where practical
    - Lower and retrieve one test package at a time

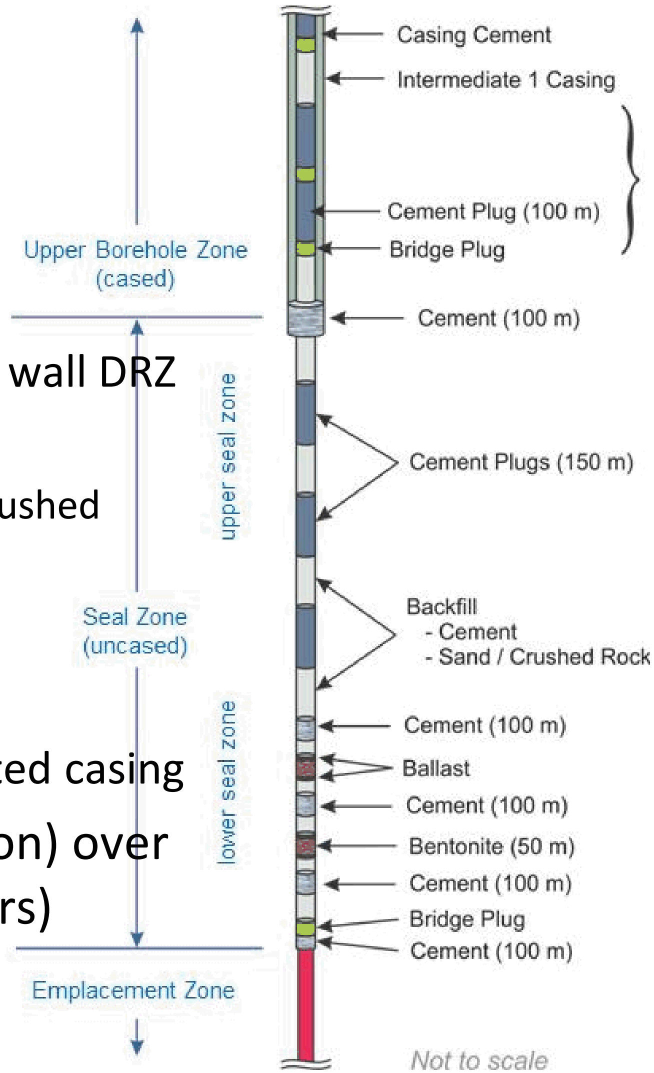




DBFT Objective – Seal Design

Freeze et al. (2016)

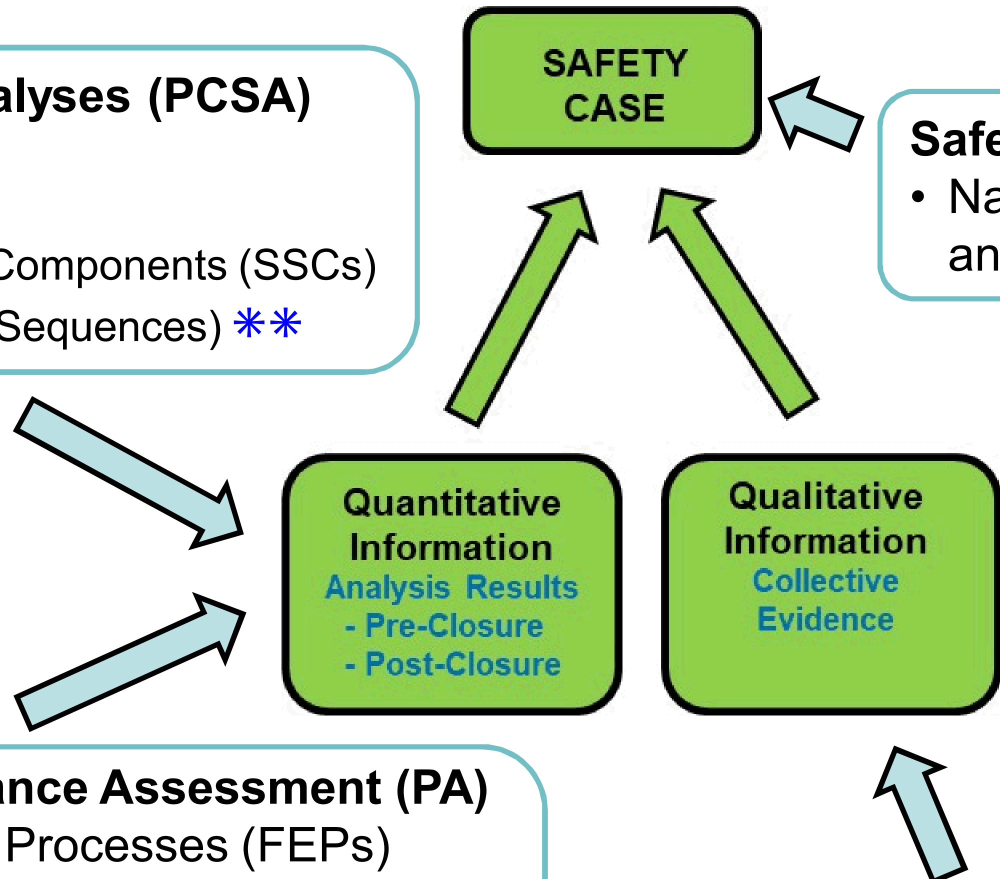
- Preliminary reference design
  - Seal Zone (SZ)
    - Entirely within competent basement rock
    - Seals and plugs emplaced directly against borehole wall DRZ
    - Alternating sequence of materials
      - bentonite seals, cement plugs, ballast (silica sand/crushed rock)
  - Upper Borehole Zone (UBZ)
    - Primarily within sediments
    - Cement plugs and ballast emplaced against cemented casing
  - Seal materials maintain integrity (some degradation) over period of thermally-induced upward flow ($\lesssim$ 500 yrs)
- Other potential sealing methods
  - Ceramic plugs
  - Rock welding



DBFT Objective – Safety Case

Pre-Closure Safety Analyses (PCSA)
- Transportation Safety
- Operational Safety
  - Structures, Systems, Components (SSCs)
  - PCSA Model (Activity Sequences) ✳✳

Safety Strategy
- National Policy and Regulations

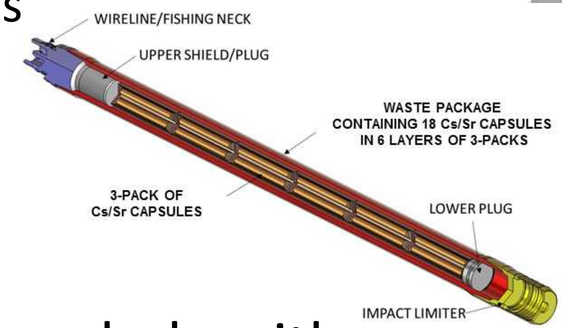


Post-Closure Performance Assessment (PA)
- Features, Events, and Processes (FEPs)
- Scenario Development
- PA Model [PFLOTRAN]
  - Undisturbed (Nominal) Scenario ✳✳
  - Disturbed (Stuck Package) Scenario ✳✳

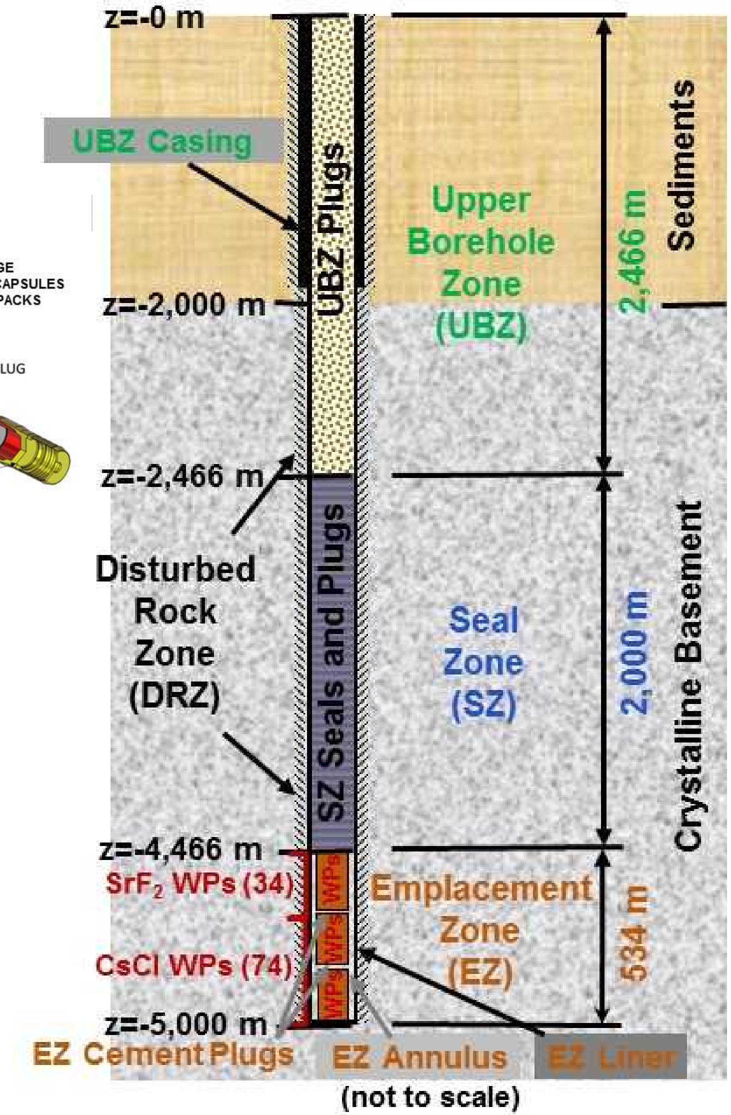
Confidence Enhancement
- Natural Analogs
- Independent Evidence

DBD Safety Case Reference Design

- 108 waste packages (WPs)
  - 1936 Cs and Sr capsules
  - 18 capsules per WP
    - 6 layers of “3-packs”
  - WP length = 4.76 m



