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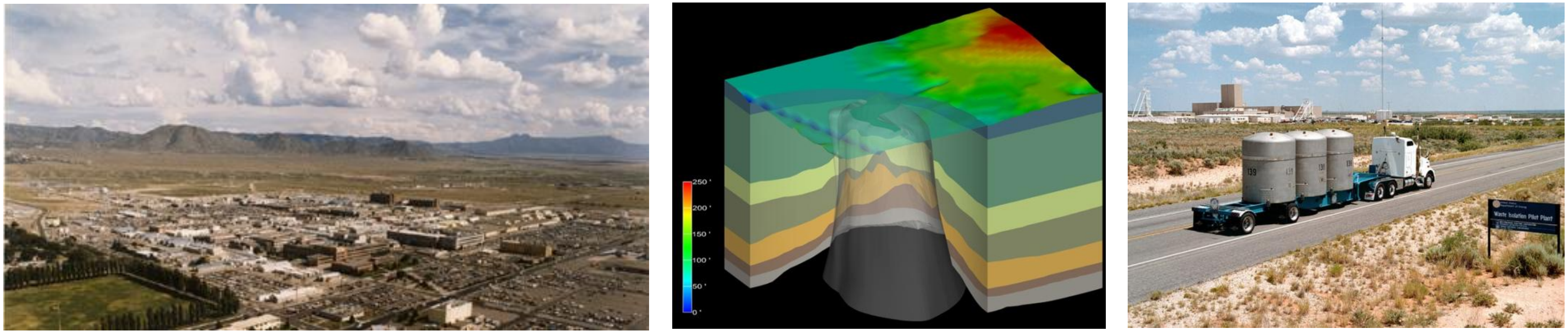


# Deep Borehole Disposal of High-Level Radioactive Waste: Concept and Demonstration Project

## Meeting in Rapid City, South Dakota – February 5, 2013

Bill Arnold and Pat Brady

# Outline

- Introduction
- Deep borehole disposal concept
- Geological aspects of disposal system safety
- Deep borehole disposal safety analyses and modeling
- Reference design and operations for a deep borehole disposal system
- Deep borehole disposal RD&D Roadmap
- Demonstration project siting guidelines
- Conclusions

# Introduction

- Deep borehole disposal not a new idea; considered as an option by National Academy of Science in 1957
- Periodically reconsidered by U.S. and other countries for spent nuclear fuel and excess plutonium disposal
- Sandia National Laboratories (SNL) has been involved in new research for about 4 years. Major reports include:
  - Brady et al. (2009) – Report with conceptual evaluation, safety assessment, and cost estimates
  - Arnold et al. (2011) – Report on deep borehole disposal system reference design and operations
  - Vaughn et al. (2012) – Report on site characterization, logging, and testing for deep borehole disposal
  - Arnold et al. (2012) – Research, Development, and Demonstration (RD&D) Roadmap for Deep Borehole Disposal

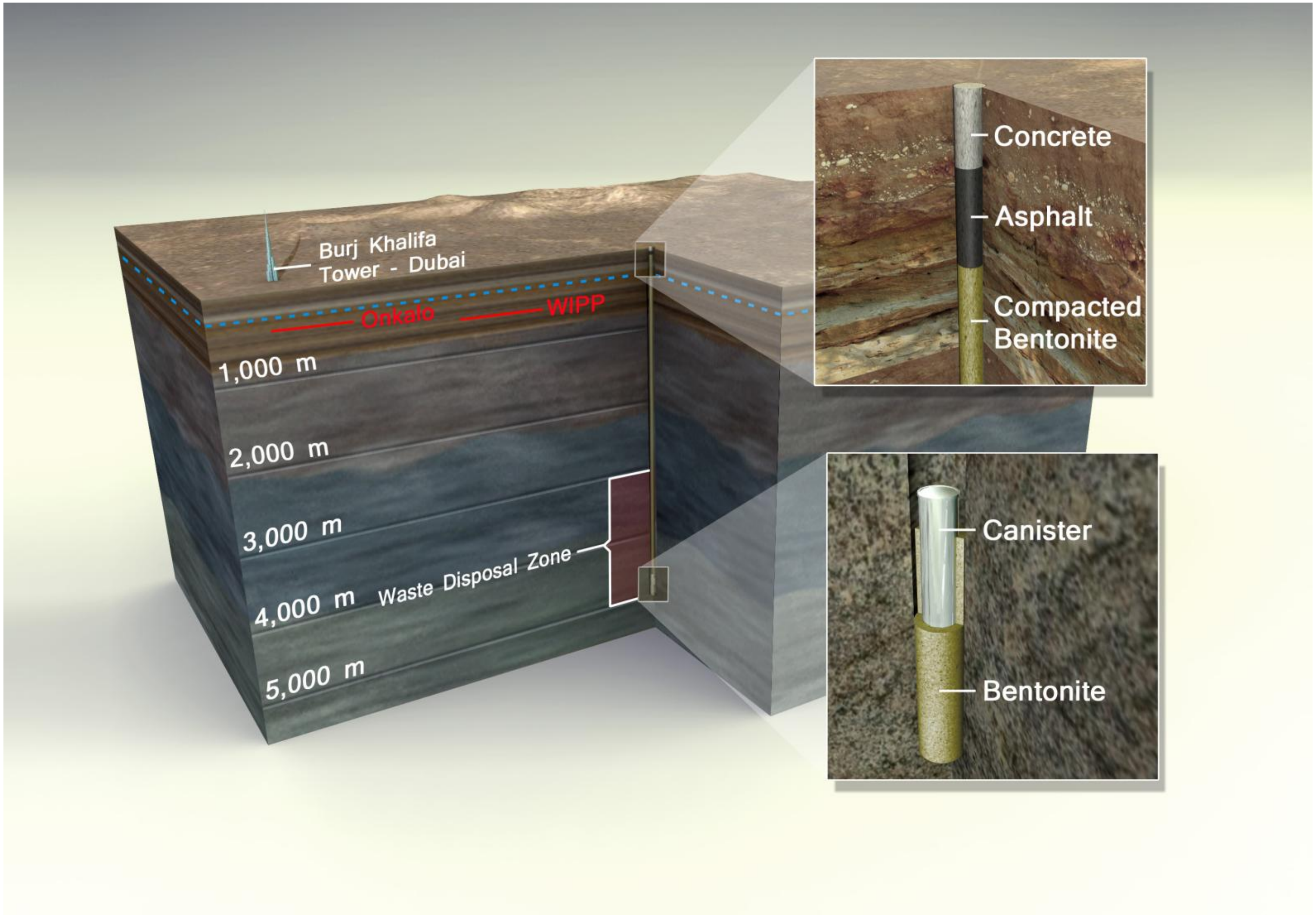
# Introduction

- Blue Ribbon Commission on America's Nuclear Future (BRC, 2012) made a recommendation for "further RD&D to help resolve some of the current uncertainties about deep borehole disposal and to allow for a more comprehensive (and conclusive) evaluation of the potential practicality of licensing and deploying this approach …"
- Sandia is working in collaboration with several other institutions on deep borehole disposal, including:
  - Massachusetts Institute of Technology (Mike Driscoll and students)
  - University of Sheffield (Fergus Gibb)
  - New Mexico Institute of Mining and Technology
  - Lawrence Livermore National Laboratory (Bill Halsey)
  - Los Alamos National Laboratory (Frank Perry)

# Deep Borehole Disposal Concept

- Disposal concept consists of drilling a borehole or array of boreholes into crystalline basement rock to about 5,000 m depth
- Borehole casing or liner assures unrestricted emplacement of waste canisters
- Waste would consist of spent nuclear fuel and/or high-level radioactive waste
- Approximately 400 waste canisters would be emplaced in the lower 2,000 m of the borehole
- Upper borehole would be sealed with compacted bentonite clay , cement plugs, and cemented backfill

