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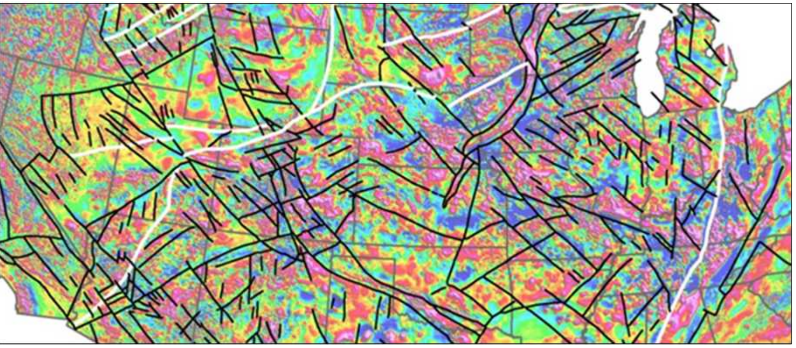

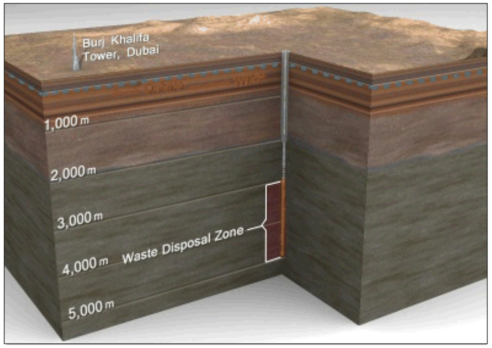

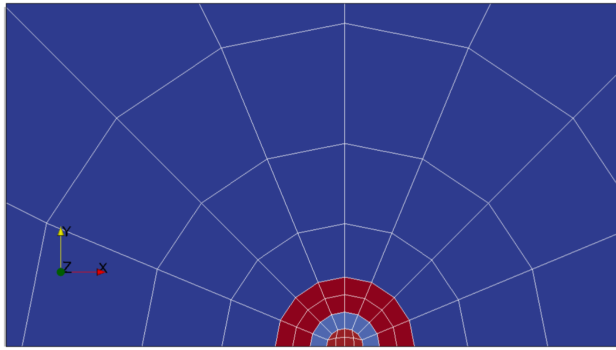

Deep Borehole Disposal and Field Test

Patrick V. Brady
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Albuquerque, NM USA

CNPE, Beijing CHINA
November 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-mission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

CNPE, Beijing 10/2014

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DOE Borehole Science Needs Workshop, Albuquerque 11/2014

US Borehole Field Test:

US Nuclear Waste Technical Review Board Workshop, Washington 10/2015

Rugby, North Dakota Site Selected/Rejected, 02/2016

Spink, South Dakota Site Selected/Rejected, 06/2016

Site selection re-started

TODAY
CNPE, Beijing 11/2016

Team Members

R. J. MacKinnon – Head

E. L. Hardin – Waste Emplacement

D. Sassani – Site Selection

K. Kuhlman – Site Characterization

G. Freeze – Performance Assessment

+ F. Gibb/K. Travis (Sheffield), F. Perry (Los Alamos National Labs), P. Brady, J. Cochran, and others.

Presentation Overview

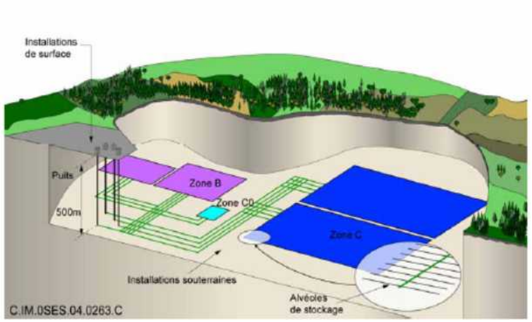
- Deep Borehole Background
  - History, Progress
- Science Needs for Deep Boreholes
  - Necessary science vs. desired science.
- US Deep Borehole Field Test (DBFT) Background
  - Site selection
  - Site Characterization
  - Progress/Obstacles

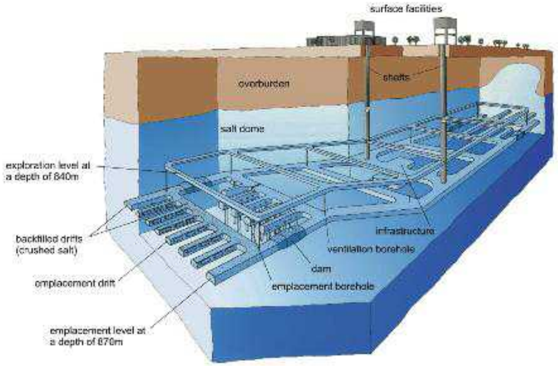
Deep Borehole Overview

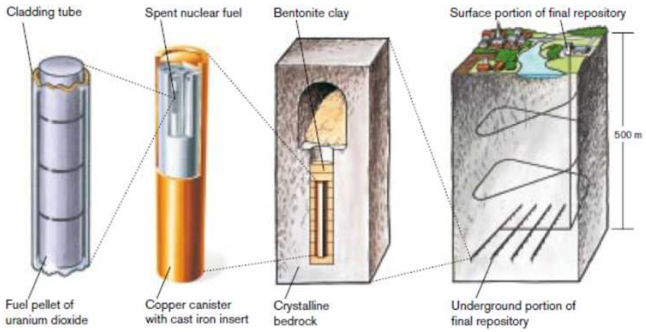
Deep Geologic Disposal Remains an Essential Element of Nuclear Waste Management

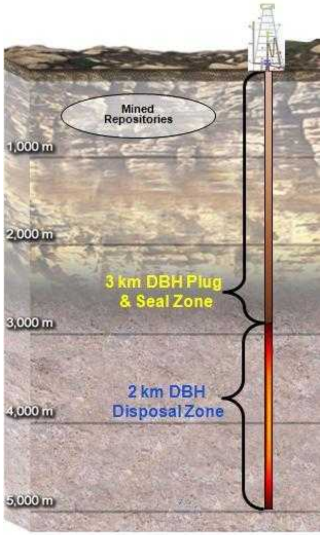
"The conclusion that disposal is needed and that deep geologic disposal is the scientifically preferred approach has been reached by every expert panel that has looked at the issue and by every other country that is pursuing a nuclear waste management program."

Blue Ribbon Commission on America's Nuclear Future, 2012









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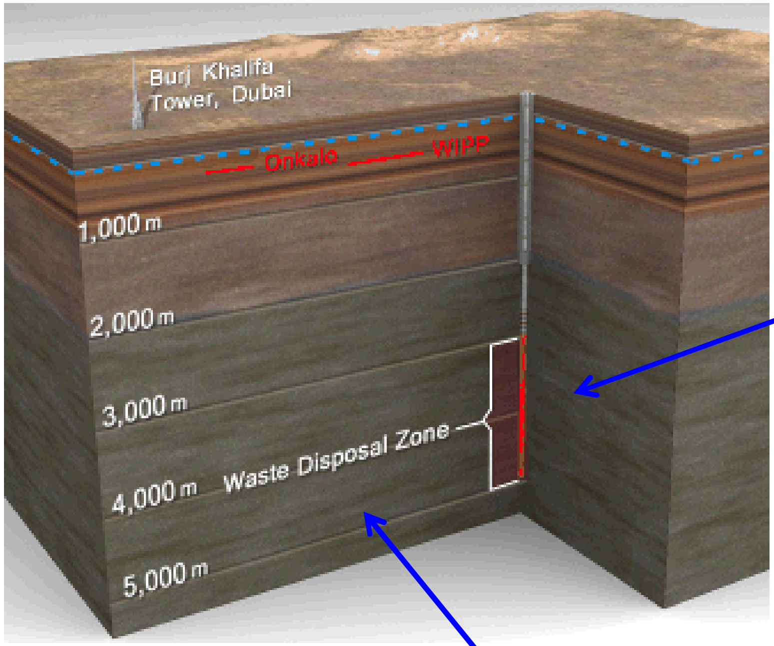
Long-Term Waste Isolation (hydrogeochemical considerations)



Waste emplacement is deep in crystalline basement

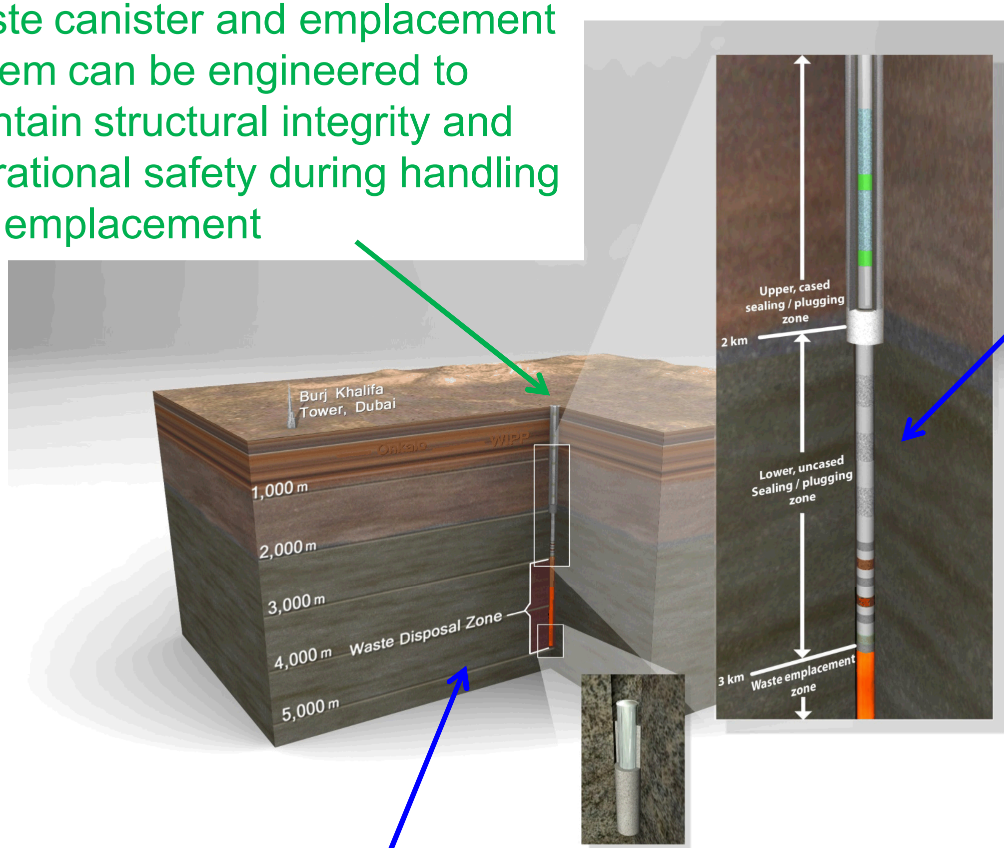
- at least 1,000 m of crystalline rock (seal zone) overlying the waste disposal zone
- Crystalline basement within 2,000 m of the surface is common in many stable continental regions

Deep groundwater in the crystalline basement:

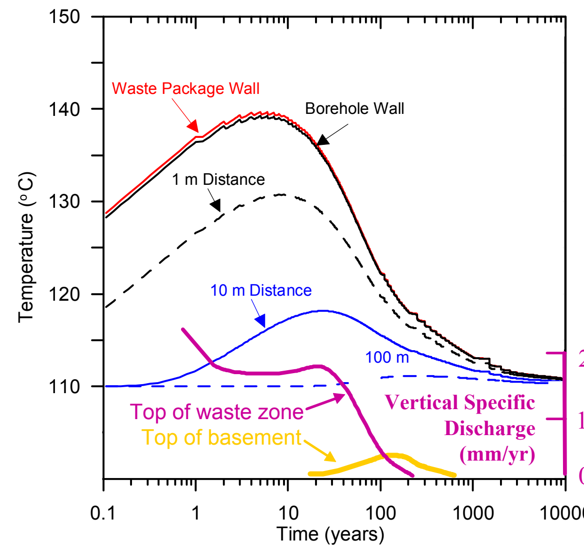
- has very long residence times – isolated from shallow groundwater
- has high salinity and is geochemically reducing – limits the solubility and enhances the sorption of many radionuclides in wastes
- exhibits density stratification (saline groundwater underlying fresh groundwater) – opposes thermally-induced upward groundwater convection

Deep Borehole Disposal Concept – Safety Case (Preclosure and Postclosure)

Waste canister and emplacement system can be engineered to maintain structural integrity and operational safety during handling and emplacement



Borehole seals (and DRZ) can be engineered/evolve to maintain a low-permeability barrier over the period of thermally-induced upward flow



Deep crystalline rocks typically have low permeability and lack hydraulic connection to shallow groundwater

