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Deep Borehole Field Test Laboratory and Borehole Testing Strategy

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ACRONYMS

CCSD	China continental scientific drilling project
CB	characterization borehole (component of the DBFT)
DBD	deep borehole disposal
ECP	external casing packer
FTB	field test borehole (component of the DBFT)
DBFT	deep borehole field test
DOE	US Department of Energy
DQO	data quality objectives
DRZ	disturbed rock zone
ECP	external casing packer
ICP-MS	inductively coupled plasma mass spectrometry
KTB	Kontinentale Tiefbohrprogramm der Bundesrepublik Deutschland
NMR	nuclear magnetic resonance
NRC	US Nuclear Regulatory Commission
PA	performance assessment
PDC	polycrystalline diamond compact (sometimes cutter)
RFI	request for information
RFP	request for proposal
RSD	relative standard deviation
RSS	rotary steerable system
SAFOD	San Andreas Fault Observatory at Depth
SEM	scanning electron microscope
SNL	Sandia National Laboratories
SP	streaming potential
TIMS	thermal ionization mass spectrometry
TDS	total dissolved solids
TRL	technology readiness level
UFD	used fuel disposition (DOE Office of Nuclear Energy program)
US	United States
VSP	vertical seismic profile
XRD	X-ray diffraction
XRF	X-ray fluorescence

DEEP BOREHOLE FIELD TEST: LABORATORY AND BOREHOLE TESTING STRATEGY

1. INTRODUCTION

Deep Borehole Disposal (DBD) of high-level radioactive wastes has been considered an option for geological isolation for many years (Hess et al. 1957). Recent advances in drilling technology have decreased costs and increased reliability for large-diameter (i.e., ≥50 cm [19.7”]) boreholes to depths of several kilometers (Beswick 2008; Beswick et al. 2014). These advances have therefore also increased the feasibility of the DBD concept (Brady et al. 2009; Cornwall 2015), and the current field test design will demonstrate the DBD concept and these advances.

The US Department of Energy (DOE) Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste (DOE 2013) specifically recommended developing a research and development plan for DBD. DOE sought input or expression of interest from States, local communities, individuals, private groups, academia, or any other stakeholders willing to host a Deep Borehole Field Test (DBFT). The DBFT includes drilling two boreholes nominally 200 m [656’] apart to approximately 5 km [16,400’] total depth, in a region where crystalline basement is expected to begin at less than 2 km depth [6,560’]. The characterization borehole (CB) is the smaller-diameter borehole (i.e., 21.6 cm [8.5”] diameter at total depth), and will be drilled first. The geologic, hydrogeologic, geochemical, geomechanical and thermal testing will take place in the CB. The field test borehole (FTB) is the larger-diameter borehole (i.e., 43.2 cm [17”] diameter at total depth). Surface handling and borehole emplacement of test package will be demonstrated using the FTB to evaluate engineering feasibility and safety of disposal operations (SNL 2016).

The DOE has issued a Requests for Proposals (RFP) (DOE 2015; 2016) to seek competitive bids from teams to provide a site for the DBFT (accommodating both boreholes) and a site-management contractor to manage drilling and testing for the initial CB portion of the DBFT, and later manage FTB activities. The DBFT will not involve handling or emplacing any radioactive waste, but instead will confirm scientific and technological readiness to execute the DBD concept in the future at a site chosen through a consent-based siting approach.

The RFP (DOE 2015; 2016) specifies the Site Management Contractor will be responsible for preparing a detailed drilling and testing plan for final review by DOE and the DBFT Technical Lead (Sandia National Laboratories). This plan will include specific details regarding site and borehole construction, sample collection, sample handling, in situ testing procedures, and data management. This testing strategy report summarizes DBFT characterization objectives without identifying a specific field demonstration site, while the drilling and testing plans (to be prepared by the Site Management Contractor) would specify more detail and would be site specific.

The DBFT Technical Lead will coordinate analysis of samples (e.g., cores and water samples) and data (e.g., geophysical logs and hydrological/hydraulic-fracturing test data) collected during the DBFT with the Site Management Contractor.

The two-borehole DBFT design provides a robust approach to achieve the overall goals of the project. Firstly, downhole characterization can proceed in the CB with standard logging and testing technologies, whereas characterization in the larger-diameter FTB would present additional technical challenges. Secondly, by conducting characterization activities in the smaller CB, costs associated with those activities could be significantly reduced compared to costs for characterization activities in the FTB. In addition, two holes will provide the unique opportunity for cross-hole testing at depth in the crystalline basement, if such testing is deemed important in later stages of the DBFT project.

1.1 DBFT in Relation to DBD Concept

The overall goal of the five-year DBFT is to conduct research, development, and testing in several important areas to confirm the viability of the DBD concept. This goal will be achieved by completing the following objectives:

- Evaluation and verification of geological, geochemical, geomechanical, and hydrogeological conditions at a representative location (i.e., the top-level characterization objective);
- Demonstration of drilling technology and borehole construction methodologies sufficient for cost-effective waste disposal, to 5 km depth in the crystalline basement;
- Laboratory evaluation of package, waste, and seals materials at representative temperature, pressure, salinity, and geochemical conditions (e.g., Caporuscio et al. 2016);
- Development and field testing of engineering methods for test package loading, shielded surface operations, test package emplacement, and retrieval (e.g., SNL 2016); and
- Demonstration of pre-closure and post-closure safety assessments.

This document focuses on the testing strategy for the DBFT CB, specifically borehole construction and completion, and characterization activities.

In addition, key data are identified for confirming the viability of the concept, particularly unproven or especially critical components (e.g., collecting diagnostic geochemical and environmental tracer profiles from low-permeability crystalline rocks at possibly elevated temperatures), and not the broader objectives that would be required for site characterization supporting actual implementation of the DBD concept. For example, the DBFT will conduct less sampling and testing of formations in the overburden above the crystalline bedrock because such sampling and testing is standard practice in the groundwater or oil and gas industries. There is a high degree of confidence that this aspect of the DBD concept can be performed successfully (i.e., these activities have a high technology readiness level [TRL]). The focus of the DBFT is not to fully characterize a single site, but to demonstrate the process and gain experience in borehole construction and deep crystalline basement in situ testing and sampling.

1.2 DBFT Drivers

Figure 1 illustrates the DBFT drivers or motivators and how they influence the design choices of the two boreholes in the DBFT. The DBFT drivers are above all other levels, while the drilling method and borehole design choices are at the bottom and depend on all other levels. Characterization targets (i.e., things we can measure) do not directly depend on DBFT drivers, but they do constrain what characterization activities can be done in the CB.

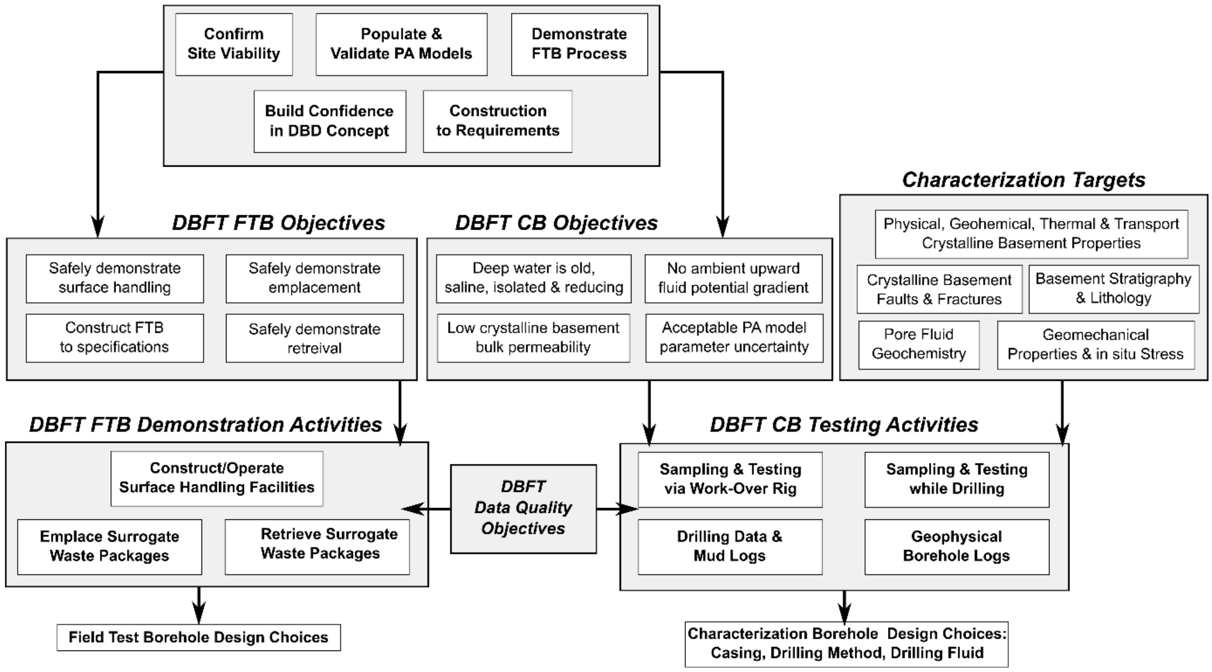

Figure 1. Conceptual relationship between borehole and casing design, testing and demonstration activities, and DBFT drivers.

There are five primary drivers for the DBFT (top level of Figure 1):

- Evaluate viability of a representative site (likely selected with limited or no deep crystalline basement information), including geological, geochemical, geomechanical, and hydrogeological conditions at depth. Site selection requirements are specified in the DBFT RFP and are not reiterated here.

- Build confidence in DBD concept viability and robustness;

- Demonstrate safe emplacement, retrieval, and surface-handling operations;

- Provide engineering data needed to drill and construct a borehole to 5 km depth in crystalline basement to requirements (e.g., mud logging data, borehole deviation control, cementing performance, in situ stress measurements, and drilling parameters); and

- Provide data necessary to evaluate pre-closure safety and assess post-closure safety (i.e., populate performance assessment [PA] models) for the DBD concept, using site-specific data and validated process models. DBD PA models have been developed for generic sites (Arnold et al. 2012; 2013) and reference designs (Arnold et al. 2011). These generic PA models will be parameterized using the characterization data collected at the DBFT site for the purposes of testing the post-closure DBD PA modeling procedure.

Figure 1 shows how the CB and FTB portions of the DBFT each have four objectives, which flow down from these five higher-level DBFT drivers. The components of the FTB will not be discussed further in this report, see SNL (2016) for more details.

1.3 CB DBFT Objectives

Based on the primary DBFT drivers, the four primary CB objectives (middle of Figure 1) are:

- Evaluate methods to determine whether deep groundwater in the crystalline basement is old, saline, and reducing. Collect and analyze samples and data to determine if groundwater has been isolated from the surface environment for a long time, the fluid density gradient is stable and opposes regional vertical circulation, and fluid geochemistry is rock-dominated and associated with chemically reduced or reducing conditions (which generally decreases the mobility of radionuclides and colloids);

- Measure the in situ fluid flow potential gradient, to determine whether an upward gradient exists that could drive flow from below 3 km depth to the shallow biosphere (i.e., whether overpressured conditions are present at depth);

- Measure permeability of the host rock, including the borehole disturbed rock zone (DRZ), to determine if it is sufficiently impermeable to inhibit thermally driven convection and contaminant advection (i.e., permeability at the borehole scale, rather than the core scale); and

- Reduce uncertainty to acceptable levels regarding host rock and DRZ properties and parameter values used in site-specific numerical models (i.e., geochemical, thermal, geomechanical, hydrogeological properties, and constitutive laws).

There are data requirements related to achieving each of these objectives. The testing and sampling approaches used to collect the data themselves have limitations and requirements affecting the details of the drilling method, drilling and workover fluid properties, and casing design.

To interpret the collected data, we will construct conceptual and numerical models of the subsurface. The geological, hydrological, geochemical, and geomechanical models will integrate as many data as possible, to better understand the subsurface processes that have led to the conditions observed, and which could affect DBD performance.

The CB objectives of the DBFT must be considered in light of practical data quality objectives (DQOs) – see bottom middle of Figure 1. The DQOs serve two purposes: 1) they ensure data of appropriate types and sufficient quality are collected to answer the questions motivating the DBFT, and 2) they indicate when "enough" data have been collected to satisfy the requirements. The DOE does not intend the DBFT to become an open-ended research project, but instead a demonstration. DQOs will be considered explicitly in the drilling and testing plan. Further high-level discussion of DQOs is included in Section 7.1, where a distinction is made between the minimum set of data required from the CB and those data that are of secondary importance in achieving DBFT project goals.

If the DBFT science objectives are not met at a particular site due to unacceptable site geological conditions (e.g., recently recharged groundwater within the deep crystalline basement) or formation instability (e.g., the borehole cannot be maintained open long enough to perform required testing or demonstration activities), the drilling and completion of the subsequent FTB may be delayed, moved, or canceled. The options will be detailed in the drilling and testing plan. The site chosen for the DBFT does not necessarily need to have conditions required for an actual disposal site for DBD; a site with characteristics not amenable to disposal operations could still prove useful for demonstration purposes (see bullets in Section 1.1).

1.4 DBFT Characterization Targets and CB Testing Activities

This section discusses CB testing activities that flow down from DBFT Objectives. Tables 1 through 5 summarize the testing activities discussed in the following sections, grouping them by characterization target (middle-right in Figure 1). Table 6 summarizes the contents of Tables 1 through 5 in matrix form. Section 6 discuss the testing activities in more detail.