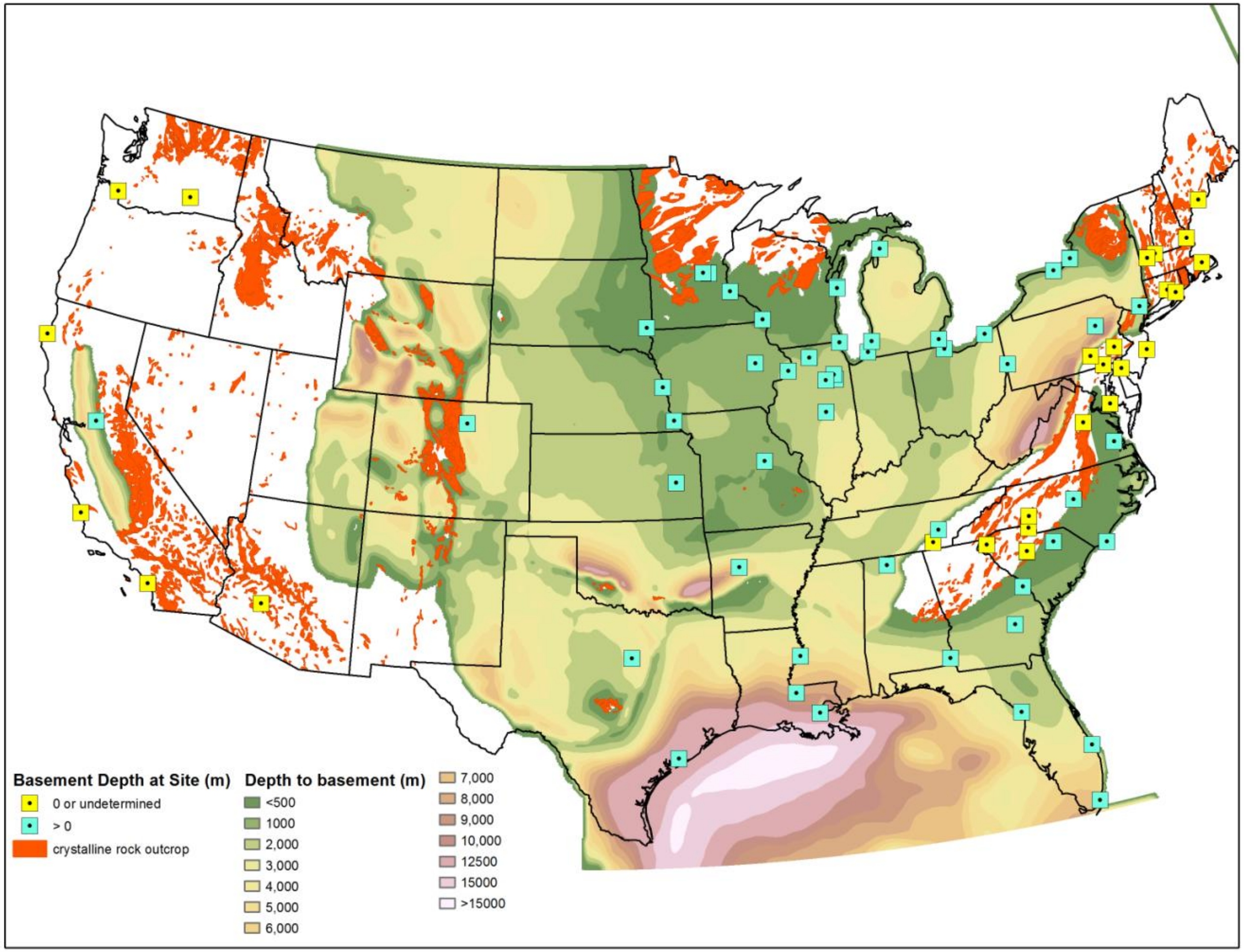
# Deep Borehole Disposal Concept



# Deep Borehole Disposal Concept: Viability and Safety

- **Crystalline basement rocks are common in many stable continental regions**
- **Existing drilling technology permits reliable construction at acceptable cost**
- **Low permeability and long residence time of high-salinity groundwater in deep continental crystalline basement at many locations suggests very limited interaction with shallow fresh groundwater resources**
- **Geochemically reducing conditions at depth limit the solubility and enhance the sorption of many radionuclides in the waste**
- **Density stratification of saline groundwater underlying fresh groundwater would oppose thermally induced groundwater convection**

# Geological Aspects of Safety and Siting



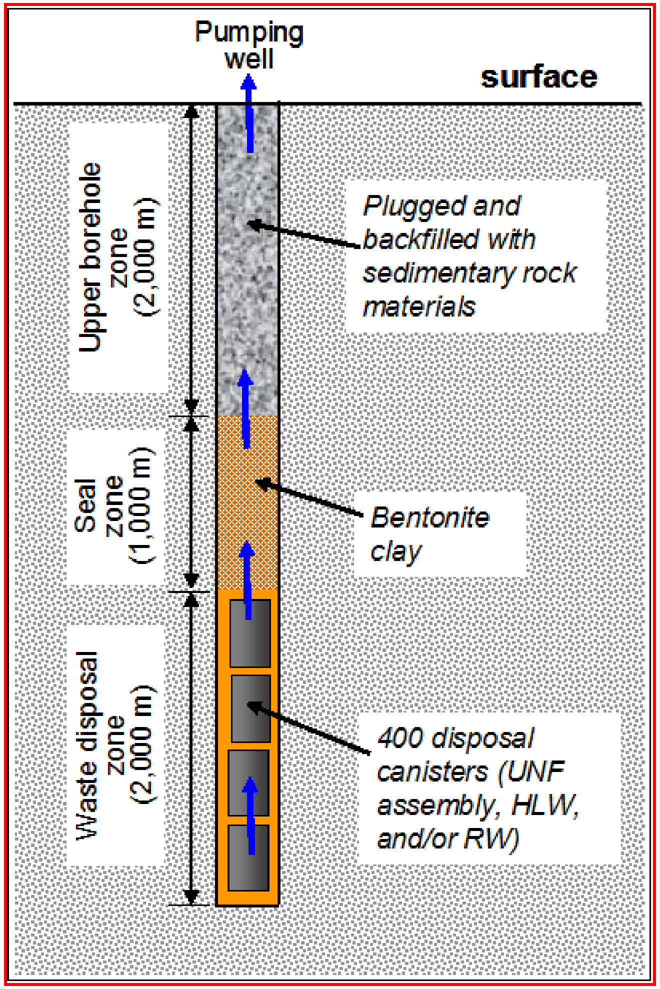
from Perry (2011)

# Geological Aspects of Safety and Siting

- **Geological characterization should focus on conditions that are undesirable for the deep borehole disposal concept and waste isolation:**
- **Young meteoric groundwater at depths of greater than 3 km**
- **Low-salinity, oxidizing groundwater at depths of greater than 3 km**
- **Economically exploitable natural resources at depths of greater than 3 km depth**
- **Significant upward gradient in fluid potential (overpressured conditions) from below 3 km depth**
- **Natural interconnected zone of high permeability from the waste disposal zone to the surface or shallow subsurface environment (e.g., fault zone)**
- **High geothermal heat flow**
- **Significant differential in horizontal stress at depth**

# Deep Borehole Disposal Safety Analyses and Modeling

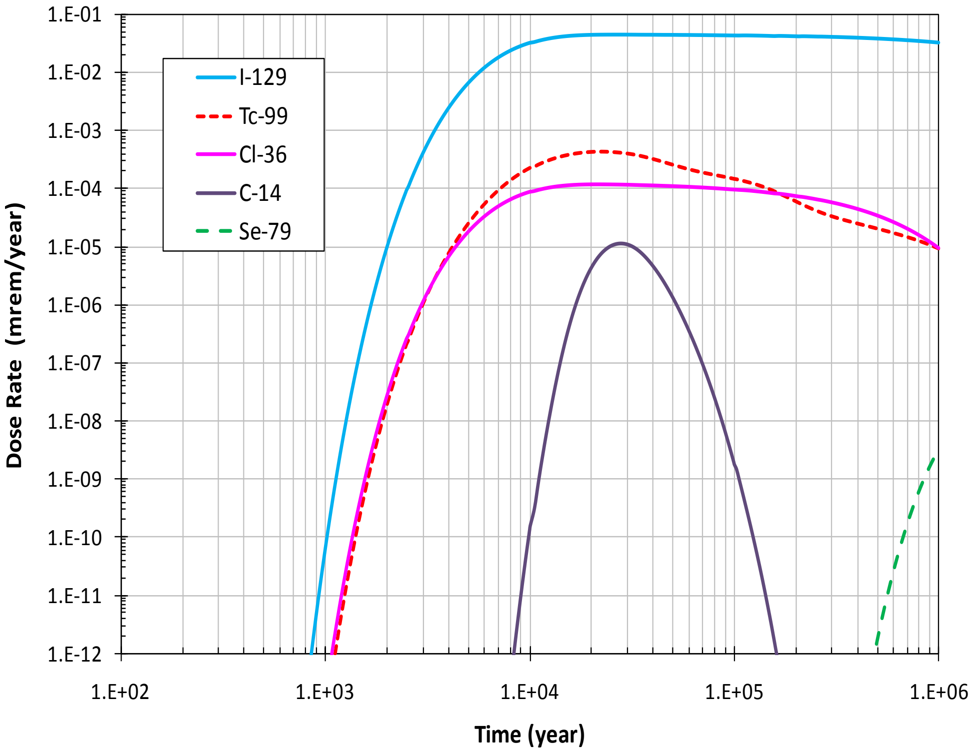
- **Model domain consists of three components:**
  - **Waste-disposal zone**
  - **Seal zone**
  - **Upper-borehole zone and aquifer**
- **Groundwater flow driven by thermal-hydrologic effects (thermal expansion and thermal buoyancy) – no ambient gradient in fluid potential**
- **Groundwater flow in the upper-borehole zone driven by 3D radial flow to a water supply well (Brady et al., 2009)**
- **Flow and radionuclide transport in waste-disposal and seal zones occurs in 1 m$^2$ cross-sectional area consisting of the borehole, borehole seals or canisters plus grout, and disturbed rock zone (DRZ) surrounding borehole**