Deep Borehole History

Early Deep Boreholes - Sichuan Province, China

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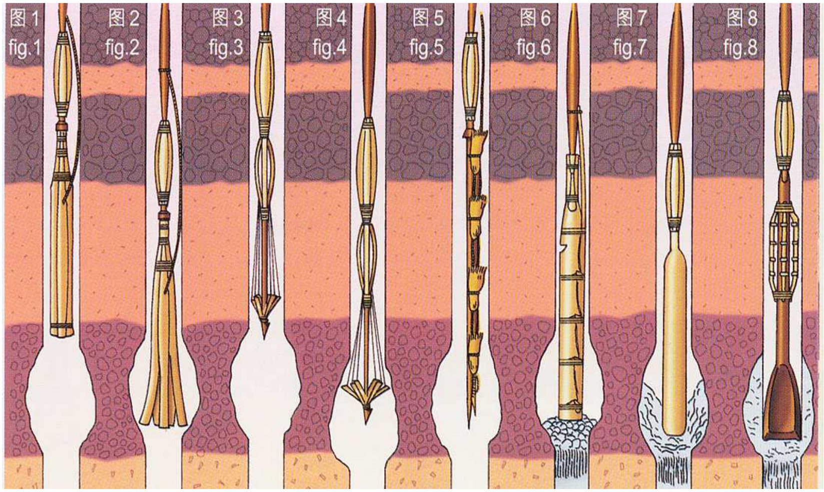
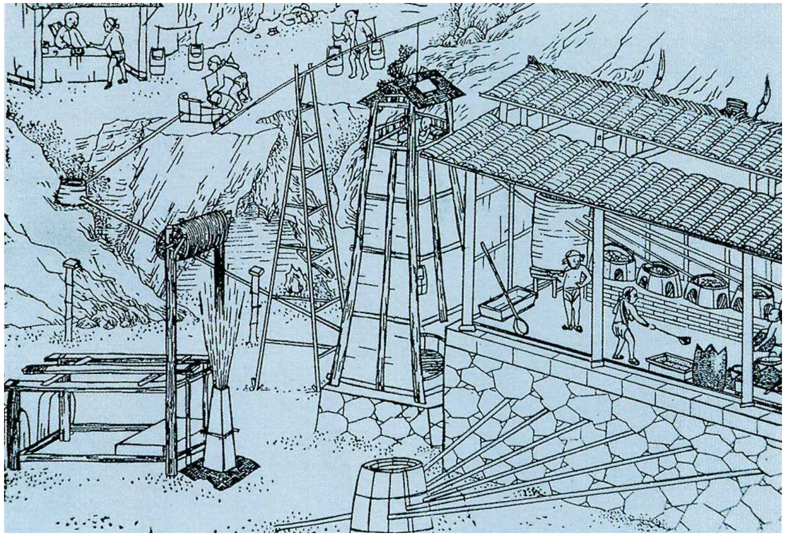
240 meters depth in 347 AD using percussion drilling with bits attached to bamboo poles. Oil was used to evaporate brine to produce salt. **By 1835 Chinese boreholes exceeded 1000 m depth.** In the meantime, the Chinese had worked out pipelines (split bamboo), well casing (logs), down-hole cables (bamboo twine), variable speed drilling, and "fishing" techniques for retrieving objects from the bottom of the well (after Kuhn 2004 http://csegrecorder.com/articles/view/ancient-chinese-drilling).



Borehole repair



More recent work…

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.

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Very Deep Hole Systems Engineering Studies.

Juhlin & Sandstedt (1989) SKB 89-39

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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.

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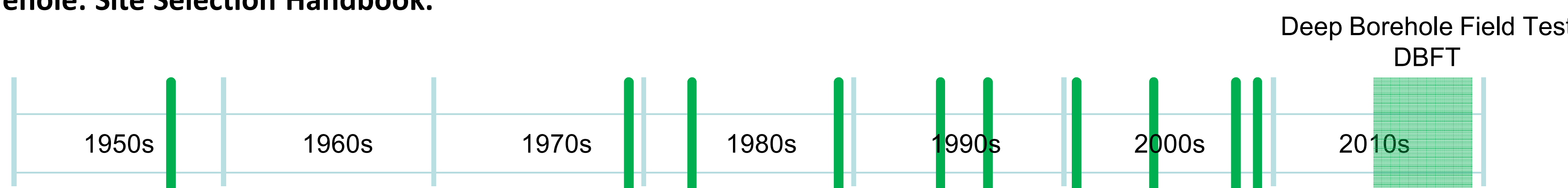
Harrison (2000) SKB-R-00-35 Very Deep Borehole – Deutag's Opinion on Boring, Canister Emplacement and Retreivability.

Nirex (2004) N/108 A Review of the Deep Borehole Disposal Concept.

Driscoll (2005 onwards) Multiple MIT theses and publications.

Beswick (2008) Status of Technology for Deep Borehole Disposal

Sandia (2009 onwards) Multiple reports.



Deep Continental Drilling

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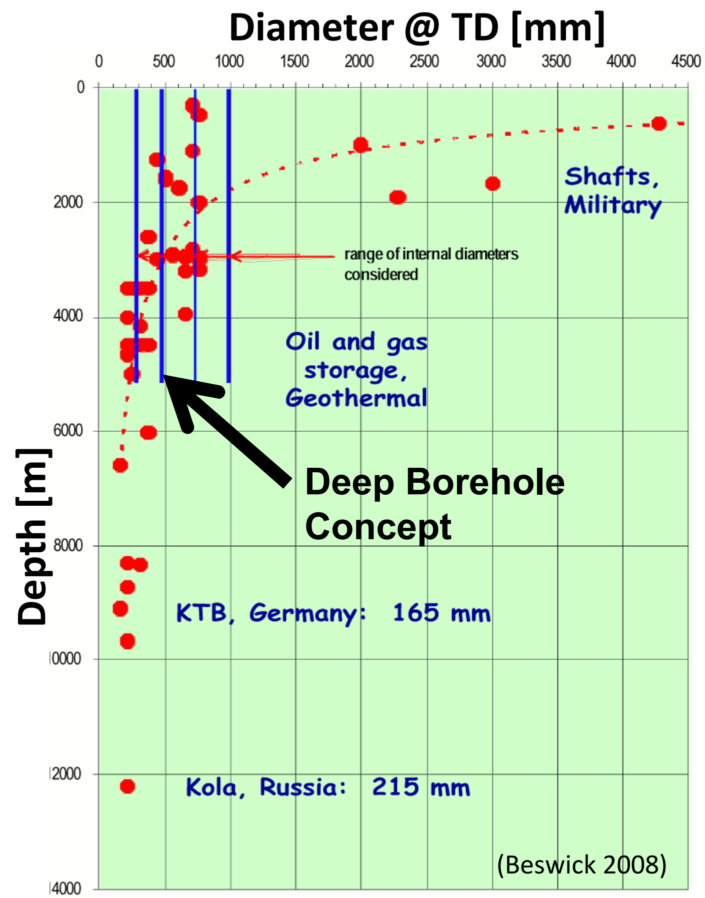
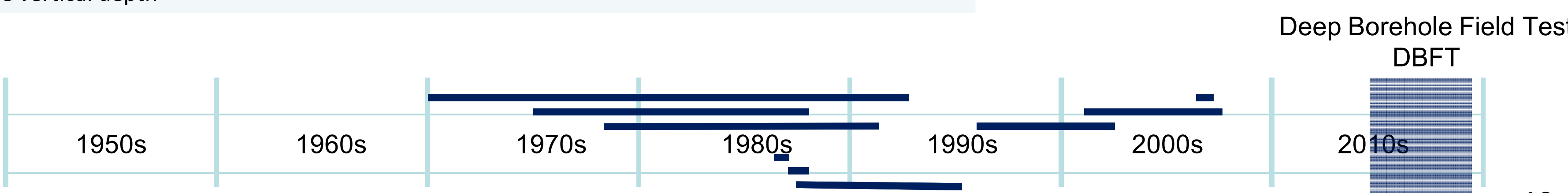
Site	Location	Years	Depth [km]	Diam * [in]	Purpose
Kola SG-3	NW USSR	1970-1992	12.2	8½	Geologic Exploration + Tech. Development
Fenton Hill	New Mexico	1975-1987	4.6	9⅞	Enhanced Geothermal
Urach-3	SW Germany	1978-1992	4.4	5½	Enhanced Geothermal
Gravberg	Sweden	1986-1987	6.6	6½	Gas Wildcat
Cajon Pass	S California	1987-1988	3.5	6¼	Geologic Exploration
KTB	SE Germany	1987-1994	9.1	6½	Geologic Exploration + Tech. Development
Soultz-sous-Forêts GPK	NE France	1995-2003	5.3	9⅝	Enhanced Geothermal
SAFOD	Central California	2002-2007	4 (3)#	8¾	Geology Exploration
Basel-1	Switzerland	2006	5	8½	Enhanced Geothermal

* borehole diameter at total depth

true vertical depth





NEWS IN FOCUS

ENERGY POLICY Three years after Fukushima, Japan is at nuclear crossroads p.16

GENETICS New prenatal screens may mean hard choices for expectant parents p.19

PALAEONTOLOGY Brazil cracks down on illegal fossil trade, rekindling export debates p.20

TECHNOLOGY Researchers strive to kick the lithium-ion battery from its throne p.26

ASSOCIATED PRESS

The Waste Isolation Pilot Plant's salt beds hold radioactive materials from US nuclear-weapons labs.

NUCLEAR POLICY

US seeks waste-research revival

Radioactive leak brings nuclear repositories into the spotlight.

BY JEFF TOLLEFSON

A radiation leak has raised questions about the safety of the United States' only deep nuclear-waste repository, and has given fresh voice to scientists calling for more research into underground waste storage.

On 14 February, radioactive plutonium and americium leaked out of the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, where thousands of drums of contaminated material from the US nuclear-weapons programme are stored in salt beds more than half a kilometre below the surface. The health and environmental impacts seem to be minor, but 13 employees have tested positive for low-level contamination. The Department of Energy (DOE) and its contractors are still working on a plan to re-enter the WIPP and find out what caused the leak.

The incident also brings renewed attention to a problem that policy-makers have been avoiding: what to do with a mounting stockpile of spent fuel from commercial reactors, which is currently stored at reactor sites. In 2010, the DOE mothballed plans to develop Yucca Mountain in Nevada, which since 1987 had been designated as the future site of an underground repository (see *Nature* 473, 266–267; 2011). Researchers at the DOE and universities want to explore a variety of alternatives. But they say that they have been hobbled by small budgets and the Nuclear Waste Policy Act, which prevents the DOE from investigating any specific site apart from Yucca Mountain.

"Basically, all of the old ideas have come back out of the woodwork," says Michael Driscoll, a nuclear engineer at the Massachusetts Institute of Technology in Cambridge. "But the first thing we need is Congress to wrestle with this and revise the Nuclear Waste Policy Act."

For now, researchers are pursuing generic repository science that does not conflict with the law. In one large proposed experiment, DOE scientists wanted to assess whether salt beds at the WIPP could store radioactive waste that is hotter than the material they currently hold. In 2011, the team began developing a US$31-million experiment that would have tested how the salt deforms when it is heated, and how water moves through it.

Other researchers are investigating the concept of dropping cylinders of nuclear waste into 5-kilometre-deep boreholes in hard rock such as granite. Sandia National Laboratories in Albuquerque, New Mexico is leading a consortium of researchers and companies seeking to drill an experimental borehole costing approximately $25 million. The hot-salt and borehole proposals are now competing for funding within the DOE's relatively small $15-million annual budget for this kind of research. "Big tests like either of those would completely overwhelm the current budget," says Peter Swift, who heads the DOE's nuclear-waste science programme at Sandia.

In Europe, scientists have developed expertise with other types of rock. Finland and France have homed in on proposed underground repositories in granite and shale, respectively. Germany has buried low- and medium-level wastes in underground domes of salt, and it is evaluating the terrain for a controversial high-level waste repository.

International collaboration gives researchers access to the basic science on all of these environments, says Jacques Delay, secretary-general of the Implementing Geological Disposal of Radioactive Waste Technology ▶

Nature, 2014

FEATURES

DEEP SLEEP

Boreholes drilled into Earth's crust get a fresh look for nuclear waste disposal

By Warren Cornwall

One of the world's biggest radioactive headaches sits in an aging cinderblock building in the desert near Hanford, Washington, at the bottom of a pool of water that glows with an eerie blue light. The nearly 2000 half-meter-long steel cylinders are filled with highly radioactive cesium and strontium, leftover from making plutonium for nuclear weapons. The waste has been described as the most lethal single source of radiation in the United States, after the core of an active nuclear reactor. It could cause a catastrophe if the pool were breached by an unexpectedly severe earthquake, according to the U.S. Department of Energy (DOE), the waste's owner.

For decades, the federal government has been floundering over what to do with the cylinders. They're too hot to be easily housed with other waste. And the government's quest to create a single permanent burial ground for all the nation's high-level nuclear waste, from both military and civilian activities, is in disarray (see sidebar, p. 135).

Now, a deceptively simple-sounding solution is emerging: Stick the cylinders in a very deep hole. The approach, known as deep borehole disposal, involves punching a 43-centimeter-wide hole 5 kilometers into hard rock in Earth's crust. Engineers would then fill the deepest 2 kilometers with waste canisters, plug up the rest with concrete and clay, and leave the waste to quietly decay.