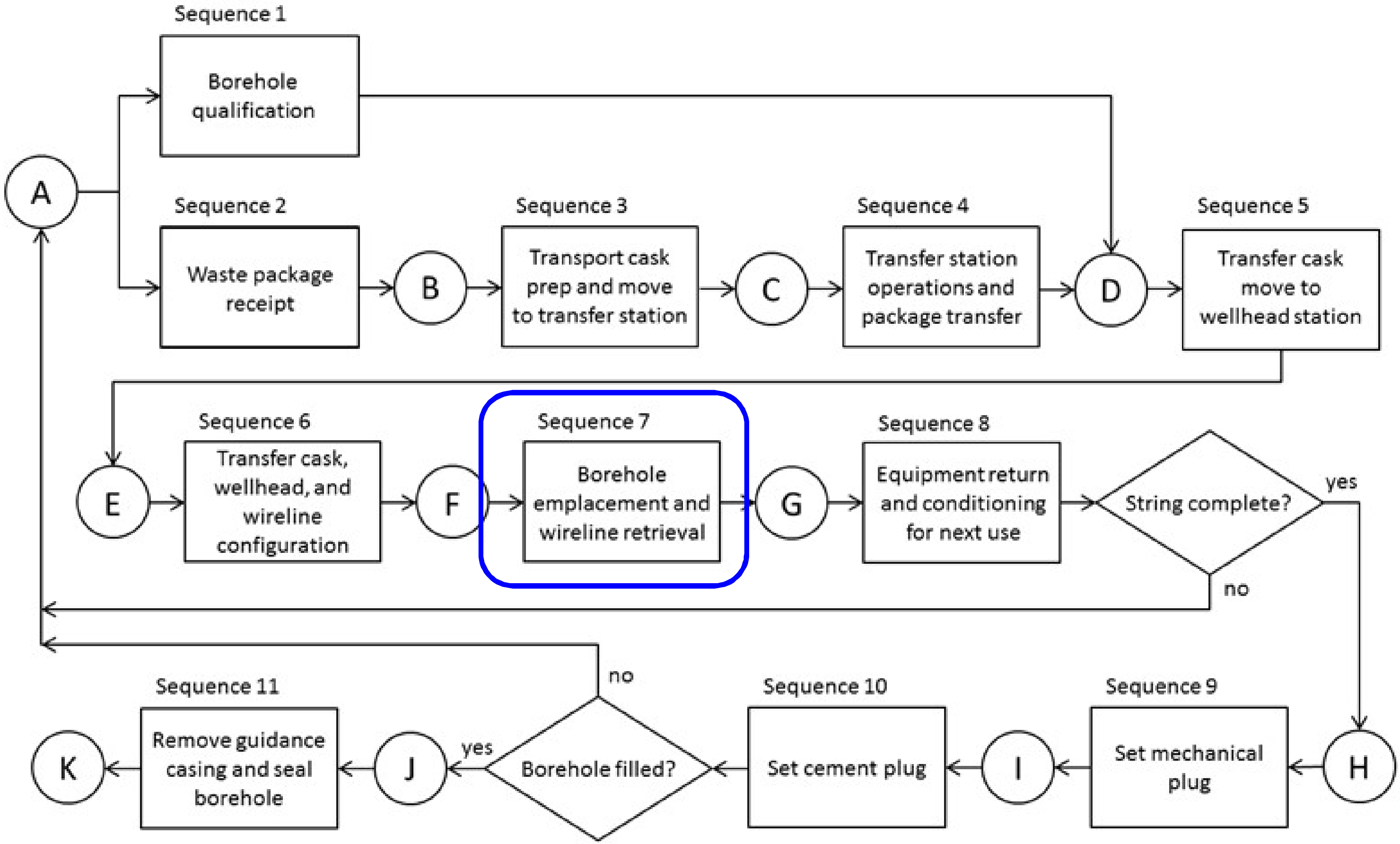
- All WPs fit in a single borehole with a 534-m Emplacement Zone (EZ)
  - bottom-hole diameter of 12.25 in (31 cm)
- WPs are lowered, one at a time, on wireline inside a removable guidance casing
- SNF reference design and safety case
  - Arnold et al. (2013. App. A); Freeze et al. (2013)



DBD Pre-Closure Safety Analysis (PCSA)

Hardin et al. (2017a)

- Identification of activity sequences and risk factors for disposal operations
- PCSA modeling (fault trees, event trees, and probability estimates)

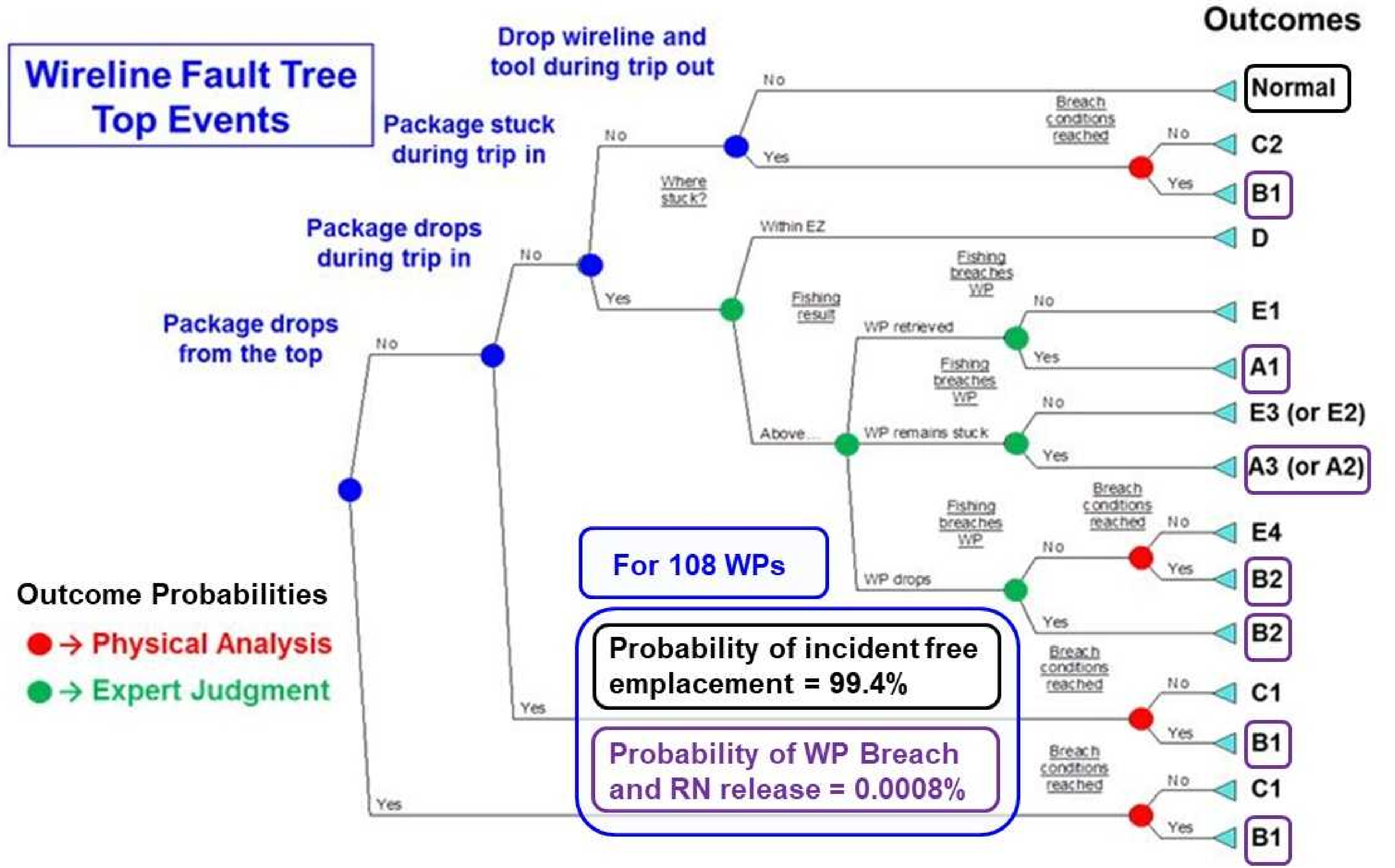


Source: Hardin et al. 2017a, Figure 1

DBD PCSA – Wireline Emplacement Event Tree

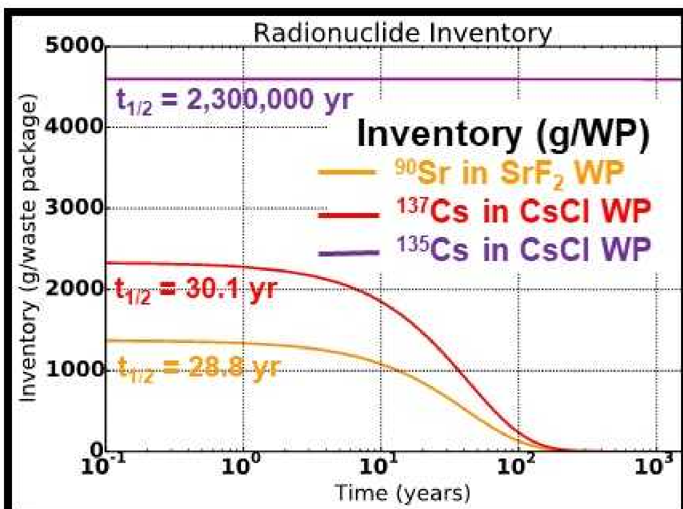
Sandia National Laboratories

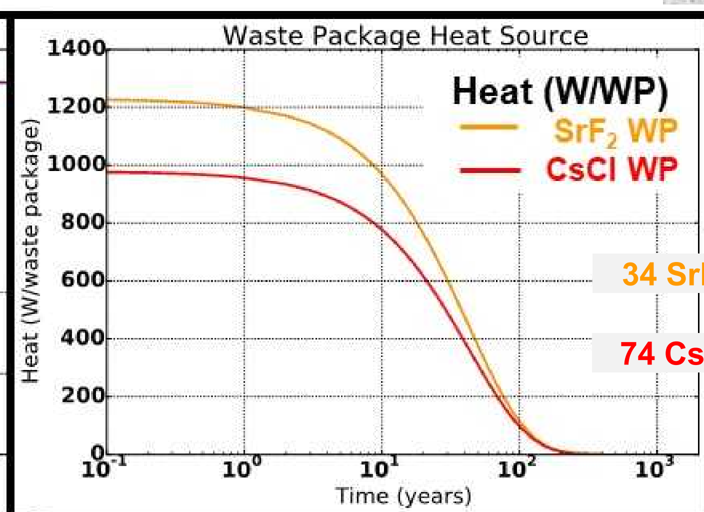
Freeze et al. (2016, Section 5.1), SNL (2016b)