# Deep Borehole Disposal Safety Analyses and Modeling

- **High permeability case (fully degraded seals) results in an estimated peak mean annual dose less than 0.001 mSv/yr**
  - **I-129 is primary contributor, lesser contributions from Cl-36,Tc-99, C-14, and Se-79**
  - **Peak dose rate limited by the fractional dissolution of the used fuel**
- **Relatively higher (but still small) estimated doses for high permeability case indicate the importance of a robust seal design**

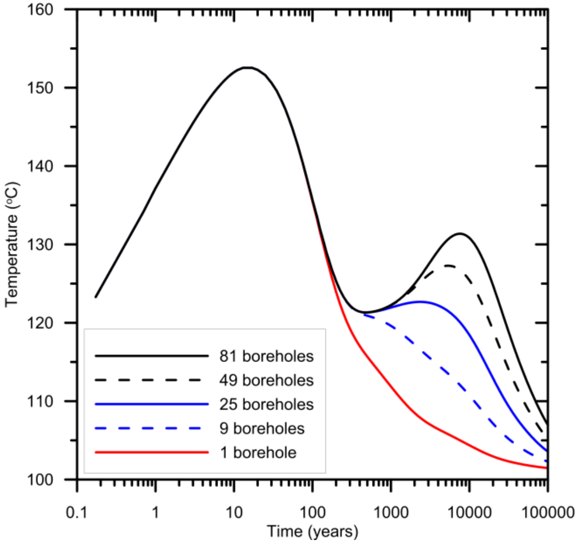
Results shown for a single borehole

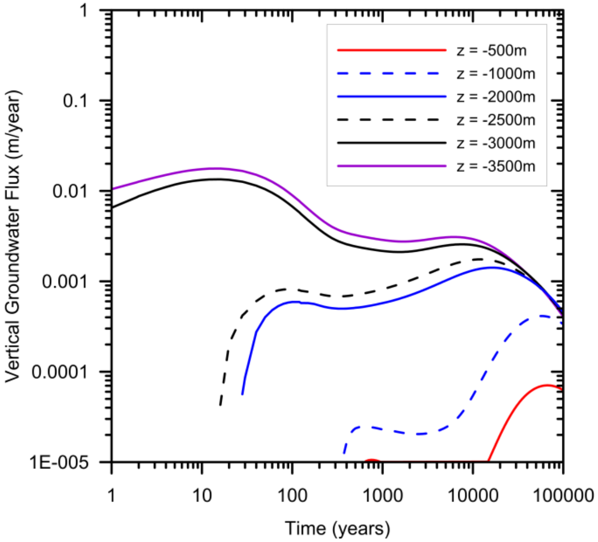


High permeability case: rock permeability = $10^{-16}$ m$^2$ and borehole/DRZ permeability = $10^{-12}$ m$^2$ (equivalent to fine sand, conceptually intended to provide a conservative representation of a fully-failed seal system)

# Deep Borehole Disposal Safety Analyses and Modeling

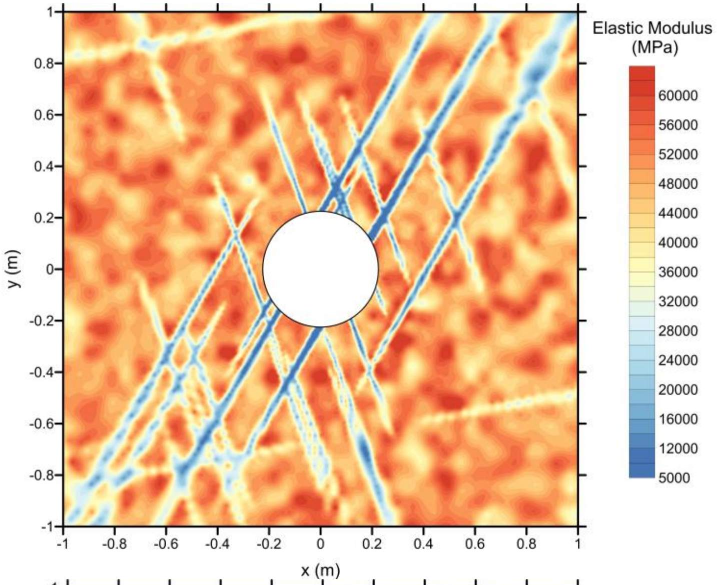
- Simulations use the reference design from Arnold et al. (2011) and average used PWR fuel from Carter et al. (2011)
- Model results show the temperature at 3,000 m depth in the central borehole of the array, with larger arrays producing a second peak temperature due to interaction among boreholes
- Simulated upward vertical flow in the central borehole of an 81-borehole array shown for various depths, with small flow rates persisting out to 100,000 years
- Long-term vertical flow rates are significantly lower for fewer boreholes in the array

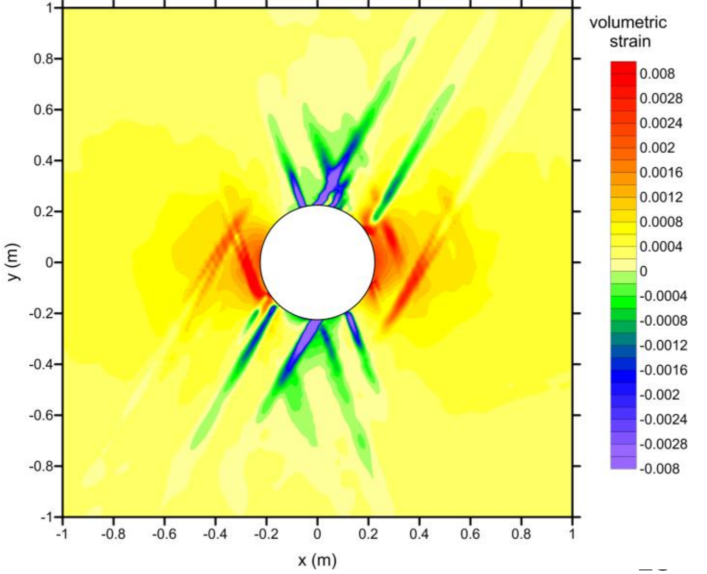




# Deep Borehole Disposal Safety Analyses and Modeling

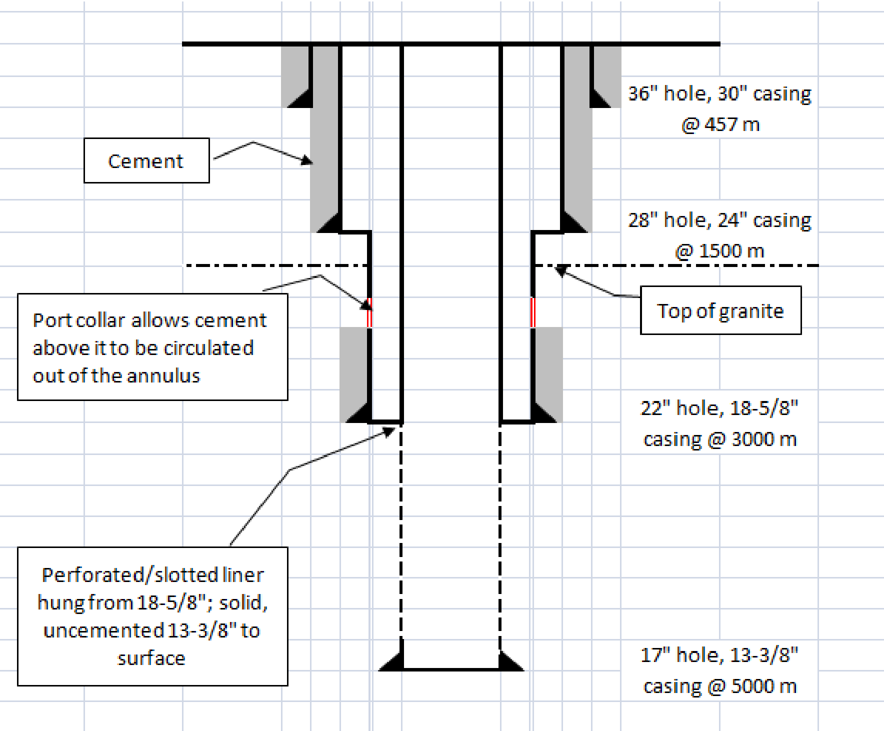
- For differential horizontal stress, the host rock near the borehole is placed in extension in the direction of minimum horizontal stress
- Permeability will be increased by extensional strain and decreased by compression
- Coupled thermal-mechanical modeling results for heterogeneous fractured granite and anisotropic horizontal stress shown for disposal of average used PWR fuel assembly – 5 years after disposal
- Higher temperatures near the borehole and related thermal expansion place much of the host rock in compression
- Some of the fractures in the general direction of the minimum principal horizontal stress remain in extension and would have increased permeability relative to the undisturbed rock