The idea has been around for decades, but not long ago scientists had all but abandoned it. Over the past 5 years, however, as improved drilling technologies converged with the political and technical woes bedeviling other nuclear waste solutions, boreholes have regained their allure. DOE has gone from spending almost nothing on borehole research to planning a full-scale field test, costing at least $80 million. And earlier this year U.S. Energy Secretary Ernest Moniz gave boreholes a dash of publicity during a major speech, mentioning them as a promising way to deal with the cesium and strontium waste at DOE's Hanford Site nuclear complex.

U.S. high-level nuclear waste

70,000
metric tons of civilian waste stored at 75 sites

13,000
metric tons of military waste stored at five sites

Boreholes have "been plan B and just missed the boat for years," says nuclear engineer Michael Driscoll, a retired professor from the Massachusetts Institute of Technology (MIT) in Cambridge and one of the concept's leading advocates. "Maybe now is the time."

Many nuclear waste veterans, however, are skeptical. The technical challenges are daunting, they argue, and boreholes won't end political opposition to building new nuclear waste facilities. "The borehole thing to me is a red herring," says attorney Geoff Fettus of the Natural Resources Defense Council (NRDC) in Washington, D.C., which supports underground disposal in a shallower mine, but has sued DOE over now abandoned plans to bury the waste inside Nevada's Yucca Mountain.

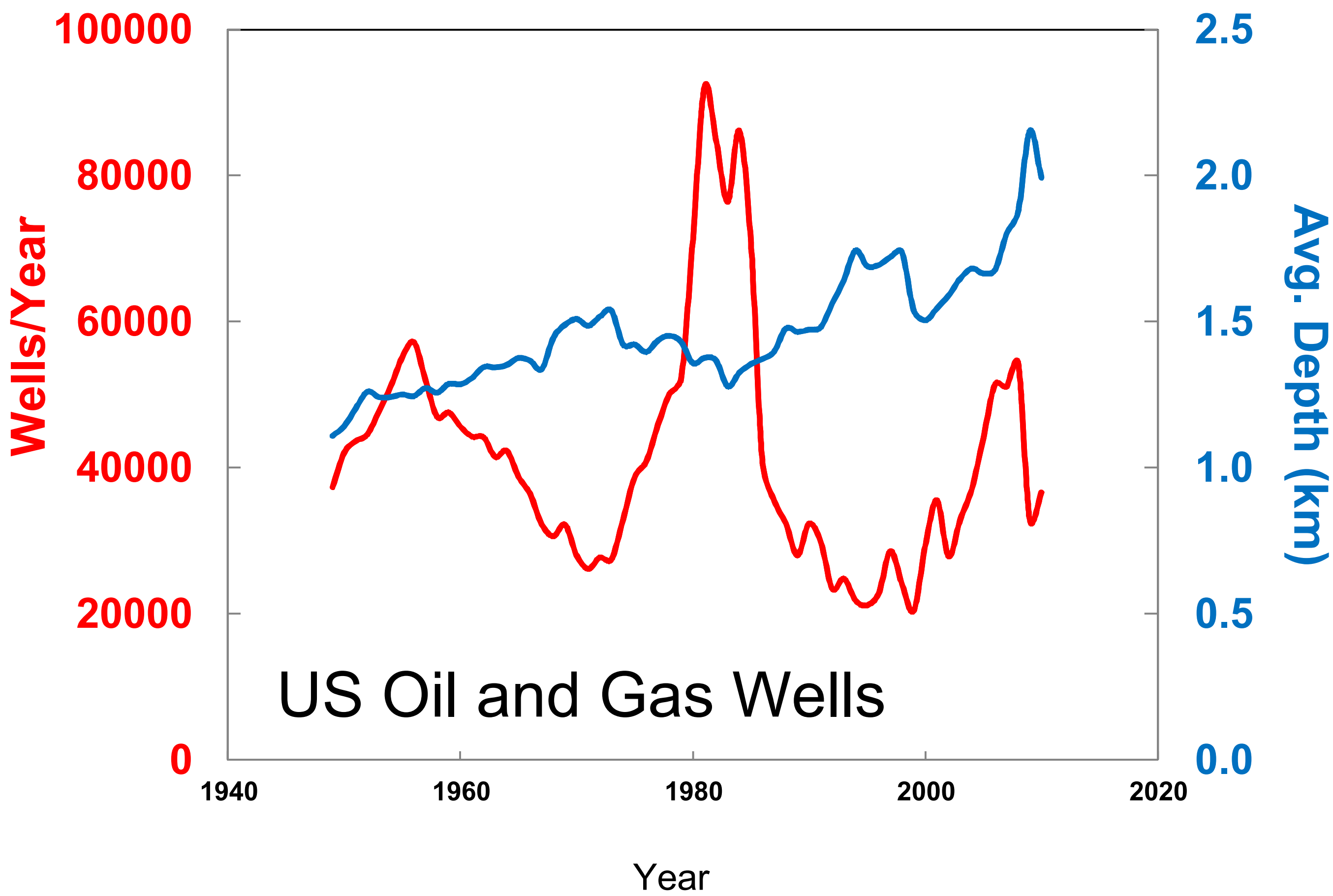
Still, even some doubters say that given the current deadlock over nuclear waste, boreholes deserve a second look, at least for those troublesome cylinders at Hanford.

PHOTO: U.S. DEPARTMENT OF ENERGY

Published by AAAS

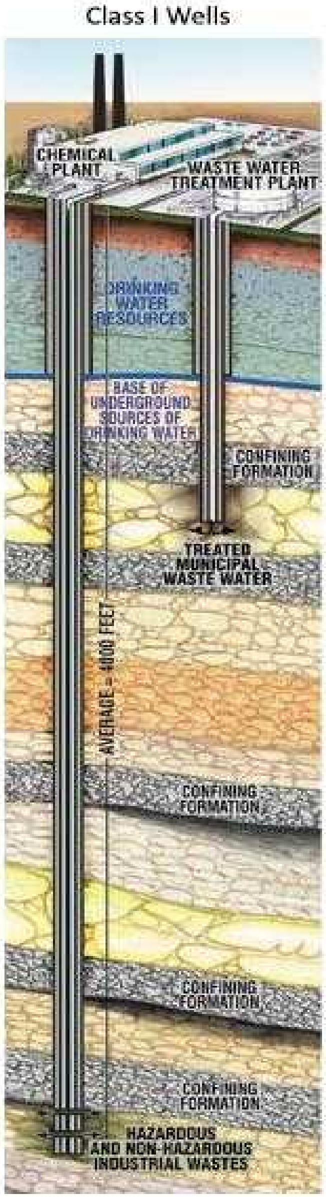
Science, 2015

US Deep Boreholes with no wastes



Source: Energy Information Administration (US)

US Deep Boreholes with wastes



0.4 to 2 km

Source: US EPA

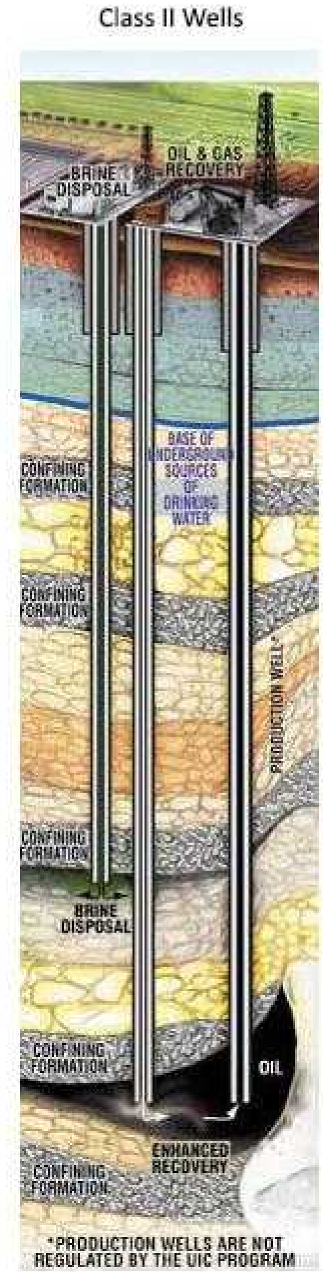
800 Class I wells - hazardous and non-hazardous industrial waste and municipal wastewater.

44 Class 1 wells - hazardous waste.

36,000 Class II wells - Oil and gas waste.

10,000 year No Migration Petition requires description of:

- Well design, construction, and performance information
- Waste description and injection history
- Regional understanding of the geology and stratigraphy
- Hydrologic parameters of the injection zone and confining layer(s), e.g. porosities, permeabilities
- Local seismicity
- Presence of transmissive faults
- Borehole geochemistry and waste compatibility.



WHAT IS DIFFERENT ABOUT DEEP BOREHOLES FOR NUCLEAR WASTE?

Radius and depth,

Emplacement: Canisters vs. pumped fluids,

Disposal Zone: Crystalline basement vs. Sedimentary formations,

Heat generation,

Characterization,

Safety Case/Performance Assessment …

Deep Borehole Science Needs

RESEARCH NEEDS FOR DEEP BOREHOLES

Patrick V. Brady, Bill W. Arnold, Robert J. MacKinnon, Ernest L. Hardin, David C. Sassani, Kristopher L. Kuhlman, and Geoff A. Freeze
Sandia National Laboratories
Albuquerque, New Mexico

Sandia National Laboratories

Attendees at the Deep Borehole Science Needs Workshop, Albuquerque, New Mexico November 12, 2014. Participants from left to right: Paul Johnson/LANL, Pat Brady/Sandia, Bill Arnold/Sandia, Kris Kuhlman/Sandia, Hari Viswanathan/LANL, Andrew Manning/USGS, John Cochran/Sandia, Dave Sassani/Sandia, Ernie Hardin/Sandia, Teklu Hadgu/Sandia, Frank Perry/LANL, Tom Daley/LBNL, Florie Caporuscio/LANL, Jim Houseworth/LBNL, Bob MacKinnon/Sandia, Dave Sevougian/Sandia, Dan King/DOE, Geoff Freeze/Sandia, Mark Freshley/PNNL, Tim Gunter/DOE, Lance Roberts/SD School of Mines, Mark Everett/Texas A&M, Jason Heath/Sandia, Mary Lou Zoback/NWTRB, Jack Tilman/Sandia, Paul Reimus/LANL. Not shown: Peter Davies/Sandia, Marianne Walck/Sandia, Erik Webb/Sandia, Fergus Gibb/Sheffield, Karl Travis/Sheffield, Frank Hansen/Sandia, Susan Altman/Sandia.

U.S. DEPARTMENT OF ENERGY NNSA

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Elements of Science Needs

- 1 - Groundwater in the deep crystalline basement at disposal zone depths is very old and has been isolated from the surface for very long times.
- 2 - Ambient fluid potential does not have a significant upward gradient between the disposal zone and the shallow subsurface (i.e., overpressured conditions are not present).
- 3 - Deep groundwater has high salinity, well known chemical composition, and is chemically reducing.
- 4 - Bulk permeability of host rock and the borehole DRZ are acceptably low.
- 5 - Borehole seals, plugs, and grout have sufficient integrity and durability to meet safety requirements.
- 6 – Basic parameter values chemical, thermal, hydrology
- 7 – Equipment and approaches for monitoring post-closure data

Element 1
Groundwater in the deep crystalline basement at disposal zone depths is very old and has been isolated from the surface for very long times.

- **Dating the water using isotopic tracers** and best tools – history/provenance; which isotopes, which tracers? What mixtures?
- **Identification of the fluid source, profiling**
- Fluid inclusions vs. fracture fluids
- Mineral equilibria in fractures
- Disequilibria between rocks and waters; can we reproduce water compositions theoretically?
- Multiple source water mixing(?)
- **How to get GOOD samples (consistent data from multiple methods).**

Element 2

Ambient fluid potential does not have a significant upward gradient between the disposal zone and the shallow subsurface (i.e., overpressured conditions are not present).

- **How to get GOOD data (e.g. pressures) at great depth in relatively impermeable formations?**
- What scales (time, distance) are the measurements interrogating?
- **How will it all change once temperature changes, corrosion occurs, etc.?**
- Determine fracture pressure; how close to ambient pressure?
- How to use flow survey to integrate pressure? What tools?
- Salinity profile links to pressure.
- Long-term monitoring of microseismicity to infer shear state and evolution.
- How to model time-dependent rock mechanics and hydrology.
- **Are we causing/will we cause over-pressured conditions?**

Element 3
Deep groundwater has high salinity, well known chemical composition, and is chemically reducing.