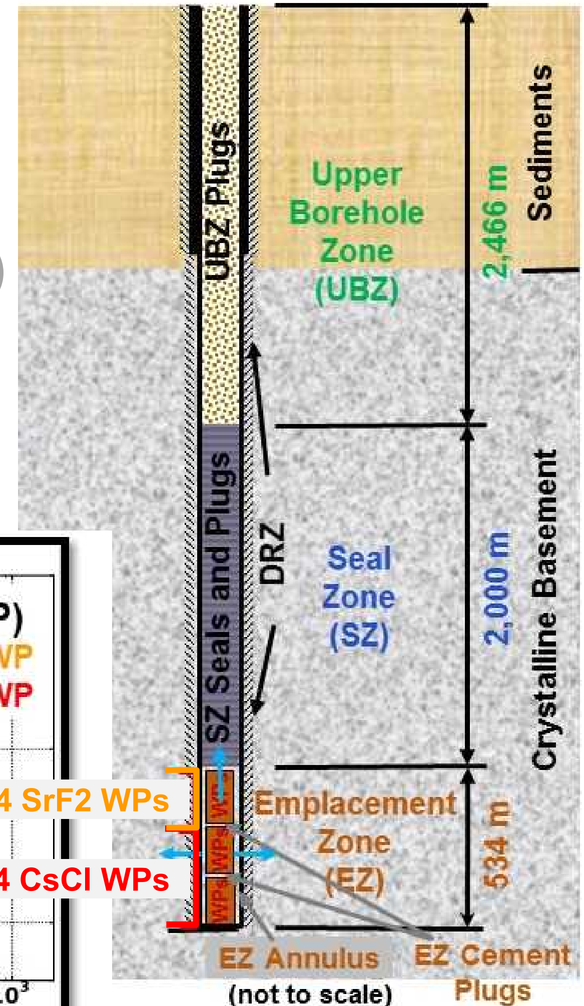


DBD Post-Closure PA – Nominal Scenario

- Radionuclide Inventory (SNL 2014b)
  - Time 0 = Year 2050
  - 1335 CsCl capsules @ ~18 per WP = 74 Cs WPs
    - 2050 Thermal output (avg.) ~ 972 W / WP
    - 2050 Inventory = ^{137}Cs (129 g), ^{135}Cs (258 g), ^{137m}Ba (0 g)
  - 601 SrF_2 capsules @ ~18 per WP = 34 Sr WPs
    - 2050 Thermal output (avg.) ~ 1242 W / WP
    - 2050 Inventory = ^{90}Sr (75 g), ^{90}Y (0 g)

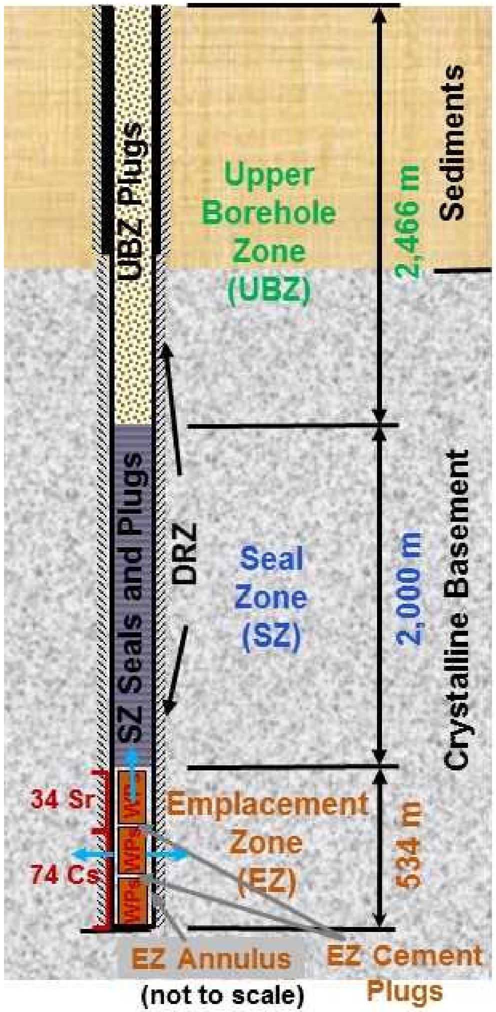






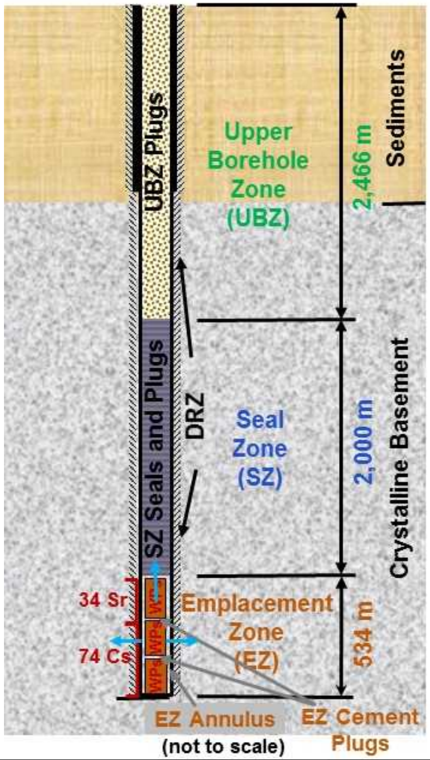
DBD Post-Closure PA – Nominal Scenario

- Emplacement Zone
  - Decay heat effects:
    - Thermal perturbation produces thermally-driven upward groundwater flow in borehole and DRZ (for < ~500 yrs)
    - Heat conduction in surrounding crystalline basement rock
  - Radionuclide dissolution and transport in groundwater
    - No credit for WF or WP integrity
    - Advection, diffusion, and decay (no sorption in EZ)
- Post-Closure Release Pathways
  - Radionuclide transport in groundwater by advection (thermally-induced upward flux), diffusion (upward and lateral), sorption, and decay
    - Up borehole through seals / DRZ
    - To host rock surrounding EZ
      - No regional flow gradient in crystalline basement
- Biosphere (dose) = not modeled



DBD Post-Closure PA – Nominal Scenario

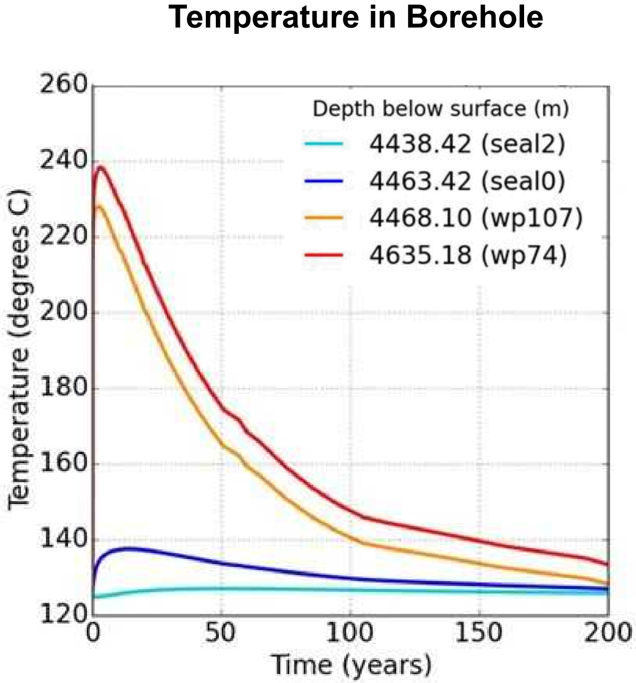
- Crystalline Basement
  - Sparsely fractured granite
  - Heat flux = 60 W/m^2 at 6000 m
    - Thermal gradient ~ 25°C/km
    - Ambient temperature
      - 10°C at surface
      - 125°C to 140°C in EZ
  - Reducing geochemical conditions at depth
- Sediments = not modeled



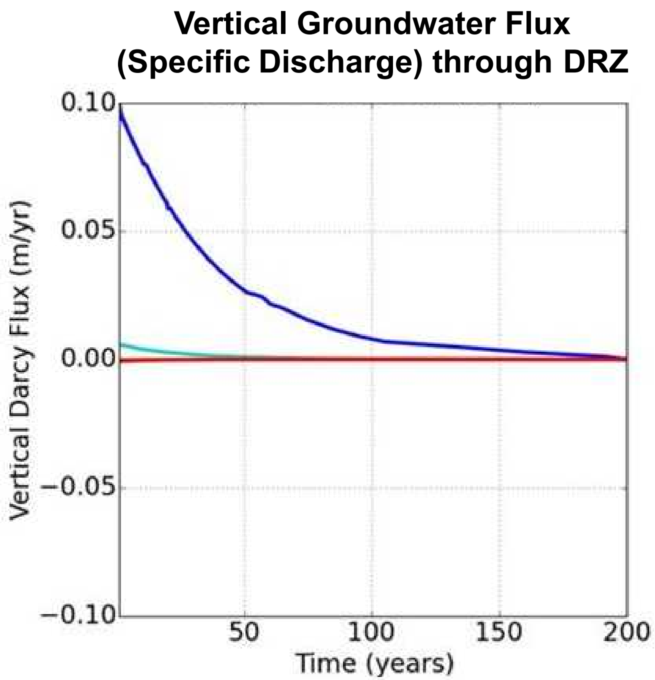
Material	Perm. (m^2)	Porosity (-)	Diffusion Coeff. (m^2/s)	Thermal Cond. (W/m·K)	Heat Capacity (J/kg·K)	Sr K_d (ml/g)	Cs K_d (ml/g)
EZ Annulus	1×10^{-12}	0.99	9.9×10^{-10}	0.58	4192	0	0
Cement Plug	1×10^{-18}	0.175	3.1×10^{-11}	1.7	900	0	0
Bentonite Seal	1×10^{-18}	0.45	2.0×10^{-10}	1.3	800	1525	560
Ballast	1×10^{-14}	0.20	4.0×10^{-11}	2.0	800	0	0
Crystalline Rock	1×10^{-18}	0.005	1.0×10^{-12}	2.5	880	1.7	22.5
DRZ	1×10^{-16}	0.005	1.0×10^{-12}	2.5	880	1.7	22.5