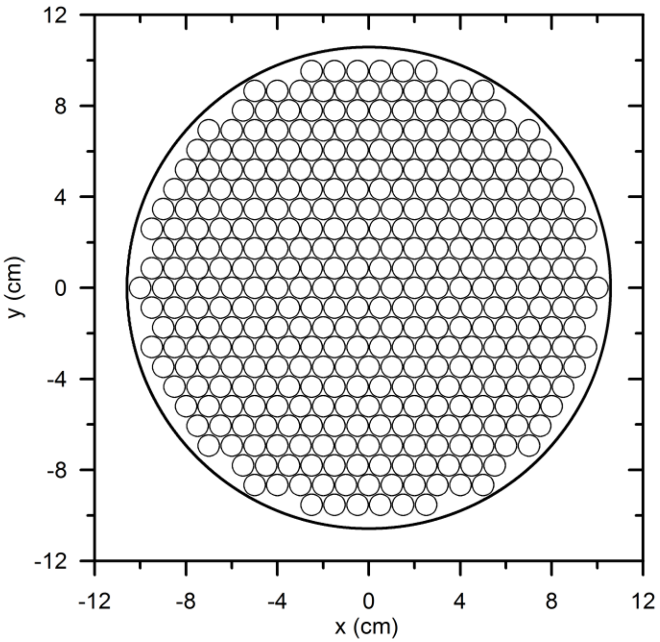
# Reference Design and Operations: Borehole Design

- **Drilling to 5 km depth is not exceptional for geothermal development and 17 inches diameter should be feasible with current technology**
- **Testing and logging for the large diameters specified in the nested borehole design may be difficult to achieve, leading to consideration of a pilot hole**
- **The perforated liner will be left in place in the disposal zone, but will be removed in the seal zone, along with most of the intermediate casing**



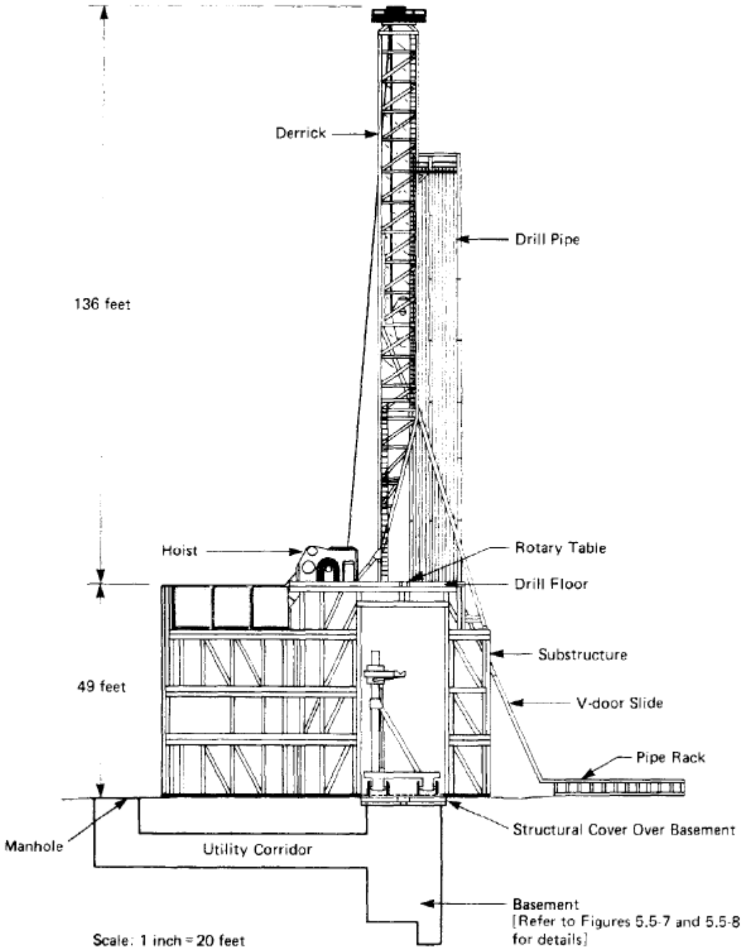
# Reference Design and Operations: Canisters and Emplacement

- Canisters are designed to withstand projected hydrostatic pressure and mechanical load of overlying canisters
- Used PWR fuel assemblies would be dismantled and 367 fuel rods would be placed in the canister (lower-temperature design)
- Strings of 40 canisters (about 200 m) would be attached to the pipe string with a J-slot assembly and lowered to the disposal zone
- A synthetic oil-base mud with a high bentonite concentration would be present in the disposal zone, forming a grout around the waste canisters
- Each canister string would be separated from overlying canister strings by a bridge plug and cement plug



# Reference Design and Operations: Waste Emplacement

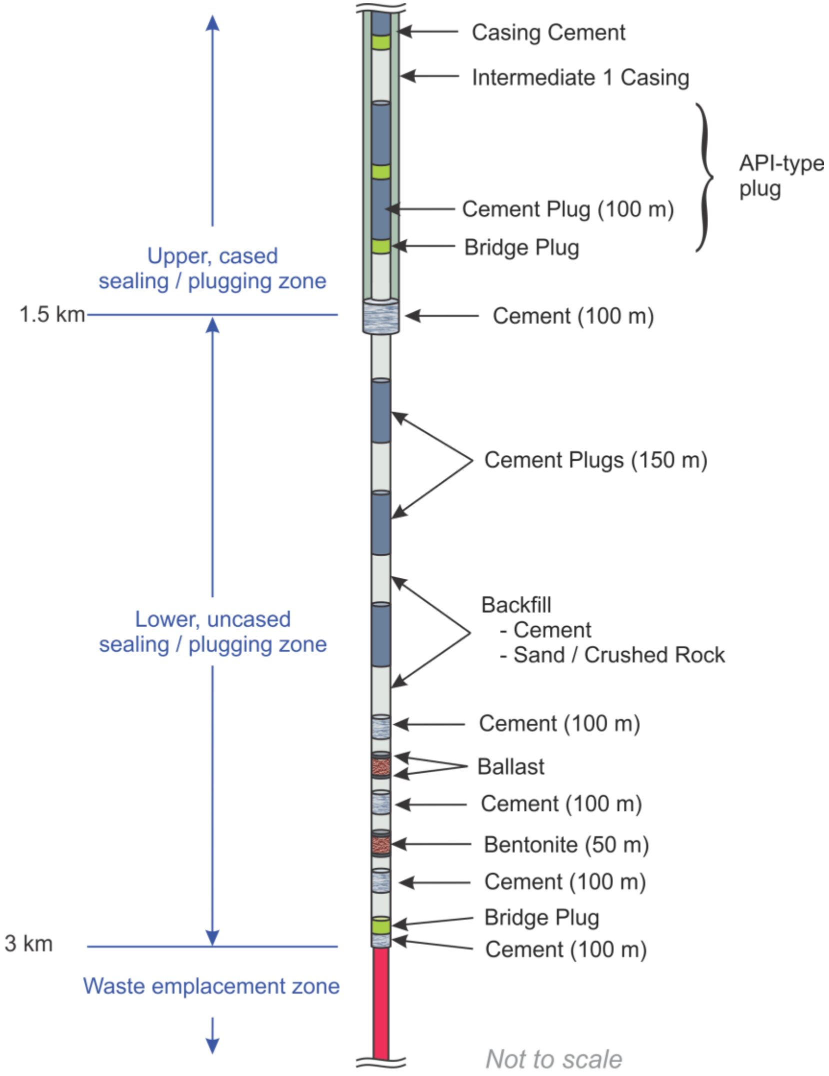
- **Loaded waste canisters would be transported to the site by tractor trailer using shipping casks**
- **Surface handling would rotate the shipping cask to a vertical position, move the cask by a short rail system over the borehole, attach the canister to the canister string and lower it into the borehole by remote operation**
- **Strings of 40 canisters (about 200 m) would be attached to the pipe string with a J-slot assembly and lowered to the disposal zone for disengagement**
- **A synthetic oil base mud with a high bentonite concentration would be present in the disposal zone, forming a grout around the waste canisters**
- **Each canister string would be separated from overlying canister strings by a bridge plug and cement plug**



from Woodward-Clyde Consultants (1983)