- **Quality of sampling methodologies; how much will drilling perturb situation? “Tag” the drilling fluids? Use small well results to inform big well analyses.**
- Sorption coefficients and solubilities in high TDS brines at T > 100C, especially anions. Pitzer coefficients available?
- Reactive transport modeling approaches
- Fracture mineralogy and whole rock mineralogy; isotopic analysis of fracture mineralogy
- Multi-method distinguishing of scale-dependent permeabilities
- Tailored backfills
- **Redox disequilibria/reducing conditions**
- Microbial activity? Colloids?
- Use high value characterization targets to choose drilling fluids (if we can)
- What will corrosion do to geochemical behavior?
- **Surface-based geophysics for e.g. salinity/fracture determination (Seismic/EM/Gravity/Aeromagnetic)**

Element 4
Bulk permeability of host rock and the borehole DRZ are acceptably low.

- **Characterization of fractures, how they might change, which ones are conductive.**
- Borehole televiewer to provide 3D fracture imaging.
- Packer bleedoff measurements
- **Vertical dipole pump test/tracer tests**
- Time-phased sampling of groundwater to track DRZ reactivity.
- Cross-well and surface-borehole hydrogeologic/geophysical analysis
- 4d seismic, passive imaging tracked through time
- Reaction-transport analysis of long pump time geochemical results.
- Standard borehole fractured rock permeability testing

Element 5
Borehole seals, plugs, and grout have sufficient integrity and durability to meet safety requirements.

- **Long-term monitoring (using new materials? – e.g. self-monitoring fibers); seals that communicate their performance. New techniques – e.g. that sense seals wall rock bonding, fracture densities.**
- Keep track of international URL's (Canadian)
- Alternative sealing materials – e.g. tailored epoxies
- **Evolving seals mineralogy over T, P, time.**
- **Gas generation/movement past seals.**
- How to demonstrate better seals performance
- Seals sensitivity to heat/pressure from waste.
- Seals cross-interaction
- Better waste forms; resistant to corrosion, etc.

Element 6. Basic parameter values chemical, thermal, hydrology Equipment and approaches for monitoring post-closure data

- **Geomechanical predictors of borehole stability = in situ stress measurements,**
- Thermodynamic gaps = e.g. Green rust, RN sulfides.
- High T, P, high salinity, sensors
- Data collection while drilling

UK Science Needs

- 1 - Sealing the borehole above the waste
  - Rock welding
- 2 - Sealing and support matrices
  - High density support (HDSM)
  - Class G cement formulation
- 3 - Fluid mechanics and package deployment
- 4 - Thermal modeling
- 5 - Thermal hydrologic modeling
- **6 - Formation and behavior (fluid mechanics) of disturbed rock zone**
- Larger diameter borehole/canisters

Collected **Red (Necessary)** Issues

- **(3) Surface-based geophysics for e.g. salinity/fracture determination (Seismic/EM/Gravity/Aeromagnetic)**
- **(1) Dating the water using isotopic tracers; Identification of the fluid source, profiling**
- **(1) How to get GOOD samples (consistent data from multiple methods).**
- **(2) How to get GOOD data (e.g. pressures) at great depth in relatively impermeable formations?**
- **(2) Are we causing/will we cause over-pressured conditions?**
- **(3) Quality of sampling methodologies; how much will drilling perturb situation? "Tag" the drilling fluids? Use small well results to inform big well analyses.**
- **(4) Characterization of fractures, how they might change, which ones are conductive.**
- **(5) Long-term monitoring (using new materials? – e.g. self-monitoring fibers); seals that communicate their performance. New techniques – e.g. that sense seals wall rock bonding, fracture densities.**
- **(6) Geomechanical predictors of borehole stability = in situ stress measurements**
- **(UK) - Formation and behavior (fluid mechanics) of disturbed ro[illegible]**

Collected **Green (Desired)** Issues

(4) Vertical dipole pump test/tracer tests

- **(2) How will it all change once temperature changes, corrosion occurs, etc.?**
- **(3) Redox disequilibria/reducing conditions**
- **(5) Evolving seals mineralogy over T, P, time.**
- **(5) Gas generation/movement past seals.**

Deep Borehole Field Test (DBFT)

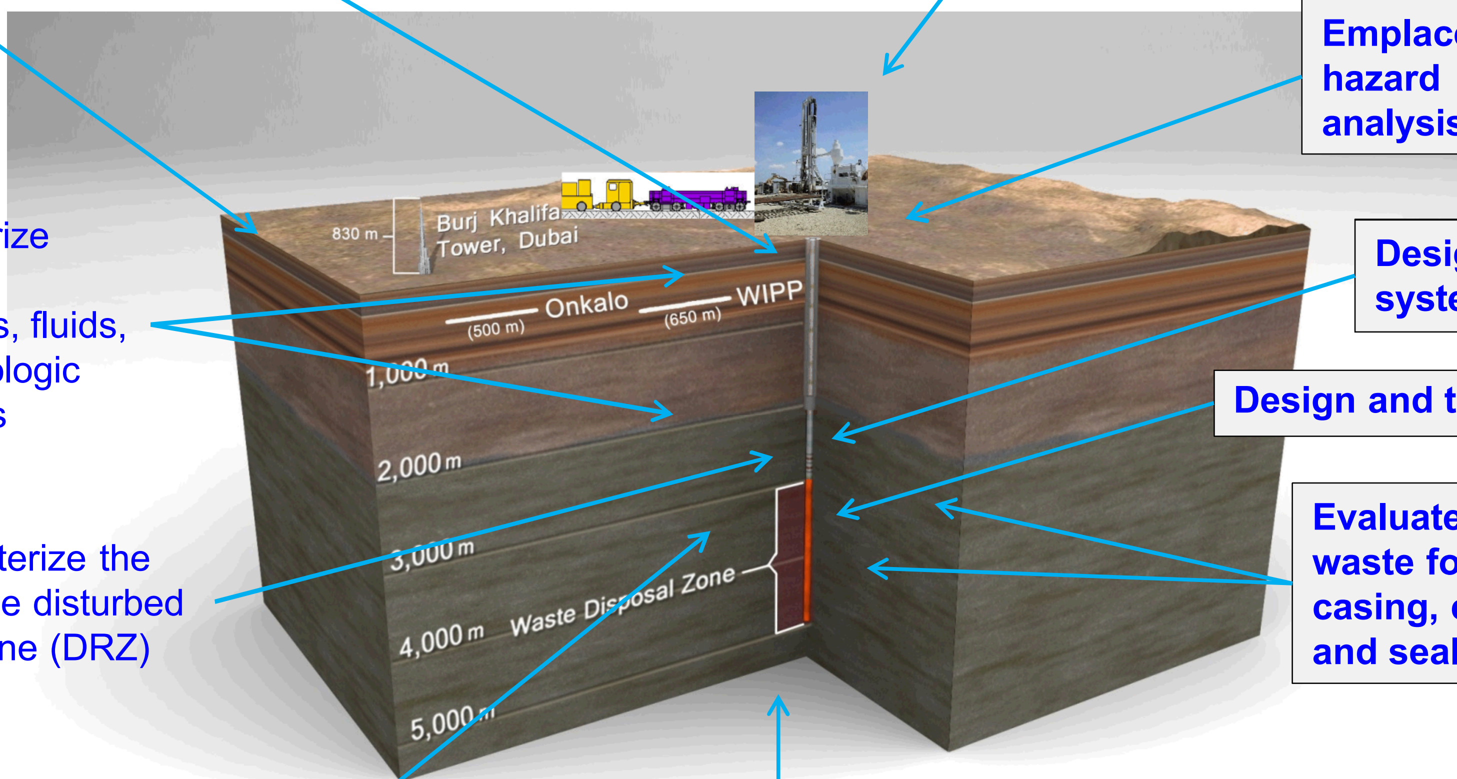
Deep Borehole Field Test Objectives

Sandia National Laboratories

- The RD&D objectives for deep borehole disposal are being met with a borehole field test that is conducted to a depth of 5 km in a suitable location (without emplacement of radioactive wastes)
- The DBFT includes the following major activities:
  - Obtain a suitable test site
  - Design, drill and construct the Characterization Borehole (8.5” diameter) to requirements
  - Collect data in the Characterization Borehole to characterize crystalline basement conditions and evaluate expected hydrogeochemical conditions
- Accommodate a subsequent Field Test Borehole (17” diameter)
  - Design, drill and construct the Field Test borehole to requirements
  - Design and develop surface handling and emplacement equipment systems and operational methods for safe canister/waste package handling and emplacement

Objectives of the Deep Borehole Field Test

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



In no case will the US Government place or otherwise have nuclear material, waste, or other waste disposal material on the property (RFP 2015).

Deep Borehole Field Test (DBFT)

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

- **Test Ability To:**
  - **Drill deep, wide & straight in crystalline rocks (CB + FTB)**
  - **Characterize bedrock via geophysics (CB)**
  - **In situ tests in basement ≤150^{o}C & 50 MPa (CB)**
  - **Geochemical profiles (CB)**
  - **Emplace/retrieve test waste packages (FTB)**

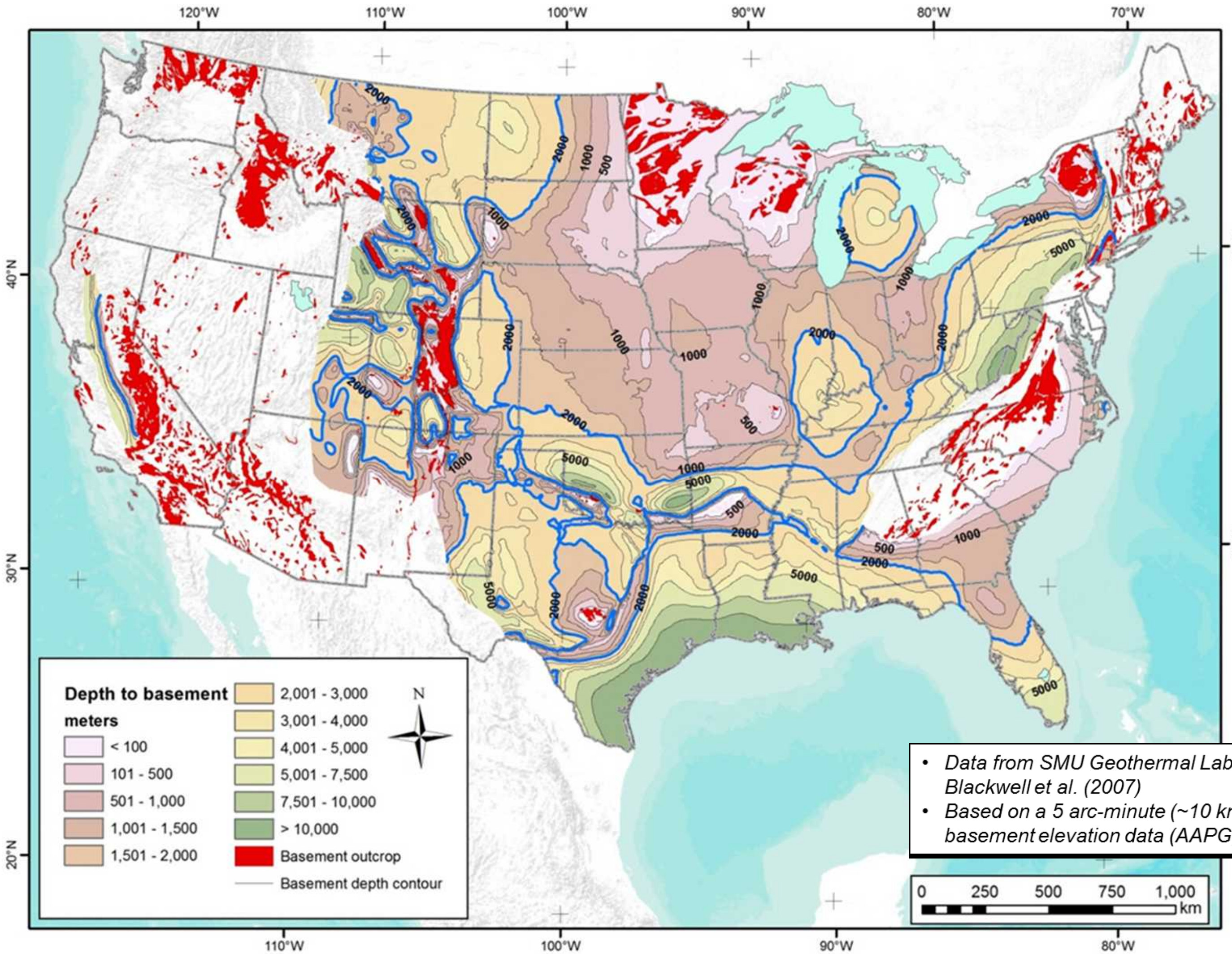
SAND2010-6048

Geoscience Guidelines Considerations

- Crystalline Basement
  - Depth
  - Rock Fabric & Stress State
  - Regional Structure(s)
  - Hydrology and Geochemistry
- Heat Flow
- Recent Seismicity/Volcanism
- Resources
- Anthropogenic Contamination