Nominal Scenario Deterministic Results – Thermally-Induced Upward Flow

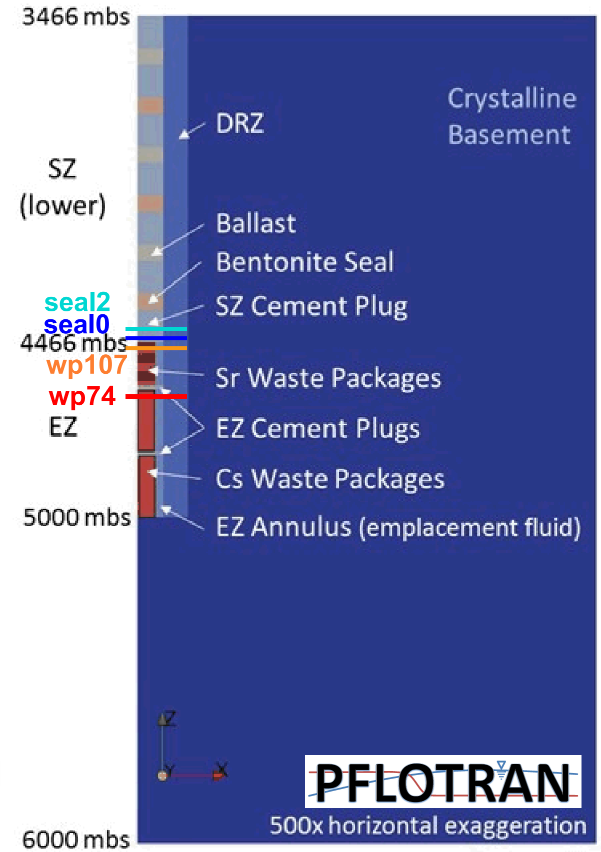
- Short-term temperature increase of ~100°C in EZ (from waste decay)
- Upward Darcy flux (specific discharge)
  - Highest in EZ annulus, overlying seal diverts flux to DRZ
    - (0.006 m/yr)(50 yrs)/(0.005 porosity) ~ 60 m
    - advection is even less with sorption



from Freeze et al. (2016), Figure 5-4



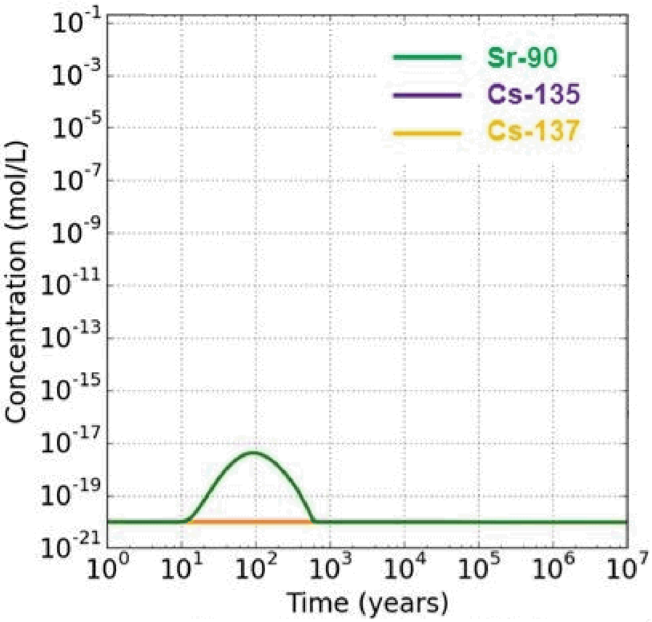
from Freeze et al. (2016), Figure 5-5



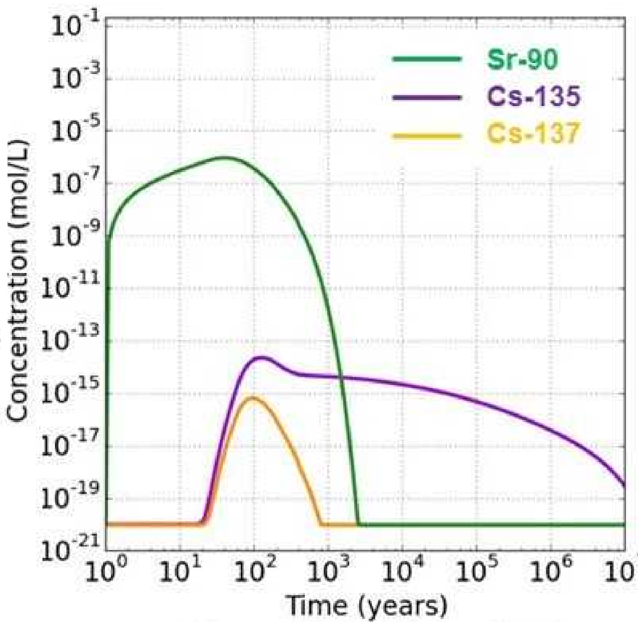
Nominal Scenario Deterministic Results – Dissolved Concentrations (mol/L)

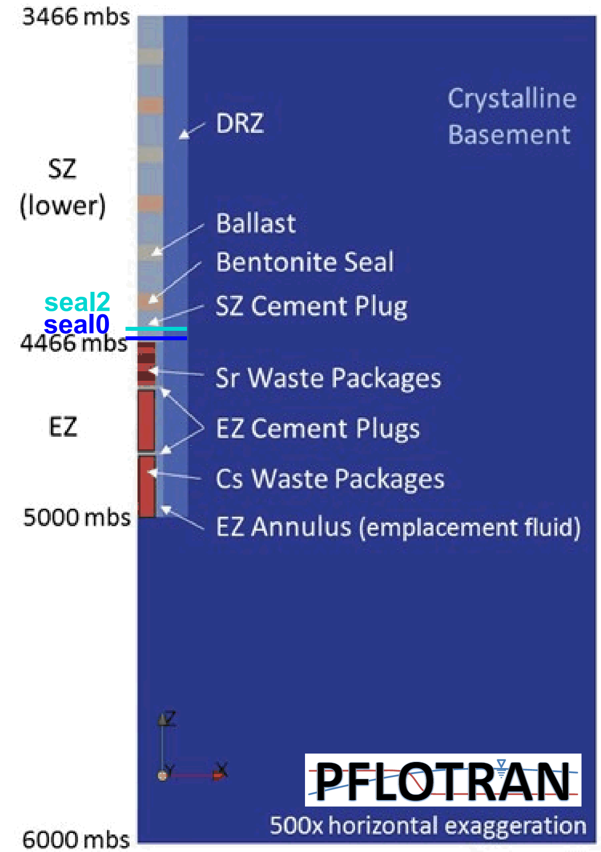
- Concentrations in SZ cement plug at 2 elevations, shown below
- Concentrations in DRZ at same elevations are similar

In SZ Cement Plug at z=4438.4 m (seal2)



In SZ Cement Plug at z=4463.4 m (seal0)