1.4.1 Crystalline basement faults and fractures

Fractures and faults are typically the primary source of bulk permeability at depth (i.e., compared to core permeability determined from small intact samples; Clausser 1992) and therefore are primary characterization targets (Table 1) to measure bulk permeability of the basement rock. This key characterization target is also related to the safe and efficient construction of the borehole or the quantification of parameters and their uncertainty for PA modeling.

Table 1. Activities to characterize crystalline basement faults and fractures

Method	Section	Result
Coring and Laboratory Core Testing	6.2.1	Identify smaller fractures in cores. Larger fracture zones could affect core recovery. Determine absolute fracture orientations. Provide samples for geomechanical lab testing.
Hydraulic Fracturing Tests	6.6	Determine in situ stress profile with depth (estimate magnitudes of the vertical stress and the horizontal principal stresses), and relate stress conditions to pre-existing and induced fractures and their permeability.
Spontaneous Potential Log	6.7.3	Identify fracture zones with different fluid salinity than borehole fluid.
Induced Polarization Log	6.7.4	Evaluate changes in formation mineralogy (clays, primary minerals) and indirectly estimate formation permeability.
Neutron Porosity Log	6.7.5	Identify more porous rocks or fractured zones.
Gamma Density Log	6.7.6	Identify more porous rocks or fractured zones.
Photoelectric Effect Log	6.7.7	Identify changes in lithology across fractures and faults
Full-Waveform Sonic Log	6.7.8	Identify and characterize features such as fractures and fracture zones with different mechanical and flow properties.
Borehole Imaging and Caliper Logs	6.7.9	Map locations and orientations of natural fractures and fracture zones intersecting the borehole. Map locations and orientation of drilling-induced breakouts and tensile fractures and their relationship with principal stresses.
Borehole Radar Polarimetry	6.7.10	Estimate depth and extent of borehole breakouts and near-borehole fractures. Estimate location and orientation of near-borehole rock fabric and fractures.
Borehole Gravity Log	6.7.11	Identify larger features such as through-going fault zones with different bulk density. Identify juxtaposition of different density formations across displaced faults. Integrate formation density to estimate vertical stress.

Method	Section	Result
Nuclear Magnetic Resonance Log	6.7.12	Indirectly estimate formation permeability and tortuosity, related to formation fracturing and faulting.
Vertical Seismic Profiling	6.7.13	Identify fracture zones and large-scale lithologic heterogeneity, providing indication of orientation and lateral continuity of features away from borehole.
High-Resolution Temperature Log	6.7.14	Identify flowing fractures and fracture zones. Used in conjunction with borehole imaging.
Open Borehole Dynamic Fluid Logging	6.8	Identify productive fractures and fracture zones by borehole flow metering using repeated fluid temperature or conductivity during extended borehole fluid extraction. Used in conjunction with borehole imaging and high-resolution temperature logging.
High & Low Permeability Packer Pumping Tests	6.9	Estimate hydraulic conductivity, compressibility, and static formation pressure in all intervals (i.e., fracture zones). High-permeability intervals are indicative of fracture connectivity.

1.4.2 Lithology and stratigraphy

Characterization of lithology and stratigraphy (Table 2) is directly related to most CB science objectives because lithology and stratigraphy are correlated with hydrogeological, geomechanical, geochemical, and thermal characteristics of the host rock.

Table 2. Activities to characterize lithology and stratigraphy

Method	Section	Result
Drilling Parameters	6.1.1	Provide semi-continuous record of rock types and lithology changes encountered during drilling.
Drill Cuttings and Rock Flour Lithology Log	6.1.2	Provide a semi-continuous vertical profile of overlying sedimentary rock and crystalline basement lithology, to correlate with core and geophysical log data.
Laboratory Geological Core Testing	6.2.1	Provide a discontinuous vertical profile of basement rock characteristics to correlate with geophysical log data, drilling cuttings, and rock flour.
Spectral Gamma-Ray Log	6.7.1	Differentiate rock origins and sources of radioactivity (K, U, and Th radioactivity).
Resistivity Log	6.7.2	Estimate formation fluid conductance, which depends directly on salinity, and can be correlated with lithology.
Spontaneous Potential Log	6.7.3	Estimate variations in rock and formation fluid composition, which can be correlated with lithology.
Neutron Porosity Log	6.7.5	Estimate porosity contrasts, in conjunction with density, sonic and other logs, to characterize lithology in a continuous manner at a smaller scale than gravity data.
Gamma Density Log	6.7.6	Estimate porosity contrasts, in conjunction with neutron porosity, sonic and other logs, to characterize lithology in a continuous manner at a smaller scale than gravity data.
Photoelectric Effect Log	6.7.7	Estimate rock mineral composition used for advanced lithology logs.

Method	Section	Result
Full-Waveform Sonic Log	6.7.8	Estimate rock geomechanical properties, to characterize lithology in a continuous manner at a smaller scale than gravity data.
Borehole Imaging and Caliper Logs	6.7.9	Image natural foliation or fabric in rock, even where not cored. Identify transitions, discontinuities, and unconformities. Provide continuous imagery across the sedimentary-basement contact. Provide fracture distribution, density, and orientation data to orient and depth-correct core. Provide data for locating packer test intervals.
Borehole Radar Polarimetry	6.7.10	Estimate location and orientation of near-borehole rock fabric and fractures.
Borehole Gravity Log	6.7.11	Estimate rock density contrasts, related to differences in porosity and lithology, at a larger scale than density and porosity logs.
Multi-component Vertical Seismic Profiling	6.7.13	Image compressional and shear wave velocity structure. Identify faults, fracture zones, and other large-scale discontinuities, and provide indication of their lateral continuity and orientation away from the borehole.

1.4.3 Physical, chemical, and transport parameters

Characterizing physical, geochemical, and transport parameters (Table 3) is directly related to developing input parameters for PA models and reducing uncertainty in these parameters.

Table 3. Activities to determine system physical, geochemical, and transport properties

Method	Section	Result
Drilling Parameters Logging	6.1.1	Provide a semi-continuous record of rock properties encountered while drilling.
Drilling Fluids Log at the Surface	6.1.2	Provide semi-continuous information about changes in fluid inflow/outflow and composition during drilling.
Laboratory Core Tests	6.2.1	Provide samples for laboratory testing to estimate parameters such as bulk density, porosity, core-scale permeability, geomechanical properties, and thermal properties. Use core properties to calibrate geophysical data.
Hydraulic Fracturing Tests	6.6	Determine in situ stress profile with depth, and correlate principal stress directions and magnitudes with indications of directional permeability.
Resistivity Log	6.7.2	Identify changes in lithostratigraphy, fluid saturation, and groundwater salinity.
Induced Polarization Log	6.7.4	Estimate fluid-formation interface properties. Indirectly related to sorption and hydraulic permeability.
Neutron Porosity Log	6.7.5	Estimate formation porosity structure at smaller scale than gravity log.
Gamma Density Log	6.7.6	Estimate formation porosity structure at smaller scale than gravity log.

Method	Section	Result
Photoelectric Effect Log	6.7.7	Estimate rock mineral composition for advanced chemical characterization.
Full-Waveform Sonic Log	6.7.8	Estimate variation in seismic velocities near the boreholes that can be correlated with other physical and chemical properties.
Borehole Imaging and Caliper Logs	6.7.9	Characterize the distribution of open permeable fractures in that are active during flow logging tests.
Borehole Gravity Log	6.7.11	Identify large-scale trends in formation composition.
Nuclear Magnetic Resonance Log	6.7.12	Estimate types of formation water (bound vs. free) and identify changes in composition.
Multi-component Vertical Seismic Profiling	6.7.13	Identify faults, fractures zones, and other large-scale discontinuities, and provide indication of their lateral continuity and orientation away from the borehole.
High-Resolution Temperature Log	6.7.14	Measure geothermal gradient. In conjunction with borehole televiewer or formation micro-resistivity image log, identify zones where thermal anomalies are associated with flowing fractures. Use in situ temperature to correct other logs where necessary.
Fluid Density or Downhole Pressure Log	6.7.15	Estimate borehole fluid salinity. Use salinity and density for interpreting other logs.
Open Borehole Dynamic Fluid Logging	6.8	Estimate permeability of fracture zones and individual fractures.
Low and High Permeability Packer Hydraulic Tests	6.9	Estimate permeability, formation compressibility, and static formation pressure. Fluid samples from high-permeability intervals may be used to constrain density profiles.
Injection-Withdrawal Packer Tracer Testing	6.9.6	Estimate in situ sorption coefficient, and matrix diffusion coefficients. Estimate background in situ groundwater flow rate from rest period.
Borehole Radar Polarimetry	6.7.10	Estimate depth and extent of borehole breakouts and near-borehole fractures. Estimate location and orientation of near-borehole rock fabric and fractures.

1.4.4 Fluid geochemistry

Characterization of fluid geochemistry (Table 4) through vertical profiles is the primary evidence used to indicate deep groundwater is old, isolated, saline, and reducing. The quantification and reduction of uncertainty in PA models is also related to these activities.

Table 4. Activities to characterize fluid geochemistry

Method	Section	Result
Drilling Fluids Log at the Surface	6.1.2	Provide semi-continuous information about changes in fluid inflow/outflow and composition during drilling. Use fluid gain/loss information to constrain formation invasion. Analyze samples of circulating fluid taken at the surface for chemical and isotopic indicators of formation fluid inflow, and for correcting analyzed compositions of fluid samples from rock cores and other sampling methods.

Method	Section	Result
Fluid Samples Extracted from Cores and Whole-Rock Chemical Analyses	6.2.1	Provide small-volume water samples from crystalline basement rock for groundwater geochemistry testing and environmental tracer profiling. Whole-rock geochemical analyses will be used to quantify water-rock interactions.
Spectral Gamma-Ray Log	6.7.1	Differentiate sources of radioactivity (U and Th) that are sources for ^{4}He generation in the local subsurface.
Resistivity Log	6.7.2	Estimate formation fluid quality (e.g., salinity and ionic strength).
Spontaneous Potential Log	6.7.3	Estimate formation fluid quality (e.g., salinity and ionic strength).
Induced Polarization Log	6.7.4	Estimate fluid-solid interface properties (e.g., clay distribution in fractures) through chargeability measurements.
Nuclear Magnetic Resonance Log	6.7.12	Identify changes in formation fluid type and composition.
Fluid Density or Downhole Pressure Log	6.7.15	Estimate borehole fluid salinity. Use salinity and density for interpreting other logs.
Fluid Samples from Higher-Permeability intervals	6.9.3	Provide pressurized in situ and surface-collected water samples from higher-permeability fracture zones for groundwater geochemistry testing and environmental tracer profiling.
Injection-Withdrawal Packer Tracer Testing	6.9.6	Sampling for introduced tracers will also provide time series data on pore or fracture zone fluid geochemistry.

1.4.5 Geomechanical parameters

Characterization of geomechanical properties (Table 5) is related to safe and efficient construction of the borehole, and reduction of parameter uncertainty in PA models. Estimation of in situ stress state and strength properties of the basement rock will be important for controlling borehole stability, affecting both the CB and FTB.

Table 5. Activities to characterize geomechanical properties

Method	Section	Result
Laboratory Geomechanical Tests on Core	6.2.1	Estimate rock geomechanical characteristics. Estimate principal stress directions from anelastic strain recovery.
Hydraulic Fracturing Tests	6.6	Determine in situ stress vertical profile, estimating orientations and magnitudes of the horizontal principal stresses.
Gamma Density Log	6.7.6	Estimate rock bulk density and porosity, used with other logs to estimate the vertical principal stress.
Full-Waveform Sonic Log	6.7.8	Estimate elastic properties from compressional and shear seismic wave velocities. Identify breakouts and permeable features from log attenuation. Estimate horizontal stress anisotropy from apparent shear wave birefringence.

Method	Section	Result
Borehole Imaging and Caliper Logs	6.7.9	Map locations and orientations of natural fractures and fracture zones intersecting the borehole. Map locations and orientations of drilling-induced breakouts and tensile fractures, and their relationships with principal stresses. Map locations and orientation of newly created fractures when run after hydraulic fracturing tests.
Borehole Radar Polarimetry	6.7.10	Estimate depth and extent of borehole breakouts and near-borehole fractures. Estimate location and orientation of near-borehole rock fabric and fractures.
Multi-Component Vertical Seismic Profiling	6.7.13	Identify faults, fracture zones, and other large-scale discontinuities, and provide indication of their lateral continuity and orientation away from the borehole. Estimate large-scale average rock geomechanical properties.
High-Resolution Temperature Log	6.7.14	Estimate location and orientation of flowing fracture sets in conjunction with borehole imaging. Evaluate orientation of flowing fractures relative to in situ principal stresses.
Fluid Density or Downhole Pressure Log	6.7.15	Provide borehole fluid pressure correction to formation pressure (shut-in) measurements, for determining the formation pore pressure profile. Use with hydraulic fracturing (i.e., minimum horizontal stress), to establish borehole fluid pressure limits for borehole stability.
High and Low Permeability Packer Tests	6.9	Estimate formation permeability, compressibility, and static formation pressure.

Characterization methods in Tables 1 through 5 are summarized in Table 6, sorted by the number of columns/tables associated with each method. Although inclusion or exclusion of a method from any given category may be subjective, this generally indicates which characterization methods have wide applicability and which have a more limited application. This matrix does not indicate dependence of tests on each other. For example, the flowing borehole log will be important for locating higher-permeability intervals for later packer tests (pumping and tracer), and ensuring high-permeability intervals are not overlooked.