DBFT Site Selection

Depth to Basement – National Scale

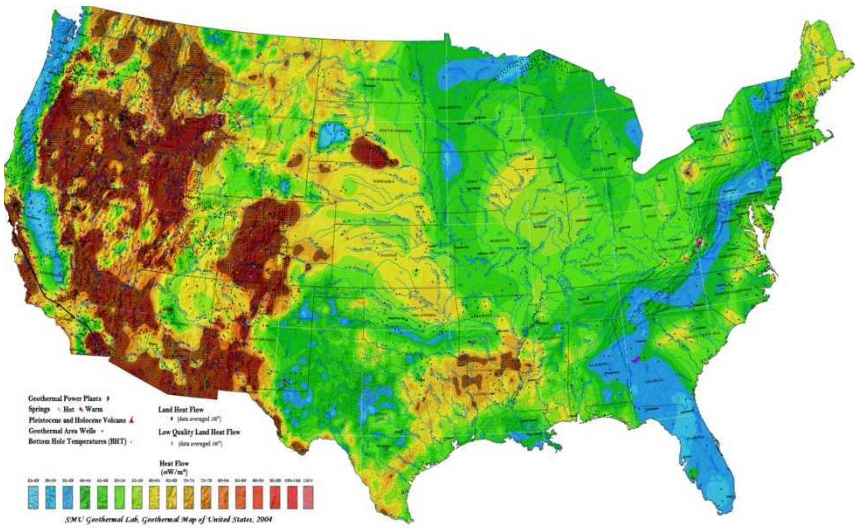


- *Data from SMU Geothermal Laboratory - Blackwell et al. (2007)*
- *Based on a 5 arc-minute (~10 km) grid spacing of basement elevation data (AAPG, 1978)*

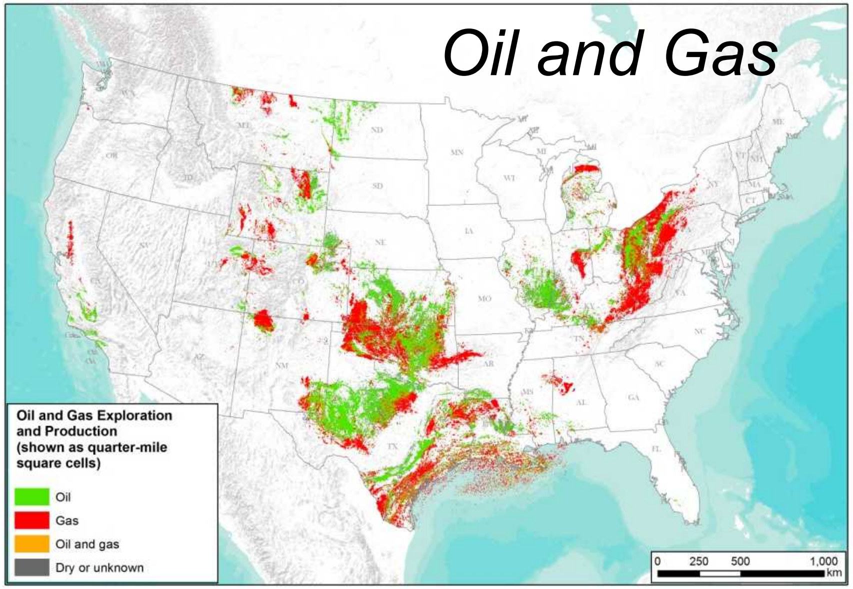
Distribution of crystalline basement at a depth of less than 2 km (tan shading) and granitic outcrop (red) in the contiguous US (from Figure 3-2 in Perry et al., 2015)

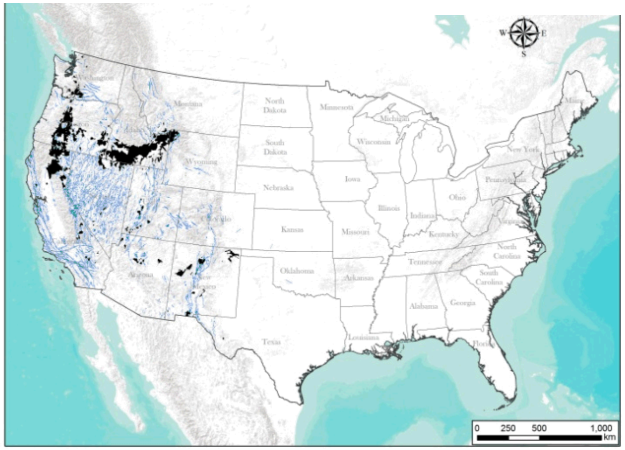
Geologic Aspects of DBFT Siting

Heat Flow



Oil and Gas



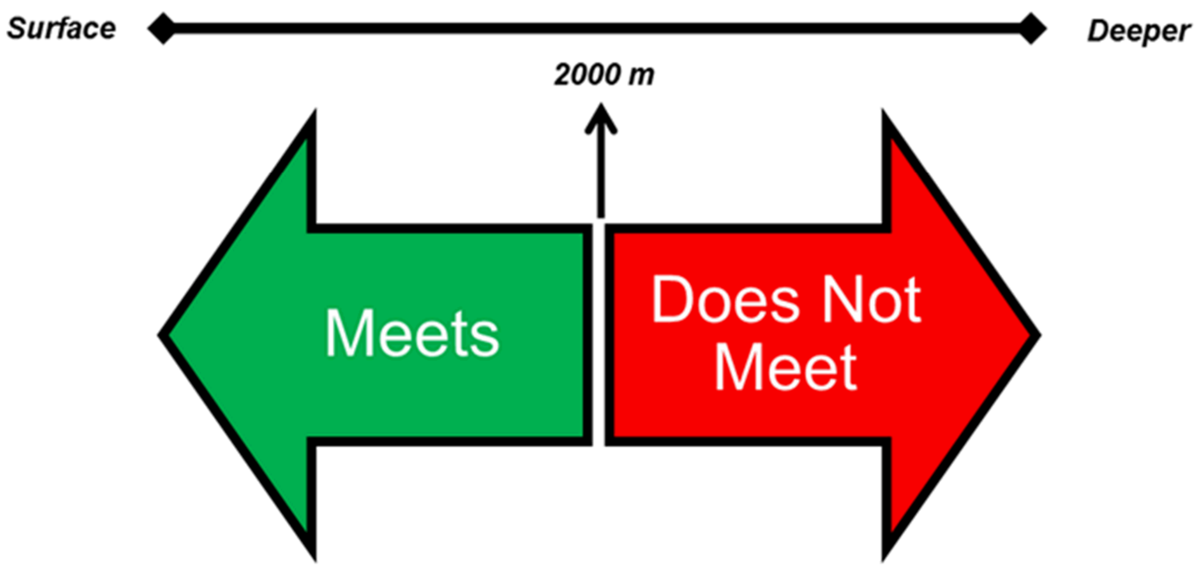


Volcanoes and recent faults

Depth to Basement Guideline

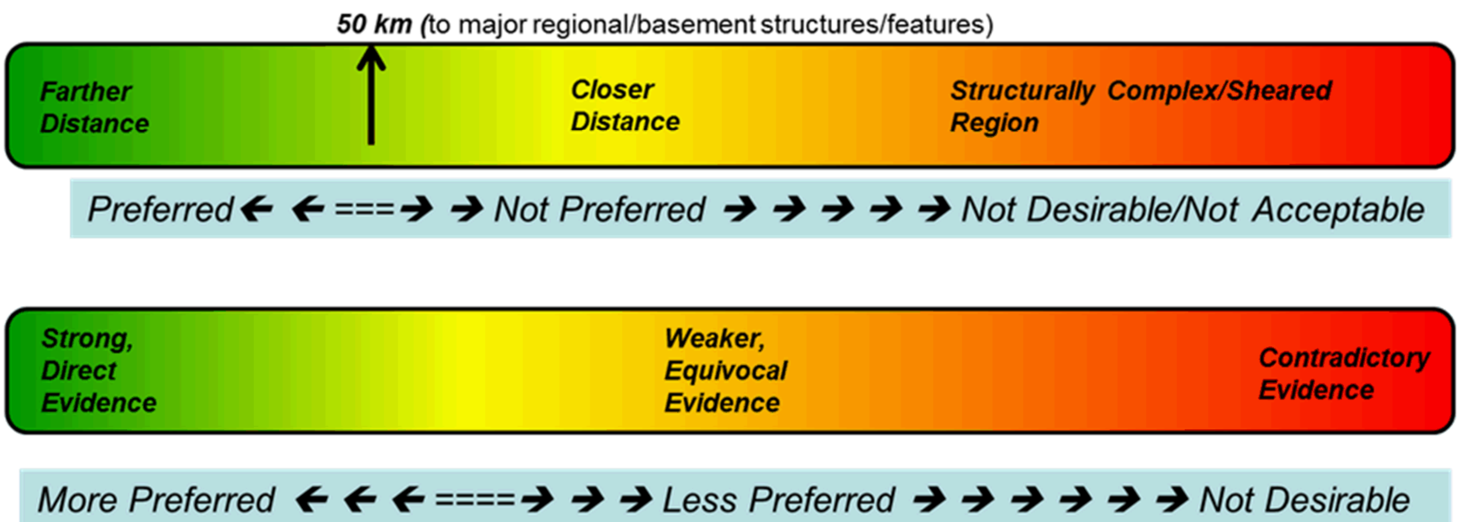
- Guideline is based on reference design
- Uncertainty in data is considered
  - Local boreholes with basement contact – highly certain
  - Regional data sets constrained by points within 50 km
  - National scale data set
    - Basement surface gradients

Depth to Basement--The depth to the crystalline basement is 2 km (1.2 miles) or less (note that all depths shallower than 2 km are considered equivalent, although the uncertainty of the data is considered).



Major Regional Structures Guideline

Major Regional Structures, Basement Shear Zones and Other Tectonic Features-- Geologic information and bases identifying any major regional structures, basement shear zones, or other tectonic features within 50 km of the proposed site. The absence within this distance of known major regional structures, major crystalline basement shear zones, or major tectonic features is preferred.

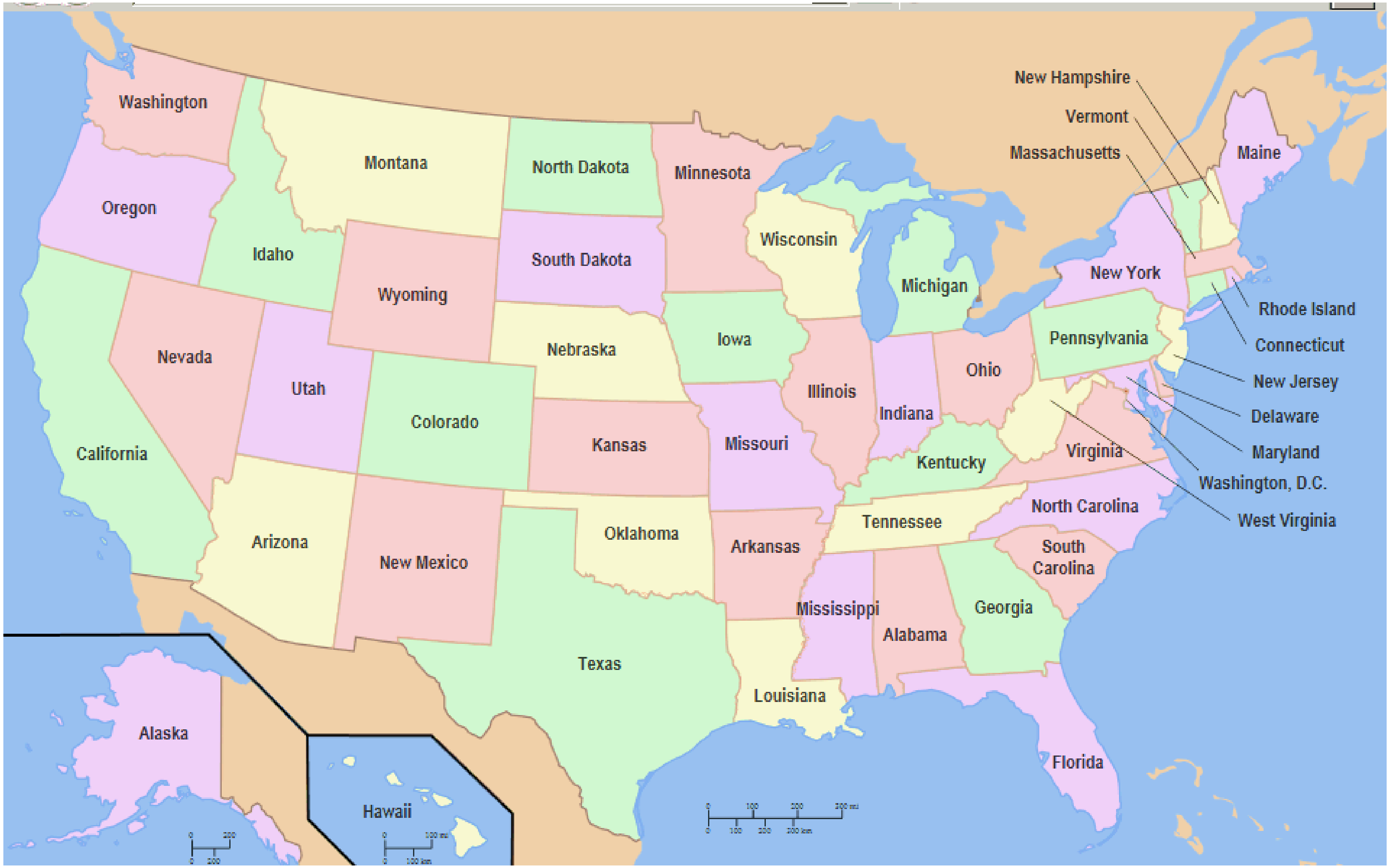


- Simpler structure is preferred, though not essential
- Specific structures closer than 50 km would be evaluated on a case-by-case basis