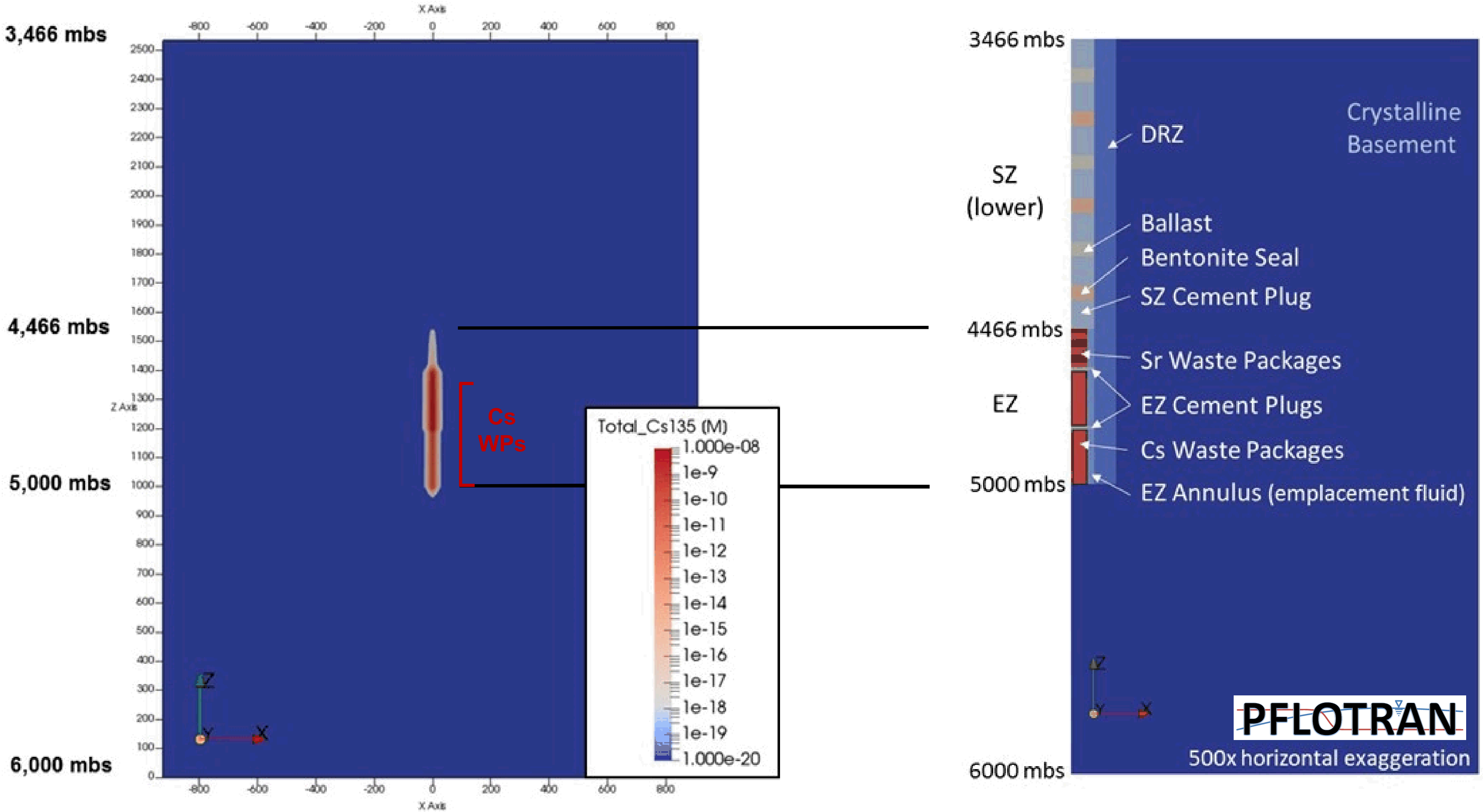




from Freeze et al. (2016), Figure 5-6

Nominal Scenario Deterministic Results – ^{135}Cs Dissolved Concentration (mol/L)

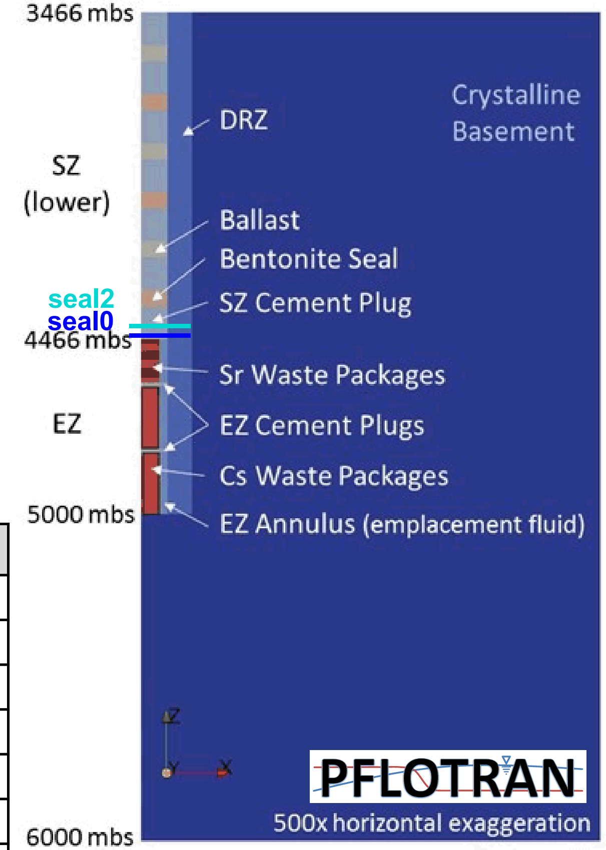
- Dissolved Concentration of ^{135}Cs at 10,000,000 years
  - Minimal migration beyond Emplacement Zone



from Freeze et al. (2016), Figure 5-8

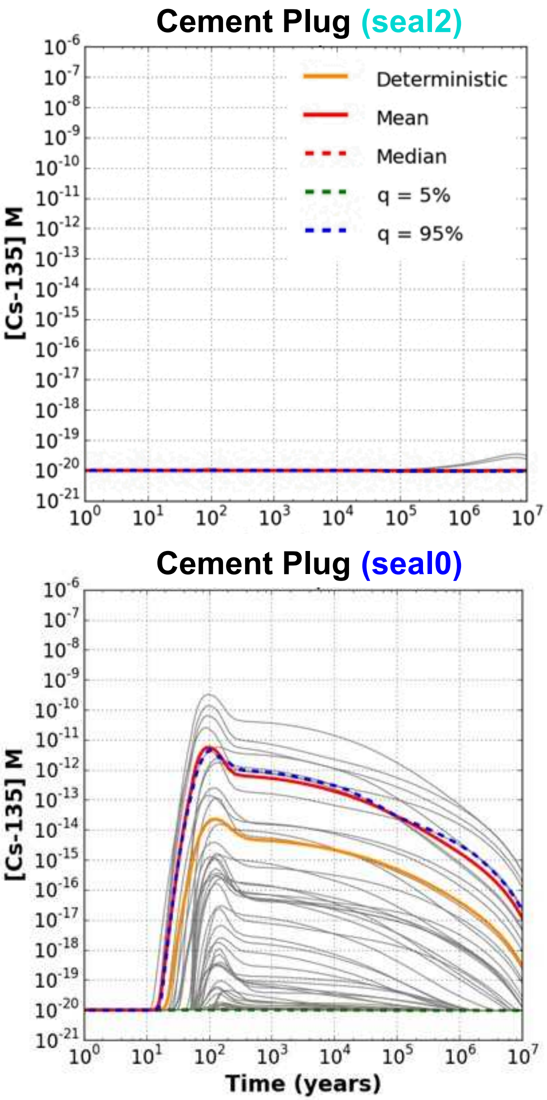
Nominal Scenario Probabilistic Results

- 100 realizations with 12 sampled parameters
- Sensitivity (Spearman rank correlation) to maximum ^{135}Cs concentration
  - calculated at several locations
  - shown at seal0 and seal2 in the cement plug

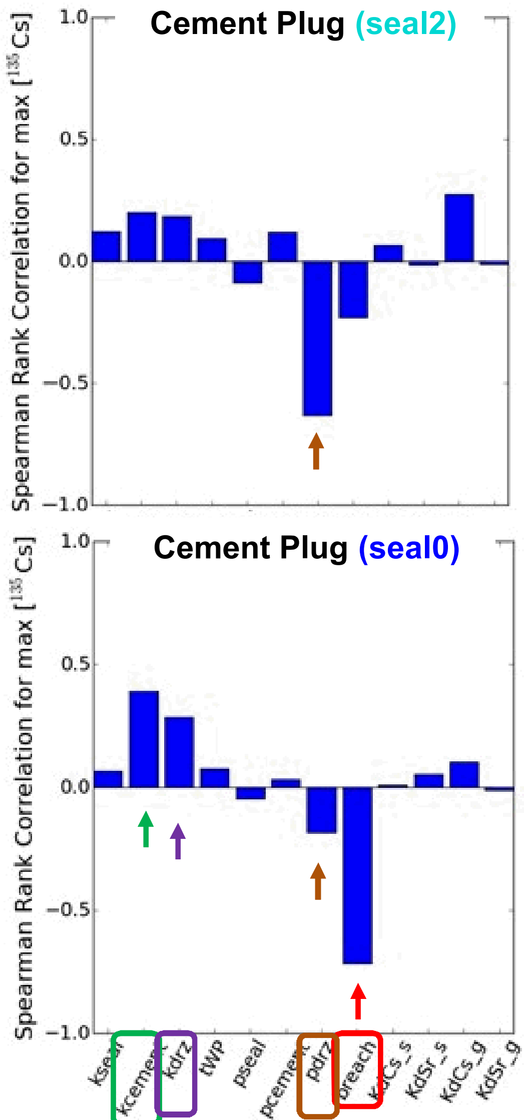


Parameter	ID	Range	Units	Distribution
Bentonite Permeability	kseal	$10^{-20} – 10^{-16}$	m^2	log uniform
Cement Permeability	kcement	$10^{-20} – 10^{-16}$	m^2	log uniform
DRZ Permeability	kdrz	$10^{-18} – 10^{-15}$	m^2	log uniform
WP Tortuosity	tWP	0.01 – 1.0	--	log uniform
Bentonite Porosity	pseal	0.40 – 0.50	--	uniform
Cement Porosity	pcement	0.15 – 0.20	--	uniform
DRZ Porosity	pdrz	0.005 – 0.01	--	uniform
WP Breach Time	breach	1 – 100	yr	uniform
Cs K_d Bentonite	KdCs_s	120 – 1000	ml/g	uniform
Sr K_d Bentonite	KdSr_s	50 – 3000	ml/g	uniform
Cs K_d Crystalline/DRZ	KdCs_g	5 – 40	ml/g	uniform
Sr K_d Crystalline/DRZ	KdSr_g	0.4 – 3	ml/g	uniform