Table 6. Matrix of characterization methods and characterization targets

Method	Faults & Fractures (Table 1)	Lithology & Stratigraphy (Table 2)	Physical, Chemical & Transport Properties (Table 3)	Geochemistry (Table 4)	Geomech. (Table 5)
Laboratory Core Testing	●	●	●	●	●
Borehole Imaging	●	●	●		●
High-k Packer Tests	●		●	●	●
VSP	●	●	●		●

Method	Faults & Fractures (Table 1)	Lithology & Stratigraphy (Table 2)	Physical, Chemical & Transport Properties (Table 3)	Geochemistry (Table 4)	Geomech. (Table 5)
Gamma Density Log	●	●	●		●
Full-Waveform Sonic Log	●	●	●		●
SP Log	●	●		●	
Hi-Res Temperature Log	●		●		●
Neutron Porosity Log	●	●	●		
Borehole Gravity Log	●	●	●		
Induced Polarization Log	●		●	●	
Photoelectric Effect Log	●	●	●		
NMR Log	●		●	●	
Fluid Density or Downhole Pressure Log			●	●	●
Borehole Radar Polarimetry	●	●			●
Hydraulic Fracturing Tests	●		●		●
Low-k Packer Tests	●		●		●
Resistivity Log		●	●	●	
Open Borehole Dynamic Fluid Logging	●		●		
Drilling Parameters		●	●		
Spectral Gamma-Ray Log		●		●	
Drilling Fluids Log at the Surface			●	●	
Packer Tracer Tests			●	●	
Drill Cuttings and Rock Flour Lithology Log		●			

2. RELEVANT PROJECTS AND RESEARCH TO DBFT

This section summarizes some relevant historical deep crystalline drilling projects and studies for the CB part of the DBFT, and summarizes some general characteristics of deep continental crust.

2.1 Relevant Deep (>3 km) Borehole Drilling and Testing

One of the goals of the DBD concept is to use existing off-the-shelf technology and hardware from oilfield and geothermal (Otte et al 1990) as much as possible; but drilling a straight large-diameter deep hole into crystalline basement rocks is difficult. Several previous well-known scientific deep crystalline drilling projects are being used to guide expectations for drilling, sampling, and testing conditions for the DBFT. Previous summaries of deep crystalline drilling and characterization of fractured crystalline rock are available (Bodén & Eriksson 1988; Rowley & Schuh 1988; SKB 1989; Fuchs et al. 1990; NRC 1996; Harms et al. 2007; Stober & Bucher 2007). Table 7 summarizes a few statistics from each of the deep (>3 km [9,840'] total depth) drilling (as opposed to coring only) projects mentioned in the following subsections.

Although none of these projects have completed a borehole the size of the FTB to their total depth, the main KTB borehole had a diameter of 37.5 cm [14¾"] to a depth of 6,018 m [19,740'] and was a diameter of 31.1 cm [12¼"] from this depth to 7,790 m [25,560'] depth (Engeser 1996; §C.2.2.1). The recent Soultz and Basel geothermal projects in Europe have boreholes very similar in final diameter and total depth to the proposed CB, while the older Kola and KTB boreholes were of similar or larger diameter than the CB at 5 km depth.

2.1.1 Kola

The Kola project was a geological exploration and technology development borehole project on the Kola peninsula of the Fennoscandian Shield in the northwest of the former Soviet Union. The Kola project drilled the 21.6-cm [8½"] diameter SG-3 borehole to a total depth of 12.2 km [40,030'] by 1989. Crystalline basement is near the surface at the Kola site, with Archean age continental shield basement rocks encountered below 6.8 km [22,450'] depth (Rusanov & Shevchenko 1990). In total 3,592 m [11,785'] of core were collected (29%) from the borehole via wireline. No in situ hydraulic tests or hydraulic fracturing stress measurements were conducted. Borehole fluids indicate three geochemical regions: 0 to 800 m [2,620'] depth is meteoric-dominated water, a transition zone from 800 to 4 km [13,120'] depth, and below 4.4 km [14,440'], the fluids were considered highly mineralized and metamorphogenic (Borevsky et al. 1987; NEDRA 1992). Gas content of drilling fluid changed markedly during drilling (correlated with lithology). Different regions of the borehole had significant content of He, H_2, N_2, CO_2 or hydrocarbons (Karus et al. 1987; MacDonald 1988). Scientific and technical findings from the project (1970-1989) are summarized in two conference proceedings books dedicated to the project (Kozlovsky 1987; Fuchs et al. 1990).

This project achieved the still-record total vertical depth of 12.2 km in crystalline rock and several other "firsts" in deep scientific drilling, but many details of the Kola borehole and other boreholes in the former Soviet Union (e.g., Pevzner et al. 1992; NEDRA 1992) are unavailable in English-language publications.

2.1.2 Fenton Hill

The Fenton Hill project included drilling four deep boreholes (22.2 cm [8¾"] and 25.1 cm [9⅞"] in diameter) and several shallower boreholes as proof of concept for the first enhanced geothermal project (1974-1995; EERE 2010). The four deepest boreholes were completed into two reservoirs located in Precambrian crystalline rocks of the Valles Caldera near Los Alamos, New Mexico to total vertical depths of 2.93 km [9,613'] (GT-2), 3.06 km [10,040'] (EE-1), 4.39 km [14,403'] (EE-2), and 3.98 km [13,058'] (EE-3) (Laughlin et al. 1983; Fehler 1989; Brown 2009). The boreholes entered the Precambrian basement at a depth of approximately 730 m [2,400']. Hydraulic stimulation was performed between the deep wells to increase the permeability of the basement rock, to allow circulation of injected fluid and production of viable quantities of energy from the crystalline basement. Most of the initial fractures observed in cores from Fenton Hill were tightly sealed with minerals, largely carbonates, especially at depths where temperatures were above 200 °C and mineral-laden waters had previously circulated (Laughlin et al. 1983; Brown 1995).

2.1.3 Urach

Urach-3 was a 14-cm [5½"] diameter borehole drilled to 4.4 km [14,440'] depth in southwestern Germany as part of the Urach hot dry rock geothermal project. The borehole was originally drilled to 3.3 km [10,830'] total depth in 1978 (crystalline basement below 1,604 m [5,260']), then deepened multiple times (Tenzer et al. 1999). The crystalline basement at this site consists mostly of gneiss. Several journal papers by Stober and Bucher have documented various findings and proposed mechanisms regarding the permeability and geochemistry of deep crystalline rocks, based upon data collected from this and other boreholes in Europe (Stober 2011; Stober & Bucher 1999; 2000; 2004; 2007; 2015).

2.1.4 Gravberg

The Gravberg borehole was a 16.5-cm [6½"] diameter wildcat natural gas borehole drilled to 6.6 km [21,700'] depth in the 52-km [32 miles] wide Siljan Ring impact structure in central Sweden. Proterozoic cranitic crystalline basement is near the surface inside the impact structure (with an annular ring of Paleozoic sedimentary rocks surrounding the structure). The impact structure has been dated to the Devonian period. Interpretation of pre-drilling seismic surveys motivated exploratory drilling for what was hoped to be abiogenic natural gas rising up from the mantle, but deep reflectors turned out to be diabase sills (fine-grained granite intrusions), not natural gas reservoirs (Castano 1988; MacDonald 1988). Commercially insignificant quantities of hydrocarbons were encountered during drilling. A summary of the data collected during drilling (1986-1987) is given by SKB (1989).

2.1.5 Cajon Pass

The Cajon Pass borehole was a 15.9-cm [6¼"] diameter borehole drilled to a vertical depth of 3.5 km [11,500'], located 4 km [13,120'] laterally from the plane of San Andreas Fault in Southern California. Basement rock was encountered at 497 m [1,630'], while a borehole <50 m [164'] away encountered basement 158 m [578'] deeper (Silver & Jones 1988). The borehole was initially planned to reach 5 km depth in three stages. Scientific findings from the project (1987-1988) are featured in special issues of *Geophysical Research Letters* (August 1988 Special Supplement – Volume 15, Issue 9) and *Journal of Geophysical Research* (Zoback & Lachenbruch 1992).

2.1.6 KTB

The KTB project included coring a 15.2-cm [6"] diameter borehole to 4 km [13,120'] depth and drilling a 16.5-cm [6½"] diameter borehole to 9.1 km [29,860'] depth in southern Germany. The pilot hole (VB) was started in September, 1987 and took 560 days to reach 4 km depth. A total of

3,564 m [11,693'] of 9.3-cm [3.7"] diameter core (89%) was collected via wireline using internal and external flush-jointed 14 cm [5½"] mining drill string and 15.2 cm [6"] thin-kerfed diamond corebits (Emmermann & Lauterjung 1997). The main borehole (HB) was drilled using a specially designed drilling rig (which was still standing in 2016), designed to reach 12 km depth, using 40 m [131'] stands of drill pipe and a tailored water-based drilling fluid system (DEHYDRIL-HT: a synthetic hectorite-type Li-bearing Na-Mg silicate and HOSTADRILL: an organic polymer). The main borehole began drilling in October, 1990 and reached 5 km depth by November, 1991 (at a diameter of 37.5 cm [14¾"]); the total depth (9.1 km) was reached in October, 1994 (Engeser 1996). Drilling progress slowed and deviation issues became worse below approximately 6 km depth (when directional drilling downhole electronics failed due to high temperatures), and efforts to change the composition of the drilling mud to a more traditional bentonite/barite mud with commercial polymers were not successful in restoring borehole stability (Borm et al. 1997). The KTB project (1987-1994) is summarized by Bram et al. (1995) and scientific and technical findings from the project are featured in a special issue from *Journal of Geophysical Research* (Haak & Jones 1997).

2.1.7 Soultz

The Soultz-sous-Forêts GPK geothermal project drilled three 24.4 cm [9⅝"] diameter boreholes to 5.1 km [16,730'] and 5.3 km [17,390'] depth in northeastern France (Sanjuan et al. 2015). Depth to basement was 1.4 km [4,590']. Unlike the Fenton Hill project, the Soultz boreholes were completed and hydraulically stimulated across an existing high-permeability fractured hydrothermal alteration zone, to facilitate production of useful quantities of energy from a deep granitic reservoir (Tenzer 2001; Stober & Bucher 2007; Ledésert et al. 2010). Scientific and technical findings from the project are featured in a 2010 special issue of *Comptes Rendus Geoscience* (Volume 342, Issue 7-8).

2.1.8 SAFOD

The San Andreas Fault Zone Observatory at Depth (SAFOD) project included drilling the 22.2-cm [8¾"] diameter vertical pilot borehole to 2.2 km [7,220'] depth and drilling a separate deviated 21.6-cm [8½"] diameter borehole to 4 km [13,100'] total length (1.5 km [4,920'] vertical, then 60° deviation) across the San Andreas fault in central California (Zoback et al. 2011). The SAFOD project (2002-2005) is summarized by Harms et al. (2007), and preliminary geophysical results are featured in a special issue of *Geophysical Research Letters* (Hickman et al. 2004). This borehole was not entirely completed in crystalline rocks (encountered at 760 m [2,490'] depth), but dealt with difficult drilling conditions at and around the San Andreas fault. At 1.8 km [5,910'] depth the deviated second borehole drilled out of granitic rocks into a previously unmapped arkosic sandstone. Efforts to install a long-term observatory at depth near the San Andreas Fault ran into several technical problems associated with directional drilling and aggressive downhole conditions. Installed instrumentation only lasted a few weeks.

2.1.9 Basel

The Deep Heat Mining Project drilled a 21.6-cm [8½"] diameter borehole to 5 km [16,400'] depth in Switzerland (Häring et al. 2008). The borehole was drilled to 4.6 km [15,390'] at 25.1 cm [9⅞"] diameter. The Basel-1 borehole was completed through 2.4 km [7,870'] of sedimentary overburden and 2.6 km [8,530'] of granitic basement. Hydraulic stimulation efforts in the borehole below 4.6 km [15,100'] depth triggered significant microseismic activity and a >3-magnitude earthquake (Mukuhira et al. 2013).

2.1.10 CCSD

The China Continental Scientific Drilling (CCSD) engineering project drilled a pilot hole to 2,046 m [6,713'] depth and a main hole to 5,158 m [16,923'] depth to explore the metamorphic geology of the Jiangsu Province of east-central China (mainly gneiss and eclogite). The pilot hole was cored from June, 2001 to April, 2002. The main hole was completely cored, with the upper 3.4 km of the borehole later reamed out to larger diameter in multiple passes (May, 2002 to January, 2005). The borehole was cased to 4,790 m [15,715'] with the bottom 368 m [1,210'] remaining open hole. The planning, drilling, and construction of the boreholes are summarized in Wang et al. (2015).