Deep Borehole Field Test

Acquisition of Site and Services

- Initial Request for Proposal (RFP)/Award
  - Did not establish a suitable test site
- US DOE RFP (Solicitation Number DE-SOL-0010181)
  - Pre-solicitation notice posted on August 5, 2016
  - Final RFP posted on FedBizOps on August 22, 2016
  - Proposals due October 21, 2016
  - Contract award anticipated in early 2017

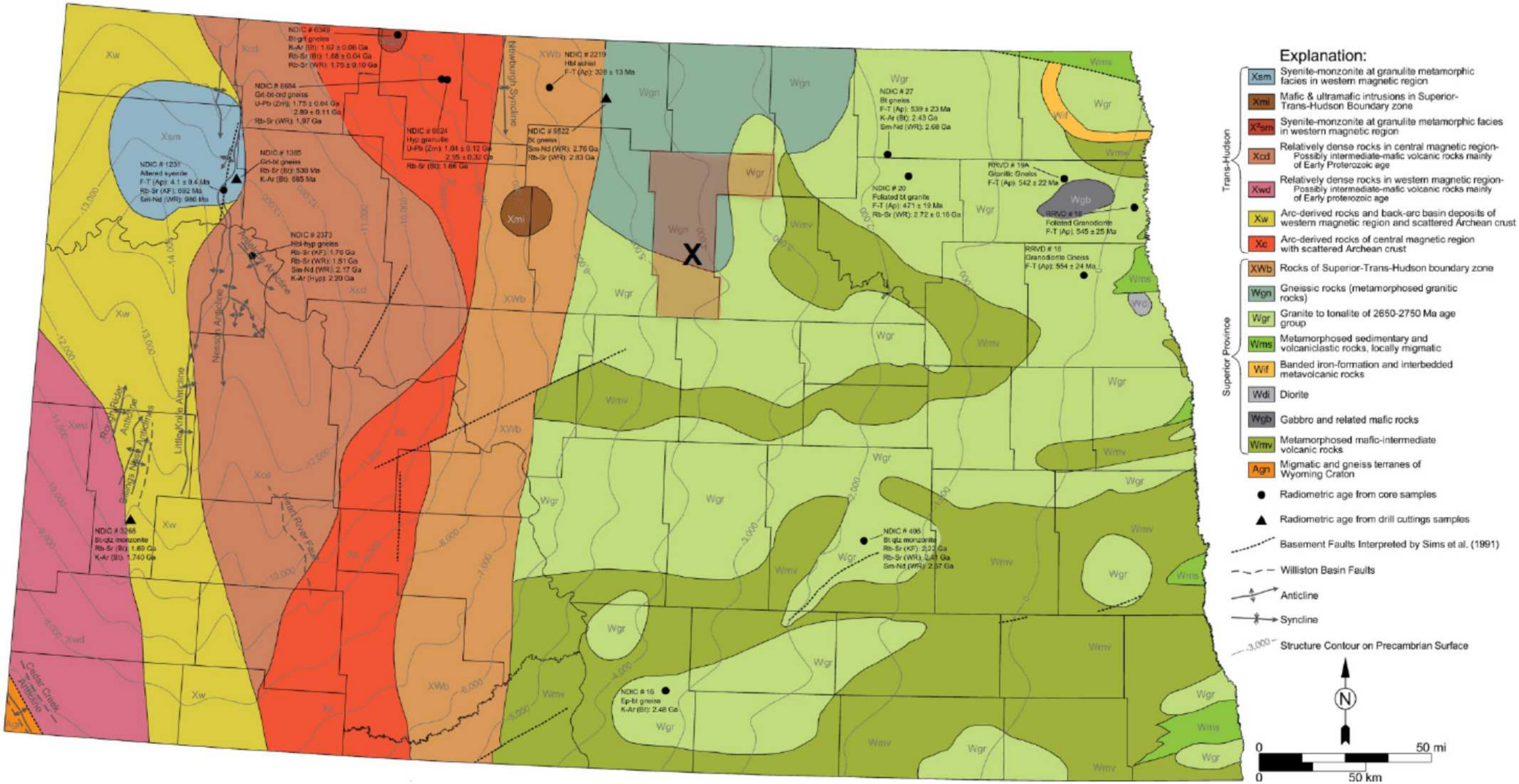


Washington
Oregon
California
Idaho
Nevada
Montana
Wyoming
Utah
Arizona
Colorado
New Mexico
North Dakota
South Dakota
Nebraska
Kansas
Oklahoma
Texas
Minnesota
Iowa
Missouri
Arkansas
Louisiana
Wisconsin
Illinois
Michigan
Indiana
Ohio
Kentucky
Tennessee
Mississippi
Alabama
Georgia
Florida
South Carolina
North Carolina
Virginia
Pennsylvania
New York
Maine
New Hampshire
Vermont
Massachusetts
Rhode Island
Connecticut
New Jersey
Delaware
Maryland
Washington, D.C.
West Virginia
Alaska
Hawaii

Example Site: Pierce County, ND

Location and Crystalline Basement Map

Sandia National Laboratories



Map of crystalline basement terrains in North Dakota, with example site location shown by the black X—lies above the 2700 ma rocks of the Superior Craton (after Nesheim, 2012).

Example Site: Pierce County, ND

Overburden Stratigraphy: Williston Basin

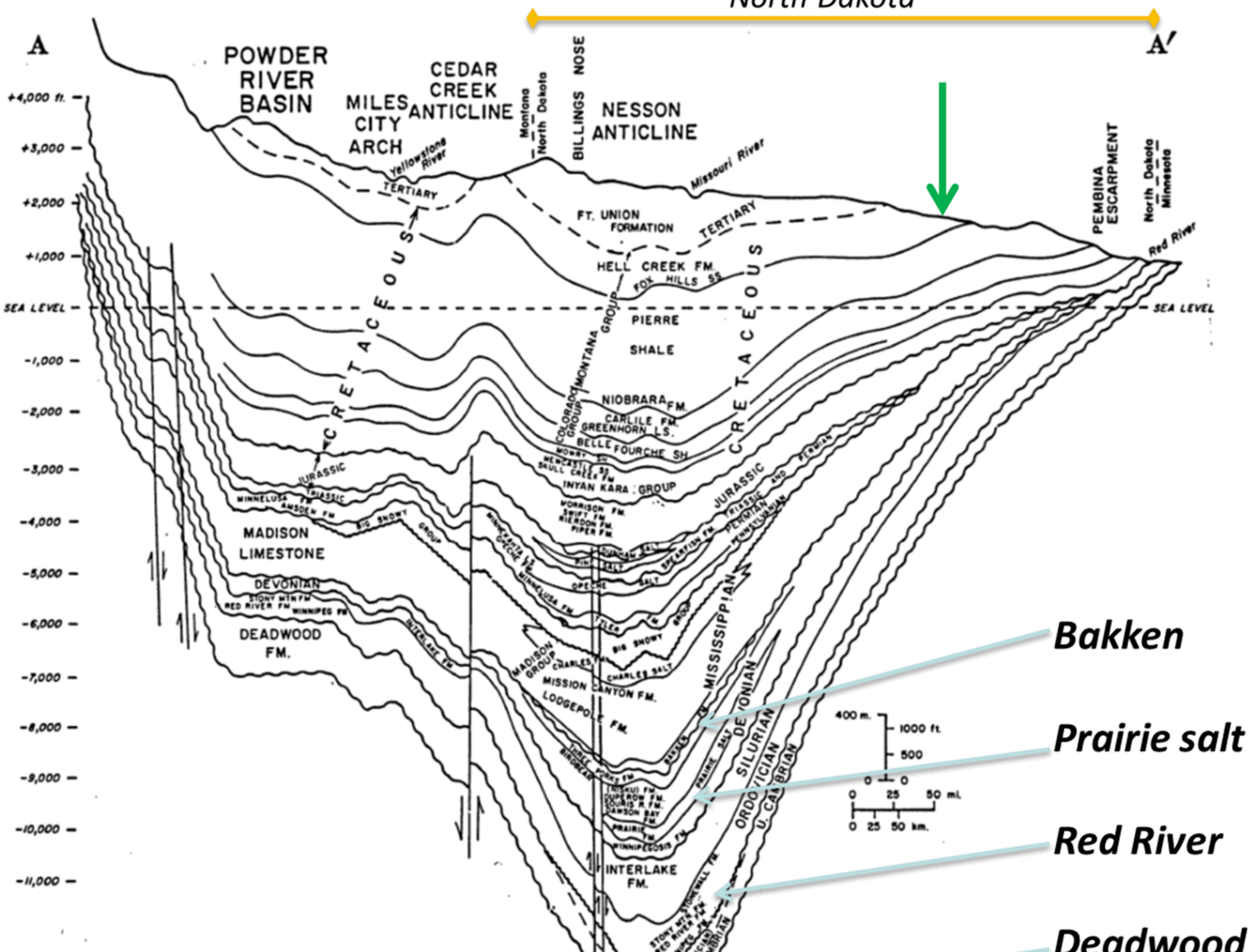
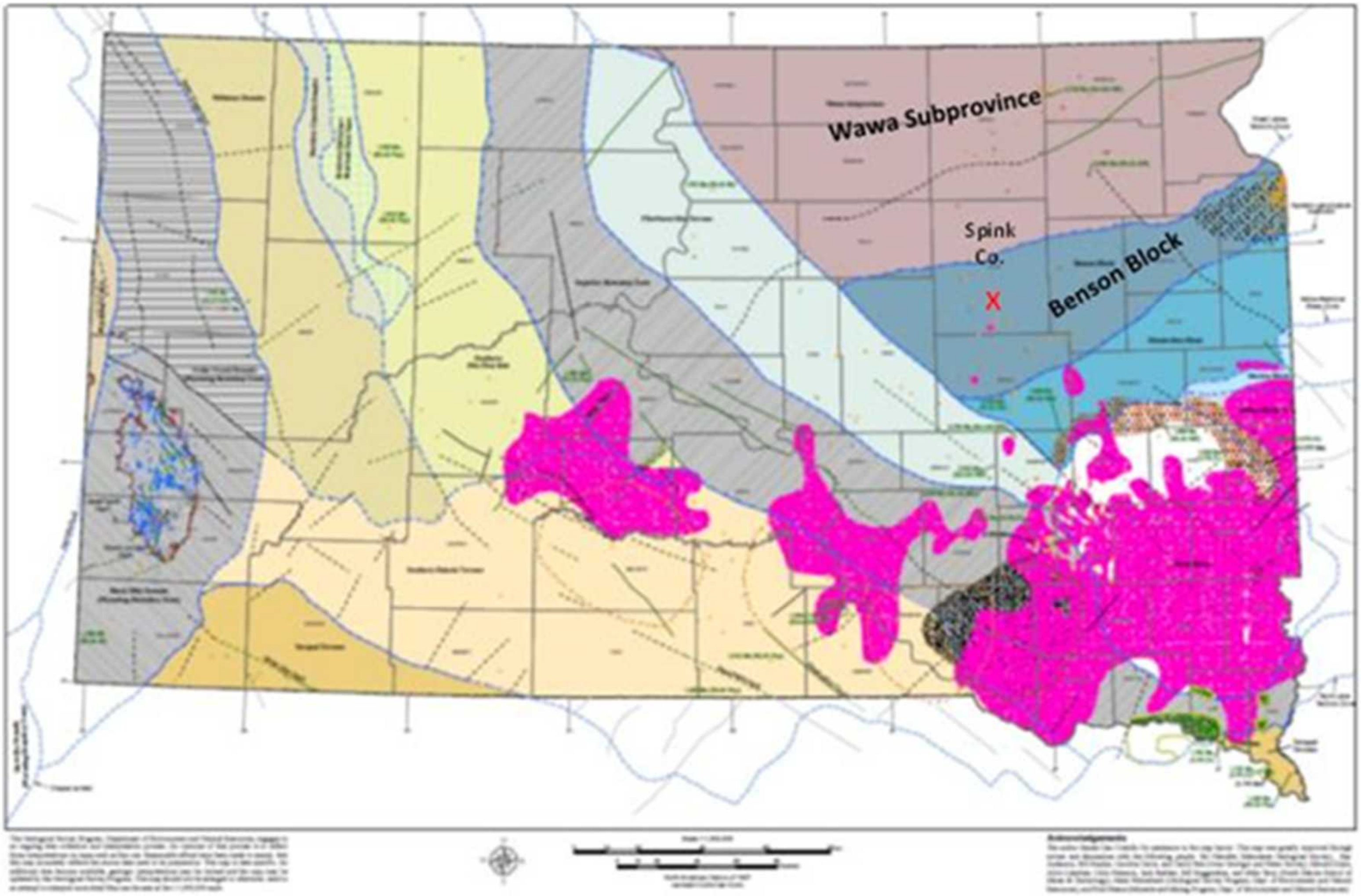


Figure 5. Generalized west-east structural-stratigraphic cross section A-A', Bighorn Mountains, Wyoming to northeastern North Dakota. Line of cross section is shown on figures 1 and 6. Modified after Peterson and MacCary, 1987.