Nominal Scenario Probabilistic Results – 135Cs Dissolved Concentration (mol/L)



from Freeze et al. (2016), Figure 5-9

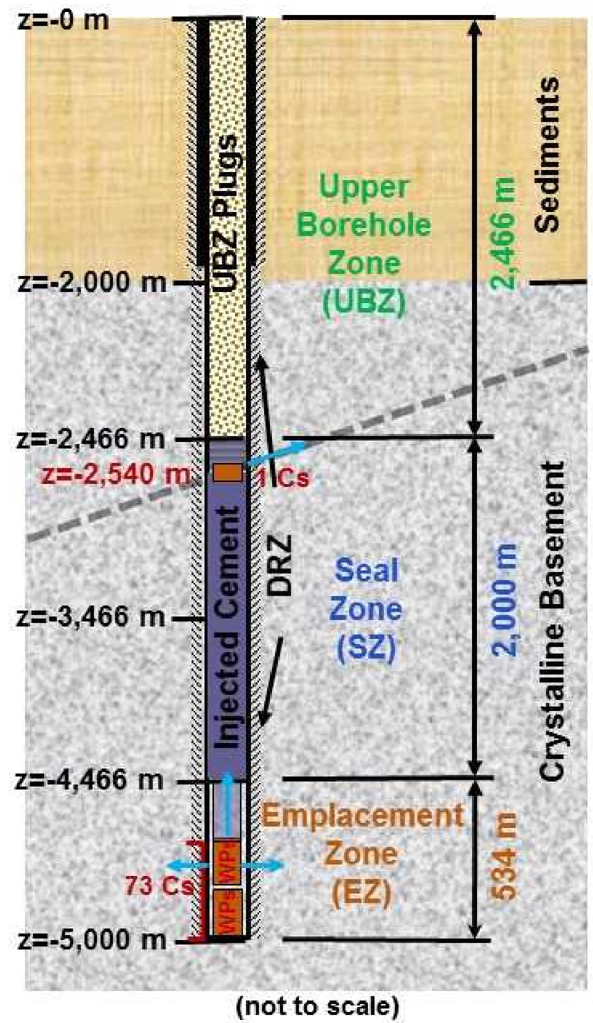


from Freeze et al. (2016), Figure 5-11

- Key parameters for seal2
  - Similar to seal0 but rank correlations not as "robust" due to minimal number of realizations with "non-zero" max. concentration
- Key parameters for seal0
  - WP breach time
  - Cement plug permeability
  - DRZ permeability
  - DRZ porosity

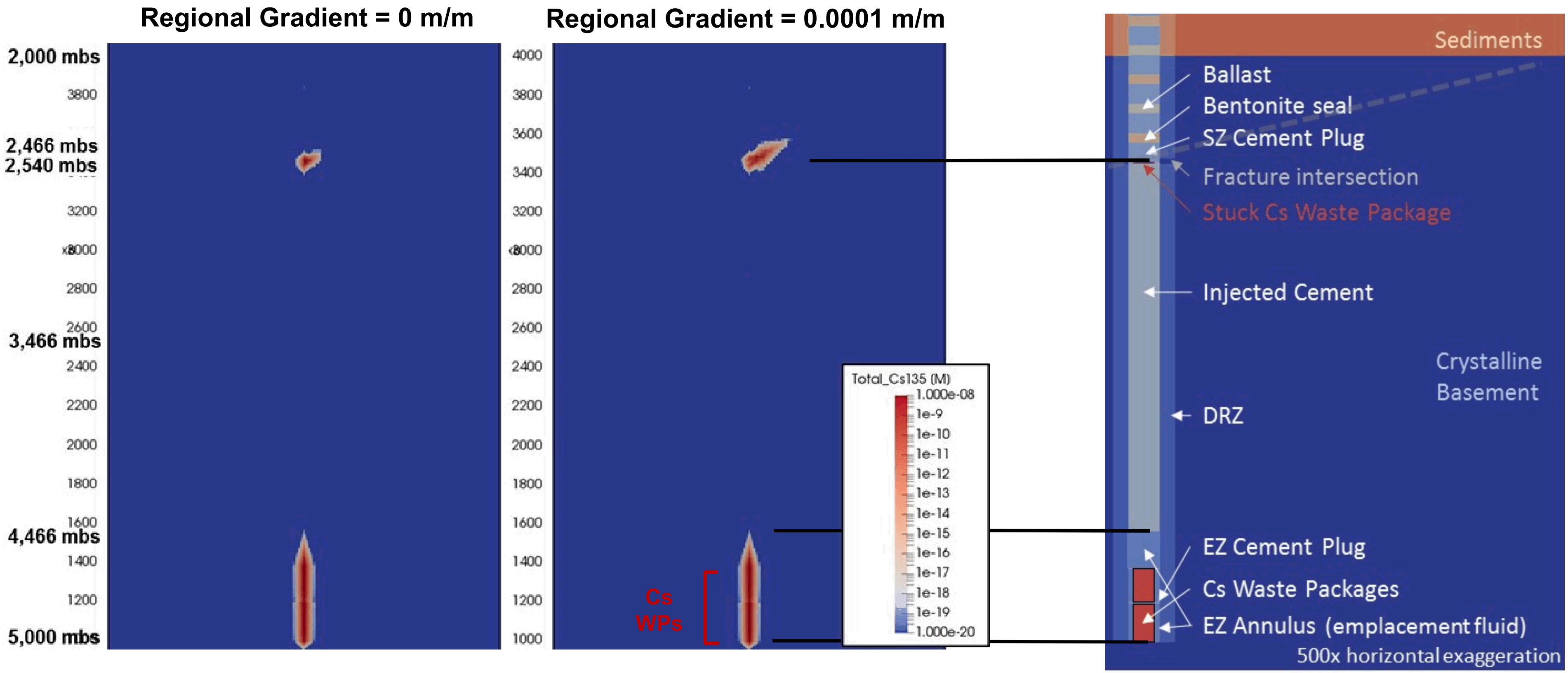
DBD Post-Closure PA – Disturbed Scenario

- Post-Closure Release Pathways
  - Undisturbed pathways from nominal scenario
  - WP (74th Cs) stuck in borehole-intersecting fracture
    - fracture: $k = 10^{-14}\ m^2$, $D_e = 1 \times 10^{-12}\ m^2/s$
    - cement injected below stuck package
    - SZ and UBZ sealed above stuck package
  - Regional flow gradient in crystalline basement
    - case 1 = 0 m/m (same as nominal scenario)
    - case 2 = 0.0001 m/m
  - Other disturbed scenarios (not yet examined)
    - Seismic, igneous, human intrusion



Disturbed Scenario Deterministic Results – ^{135}Cs Dissolved Concentration (mol/L)

- Dissolved Concentration of ^{135}Cs at 10,000,000 years
  - Advection of ^{135}Cs up fracture (~200 m) due to regional gradient
  - ^{135}Cs still remains well below sedimentary overburden