# Reference Design and Operations: Seals Design

- **After the waste canisters have been emplaced and the overlying plugs have been set, the guide casing will be removed and the intermediate casing in the seal zone will be cut and removed**
- **Seals and plugs in the seal zone will be seated in contact with the rock of the borehole walls**
- **Compacted bentonite seals that swell by the uptake of water would be set by extrusion from a container or emplacement of a perforated tube**
- **Cement seals, alternating with sand/crushed rock/cement backfill, would fill the remainder of the seal zone**



# Deep Borehole Disposal Costs

- **Costs are dominated by borehole drilling and construction**
- **There is significant uncertainty about drill rig time and cost associated with testing and logging of the borehole**
- **The estimated $27M cost shown here is for boreholes following the more intensively characterized initial borehole at a site**
- **Aside from transportation costs, estimated disposal costs are $158/kg heavy metal (HM) (compared to the U.S. nuclear waste fund fee of roughly $400/kg HM (Gibbs, 2010))**
- **Estimated time for drilling, borehole completion, waste emplacement, and sealing is about 186 days**

| | **Cost per Borehole** |
|---|---|
| Drilling, Casing, and Borehole Completion | $27,296,587 |
| Waste Canisters and Loading | $7,629,600 |
| Waste Canister Emplacement | $2,775,000 |
| Borehole Sealing | $2,450,146 |
| **Total** | **$40,151,333** |

Note: All costs are in 2011 $US and approximately for 2011 expenses.

from Arnold et al. (2011)

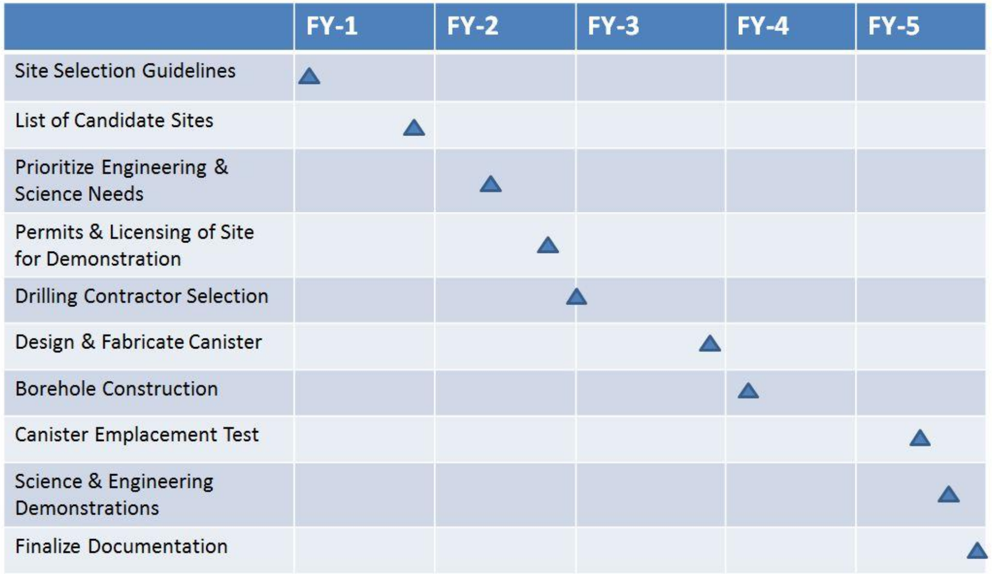
# Deep Borehole Disposal Capacity

- **Current commercial used fuel inventory could be disposed in 273 boreholes using the reference design and rod consolidation of all waste in canisters (disposal of about 240 metric tons of uranium per borehole)**
- **The slowed replacement scenario assumes half the rate of new plant construction between the no replacement and the maintain current capacity scenarios**

| | | | | Number of Boreholes Needed | | |
|---|---|---|---|---|---|---|
| **Scenario** | **PWR MTU** | **BWR MTU** | **Total MTU** | **0% Rod Consolidation** | **100% Rod Consolidation** | **PWR Only 100% Rod Consolidation** |
| 2010 Current Inventory | 42300 | 23000 | 65300 | 568 | 273 | 499 |
| No Replacement – end in 2055 | 91000 | 49000 | 140000 | 1215 | 585 | 1067 |
| Maintain Current – through 2100 | 175000 | 95000 | 270000 | 2346 | 1127 | 2062 |
| Slowed Replacement – through 2100 | 133000 | 72000 | 205000 | 1780 | 856 | 1564 |
| Maintain - 40K MTU – through 2100 | 149500 | 80500 | 230000 | 1995 | 960 | 1752 |
| Slowed Replacement - 40K MTU – through 2100 | 107250 | 57750 | 165000 | 1431 | 689 | 1257 |

# Deep Borehole Disposal RD&D Roadmap

- **Demonstration Site Selection**
- **Borehole Drilling and Construction**
- **Science Thrust**
- **Engineering Thrust**



| | FY-1 | FY-2 | FY-3 | FY-4 | FY-5 |
|---|---|---|---|---|---|
| Site Selection Guidelines | △ | | | | |
| List of Candidate Sites | △ | | | | |
| Prioritize Engineering & Science Needs | | △ | | | |
| Permits & Licensing of Site for Demonstration | | △ | | | |
| Drilling Contractor Selection | | | △ | | |
| Design & Fabricate Canister | | | △ | | |
| Borehole Construction | | | | △ | |
| Canister Emplacement Test | | | | | △ |
| Science & Engineering Demonstrations | | | | | △ |
| Finalize Documentation | | | | | △ |

# Deep Borehole Disposal RD&D Roadmap: Science Thrust

- Identification of Data Gaps and Characterization Methods
- Geology
- Hydrogeology
- Stress/Pressure Conditions and Borehole Stability
- Geochemical Environment
- Thermal Effects
- Coupled Thermal-Hydrologic-Chemical-Mechanical Behavior
- Engineered Material Performance
- Long-Term Monitoring
- Nuclear Criticality

# Deep Borehole Disposal RD&D Roadmap: Engineering Thrust

- Reference design for demonstration
- Borehole logging
- Borehole construction
- Test canisters
- Canister loading operations
- Waste handling
- Waste emplacement
- Seal design and closure
- Operational retrievability

# Deep Borehole Disposal RD&D Roadmap: Prioritization of Testing

## Example

| Activity | Maturity | Redundancy | FEPs Relevancy | Uncertainty Reduction/PA Importance | Value of Information | Combined |
|---|---|---|---|---|---|---|
| **3D Seismic Imaging** | High | High | 6 - Medium | Medium | High | 5.6 |
| **Borehole Caliper Log** | High | Medium | 1 - Low | Low | Medium | 3.65 |
| **Borehole Gravity Log** | Medium | Low | 2 - Low | Low | Low | 3.05 |
| **Dipole Shear-Wave Velocity Log** | High | High | 3 - Low | Medium | Medium | 5 |
| **Downhaul Force Mechanical Testing** | Medium | High | 5 - Medium | Medium | High | 6.05 |
| **Drill Cuttings** | High | Medium | 8 - Medium | Medium | High | 5.6 |
| **Drill Stem Pump Tests** | High | Medium | 10 - High | Medium | Medium | 5.6 |
| **Drill Stem Tests of Shut-In Pressure** | High | High | 11 - High | High | High | 6.5 |
| **Electrical Resistivity Profile** | High | Medium | 6 - Medium | Medium | Low | 4.25 |
| **Fluid Pressure Drawdown Test of Effective Permeability** | High | High | 2 - Low | Medium | High | 5.3 |
| **Fluid Samples from Packer Testing** | High | High | 49 - High | High | High | 8 |
| **Formation Micro Imager Log** | High | High | 12 - High | Medium | Medium | 6.35 |

# RD&D Roadmap: Demonstration Project Cost Estimate

| ACTIVITY | ESTIMATED COST($M) |
|---|---|
| **I. SITE CHARACTERIZATION** | $3.0 |
| **I. SITE SELECTION** | $2.0 |
| **I. REGULATORY REQUIREMENTS/PERMITS (NEPA, AIR QUALITY, DRILLING, NPDES, ETC.)** | $3.5 |
| **I. DRILLING AND CONSTRUCTION** | $45.0 |
| **I. SCIENCE R&D** | $10.0 |
| **I. ENGINEERING DEMONSTRATION** | $8.0 |
| **I. PROJECT MANAGEMENT** | $3.5 |
| **TOTAL** | $75.0 |

# Demonstration Project Siting Guidelines

- Assessment of site selection guidelines is focused on a deep borehole demonstration project
- A demonstration project should be conducted at a site that has characteristics representative of and consistent with implementation and safety of the deep borehole disposal concept
- Emphasis is placed on identification of scientific site selection guidelines associated with conditions unfavorable to deep borehole disposal
- Engineering factors and support from state/local stakeholders for a demonstration project will also be investigated in FY13