Table 7. Deep (>3km) drilled boreholes in crystalline rock

Site	Location	Years	Depth to Crystalline [km]	Total Depth [km]	Diam* [inch]	Purpose
Kola	NW USSR	1970-1992	0	12.2	8½	Geologic Exploration + Tech. Development
Fenton Hill	New Mexico	1975-1987	0.7	2.9, 3.1, 4.0, 4.4	8¾, 9⅞	Enhanced Geothermal
Urach	SW Germany	1978-1992	1.6	4.4	5½	Enhanced Geothermal
Gravberg	Central Sweden	1986-1987	0	6.6	6½	Gas Wildcat in Siljan Impact Structure
Cajon Pass	Southern California	1987-1988	0.5	3.5	6¼	San Andreas Fault Exploration
KTB	SE Germany	1987-1994	0	4, 9.1	6, 6½	Geologic Exploration + Tech. Development
Soultz	NE France	1995-2003	1.4	5.1, 5.1, 5.3	9⅝	Enhanced Geothermal
CCSD	E China	2001-2005	0	2, 5.2	6	Geologic Exploration
SAFOD	Central California	2002-2007	0.8	2.2, 4	8½, 8¾	San Andreas Fault Exploration
Basel	Switzerland	2006	2.4	5	8½	Enhanced Geothermal

* borehole diameter at total depth

2.2 General Properties of the Deep Continental Crust

Stress state and fluid pressure in porous and fractured rocks are related through the concepts of effective stress in poroelasticity (e.g., Wang 2000). The permeability of crystalline rocks is related to confining stress and their strain or deformation history (e.g., Brace et al. 1968). The permeability of the crust can be difficult to measure on a meaningful scale, especially when predictions are made using numerical models that are much larger than cores or even in situ hydraulic tests.

2.2.1 Fluid pressure and stress with depth

In competent rocks (i.e., crystalline basement, rather than soft sediments) fluid pressure may be on average hydrostatic with depth through the brittle (i.e., seismogenic) crust. Hydrostatic pressures are believed to extend down to the brittle-ductile transition, ≥12 km [39,400’] depth (Stober & Bucher 2004). Regions of overpressure and underpressure may exist (especially in sedimentary basins) where rock permeability are very low or active deposition and structural tectonics provide geomechanical driving forces (Neuzil 2003).

Several lines of evidence exist illustrating that the permeability of the crust and the fluid pressure of crystalline basement are tied (Townend & Zoback 2000; Zoback & Townend 2001). The crust is generally considered to be in a state of incipient failure, meaning the mechanical loading of faults is commonly at a physically constrained maximum value, given the pore pressure. Manning & Ingebritsen (1999) and Townend & Zoback (2000) contend the permeability of the crust at a large (kilometer) scale is relatively high (10^{-16} to 10^{-17} m^2) because if it was lower than this value, overpressures would build up and allow faults to slip, which would therefore relieve the elevated pore pressure.

Stober & Bucher (2004) contend that deep fluid pressures are often less than hydrostatic, based on long-term water table observations from several deep boreholes (Urach-3, Kola & KTB). They contend hydration reactions with rock minerals at depth are consuming water, causing a downward gradient in the deep crust (Yardley & Bodnar 2014). Observations of low hydraulic head in Urach-3 were associated with replacing borehole fluids with low-salinity water. Osmotic effects may contribute to lower observed heads under these circumstances (Neuzil 2000).

2.2.2 Rock permeability with depth and scale

Brace (1980; 1984) and Clausser (1992) present summaries of permeability data for crystalline rocks across a range of scales. Hydraulic parameters estimated from cores tend to be associated with the lowest observed permeabilities ($<10^{-19}$ m^2). Fractures are the primary source of permeability in crystalline rocks and recovered cores will preferentially sample intact unfractured rock. Observations also indicate permeability tends to increase as the observation scale increases, with the largest observations coming from interpretation of regional metamorphism, heat-flow, and dam impoundment phenomena (Bickle & McKenzie 1987; Manning & Ingebritsen 1999; Townend & Zoback 2000; Ingebritsen & Manning 2010).

Precambrian rocks have been through multiple tectonic regimes during their long life, and will typically have multiple joint sets at different orientations. Most joints will not be oriented perpendicular to the current least principal stress in the rock, and will therefore be hydrologically inactive (Barton et al. 1995). Not all fracture sets in a rock will contribute to the permeability in the current stress state. Drilling a borehole locally perturbs the existing stress state, and makes the least principal stress radial, which may contribute to the development of a disturbed rock zone surrounding the borehole, with enhanced circumferential (i.e., onionskin) permeability (Kelsall et al. 1984).

Stober & Bucher (2005; 2007) present a summary of deep crystalline rock permeability and salinity data from boreholes, and propose a depth/permeability relationship for boreholes in the Black Forest of Germany, similar in form but with lower permeability than the relationship proposed by Manning & Ingebritsen (1999). Stober & Bucher (2007) indicate the permeability of gneissic rocks tend to be lower than the permeability of granitic rocks, but granite permeability seems less depth-dependent than gneiss. In general, a wider variation of permeability is observed in granite than in gneissic rocks.

Observations of smaller-scale permeability have been seen to decrease with depth, due to increased overburden confinement, and increased propensity for precipitation of fracture-plugging minerals from circulation of hotter (≥200 °C) strongly mineralized deep water (Stober & Bucher 2015). Presence of significant shear zones, or other large-scale conductive structures will clearly increase the permeability of deep crystalline rocks.

Rojstaczer et al. (2008) posit that permeability of the continental crust adjusts to accommodate external fluid flux forcing. In the deep continental crust this forcing includes fluid fluxes from metamorphism, magmatism, and mantle degassing, while in the shallow crust the hydrologic cycle is proposed as the primary hydraulic forcing mechanism.

Clearly, the permeability of fractured crystalline rocks depends on scale and effective stress (including pore pressure). Fluid pressure is likely near hydrostatic at the kilometer scale in crystalline rocks associated with permeable faults and fracture zones. These factors present a challenge for in situ characterization of the permeability of flow systems near a borehole, which necessarily changes the stress state and pore pressure of the rock (i.e., the DRZ). The primary line of evidence that will be sought in future deep borehole disposal sites is through geochemical evidence (i.e., existence of ancient, saline and reducing water in the crystalline basement). If the deep borehole disposal safety case solely rested on the complete characterization of the crystalline basement permeability at all possible scales (i.e., cm to km scales), implementation of DBD would be impractical.

3. CHARACTERIZATION BOREHOLE CASING DESIGN

This section presents the nominal design for the CB, prior to applying new site-specific information or refinements that will likely be made to the design. Once a final site and Site Management Contractor have been chosen as part of the RFP process (DOE 2015; 2016), a detailed site-specific drilling and testing plan will be prepared.

The five primary testing activities and their individual testing components are discussed in Section 6; they can be related to three primary requirements for CB drilling and completion:

1. Representative crystalline basement fluid and rock sampling;
2. Representative in situ crystalline basement hydraulic, mechanical and geochemical testing;
3. Minimal casing or liner in the crystalline basement interval to increase the depth interval available for later packer-based testing via workover rig.

To the extent possible, testing and fluid sampling will be conducted after borehole completion, and after releasing drilling equipment that is no longer needed, to reduce the cost of rig standby time. The only sampling to be conducted from a wireline-conveyed packer system during drilling of the borehole will be for zones that will eventually be cased or lined (with or without cement) in the completed borehole. This includes the overburden and possibly zones in the crystalline basement that are cased or lined for borehole integrity (i.e., the uppermost portion of the basement). At least one in situ hydraulic fracture stress measurement and one estimate of static formation pressure will be completed before reaching total depth in the CB, to provide information for drilling the remainder of the CB and for the FTB procurement and construction process.

The DBFT science objectives are to be considered when selecting the drilling method, drilling fluid type, and casing/liner design. Choices should be made to balance experience of the CB Drilling Contractor with efficacy of drilling and meeting the DBFT CB science objectives (Figure 1).

Figure 2 illustrates a conceptual borehole design of the CB for a generic site. Overburden here refers to the non-basement portion of the material encountered in the borehole (see labels on right side in Figure 2). The crystalline basement interval is the focus of testing in the DBFT. The preferred geology in the crystalline basement is igneous intrusive crystalline rock. Typically, the crystalline basement will be older (i.e., Paleozoic or Precambrian), while the overburden will consist of younger sedimentary rocks. Other site configurations are allowable as part of the site selection process (DOE 2015; 2016), including depth-to-basement of less than 2 km.

An important site selection requirement on depth to the crystalline basement specifies: 1) the borehole must be 5 km total depth, and 2) at least 3 km of the borehole must be in the crystalline basement. It is viable for crystalline basement to extend to the surface (no sedimentary overburden), but drilling costs would be higher and drilling would be slower through 2 km of overlying crystalline rocks, rather than 2 km of sedimentary rocks. An overlying sedimentary sequence could also provide an additional degree of isolation of the crystalline basement groundwater flow system from a shallow modern flow system.

Conductor casing will be set to prevent caving and possible inflow of shallow groundwater. Surface casing will then be set to approximately 460 m [1,510’] (see discussion below). An intermediate liner (i.e., casing that does not extend to the surface) will then be set across the remainder of the overburden and will penetrate into the top of the crystalline basement (up to a few tens of meters), until competent basement rock is encountered. Figure 2 illustrates a design with two casing/liner diameters across the overburden. If drilling conditions in the overburden require further telescoping of casing diameter, then the intermediate borehole and casing diameters will be selected to maintain the capacity for 21.6 cm [8.5”] diameter at total depth. If crystalline basement is encountered shallower than 2 km depth, the intermediate casing will only extend as deep as needed to access competent basement rock.

To maximize access to the crystalline basement for later in situ packer testing purposes, minimal casing will be used in the crystalline basement interval. A common oilfield technology is to cement casing into place and use shot-perforation to access the formation behind the casing. For the CB, however, shot-perforated sections would not provide representative fluid samples or support representative hydraulic testing. Casing and shot-perforation strategies should be used only as a last resort, if no other viable completions can be implemented for a given interval (e.g., due to extensive breakouts). Wireline-conveyed packer-based pressure testing and fluid sample collection, with wireline geophysical logging, should be considered before cementing any part of the crystalline basement.

Borehole and casing schedule (recommended nominal diameters and depths) for the generic CB (shown in Figure 2) are:

- **Conductor** (50.8 cm [20”] casing in 66 cm [26”] hole): The conductor is usually set to a depth of 15 to 30 m [50-100’] and cemented to the surface. Often the conductor borehole is drilled with a separate drilling rig and installed as part of the site construction, including possible sub-grade completions required for drilling fluid plumbing and electrical connections to the drilling rig used for the crystalline basement section.

- **Surface** (34 cm [13⅜”] casing in 44.5 cm [17½”] hole): Maximum depth of the surface casing is controlled by requirements on blow-out preventer equipment. The total depth will be as required by regulatory agencies for well control (assumed 460 m [1,510’] in Figure 2). This casing is cemented to the surface. If required by local regulations, it will have a blow-out preventer installed after cementing.

- **Intermediate** (24.4 cm [9⅝”] liner in 31.1 cm [12¼”] hole): This liner runs from the bottom of the surface casing through the base of the overburden (2 km in the nominal design) and far enough into the crystalline basement to reach competent rock; the annulus behind this liner is cemented at least up into the surface casing, and possibly all the way to the surface.

- **Crystalline Basement** (unlined 21.6 cm [8½”] hole): This unlined interval extends from the bottom of the intermediate liner to total depth.

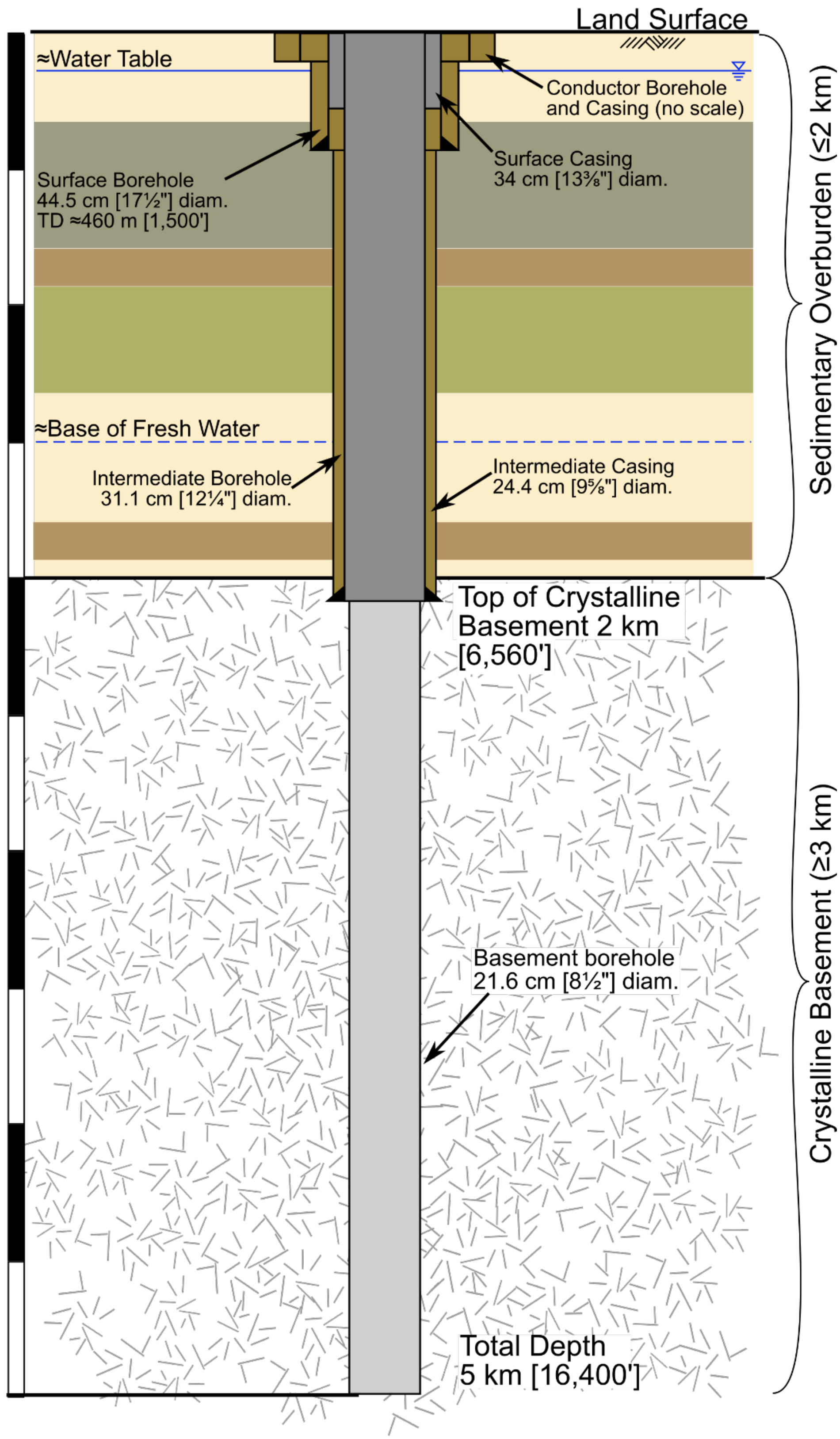

Figure 2. Characterization Borehole (CB) schematic. Dark gray is permanent casing or liner, olive is cemented annulus, light gray is open borehole.