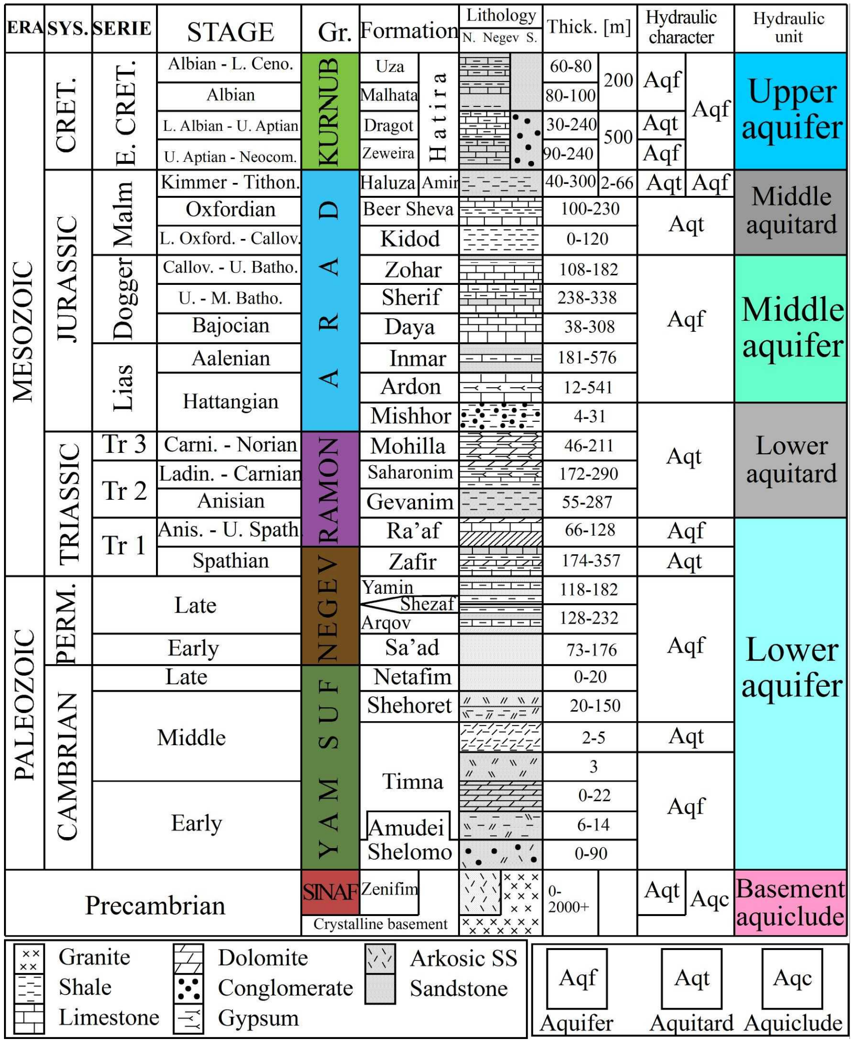
from Freeze et al. (2017), Fig. 9

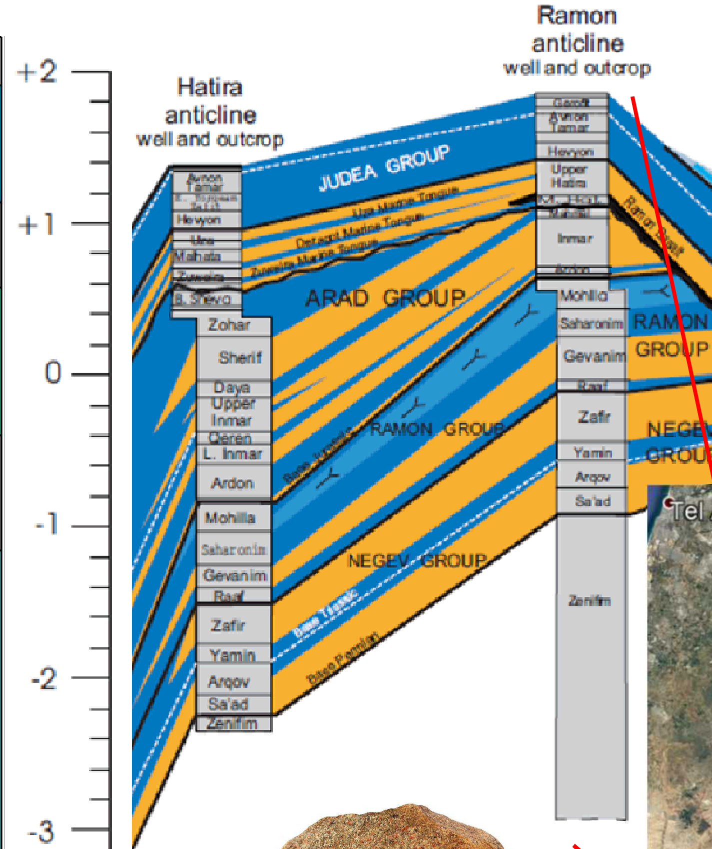
PFLOTRAN

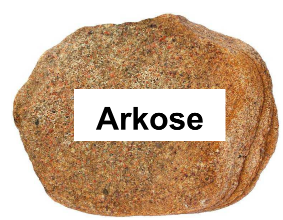
DBD Siting Guidelines

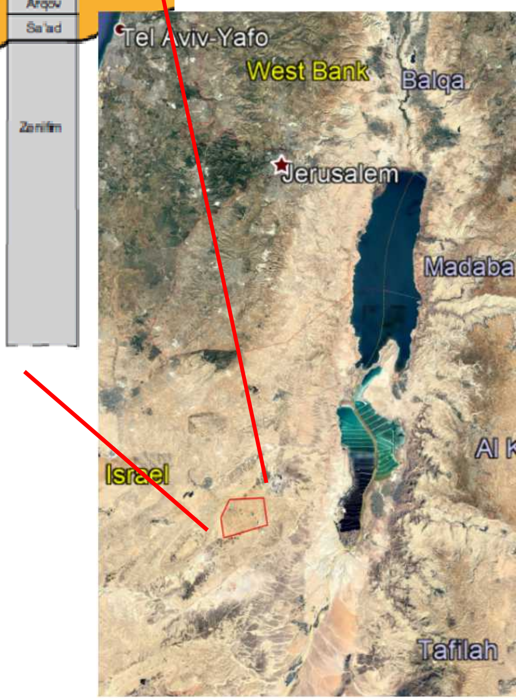
- Developed based on historical guidelines and regulatory criteria for mined repositories
  - Include technical, logistical, and socio-political factors
- Sites that exhibit stronger combinations of favorable attributes are more likely to provide long-term isolation of radionuclides in the deep geologic environment
  - However, it is not necessary, nor likely, for a site to meet all of the guidelines. A site that meets only certain guidelines may still be able to safely isolate waste.
- Site evaluation typically also considers the attributes of the engineered components of the system, and how they would be expected to function in conjunction with the site conditions

DBD Site Evaluation



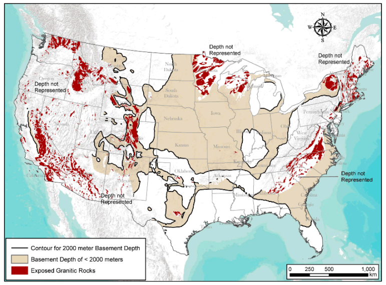






DBD Siting Guidelines – Technical Factors

Freeze et al. (2016, Section 3.2.1.2)

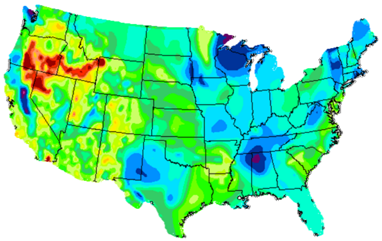


- Depth
  - crystalline basement ≤ 2,000 m
- Nature of Crystalline Basement Fabric and Stress State
  - lack of steeply dipping foliation or layering
  - low horizontal differential stress
- Absence of Regional Structures, Basement Shear Zones, or Other Tectonic Features
  - within 50 km of site
- Lack of Groundwater Flow at Depth
  - conditions/features might include, for example:
    - lack of significant topographic relief that would drive deep recharge
    - evidence of ancient groundwater at depth
    - data suggesting high-salinity groundwater at depth

DBD Siting Guidelines – Technical Factors

Freeze et al. (2016, Section 3.2.1.2)

- Favorable Geochemical Environment at Depth
  - high-salinity, increasing with depth to produce stable density stratification
  - geochemically-reducing conditions
- Low Geothermal Heat Flux
  - $\leq 75\ mW/m^2$



- Low Probability of Seismic/Tectonic/Volcanic Activity
  - less than 2% probability within 50 years of peak ground acceleration > 0.16 g
  - distance to Quaternary age volcanism or faulting > 10 km
- Absence of Natural Resources Potential or Interfering Conditions
  - resource exploration and/or production might include, for example, drilling or mining for petroleum, minerals, or water
  - interfering conditions might include, for example, wastewater disposal by deep well injection, CO_2 injection, strategic petroleum reserve sites

Deep Borehole Disposal - Summary

- Recent studies have identified no fundamental flaws regarding safety or implementation of the DBD concept
  - Preliminary DBD safety case analyses suggest:
    - Pre-closure – low probability of operational failures
    - Post-closure – robust waste isolation for >1,000,000 years (^{129}I, ^{135}Cs)
- Additional R&D is necessary to address several open issues (Freeze et al. 2016, NWTRB 2016):
  - Drilling feasibility and borehole breakout
  - Operational feasibility
  - Waste form and waste package longevity
  - Seal (and DRZ) characteristics and evolution
  - Deep subsurface characterization
  - Effects of gas generation (from metal corrosion), microbes, and/or radiolysis

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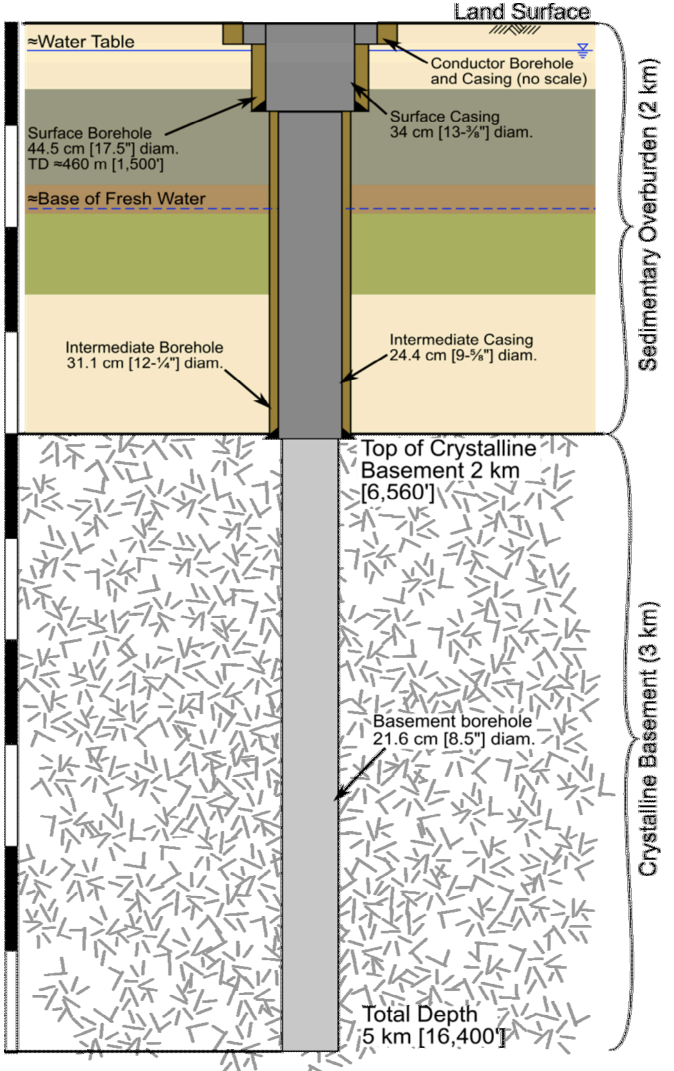
Backup Slides

DBFT – Characterization Borehole (CB)