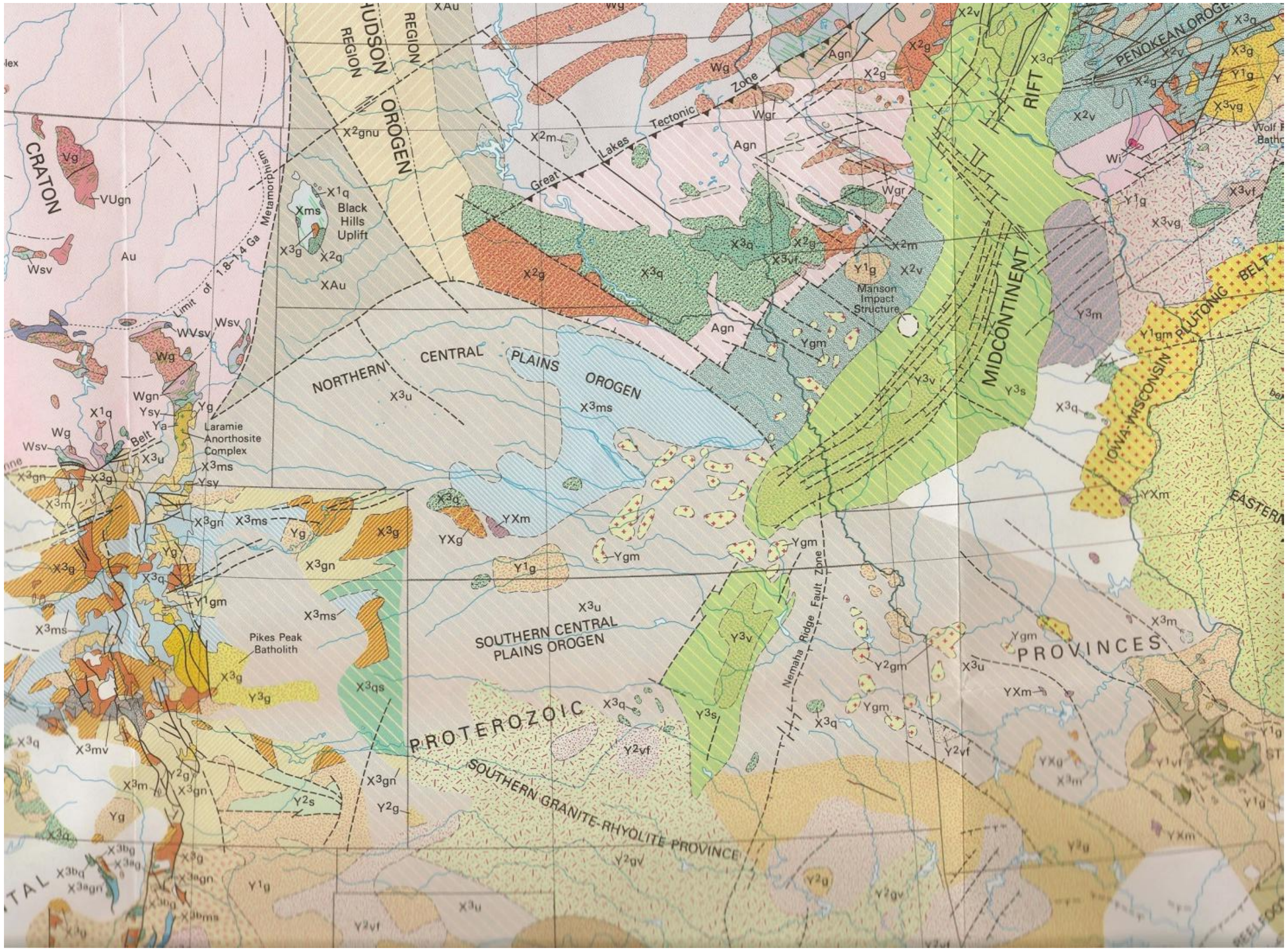
# Demonstration Project Siting Guidelines

- **Important features related to potentially unfavorable conditions for deep borehole disposal include:**
  - **Depth to crystalline basement**
  - **Deep groundwater circulation**
  - **Tectonically unstable conditions**
  - **Overpressured fluids at depth**
  - **Major faults**
  - **Volcanism**
  - **High geothermal heat flow**
  - **Potential for economically valuable mineral deposits**
  - **High differential horizontal stress**

# Demonstration Project Siting Guidelines

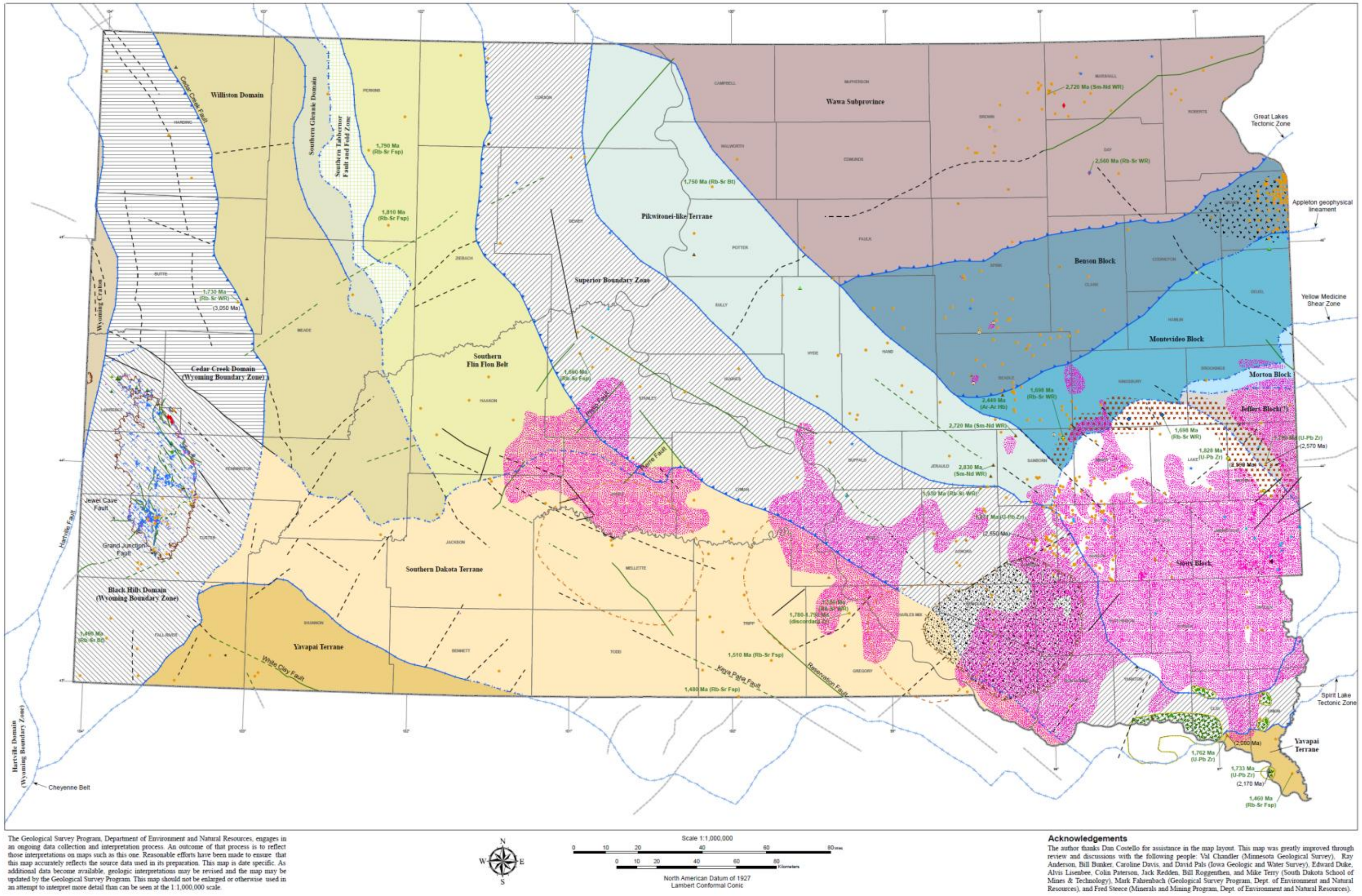
- **Technical factors relevant as guidelines:**
  - **Depth to crystalline basement**
  - **Crystalline basement lithology**
  - **Basement geological structural complexity**
  - **Topographic relief with 100 to 200 km of site**
  - **Geothermal gradient**
  - **Geothermal heat flux**
  - **Mineral resources**
  - **Tectonic activity and seismicity**
  - **Faults**
  - **Volcanism**

# Demonstration Siting Guidelines: Crystalline Basement Lithology



from Reed (1993)