4. CHARACTERIZATION BOREHOLE CONSTRUCTION

Many recent oilfield drilling technology advances have been associated with directional control developed for horizontal oil and gas production wells in sedimentary rocks. Similar directional drilling technology can be used to maintain borehole straightness (i.e., dogleg-severity or maximum angular deviation across a specified distance) and verticality (i.e., borehole plumbness), even when the rock structure, fabric, or fractures would tend to cause the drill to deviate.

Deep drilling methods are grouped in the following subsections by how drilling torque is applied to the drill bit, how directional control is maintained, the type of drill bit, and drilling fluid type. These choices are all interrelated. Each component cannot be chosen independently, but they are discussed here in a somewhat independent fashion for simpler presentation.

The first four subsections give context for possibly viable alternative drilling technologies, while Section 4.5 discusses these options and presents preliminary recommendations for the DBFT.

4.1 Drilling Method

Historically, rotary drill rigs applied the torque to the drill bit through the drill pipe by torqueing an uppermost "kelly" section. The kelly is a piece of non-round cross-section drill pipe that is turned using a similarly shaped bushing fixed to a rotating table at the drill rig floor. The entire length of drill pipe is torqued to turn the drill bit at the bottom of the hole. The kelly is lifted and pipe is added to its bottom when advancing the borehole.

Top-drive motors are now commonly used to turn the drill string. These involve the rotary motor being directly connected to the drill pipe at its top. The rotary motor assembly moves up and down the drill rig mast during drilling operations. The top-drive arrangement provides more flexibility to the drilling operator, including the ability to use drill pipe of longer length (e.g., double and triple pipe sections), which speeds up the process of tripping into and out of the borehole.

Downhole mud motors apply torque near the drill bit. In these systems the drill pipe does not need to be rotated (but it can); a positive displacement motor is placed near the bottom of the drill string above the drill bit. Pumping drilling fluid down the drill string (i.e., direct circulation) turns the pump, which translates into torque applied directly above the drill bit. Early directional drilling relied exclusively on this method, utilizing non-straight drill pipe (i.e., bent subs or bent housing, which could not be rotated) above the mud motor to achieve the deviation required to perform horizontal drilling.

Both top-drive and kelly-drive systems can be configured to utilize reverse circulation, which pumps the drilling fluid down the annulus and up the drill pipe, rather than down the drill pipe and up the annulus (direct circulation). Reverse circulation can result in more depth-specific cuttings retrieval than direct circulation. Very large borehole diameters sometimes require reverse circulation to effectively remove cuttings, since drilling fluid flow velocities drop off as the annulus diameter increases (larger cuttings fall out of the drilling fluid when it slows down), while velocity up the drill pipe remains high. Reverse circulation is incompatible with many modern directional-drilling approaches (e.g., downhole mud motors or rotary steerable systems) and most downhole hammer drilling, or requires specialized reverse-circulation-specific equipment.

4.2 Directional Control

For modern directional control, several different types of hybrid rotary steerable systems (RSS) exist. These methods typically require the drill string to turn, but have active directional controls located at the bottom of the drill string above the drill bit. Methods either apply a horizontal force to the drill pipe (i.e., synchronized pads push against one side of the borehole wall to divert the bit in the opposite direction) a few meters above the drill bit (i.e., push-the-pit), or dynamically bend the drill string during rotation to get the proper pointing of the drill bit (i.e., point-the-bit). RSS systems have significant downhole electronics that can maintain precise control of the straightness and verticality of the borehole through near-continuous gyroscopic surveying and downhole measurement while drilling, including automatic feedback on directional drilling without sending data to the surface for processing or decision making.

Downhole mud motors and several prototype steerable systems (predecessors of most modern RSS) were used in the German 9.1 km KTB borehole (Section 2.1.6) which had excellent verticality to approximately 6 km depth (Bram et al. 1995). At that depth the downhole electronics failed in the high temperature environment (250 °C at 9 km depth; Engeser 1995; Clauser et al. 1997). Modern electronics in rotary steerable systems are now typically tolerant of elevated temperatures and downhole temperatures above 175 °C are not foreseen in the DBFT. Typical off-the-shelf RSS with 150 °C continuous operating temperature capability are expected to perform satisfactorily for the DBFT drilling.

4.3 Drill Bit

Drilling bits used in hard rock are traditionally rotary roller-cone type bits with multiple rotating components covered in carbide buttons, that rotate and break up the rock at the bottom of the hole through compressive failure (i.e., by applying weight on the bit). Polycrystalline diamond compact (PDC) bits are a newer drill bit technology made popular through use in directional drilling of sedimentary rocks. These bits have no moving parts, and instead break the rock through shear failure; cutter faces are dragged along the bottom of the borehole. Individual PDC bits are more expensive than roller-cone bits, but they have very high penetration rates and typically last much longer (requiring fewer trips out of the borehole for bit replacement). Some advanced PDC bits and hybrid roller-cone/PDC bits have recently been developed for drilling in crystalline rock, but there is less experience with these bits in crystalline rock, compared to the extensive experience with PDC bits in sedimentary rocks and the long history of using roller-cone bits in crystalline rock. Multiple, early prototype hybrid roller-cone/fixed-cutter bits were used in the Fenton Hill enhanced geothermal project (Section 2.1.2) from 1978-1980 (Pettitt et al. 1980).

Down-the-hole hammer drilling is an alternative technology that conceptually replaces the downhole mud motor with a drilling-fluid activated axial drilling hammer. The hammer compressively breaks up the rock at the bottom of the hole through rapid axial hammering. Traditionally, hammer drilling is done with compressed air or nitrogen to activate the hammer and circulate cuttings, but some water-based hammer drilling methods are available (Wittit et al. 2015). Water-based down-the-hole hammer drilling requires clean drilling fluids to protect the downhole mechanism (e.g., a once-through drilling fluid system). The KTB project seriously considered using hammer drilling, including the concept of hammer coring (Deutsch et al. 1990). While hammer drilling can achieve very high penetration rates in crystalline rock, using air as drilling fluid is often undesirable or infeasible at significant depth. Using air as a drilling fluid involves the following complications: 1) it is difficult to remove significant water inflow, 2) air compressibility and leakage through joints becomes significant in long drill strings, 3) drilling is completely underbalanced (i.e., air hydrostatic weight does not resist formation fluid inflow or contribute to the stability of the borehole), and 4) fluid samples airlifted to the surface would not have representative dissolved gas content, pH, or Eh. One benefit of using air as the drilling fluid is that the quantity and timing of formation water inflow is straightforward to detect, if the inflow rate does not exceed the air's lifting capacity.

Down-the-hole hammer drilling has the following possible issues: 1) it is incompatible with modern directional RSS drilling methods, 2) the fast penetration rates achieved with hammer drilling are typically at the expense of straight and vertical drilling, and 3) when using air as a drilling fluid, additional lubricant is required to cool and lubricate the downhole hammer (oil-based lubricant circulating through the borehole would further complicate obtaining representative water samples).

4.4 Drilling Fluid

The fluid circulation system is composed of pumps, connections to the drill string, fluid recovery equipment, and surface equipment for fluid makeup and removal of cuttings (e.g., shale shakers and cyclones). Depending on the drilling method, the circulating fluid could be composed mostly of water, oil, or air. Its functions are to cool and lubricate the bit, lubricate the drill string, remove cuttings from the borehole, provide filter cake to limit sloughing and lost circulation, and control downhole pressure. Drilling fluid often requires a suite of additives that control different aspects of the drilling process. For water-based circulation systems, additives are used to control weight of the drilling fluid (e.g., barite, bentonite, or salt), while others maintain the viscosity and cuttings-carrying capacity (e.g., gel viscosifier or solids encapsulator). Still other water-based additives are primarily for hole or equipment maintenance (e.g., biocide, soda pH buffer, or rust inhibitor).

The effect drilling fluid additives have on in situ fluid sampling, coring, and borehole geophysics should be considered during the development of the drilling and testing plan. From the point of view of geochemical sampling, it is better to introduce fewer chemicals into the borehole. It is difficult to specify beforehand what chemical and physical interactions will occur between the drilling fluid additives, formation water, rock cuttings, and make-up water. Minimizing the complexity of the drilling-fluid system is the preferred overall approach for the DBFT.

Managed pressure drilling is one possible drilling fluid system approach, whereby pressure is controlled dynamically at the surface, rather than hydrostatically through the weight of the fluid column. Managed pressure drilling increases complexity of drilling fluid plumbing at the surface, but may allow a simpler water-based drilling fluid to be used in place of a heavy barite and bentonite mud that has other geochemical consequences. As long as the objectives are met, the chosen drilling fluid and tracers are flexible, although a drilling method and circulation fluid choice must be agreed upon between the contractor and the DBFT Technical Lead early in the design process.

Drilling fluid often has a significant impact on the cost of the borehole, particularly when the borehole is large diameter or has lost circulation. The drilling fluid used in drilling the overburden section of the borehole will be selected to efficiently maintain a stable borehole across the overburden (e.g., water- or oil-based fluid with bentonite). Depending on the geology of the overburden, and the potential for clay sloughing or swelling, some sections of the hole may require oil-based fluid (e.g., for swelling clays) or brine (e.g., in lieu of oil-based fluid where extensive evaporite minerals are present).

4.5 DBFT Drilling and Completion Design Discussion

Key criteria for selecting a suitable modern directional-drilling capable drilling rig in addition to borehole depth, diameter, and rock type include the expected weight of the drill string and the weight of any casing or liner to be installed. Oil-field drilling rigs are available up to 4,000 horsepower size with lifting capacities up to 900 metric tons (Beswick 2008). Within the range of available land-based rigs, there are many rigs capable of drilling a 21.6 cm [8.5”] diameter borehole to 5 km in crystalline basement rock.

Top-drive rotary drilling in crystalline basement would likely be performed using a hard-formation, tungsten-carbide insert, journal bearing, roller-cone bit with an RSS for directional control. This drilling system could alternatively be fitted with hybrid roller-cone/PDC bits. The DBFT should take advantage of recent advances in drilling technology, but the DBFT will not be relying on experimental approaches unless the consequences of failure for these approaches are acceptably low.

From the perspective of achieving the scientific goals of the project, the drilling fluid will likely be water-based, with salt added for weight and chemical similarity to formation fluid, and with minimal other additives (viscosifiers, rust inhibitors, biocides, etc.). Drilling fluid will be made up from consistent and clean makeup water sources and consistent, new additive materials. The DBFT will avoid recycled or produced brines as makeup water, which may vary significantly by source well or field and could introduce unneeded complexity to the drilling fluid composition, especially with respect to trace metals and hydrocarbons.

In low-strength sedimentary rocks the mud window (i.e., difference between the least principal stress where hydraulic fracture occurs and the fluid pressure where inflow of formation fluid or gas occurs) may be very narrow, requiring complex telescoping casing design and significant additives to minimize breakouts and possible well collapse. When drilling through stronger crystalline rocks like granite, less benefit may be derived from maintaining high fluid pressure in the borehole than is seen in weaker sedimentary formations. Borm et al. (1997) indicated at KTB in the main hole:

> The generation of supporting pressure by an increase of the mud density proved to be less effective than expected because of rather poor sealing capacity of the mud in the rock joints, on the one hand, and the extremely low permeability of the intact crystalline rocks, on the other, where the creation of a filter cake (as in boreholes in sedimentary rock) did not succeed.

The choice of drilling method, and the selection of specific bits and operating parameters (rotary speed, bit weight, and drilling fluid hydraulics), will be driven by drilling experience in similar rock types and rock characteristics encountered at the DBFT site. Drilling in crystalline basement rock will be slow, with penetration rates possibly as low as 1 m/hr. Hard granitic crystalline basement rock (e.g., high silica content) will typically limit drill bit life. Frequent bit changes will increase the number of trips in and out of the borehole. Coupled with the larger diameter, drilling times and costs are necessarily somewhat uncertain. When drilling and testing deep boreholes the amount of time spent tripping into and out of the borehole (e.g., to change the drill bit, retrieve core samples, conduct a wireline-conveyed packer test, or perform hydraulic fracture stress measurement tests) can be a significant portion of the total time. This can be minimized by using longer drill pipe sections, and/or triple-stands of pipe, automatic pipe handling, top-drive rig design, longer-life drill bits including new hybrid types, and wireline coring.