Geologic cross section (note large vertical exaggeration) of the Williston Basin overlying crystalline basement rocks in North Dakota (after Figure 5 in Peterson, 1988).

Example Site: Spink County, SD

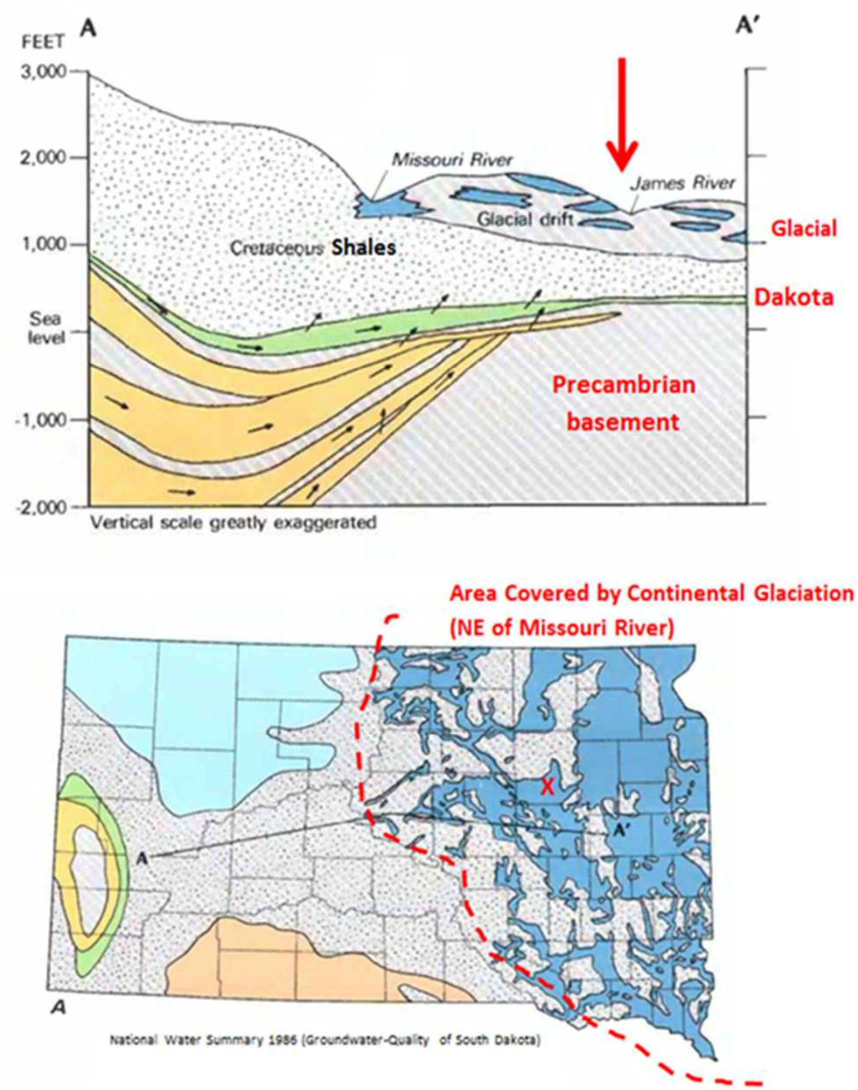
Location and Crystalline Basement Map

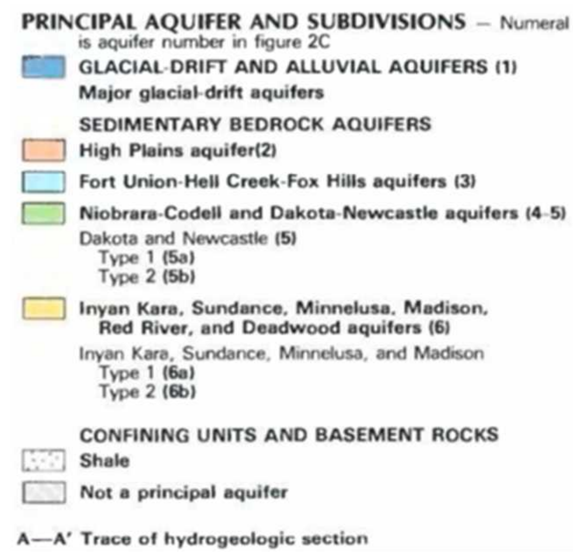


Terrane Map of the Precambrian Basement of South Dakota (after McCormick, 2010, Plate 1)

Example Site: Spink County, SD

Overburden Stratigraphy: Dakota Sandstone





Generalized hydrologic cross-section (Top) across SD along A – A' shown (Bottom) in map view (figure after Figure 2 from Koch et al., 1986).

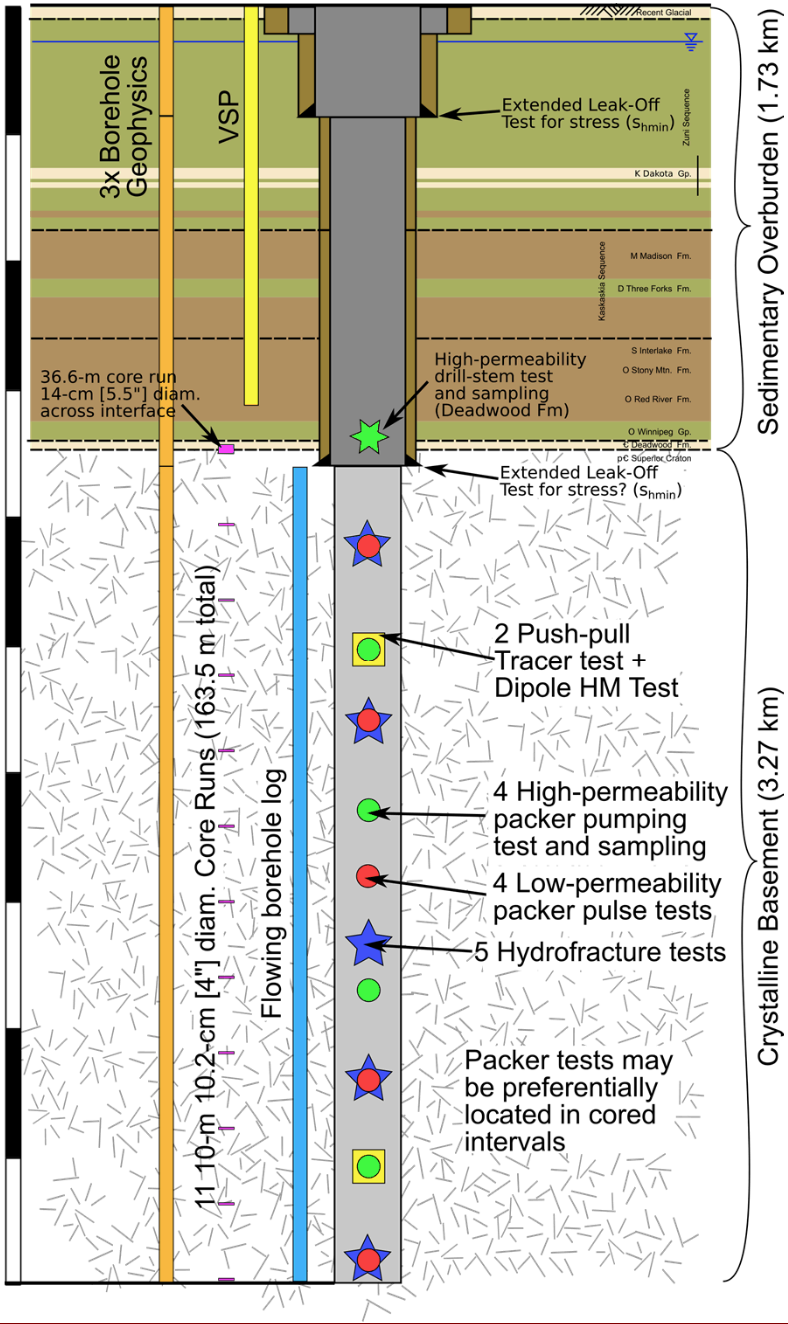
Summary and Conclusions

- Many Sites within U.S. with Functional Geology
  - Multifaceted Objectives of DBFT Provide Opportunities for Success
- Choosing Site will be based on Uncertain Geologic Information
  - Generally regions lacking exploration
  - Based on the Weight of the Sum of the Evidence
- Each Site will have its own Geologic Challenges
  - Nature of Scientific Exploration
  - Will Provide Substantial Direct Data and Understanding
- Current US DOE Approach has more Explicit/Earlier Community Outreach/Involvement

DBFT Site Characterization

Sampling Profiles

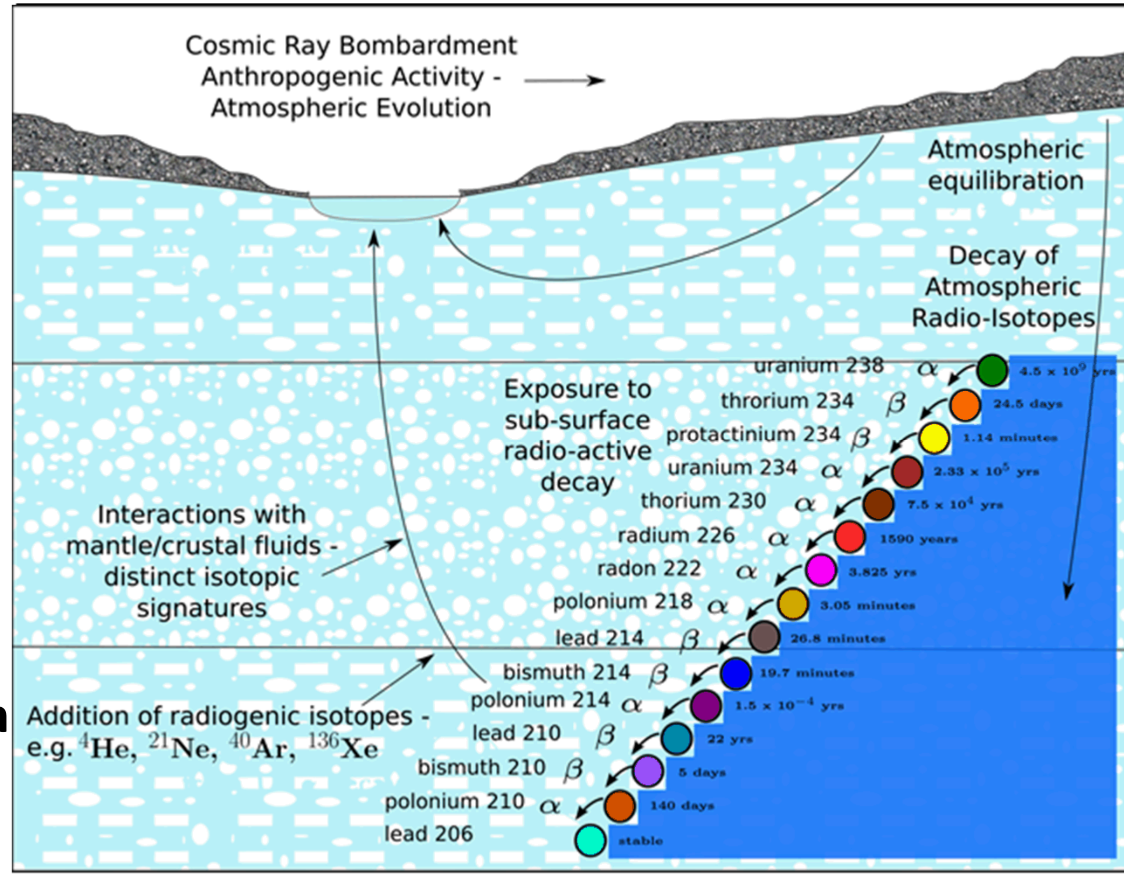
- **Borehole Geophysics**
- Logging During Drilling
  - **Mud fluids/solids/tracers/dissolved gases**
  - **Torque, weight-on-bit, etc.**
- **Basement Rock Samples**
  - **Coring (150 m total)**
  - **Cuttings/Rock Flour (XRD + XRF)**
- **Basement Pore Fluid Samples**
  - **Fluid density/temperature/major ions**
  - **^{4}He sampling from cores**
  - **Stable water isotopes**
  - **U/Sr isotope ratios**
  - **Samples from**
    - **In Situ (packers) from high K zones**
    - **Extracted from cores in low K zones**
- Flowing borehole log