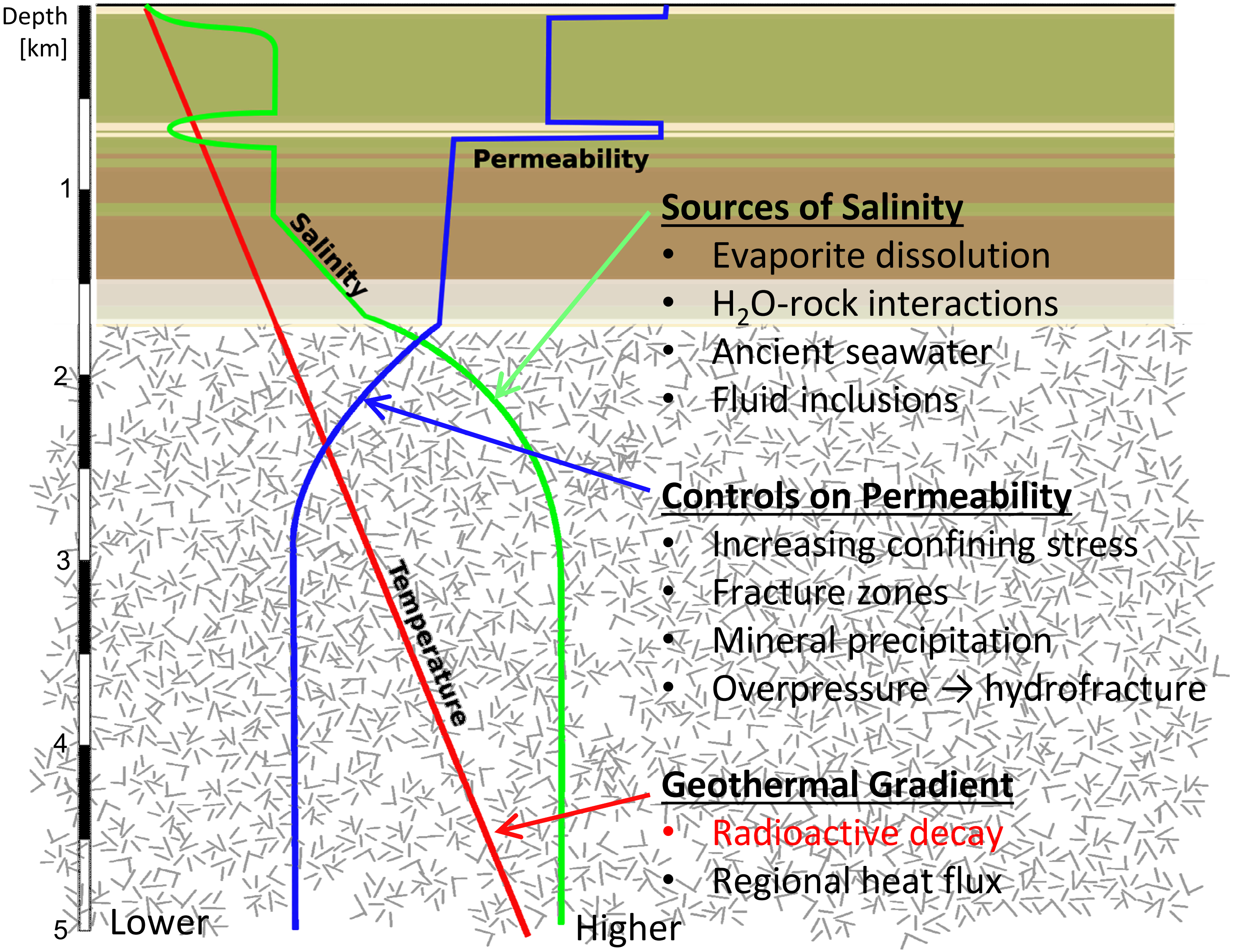
- Drill and case sedimentary section
  - minimal testing (not DBFT focus)
- Drill crystalline basement section
  - logging while drilling
  - borehole geophysics
  - rock samples (coring, cuttings/rock flour)
  - pore fluid samples (high-k and low-k zones)
  - testing while drilling (hydrofracture tests)
  - flowing borehole log
- Test crystalline basement section
  - packer shut-in tests (low-k zones)
  - packer pumping tests (high-k zones)
  - tracer tests



Kuhlman et al. (2015)

Dark gray represents permanent casing or liner, olive represents cemented annulus, light gray represents uncemented borehole.

DBD Concept – Geologic THC 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

Deep Borehole Field Test – CB Sampling

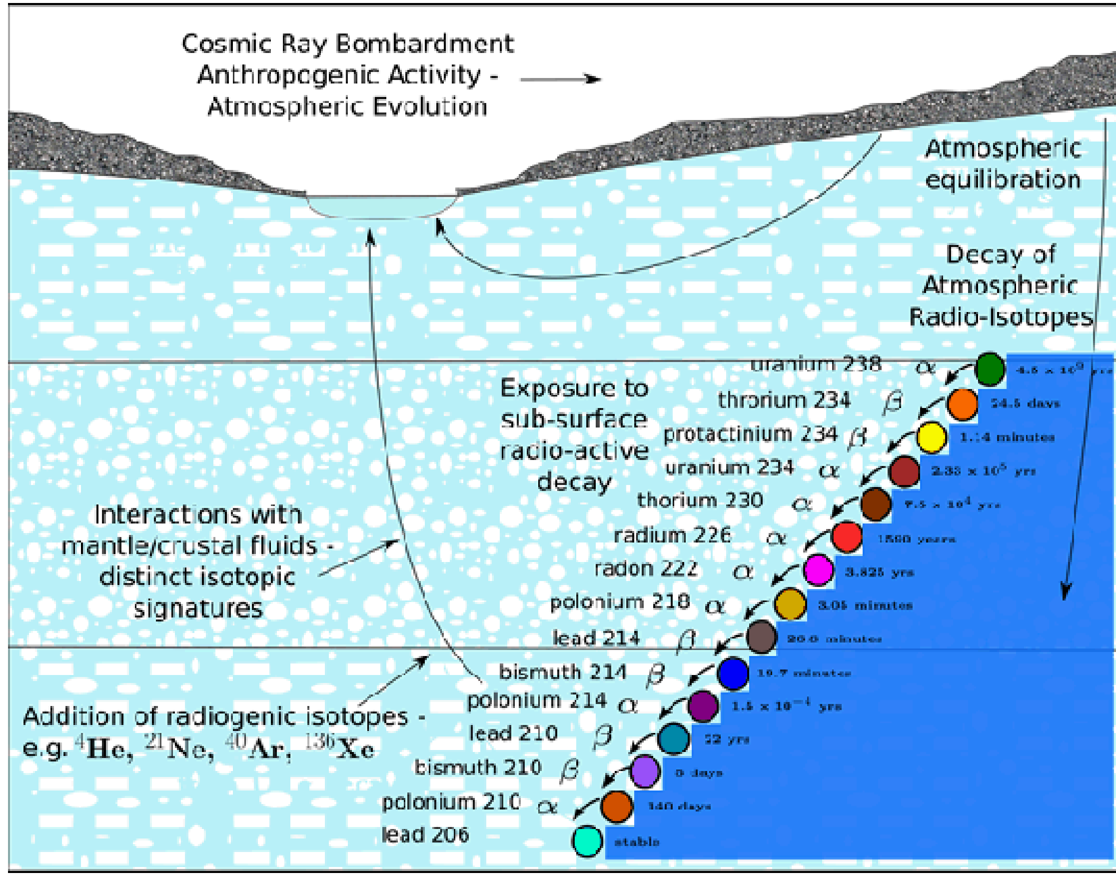
Fluid/Gas Samples	Solids Samples
Drilling fluid (surface samples, also gas separator)	Cuttings
Porewater (from core: centrifuged, squeezed, flushed)	Cores (up to 150 m)
Borehole fluid (wireline sampler)	Preserved cores (a few m)
Pumped groundwater (zone isolated by packers)	

Analyte	Sample Requirement
Water stable isotopes (e.g., ^{2}H, ^{18}O)	1 mL
Drilling fluid tracer (e.g., fluorescein or iodide)	A few mL
Major anions/cations (e.g., Na^{+}, Cl^{-}, Ca^{2+}, SO_4^{2-})	10 mL
Trace elements (e.g., Li, Sr, U)	10 mL
Dissolved inorganic and total carbon	50 mL
Other isotopic ratios for dissolved species (e.g., Li, C, N, S, Sr, U)	100's of mL
Radiogenic in situ tracers (e.g., ^{3}He, ^{4}He, ^{40}Ar)	Whole-rock samples and/or 1 to 10 L
Cosmogenic tracers (e.g., ^{81}Kr)	100 L
Scarce in situ fission products (e.g., ^{36}Cl, ^{129}I)	100's of L
Scarce terrigenic and in situ tracers (e.g., ^{3}He)	100's of L
Rare inert cases (e.g., Ne, Xe isotopes)	100's of L

Source: Hardin et al. 2017b

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

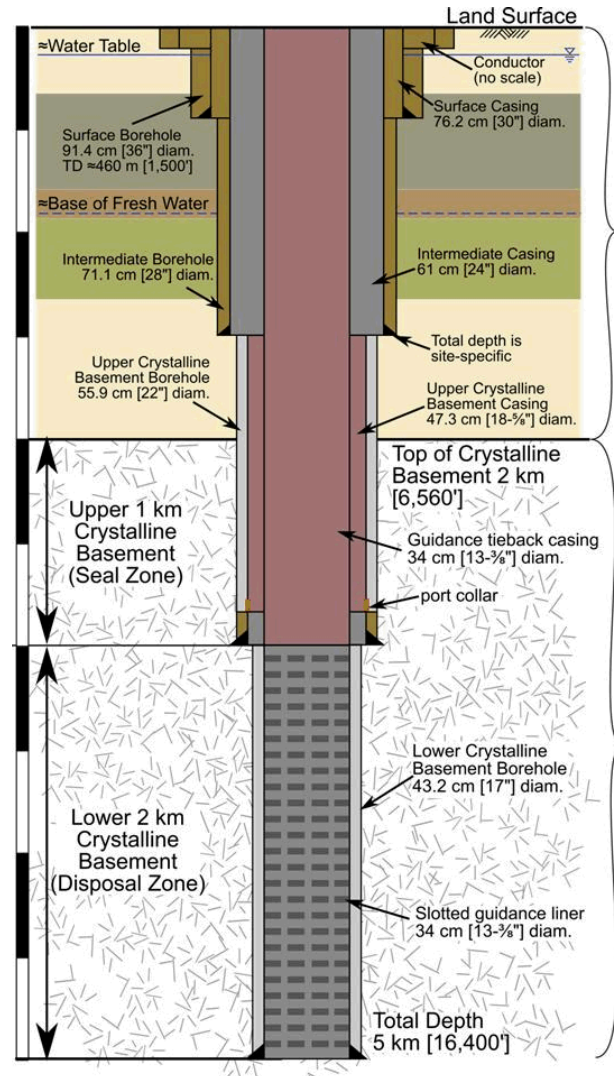


Fluid Sample Quality + Quantity *will be a Focus!*

Repeatability across drilling, packer & core samples?

DBFT – Field Test Borehole (FTB)

- Drill and case sedimentary section
- Drill upper crystalline basement (Seal Zone)
  - minimal, confirmatory testing
  - install temporary liner
    - liner to be removed after package emplacement for effective seal
- Drill lower crystalline basement (Emplacement Zone)
  - install slotted/perforated guidance liner
- Install temporary guidance tieback casing
  - constant diameter emplacement pathway



Kuhlman et al. (2015)

Dark gray represents permanent casing or liner, olive represents cemented annulus, light gray represents uncemented borehole, pink represents casing/liner to be removed.