5. DRILLING AND TESTING SEQUENCE

The CB will be drilled to a depth of 5 km [16,400'] as part of the DBFT. The DBFT will not involve handling or emplacing radioactive waste, but instead will confirm scientific and technological readiness to execute the DBD concept in the future at a site chosen through a consent-based siting approach.

5.1 Characterization Borehole Construction and Testing

The CB will be the primary location for activities to: 1) demonstrate ability to characterize and evaluate site, 2) acquire data and generate parameters to populate PA models, 3) develop specifications for drilling a larger diameter borehole, and 4) build confidence in the DBD concept (Figure 1).

The upper portions of the CB will be sized to accommodate a bottom-hole diameter of 21.6 cm [8½"]. The drilling method, drilling fluid and additives, borehole diameter, and casing schedule will be chosen to maximize likelihood of collecting representative and uncontaminated cores and water samples.

5.1.1 CB drilling, logging, and completion sequence

The following sequence summarizes drilling, logging, and completion activities in the CB for the DBFT (Figure 3).

- D1. Drill conductor borehole and set 50.8 cm [20"] diameter conductor casing (often drilled with smaller rig).
- D2. Mobilize main drilling rig.
- D3. Drill surface borehole (44.5 cm [17½"] diameter) to approximately 460 m [1,500'] depth while collecting drilling performance information, logging cuttings, and analyzing rock flour by XRD/XRF.
- D4. Geophysically log uncased portion of surface borehole (Table 9).
- D5. Install and cement 34 cm [13⅜"] diameter surface casing from the bottom to the surface.
- D6. Conduct extended leak-off test to estimate magnitude of least principal stress at bottom-hole depth.
- D7. Drill intermediate borehole (31.1 cm [12¼"] diameter) through most of the remaining overburden, to ≤150 m [500'] of expected depth to basement.
- D8. Conduct vertical seismic profile (VSP) to better constrain depth to crystalline basement, to increase likelihood of coring overburden/basement interface. If depth to basement is well-constrained from existing geophysics or nearby boreholes, VSP would not be necessary.
- D9. Drill intermediate borehole (31.1 cm [12¼"] diameter) to within ½ core barrel length from expected top of crystalline basement (nominally 2 km [6,560'] depth).
- D10. Core across overburden/basement interface.
- D11. Geophysically log open borehole. Identify candidate unit of overburden (basal unit if sufficiently permeable) for hydraulic testing.

D12. Perform hydraulic testing and fluid sampling using wireline-based packer tool on selected (higher permeability) unit of overburden (estimate hydraulic properties and static formation pressure and collect water quality samples for laboratory analyses).

D13. Depending on competence of crystalline basement rock, drill intermediate borehole deeper into crystalline basement until competent crystalline rock is encountered.

D14. Geophysically log any additional section of borehole drilled, including a high-resolution temperature log of the upper crystalline basement (which will be cased) and the lower sedimentary overburden (including where hydraulic testing and sampling were done), to determine distribution of flowing units and fractures.

D15. Perform hydraulic testing and fluid sampling using wireline-based hydraulic packer-isolated interval testing tool near top of crystalline basement (where permeability is expected to be higher, location identified by high-resolution temperature log), in the uppermost basement interval that will be cased and cemented.

D16. Collect any required rotary sidewall cores via wireline from to-be-cemented intervals of interest identified from geophysical logging.

D17. Install 24.4 cm [9⅝”] diameter casing from the surface to competent crystalline rock in the upper basement.

D18. Cement the annulus behind the 24.4 cm [9⅝”] diameter casing, from the bottom up to at least 150 m [500’] into the surface casing.

D19. Conduct extended leak-off test to estimate magnitude of least principal stress at bottom-hole depth.

D20. Switch from the drilling fluid composition used in the overburden, to drilling fluid selected for the crystalline basement interest section. Exchange all drilling fluid and begin including tracers in drilling fluid and all subsequent makeup water.

D21. Drill and core (at ~5% frequency) the 21.6-cm [8½”] borehole through the upper half of the basement interest section (nominally from 2 to 3.5 km depth), while logging drilling fluid liquid, dissolved gas, and cuttings and performing XRD/XRF analysis on rock flour.

D22. Log a bottom interval of the borehole with imaging tools, to find optimal location for hydraulic fracture stress measurement and packer-based testing (at least estimating static formation pressure).

D23. Perform hydraulic testing and fluid sampling if sufficient permeability, using the wireline-based hydraulic packer-isolated interval testing tool near the bottom.

D24. Set wireline-based packer tool on a low-permeability interval for hydraulic fracturing stress measurement.

D25. Using imaging tools, log the interval where hydraulic fracture stress measurement was conducted to determine orientation of the induced fracture.

D26. Provide CB data and analysis to support the decision point to move forward with the procurement process associated with drilling the FTB.

D27. Drill and core (~5%) the 21.6-cm [8½”] borehole through the remaining lower half of the basement interest section (nominally from 3.5 to 5 km depth), while logging drilling fluid liquid, dissolved gas, and cuttings and performing XRD/XRF analysis on rock flour.

D28. Using a suite of geophysical tools (Table 9) log the open part of the borehole (the entire crystalline basement interest section).

D29. Provide additional CB data and analysis of the full basement interest section, as needed to support the decision point to move forward with the FTB.

D30. Flush cuttings and drilling fluid from borehole, and swab if necessary. Replace drilling fluid with workover/testing fluid selected to provide long-term chemical stability and well control during subsequent testing.

D31. Based on geophysics, locate and drill any additional intervals with rotary sidewall coring via wireline tool.

D32. Demobilize non-essential drilling rig equipment before workover rig testing.

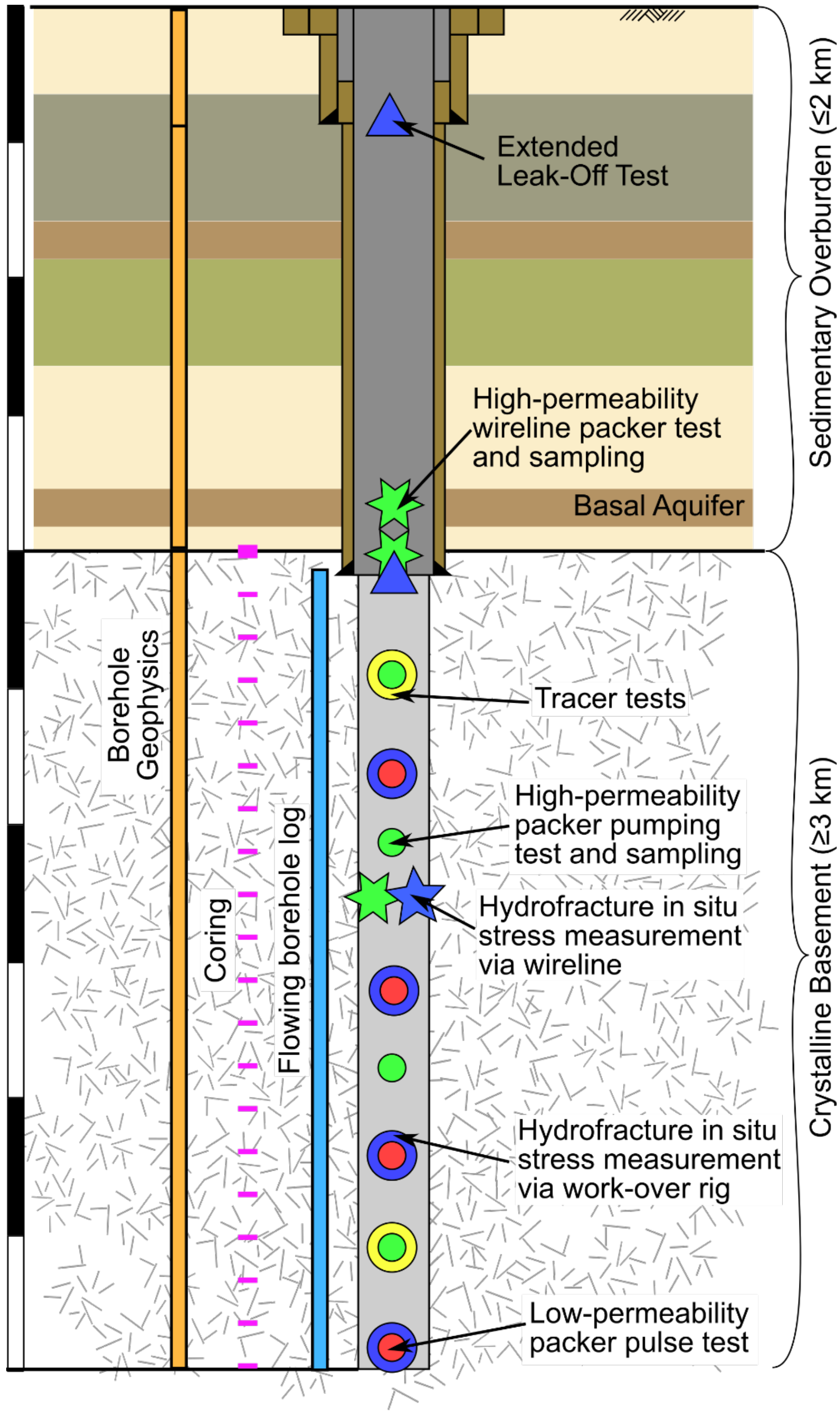

Figure 3. CB schematic with nominally located tests and samples; casing, liner and borehole details given in Figure 2. Circles represent tests conducted with workover rig; polygons represent tests conducted during drilling. Blue symbols are hydraulic fracture stress measurement tests; green symbols are high-permeability hydraulic tests; red symbols are low-permeability hydraulic tests; yellow symbols are tracer tests.

5.1.2 CB workover testing sequence

The following sequence summarizes in situ testing and post-completion activities in the CB for the DBFT (Figure 3), which follow demobilization of non-essential drilling and completion rig equipment.

T1. Conduct dynamic flowing temperature or dilution log of open borehole to locate permeable zones.

T2. Isolate, hydraulically test, and sample four ~9.1-m [30’] higher-permeability zones using packer tool. Locate zones using image and caliper logs (avoiding breakouts if possible) and flowing log test results (isolating higher permeability zones). Pump formation fluid from interval to surface using either submersible or surface-based pump.

a. Before pumping, monitor transient pressure response in packer interval to estimate static formation pressure.

b. Perform multi-step constant-head test (flowing water from formation) to collect data for estimating formation hydraulic properties. Record flowrate, packer inflation, fluid pressure above/below packers, and downhole test interval fluid pressure, temperature, and electrical conductivity.

c. Perform approximately constant flowrate extraction test to further constrain formation hydraulic properties and to remove drilling-fluid contaminated water from interval, while recording same downhole and surface parameters, and in addition the drilling fluid tracer.

d. Collect large-volume fluid samples at surface for water quality testing, and collect small-volume down-hole pressurized samples.

e. Monitor recovery of interval pressure, temperature and packer inflation after end of testing to further constrain formation hydraulic properties and estimate static formation pressure.

f. Retrieve packers and pressurized fluid sample (replacing pressurized fluid sample containers) before moving packer tool to next high-permeability test interval

T3. Isolate and hydraulically test four ~9.1-m [30’] lower-permeability zones using packer tool. Locate zones using image and caliper logs (avoiding breakouts if possible) and flowing log test results (isolating lower permeability zones).

a. Before perturbing interval pressure, monitor transient pressure response in packer interval to estimate static formation pressure.

b. Perform multi-step pulse test (including both positive and negative pressure perturbations) to collect data for estimating formation hydraulic properties. Monitor packer inflation, fluid pressure above/below packers, and downhole test interval fluid pressure, temperature, and electrical conductivity.

c. Monitor recovery of interval pressure, temperature and packer inflation after end of testing to further constrain formation hydraulic properties and estimate static formation pressure.

d. Move packers directly to next low-permeability test interval.

T4. Isolate and perform injection-withdrawal tracer test on two ~9.1-m [30’] higher-permeability zones using packer tool. Locate zones using image and caliper logs (avoiding breakouts if possible) and flowing log test results (isolating higher permeability zones). Locate interval where successful high-permeability hydraulic tests were conducted (T2 above), if possible.

a. Before pumping, monitor transient pressure response in packer interval to estimate static formation pressure.

b. Produce fluid from interval to surface (record flowrate, packer inflation, fluid pressure above/below packers, and downhole test interval fluid pressure, temperature, and electrical conductivity), divert produced water to surface mixing container. Monitor drilling fluid tracer concentrations onsite.

c. Add suite of tracers to produced water (e.g., uranine, fluorinated benzoic acids, amino-G acid, and Cs salts). Keep surface container of traced water well-mixed, regularly monitoring fluid temperature, and sample mixed fluids for laboratory analysis.

d. Inject solution of tracers at relatively constant flowrate into packed-off interval, monitoring same surface and downhole parameters.

e. Inject solution of non-traced formation water (chaser) at same relatively constant flowrate into packed-off interval, monitoring same surface and downhole parameters.

f. Stop injection (rest period) and monitor surface and downhole parameters for at least one day.

g. Pump packed-off interval at relatively constant flowrate, monitoring surface and downhole parameters.

h. During pumping collect surface samples at regular intervals and collect pressurized down-hole samples.

i. Retrieve packers and pressurized fluid sample (replacing pressurized fluid sample containers) before moving to next high-permeability tracer test interval.