# Demonstration Siting Guidelines: Crystalline Basement Lithology



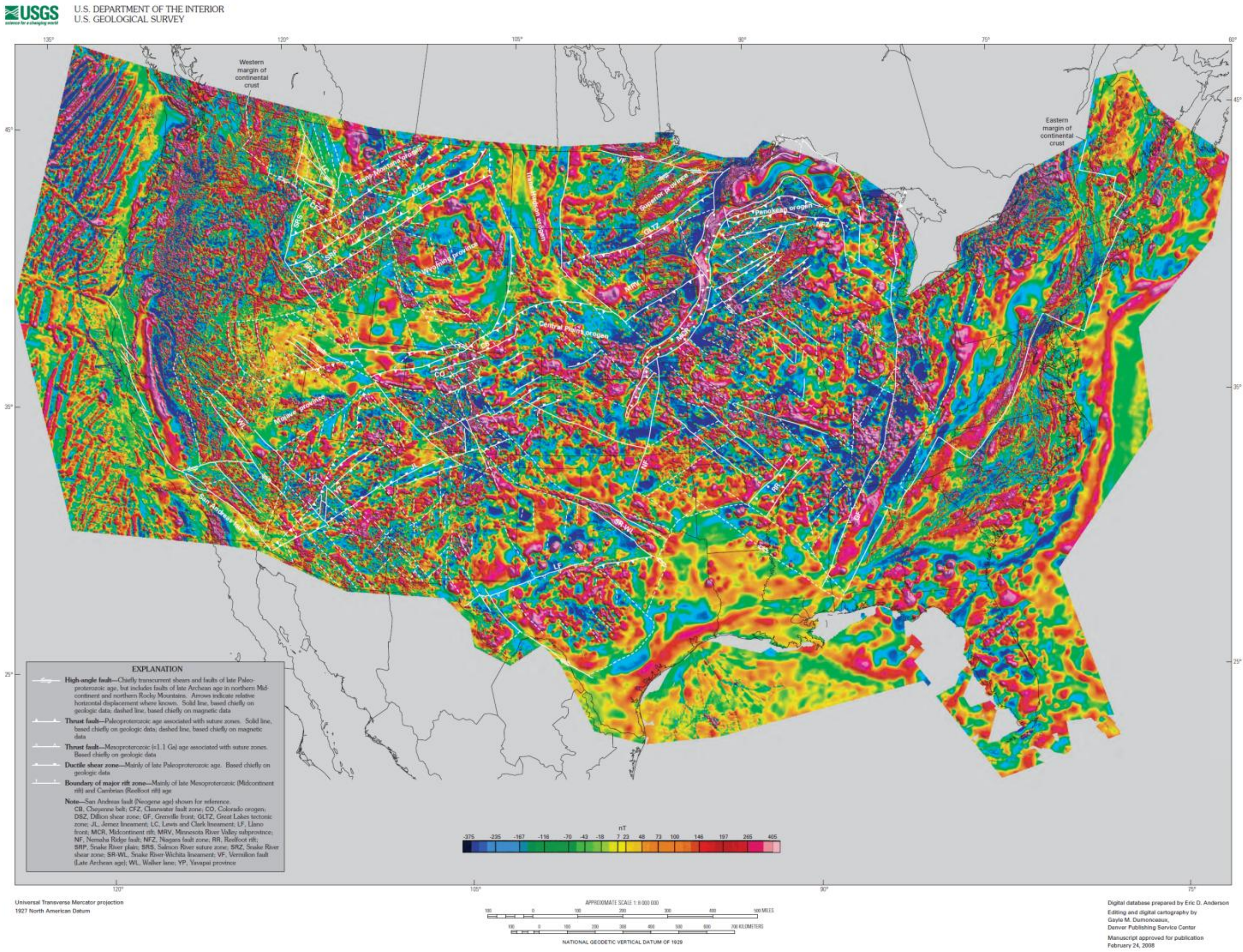
The Geological Survey Program, Department of Environment and Natural Resources, engages in an ongoing data collection and interpretation process. An outcome of that process is to reflect those interpretations on maps such as this one. Reasonable efforts have been made to ensure that this map accurately reflects the source data used in its preparation. This map is date specific. As additional data become available, geologic interpretations may be revised and the map may be updated by the Geological Survey Program. This map should not be enlarged or otherwise used in an attempt to interpret more detail than can be seen at the 1:1,000,000 scale.

**Acknowledgements**

The author thanks Dan Costello for assistance in the map layout. This map was greatly improved through review and discussions with the following people: Val Chandler (Minnesota Geological Survey), Ray Anderson, Bill Bunker, Caroline Davis, and David Pals (Iowa Geologic and Water Survey), Edward Duke, Alvis Lisenbee, Colin Paterson, Jack Redden, Bill Roggenthen, and Mike Terry (South Dakota School of Mines & Technology), Mark Fahrenbach (Geological Survey Program, Dept. of Environment and Natural Resources), and Fred Steece (Minerals and Mining Program, Dept. of Environment and Natural Resources).

from McCormick (2010)

# Demonstration Siting Guidelines: Basement Structural Complexity



EXPLANATION

**High-angle fault**—Chiefly transcurrent shears and faults of late Paleoproterozoic age, but includes faults of late Archean age in northern Midcontinent and northern Rocky Mountains. Arrows indicate relative horizontal displacement where known. Solid line, based chiefly on geologic data; dashed line, based chiefly on magnetic data

**Thrust fault**—Paleoproterozoic age associated with suture zones. Solid line, based chiefly on geologic data; dashed line, based chiefly on magnetic data

**Thrust fault**—Mesoproterozoic (≈1.1 Ga) age associated with suture zones. Based chiefly on geologic data

**Ductile shear zone**—Mainly of late Paleoproterozoic age. Based chiefly on geologic data

**Boundary of major rift zone**—Mainly of late Mesoproterozoic (Midcontinent rift) and Cambrian (Reelfoot rift) age

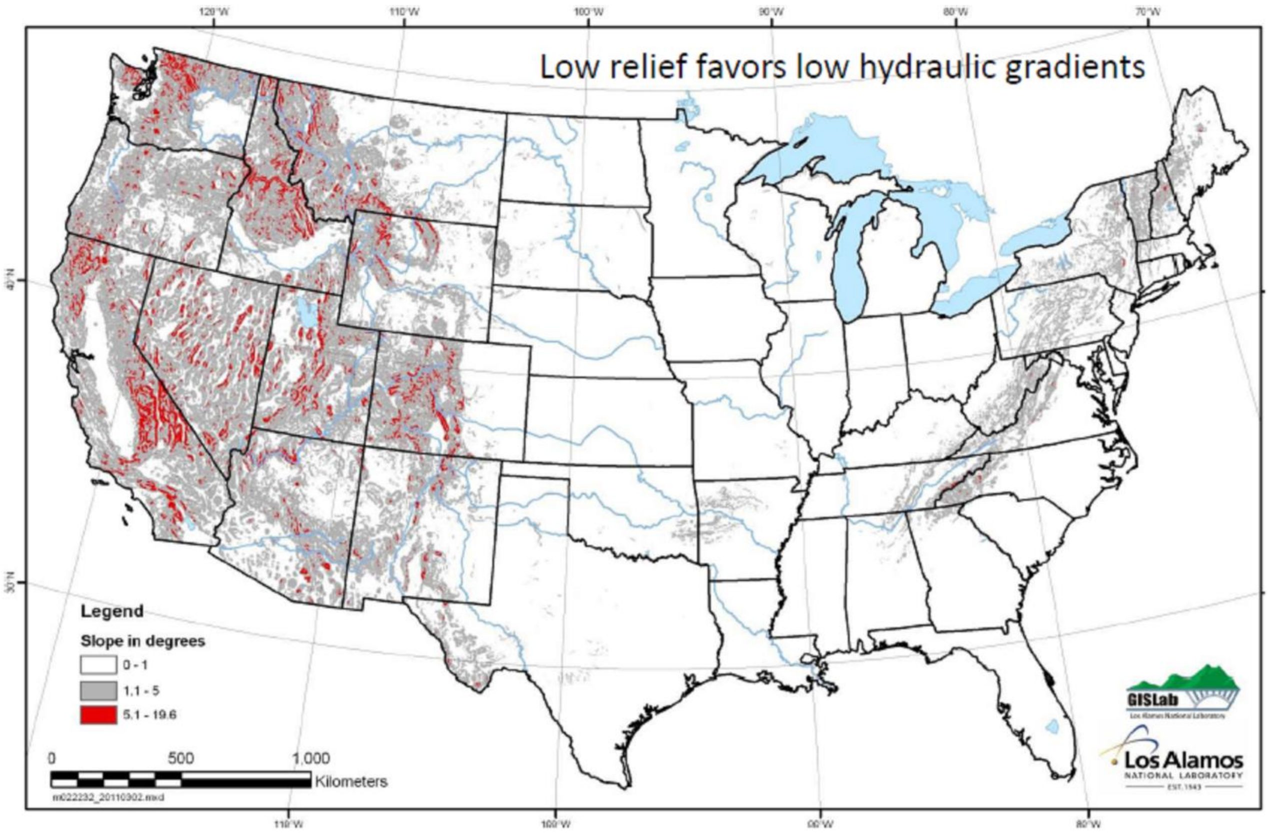
**Note**—San Andreas fault (Neogene age) shown for reference.
CB, Cheyenne belt; CFZ, Clearwater fault zone; CO, Colorado orogen; DSZ, Dillon shear zone; GF, Grenville front; GLTZ, Great Lakes tectonic zone; JL, Jemez lineament; LC, Lewis and Clark lineament; LF, Llano front; MCR, Midcontinent rift; MRV, Minnesota River Valley subprovince; NF, Nemaha Ridge fault; NFZ, Niagara fault zone; RR, Reelfoot rift; SRP, Snake River plain; SRS, Salmon River suture zone; SRZ, Snake River shear zone; SR-WL, Snake River-Wichita lineament; VF, Vermilion fault (Late Archean age); WL, Walker lane; YP, Yavapai province