CB: Environmental Tracer Profiles

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

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

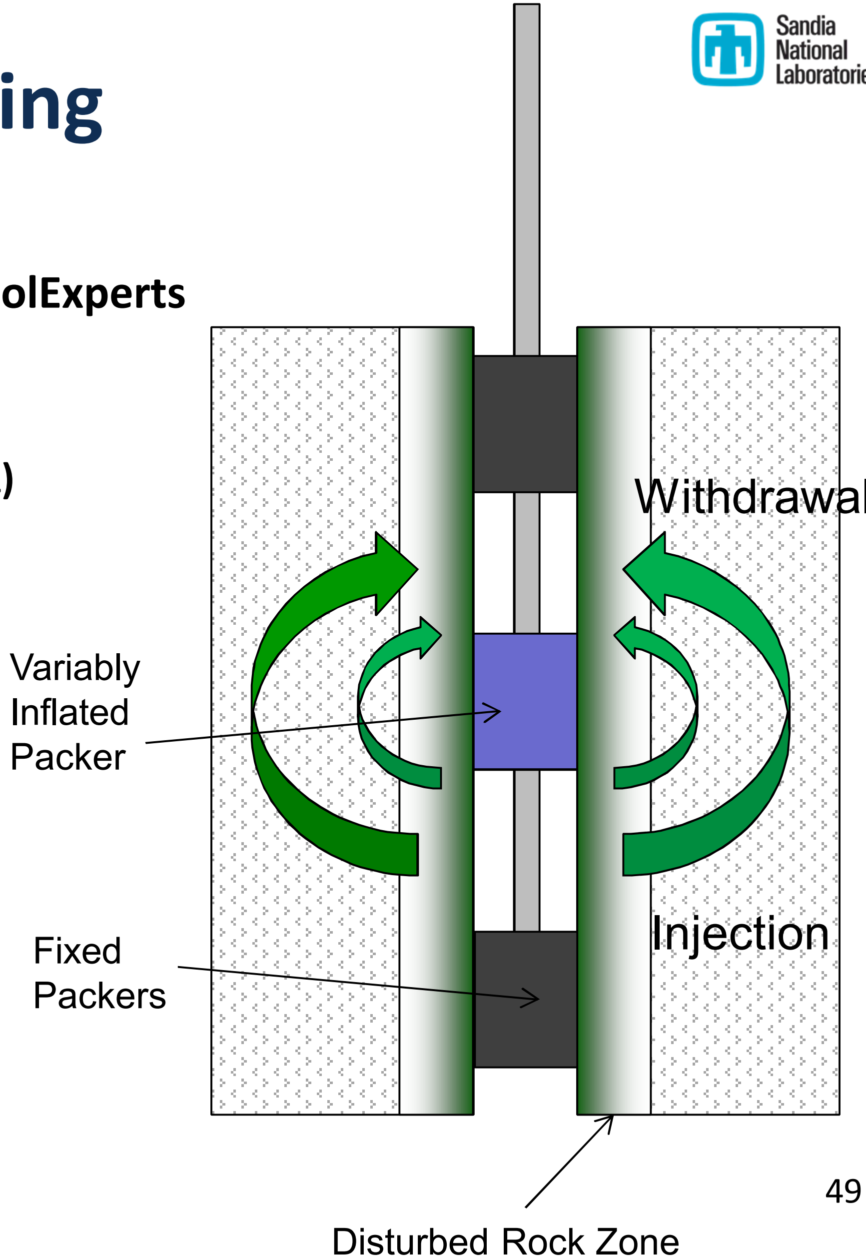


Fluid Sample Quality + Quantity *will be a Focus!*

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

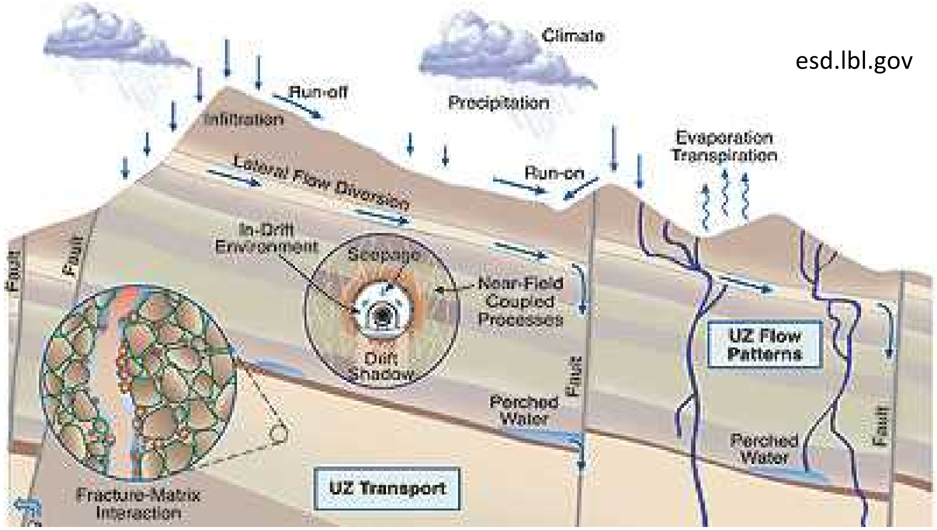
In Situ Testing

- **Test Design with Battelle/Schlumberger/SolExperts**
  - **No heater test**
  - **No dipole tracer test**
  - **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**



DBD Characterization Approach

- **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/mineral exploration**
    - **Low-permeability**
    - **Minimal mineralization**
    - **Avoid overpressure**
    - **Crystalline basement vs sedimentary rocks**
  - **Geothermal exploration**
    - **Low geothermal gradient**



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Highlights

- **Deep Borehole Disposal Concept**
  - **Robust isolation**
  - **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 test packages (FTB)**
  - ***Drilling to Begin Oct 2016!***

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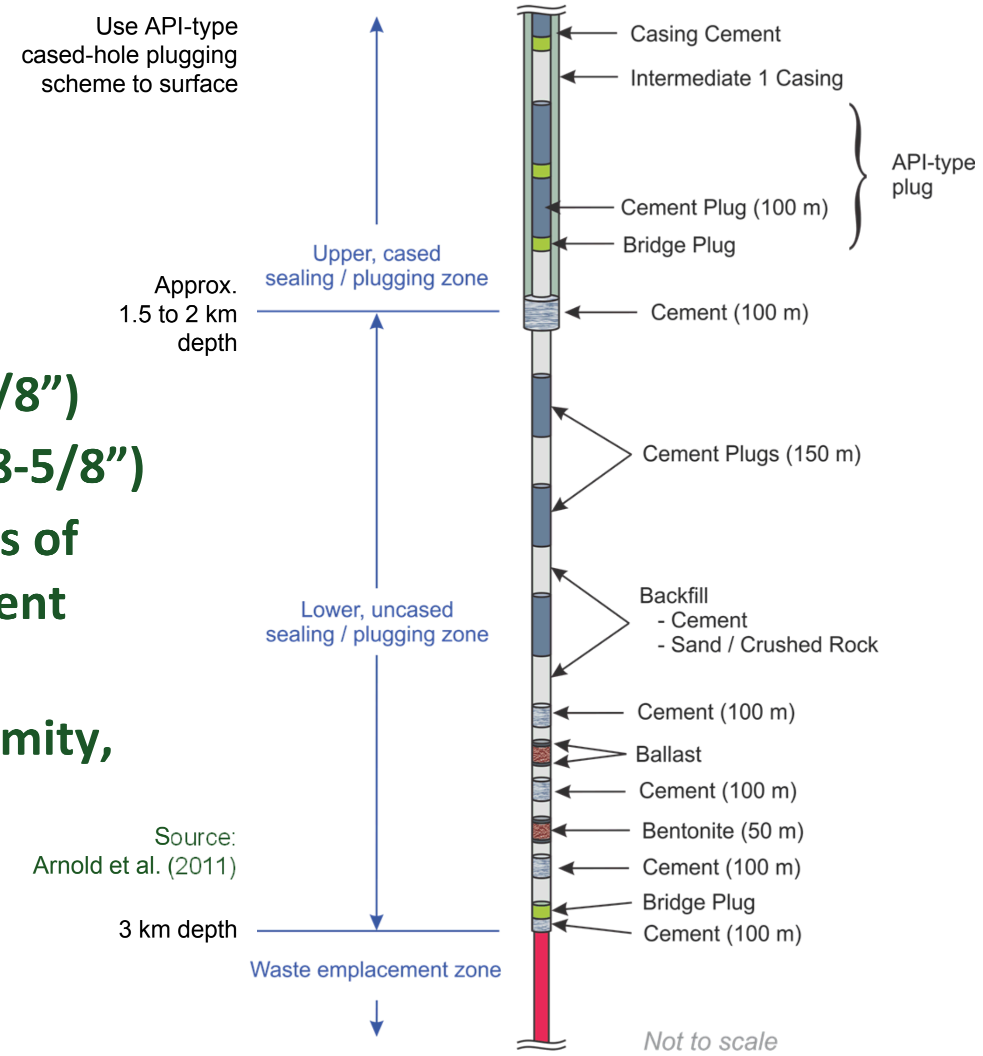
Reference Concept for Disposal Borehole Completion and Sealing

- **Disposal Zone**
  - **Cemented guidance casing**
  - **Emplacement fluid**
  - **Bridge plugs**
- **Sealing/Plugging Zone**
  - **Remove guidance tieback (13-3/8")**
  - **Remove intermediate casing (18-5/8")**
  - **Seal/plug with alternating layers of compacted bentonite clay, cement plugs, and cemented backfill**
  - **Extend upward across unconformity, into the overburden**
- **Overburden Interval**
  - **API* type plug, fully cemented**

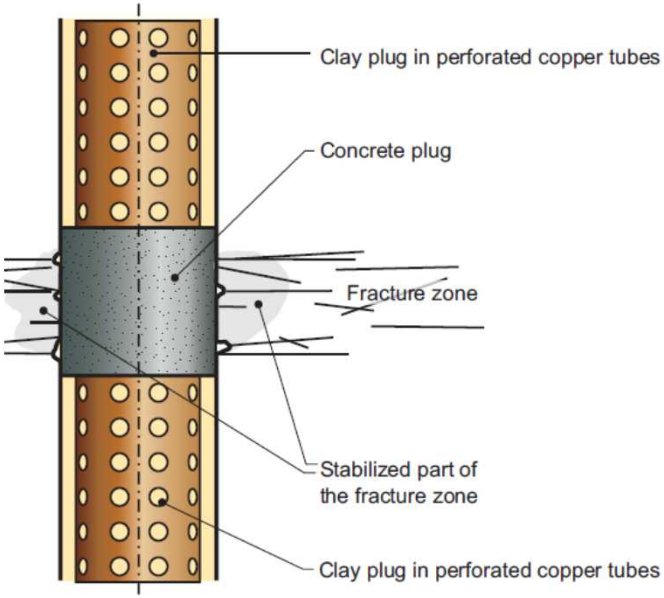
*American Petroleum Institute

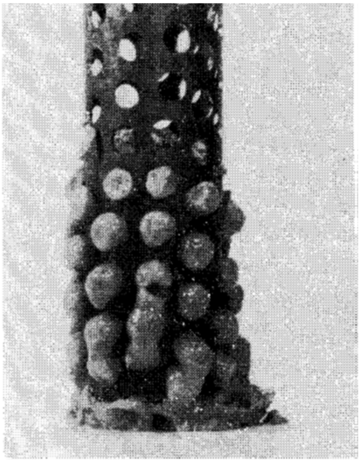


Sealing Materials and Methods

- Sealing *
  - Smectites, illites, zeolites
  - Emplacement methods
- Cement *
  - Material properties and longevity
  - Emplacement methods and setting time
- Fused Borehole Plug
- Rock Melting
  - Low permeability plug
  - Controlled annealing of host rock

Following 35+ years R&D for sealing investigation boreholes and repository shafts





Laboratory immersion 24 hr

(Pusch, R. Borehole sealing with highly compacted Na bentonite. SKB TR-81-09)

Sealing Technology Studies Underway

- DOE Small Business Innovation Research & Technology Transfer
  - RESPEC: Rock melt borehole sealing system – Electric heater (2015-2017)
  - Olympic Research: Thermally formed (thermite) plugs for deep borehole plugging and sealing (2013-2016)
  - Impact Technologies LLC/Air Force Research Lab: Deep borehole applications of millimeter wave technology (2014-2016)
  - Cimentum, Inc.: Unique cement for cementing and grouting in deep boreholes for waste disposal (2015-2016)
- Sandia Partner Labs and Subcontracts
  - University of Sheffield, UK: Deep borehole field test and borehole seal design and performance criteria (Sept. 2015 – Sept. 2016)
  - Korean Atomic Energy Research Institute (KAERI): Borehole sealing investigations collaboration (2015+)
  - Los Alamos National Laboratory: High-temperature and -pressure investigations of smectite stability
  - Participation in DOE's Subsurface Technology and Engineering Research, Development, and Demonstration (SubTER) program