T5. Isolate and hydraulically test one ~18.2-m [60’] lower-permeability zone using three-packer hydromechanical testing tool. Locate zones using image and caliper logs (avoiding breakouts if possible) and flowing log test results (isolating lower permeability zones).

a. Before perturbing interval pressure, monitor transient pressure response in packer interval to estimate static formation pressure.

b. Before inflating middle packer, perform pulse hydraulic test using both intervals together as a single interval. Monitor packer inflation, fluid pressure above/below packers, and downhole test intervals fluid pressures, temperatures, and electrical conductivities.

c. In a stepwise manner increase inflation pressure on middle packer while repeating pulse testing and observation in both test intervals (either side of middle packer).

   d. After reaching maximum inflation pressure on middle packer, in a stepwise manner decrease inflation pressure on middle packer while repeating pulse testing and observation in both test intervals.

   e. Retrieve three-packer assembly.

T6. Isolate and conduct sequence of hydraulic fracture stress measurement tests on four ~4.6-m [15’] low-permeability regions of the borehole. Locate zones using image and caliper logs (avoiding breakouts if possible) and flowing log test results (isolating lower permeability zones).

   a. Before perturbing interval pressure, monitor transient pressure response in packer interval to estimate static formation pressure.

   b. Conduct hydraulic fracture stress measurement test sequence to produce new hydraulic fracture, to collect data for estimating breakdown pressure and least principal stress. Locate packers on interval with no existing fractures, based on image log data.

   c. Conduct hydraulic fracture stress measurement test sequence on existing hydraulic fracture, to collect data for estimating other principal components of the in situ stress tensor. Locate packers on interval with existing fracture not normal to least principal stress, based on image log data.

   d. Conduct hydraulic fracture stress measurement test sequence on existing hydraulic fracture, to collect data for estimating principal components of the in situ stress tensor. Locate packers on interval with existing fracture not normal to least principal stress (and normal to fracture isolated in previous test), based on image log data.

   e. Move hydraulilc fracture stress measurement testing packer system to next interval.

T7. Demobilize testing equipment (i.e., workover rig) from borehole.

These drilling and testing sequences indicate the order in which tests will likely be conducted, but the exact design, order, and nature of testing and sampling will be resolved by the DBFT Technical Lead, the CB Drilling Contractor, and the Site Management Contractor. The drilling and testing program may be modified as these activities progress.

5.1.3 CB data required for FTB decisions

The decision to drill the larger FTB is planned in two parts. The first, preliminary decision point will be after drilling through half of the crystalline basement (nominally to 3.5 km depth; see D25 in Section 5.1.1). The decision will be whether to move forward with the FTB procurement process. In-situ stress conditions, rock fabric, and rock strength may change significantly with depth, but conditions in the upper crystalline basement in the CB are expected to provide useful indication of the prospect for successful drilling of the FTB.

The second decision point will be after the CB is drilled and logged to total depth. This decision will be whether to proceed with drilling the FTB and it will be deferred until CB total depth is reached and the geophysical logs are acquired across the entire crystalline basement interest section. These logs will include temperature profiles and borehole imagery. Other input will include the experience gained from drilling the CB (drilling penetration rates, locations and types of problems encountered while drilling, unusually hot downhole conditions, and any previously unforeseen rock or borehole issues).

Formation characteristics found while drilling the CB which may lead to a decision not to continue with the FTB include:

1. Significantly different depth to crystalline basement or rock type at depth, compared to what was predicted or expected for the site (e.g., crystalline basement is deeper than expected, or overlies more permeable sedimentary rocks at depth).
2. Unfavorable in situ stress, rock fabric, rock layering, or rock strength conditions at depth, resulting in very difficult drilling (e.g., borehole creep closure during drilling or uncontrolled borehole washout/sloughing, possibly with circulation loss).
3. Significantly elevated geothermal gradient, resulting in hotter-than-expected bottom-hole conditions that could complicate drilling of the FTB, and substantially increase costs.

The presence of high-permeability fracture zones or faults in the crystalline basement interval would not preclude the demonstration activities planned at the FTB.

6. CHARACTERIZATION BOREHOLE DRILLING AND TESTING STRATEGY

The primary focus of the CB is effectively characterizing the in situ conditions encountered in the crystalline basement at the DBFT site. A secondary focus of the CB is the demonstration of in situ testing activities in crystalline basement rock, at depths and conditions relevant to DBD.

6.1 Drilling Characterization

The CB Drilling Contractor will monitor the process of drilling, as part of their scope of work to ensure the safe completion of the borehole. The activity will include documenting all items and materials introduced to the borehole during drilling and testing, and a log of all downhole activities. This information will become part of the geologic model, which will integrate the observed responses of the basement rock, and address interference among drilling and testing activities.

6.1.1 Drilling parameters logging

The CB Drilling Contractor will monitor parameters related to the drilling rig and the drill-pipe string, including: bit penetration rate, bit weight, hook load, rotary speed, rotary torque, drilling fluid circulation rate (including any lost circulation), deviation, and mechanical, hydro-mechanical, and drilling specific energies. These data will assist in determination of lithology changes during drilling. Some drilling parameters (e.g., weight on bit, torque, and vibrations) can be measured at the bit (i.e., measurement while drilling) and either continuously transmitted to the surface or stored and retrieved with the bit on replacement trips out of the hole.

Deviation logs are important to track the amount of borehole inclination, deviation (integrated inclination), and straightness or dogleg severity (differentiated). Whereas the effects of deviation can be corrected during borehole construction (e.g., by reaming), controlled directional drilling is preferred. With the use of a RSS, deviation will be monitored while drilling. The purpose is mainly to verify RSS performance, but the deviation data will also be used with lithologic analysis (rock flour, cuttings, and core) and geophysical logs to build a geologic model.

6.1.2 Drilling fluid logging, sampling and analysis at the surface

This section describes data collection, sampling, and chemical and isotopic analyses, for fluids introduced to and recovered from the borehole. These objectives apply to drilling fluid (as written) but also to testing and workover fluids using during the testing phase of planned CB activities (Section 5.1.2)

6.1.2.1 Logging drilling fluid physical properties

The type of drilling fluid used will depend on the drilling method (Section 4) and will strongly impact sample collection and testing. Pressure, temperature, and flow rate of drilling fluid injection, and of returns at the borehole collar, will be logged. Drilling fluid properties collected by the mud engineer (e.g., density, viscosity) will be added to the dataset. Samples of drilling fluid will be collected for off-site laboratory and onsite field analyses at regular intervals.

6.1.2.2 Logging cuttings and rock flour

Onsite logging of cuttings, together with continuous monitoring of drilling parameters, provides near real-time evaluation of changes in lithology, and first alerts for contact with faults or fracture zones, and possible sites for additional advance core collection. Basic lithologic information from the borehole is central to the geologic model.

Logging of drill cuttings provides a high frequency vertical profile indicating variability of rock type, stratigraphy, mineralogy, and texture encountered during the drilling process. Drill cuttings samples (nominally collected at 3-m [10’] intervals) will be stored for possible future geochemical and petrophysical analysis (e.g., later batch sorbtion isotherm tests).

The usefulness of data obtained from drill cuttings is limited by uncertainty about the depth from which the cuttings come. Cuttings are transported by the drilling fluid from the drill bit to the surface, resulting in a delay (on the order of 1 to 2.5 hours) between when they are cut and when they are sampled. There is also mixing of cuttings from different depths during transport to the surface. It is also common to stop advancing the drill bit and pull up a few feet, while continuing to circulate, to clean out the borehole. This improves the depth-specificity of cuttings, but slows down drilling and can take a long time to perform at significant depth.

Rock flour samples centrifuged from drilling fluid will be analyzed onsite using X-ray fluorescence (XRF) and X-ray diffraction (XRD) to quantify variation in mineral and rock composition (Emmermann & Lauterjung 1990). Rock flour samples will likely require multiple washes with de-ionized water to remove any brine or drilling fluid additives signal from XRD/XRF analyses. These samples are logged to contribute to the development of geological and geochemical models, supplementing relatively infrequent rock core analyses with many more samples collected at intermediate locations.

- **Quantitation objective:** Identify major and minor minerals with reasonable confidence. Estimate percentages of major rock-forming minerals. Identify transitions with depth, and any anomalies encountered. Rock flour analyses are performed on centrifuged samples of drilling fluid.

- **Contamination or Loss Potential:** Undissolved thickening agents, lost circulation materials, and weighting agents added to drilling fluid may complicate analyses or require additional washes.

6.1.2.3 Logging drilling fluid chemical properties

The general mineral and general physical properties (e.g., temperature, pH, redox potential, major anions and cations, and salinity or total dissolved solids [TDS]) of the liquid component of drilling fluid will be monitored at a high frequency during drilling to locate inflow and outflow zones, and identify changes to the drilling fluid from groundwater inflow. A history of trace indicators of inflow (e.g., samples every 9.1 m [30’] drilled) can be obtained using an onsite ICP-MS (Inductively Coupled Plasma Mass Spectrometry). Drilling fluid that is made up and ready for re-injection into the borehole will be sampled and analyzed on a similar schedule (Section 6.1.2.5). Geochemical logging includes monitoring concentration of any added tracers onsite. Technical objectives for drilling fluid samples are given in Section 6.1.2.6.

6.1.2.4 Logging dissolved drilling fluid gases

Dissolved gas content of the drilling fluid will be monitored at the surface to provide additional information for constructing geochemical profiles of non-introduced environmental tracers and geothermal or groundwater gases evolving from the borehole fluids (Karus et al. 1987; MacDonald 1988; Lippmann et al. 2005). This logging is conducted to further qualitatively determine inflow and outflow zones, including changes in crystalline basement bulk permeability and groundwater geochemistry. Occasional gas samples (i.e., every 305 m [1000’] drilled) should be collected in cylinders for later detailed laboratory analyses of gas content and confirmation of field gas chromatograph results, including possible isotopic analyses.

- **Quantitation objective:** Identify changes in composition of dissolved gas content in drilling fluid discharged from the borehole, indicative of fluid changes in the subsurface encountered while advancing the borehole. A degasser with onsite continuous gas chromatography will be used (only a split of the drilling fluid discharged may be degassed). Major atmospheric gases (i.e., N_2, O_2, Ar, and CO_2), concentrations of noble gases (particularly He, and possibly Ne and other rarer noble gases), hydrogen, and hydrocarbons (at least methane) should be monitored.

- **Contamination or Loss Potential:** Gas sampling from the drilling fluid should occur in the fluid treatment system at the surface before the fluid has come in contact with the atmosphere.

6.1.2.5 Logging and tracing makeup water

Additional drilling fluid is added to the borehole during drilling in order to: 1) maintain the required drilling fluid system volume as cuttings are removed; 2) make up losses to evaporation and fluid handling at the surface; and 3) replace lost circulation. The chemistry of added makeup water will be monitored, and tracers will be added to maintain target concentrations.

The quantities and timing of fluid and tracer addition to the drilling fluid will be logged, with the objective to maintain constant, uniform tracer concentration in the drilling fluid system. Conservative (non-sorbing and non-reacting) drilling fluid tracers that will not significantly alter drilling fluid chemistry will be used.

Tracers will be used to: 1) indicate contamination of formation water samples pumped from higher-permeability crystalline basement portions of the borehole, and 2) indicate fluid invasion and contamination in cores. Two candidate drilling fluid tracers for water-based drilling fluid are fluorescein dye (very easy onsite determination of contamination during sampling, but may sorb to clays and organics or be temperature sensitive) and iodide (requires more complex onsite analysis than fluorescein dye, and iodide may oxidize to iodate, requiring testing for total iodine).

Tracers should be chosen that minimally interfere with determination of natural indicators of groundwater origin, apparent age, and water-rock interaction: Ca/Na, Ca/K, and Cl/Br ratios, stable water isotopes (i.e., deuterium, tritium, and ^{18}O), and Li, U, and Sr isotope ratios.

6.1.2.6 Objectives for drilling fluid sampling data

Here we discuss primary scientific objectives and possible issues related to collecting and analyzing drilling fluid related liquid samples, for onsite analysis in the field and for samples to be sent to off-site analytical laboratories for analysis. Sample locations, analytes, and analyses include:

- Onsite analysis of drilling fluid tracer
- Onsite analysis of makeup water
    - pH, electrical conductivity & temperature
- Off-site laboratory analysis of makeup water and drilling fluid before/after circulation

- Major/minor ions, trace elements, water stable isotope ratios, nitrogen, sulfur and carbon isotopes

Drilling Fluid Onsite Tracer Analysis – Drilling fluid tracer (here assumed iodide in a water-based brine drilling fluid system) will be analyzed onsite once per 9.1 m [30'] of borehole drilled (also at changes in the drilling fluid system such as new fluid additions) as the primary means of controlling tracer concentration. Sampling and analyses will be performed in "real time" so that deviations in tracer concentration can be promptly corrected. Iodide can be quantified at 1 mg/L in drilling fluid using an ion specific electrode, if the bromide concentration is less than 1,000 mg/L (bromide interference may occur if Br/I > 1,000).

- **Quantitation objective:** Determine iodide concentration at ±1 mg/L. Added tracer concentration in drilling fluid should be at least 20 mg/L iodide, or greater if bromide concentration exceeds or is expected to exceed 1,000 mg/L (Br and I will also be measured in laboratory samples as discussed below). Assume NaCl added to drilling fluid will be of evaporite origin with mass ratio of Cl/Br on the order of 3,000, and maximum concentration of ~5 M (saturated NaCl or Na-Ca-Cl brine). Formation fluid with the same chloride concentration and Cl/Br ~100 would have to displace more than 50% of the drilling fluid for bromide concentration ≥1,000 mg/L (limit for interference with the iodide specific ion electrode at 1 mg/L). Onsite measurements will be checked by lab-based ion chromatograph or ICP-MS. If a different drilling fluid tracer than iodide is proposed, a related set of quantitation objectives must be defined.