Universal Transverse Mercator projection
1927 North American Datum

Digital database prepared by Eric D. Anderson
Editing and digital cartography by
Gayle M. Dumonceaux,
Denver Publishing Service Center
Manuscript approved for publication
February 24, 2008

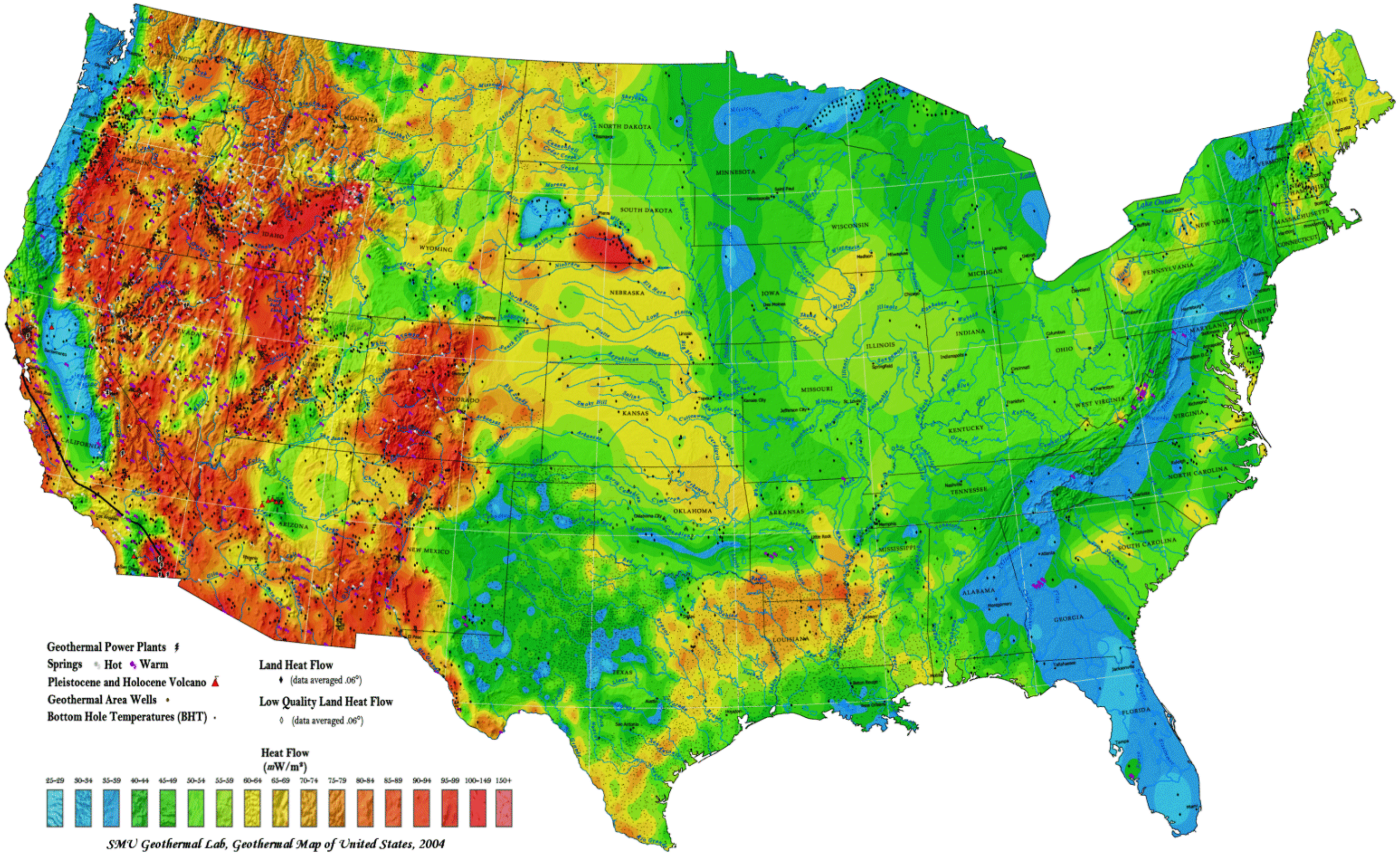
from Sims et al. (2008)

# Demonstration Siting Guidelines: Topographic Relief



from Perry (2011)

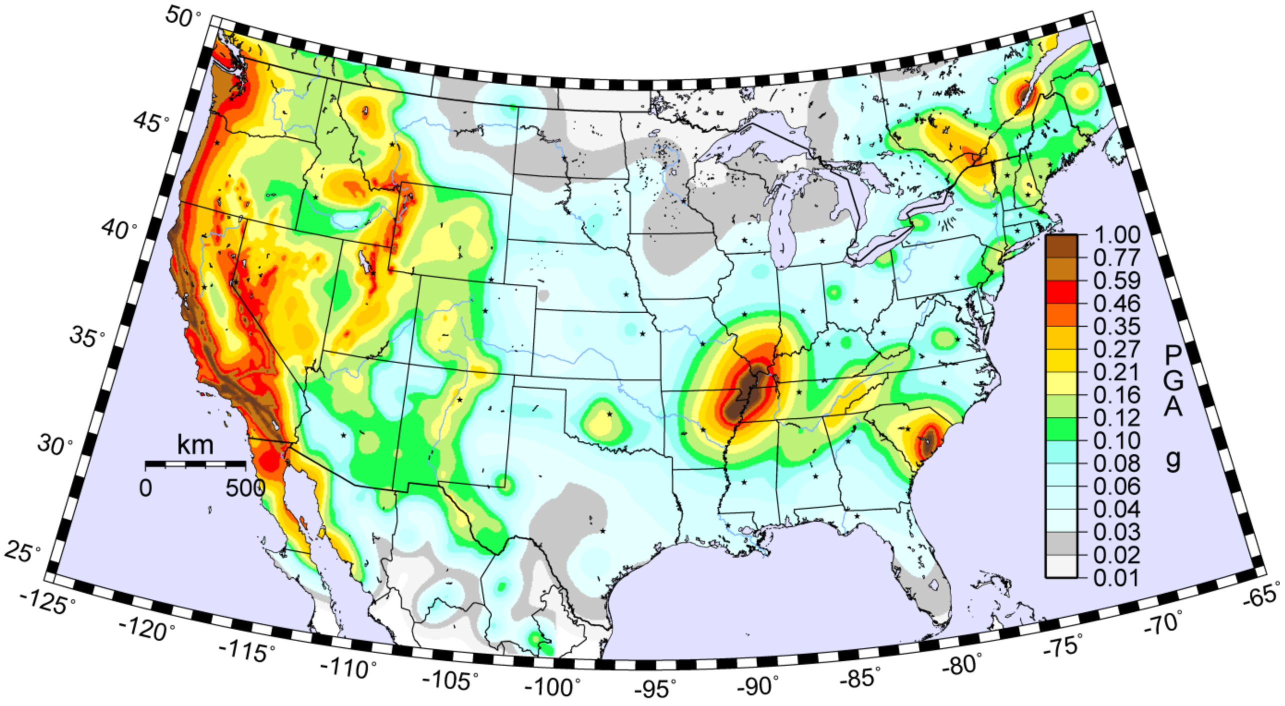
# Demonstration Siting Guidelines: Geothermal Heat Flux



*SMU Geothermal Lab, Geothermal Map of United States, 2004*

# Demonstration Siting Guidelines: Seismicity

PGA with 2% in 50 year PE. BC rock. 2008 USGS



# Conclusions

- Multiple factors indicate that deep borehole disposal is safe for widely available locations with favorable geological and hydrological characteristics
- Implementation of deep borehole disposal with a simple reference design and operations would be feasible, cost effective, and have sufficient capacity
- A RD&D Roadmap has been developed for a deep borehole disposal demonstration project, including identification of logging and testing methods and cost estimates
- Site selection guidelines are under development for locating a deep borehole disposal demonstration project

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