- **Contamination or Loss Potential:** Electrode may malfunction due to fouling or plating.

Makeup Water Onsite Analysis – Makeup water composition (i.e., source water) will be analyzed onsite once per tank or delivery of water before additives are mixed or the water is added to the circulation system. Onsite analysis of makeup water will include field pH, electrical conductivity, and temperature electrodes.

- **Quantitation objective:** Simple check on consistency of water source. Field electrodes are only accurate enough to indicate consistency or change in source water.

- **Contamination or Loss Potential:** Tanker trucks or onsite water tanks should be clean of any oilfield hydrocarbon/brine residue (i.e., steam clean tanks or use water-only equipment).

Makeup Water Off-site Analysis – Makeup water will be tested off-site once per month or at any change in water source. Samples of water will be collected before including additives or being added to the drilling fluid circulation system. Off-site testing will be conducted to determine major/minor ions, trace elements, stable water isotopes, dissolved inorganic carbon, and total organic carbon. Makeup water composition (stable water isotopes and ionic ratios) will likely be different from formation water, and therefore if properly quantified, may serve as a tracer to help quantify contamination of cores and in situ water samples.

- **Quantitation objective:** Analyses proposed for drilling fluid after circulation (see below for discussion of major/minor ions, trace elements, and stable water isotopes performed at off-site labs) should be done occasionally to source water, to quantify any changes or fluctuations in source water quality.

- **Contamination or Loss Potential:** Makeup water should be obtained from a consistent, stable source (e.g., city water supply or a dedicated water supply well). Tanker trucks or onsite water tanks should be clean of any oilfield hydrocarbon/brine residue (i.e., steam clean tanks or use water-only equipment).

Drilling Fluid Off-Site Analysis Before Circulation – Samples of fully prepared drilling fluid will be taken prior to introducing the fluid to the borehole. The samples will be analyzed off-site for major/minor ions, trace elements, and stable water, carbon, nitrogen, and sulfur isotopes. In addition, testing will be conducted to verify additives, but the nature of such testing is to-be-determined based on the selection of those additives and the capabilities of the CB Drilling Contractor. Samples will be collected once per week or after any significant change in drilling fluid additives.

- **Quantitation objective:** Sampling and analysis of prepared drilling fluid (prior to circulation) should be similar to analysis after circulation as discussed below (major/minor ions, trace elements, stable water isotopes, and other additive-specific tests, performed at off-site labs) so that changes can be identified. Sampling events should be scheduled to coincide with drilling fluid changes, although off-site analyses may be performed later (not in “real time”).

- **Contamination or Loss Potential:** Drilling fluid additives should come from the same sources throughout the duration of drilling and testing. These analyses will be used in conjunction with analyses of drilling fluid after circulation, although there are fewer concerns regarding exposure to atmosphere since samples will be collected from surface containers exposed to atmosphere during handling and mixing.

Drilling Fluid Off-Site Analysis After Circulation – Samples of circulated drilling fluid will be taken once per 30 m [100’] drilled, for off-site analysis including testing to verify additives, which is to-be-determined as discussed above. Off-site testing will include analysis of **major/minor ions**.

- **Quantitation objective:** Quantify each component at ±1% of total abundance. There are several methods for analyzing the major/minor ions listed below. Nearly all of them are associated with interference from high TDS, so 1:99 dilution with purified water is assumed here. The resulting undiluted sample reporting limits for metals (using Inductively Coupled Plasma Emission Spectroscopy – ICP-ES) would be: Na (100 mg/L), Ca (100 mg/L), K (100 mg/L), Mg (100 mg/L), Fe total (5 mg/L). Undiluted sample reporting limits for non-metals (using ion chromatography) would be: chloride (2 mg/L), bromide (1 mg/L), fluoride (10 mg/L), iodide (1 mg/L), sulfate (2 mg/L), and nitrate + nitrite (1 mg/L). These reporting limits are likely to be less than 1% of measured elemental abundance except for K, Mg, Fe, and fluoride for which less relative accuracy may be obtained. Iodide reporting limit estimate is for dilution of 1:9. Improvement in all reporting limits may be achieved by optimizing dilutions. The objective for complete analysis is charge balance to <5% relative error, which may not require measurements of pH or alkalinity species if the fluid is brine, and charge balance is dominated by electrolyte species.

- **Contamination or Loss Potential:** Contamination is possible from residues present in the drilling fluid handling equipment and from residual drilling fluid from the overburden section.

Trace elements will be analyzed to detect local elemental anomalies during drilling, at the parts-per-billion level.

- **Quantitation objective:** Low-level analyses are generally limited to metals, analyzed by ICP-MS. To avoid interference, dilution of 1:99 is assumed here. Undiluted sample reporting limits of approximately 10 μg/L can be obtained for alkalis, alkaline earths, transition metals and non-metals using ICP-MS. U can be analyzed by ICP-MS with an effective undiluted reporting limit of 10 μg/L, which could be improved using isotope dilution and chemical separation, with ICP-MS or Thermal Ionization Mass Spectrometry (TIMS). Total abundance analysis of Li, Sr, and U will be performed to support isotopic measurements (objectives: Li, Sr, and U each at an effective undiluted reporting limit of ±10 μg/L or better by ICP-MS).

- **Contamination or Loss Potential:** Exposure to crushed rock, residues or leakage from pumping equipment, filtration equipment, and other drilling fluid handling equipment. Contamination is possible from residual drilling fluid from the overburden section. Use ultra-high purity acid to treat samples for storage. Sample volumes not used should be saved for possible later isotopic analysis (Li, Sr & U).

Stable water isotopes will be analyzed to interpret formation water provenance (e.g., climate conditions when precipitated or recharged) or origin other than meteoric (e.g., ancient marine).

- **Quantitation objective:** Precision of 0.1 per mil for ^{18}O and ^{2}H (deuterium) samples can be achieved using vaporization or diffusion processes to extract pure H_2O from brine without significant fractionation. Cavity ring-down spectroscopy is a commercialized desktop method that can achieve this performance.

- **Contamination or Loss Potential:** Samples should be protected from prolonged exposure to air (more than a few minutes). Contamination is possible from residual fluids from pumping equipment and residual drilling fluid from the overburden section.

Stable isotopic ratios will be analyzed for C, N, and S to quantify any biochemical transformations of these elements and to further quantify contamination from drilling fluid in formation water samples (e.g., Cravotta 1995). The **isotopic ratios of C, N, and S** present in prepared drilling fluid at isotopic equilibrium with the atmosphere will likely be different from those present in the relatively isolated deep crystalline groundwater system.

- **Quantification Objective:** Fluid sample size requirements are related to analyte concentration (i.e., dilute solutions will require larger sample sizes). Samples will be acidified with reagent-grade HCl to 0.5 vol-% HCl concentration. Analysis will be performed using mass spectrometry, and presented as ratios ($^{13}C/^{12}C$, $^{15}N/^{14}N$, and $^{34}S/^{32}S$) in gases (CO_2, N_2, and SO_2) generated from combustion of sample material.

- **Contamination or Loss Potential:** Samples should minimize unnecessary exposure to carbon, nitrogen, and sulfur-bearing compounds during sample collection and preservation. Assuming the concentrations of dissolved C, N, and S species are high enough, the samples should not require isolation from the atmosphere. Contamination is possible from residual drilling fluid from overburden section.

6.1.3 Downhole monitoring while drilling

Some drilling fluid circulation systems can transmit data from downhole sensors to the surface via modulated drilling fluid pressure in the drill pipe. This technology (measurement or logging while drilling) supports low baud rates (approximately 10 bits/second), but is well proven and can provide information at the surface while drilling. Wired drill pipe can support much higher data transfer speeds, but may not be compatible with all drilling methods and may be prohibitively expensive. Some logging while drilling systems selectively transfer or compress data before up-hole transfer. Additional recorded data, beyond that transferred real-time to the surface, may be available when the bottom hole assembly is tripped out. The downhole dataset would be useful to complement the geologic model, even if it is not used immediately in drilling or decision making. The cost of any measurement or logging while drilling technology should be weighed against the benefits the data would provide to the project.

A minimal program of monitoring while drilling (temperature, pressure, deviation control) in conjunction with RSS directional drilling, allows monitoring of borehole deviation, and detection of drilling fluid loss or formation fluid inflow. Temperature is logged to verify that bottom-hole conditions are within RSS specifications. Additional logging while drilling (e.g., formation resistivity and natural gamma, drilling fluid resistivity) may be useful for tracking specific geologic targets with known geophysical properties. Drilling fluid resistivity in the CB will be related to salinity, which may change with inflow of formation fluid. Temperature logging may provide similar indications of inflow. Real-time drilling fluid pressure information is a status indicator on circulation, and is needed where fluid pressure balance is important.

6.2 Downhole Sampling and Testing during Drilling

Downhole sampling and testing will include intermittent (~5%) advance coring (i.e., large-diameter cores), hydraulic fracturing stress measurements, and minimal wireline-conveyed packer testing before reaching final total depth of 5 km. Fluid samples for geochemical analyses will be both extracted from cores (for low-permeability intervals) and pumped from packer-isolated higher-permeability intervals. Representative fluid samples will provide vertical profiles of formation fluid and fracture water chemistry including natural isotopic tracers to verify effective hydrologic isolation of the crystalline basement. Downhole sampling during drilling operations would minimize the potential for formation invasion and thus produce uncontaminated samples, but this approach increases rig costs. Any sampling during drilling should be carefully planned and executed to collect the required core and fluid samples to maximize return on risk and cost. Thus, a minimum but necessary scope of testing and sampling should be planned to achieve the project’s scientific goals. All drilling and completion activities should be planned to support downhole testing and sampling (Figure 1). Much of the open-hole sampling and testing in the basement interval will be conducted using a workover rig after drilling is complete (Section 6.5). However, sampling and downhole testing of selected intervals during drilling is needed to estimate the in situ stress state, and the static formation fluid pressure, which may impact how drilling proceeds.

Depths for coring and fluid sampling should be planned prior to drilling, but additional sampling locations may be identified during drilling. Without site-specific information (the present scenario), coring is planned to be done at uniformly spaced intervals.

6.2.1 Coring procedures

Advance coring will target recovery of 150 m [492’] of core across the 3 km of basement (5% of the crystalline basement interest section). If the depth to basement is significantly less than 2 km then there will be more than 3 km drilled in the basement, and the total length of cored interval will be longer, maintaining ~5%. Coring can be conducted using either traditional or wireline retrieval. Wireline may be faster or more efficient for continuous coring, but requires drilling with wireline-compatible hard rock drill bits. Instead, traditional coring will be used (i.e., trip in and out for each coring run) with the objective to coordinate coring trips with bit changes or other drill string maintenance for operational efficiency. Traditional coring will also allow larger diameter cores to be collected. Any rotary sidewall coring to be done will be conducted at the time of open-hole borehole wireline logging, and prior to setting any casing such as in the overburden interval. The majority of the core will be collected from the crystalline basement, with coring in the lower overburden as needed to interpret state of stress and wellbore stability; and to constrain vertical profiles of temperature, salinity and environmental tracers. Ideally, coring should sample changes in crystalline basement lithology or character (i.e., overburden/basement interface), with a secondary target of recovering some core from each major crystalline basement lithology. Core may be required from intervals other than those initially planned, based on fulfilling the scientific objectives of the DBFT. Rotary sidewall coring offers a robust contingency if full-diameter core recovery is poor, or if features of interest are identified later after drilling.

The overburden-basement interface is of special interest to hydrological, geomechanical, and thermal assessments, and should be cored. It is expected there will be steep gradients in rock and fluid properties across and below this interface. The initial core point should be within a few meters of the overburden-basement interface, and is contingent upon an accurate pre-drill determination of overburden thickness. The nature of the interface will likely be sharp (i.e., an unconformity), and therefore the core point should be chosen carefully. If the top of crystalline basement is missed in the CB, it may be possible to core the interval when drilling the FTB.

To better locate the overburden/basement interface, a lookahead Vertical Seismic Profile (VSP) may be conducted from a safe distance above the expected interface. The financial and schedule costs associated with additional geophysics should be weighed against the location uncertainty and the technical benefits from obtaining full-diameter core across this interface.

One of the risks associated with core collection in brittle high-stress rock is core discing, where core breaks into very short “hockey puck” shaped pieces as it is being drilled, due to large stresses that occur ahead of the coring bit. Discing makes core analysis and fluid extraction from cores more difficult. It increases core surface area, accelerating invasion by drilling fluid and loss of gases as the core is brought to the surface. Disced core is more difficult to handle and preserve.

The likelihood for core discing increases with depth, and is related to the rock strength (which is scale dependent), and the in situ stress state. Since the stress state and rock strength cannot be controlled, the primary approach to reduce discing is to obtaining larger-diameter core and core at a slower penetration rate. A possible contingency plan involves collecting less core in the deepest part of the borehole where stresses are greater, and more core at shallower depths. Rather than spacing out core collection uniformly across the ~3 km basement interval, a larger portion of the core could be collected at shallower depth in the basement. This decision would reflect a tradeoff between the amount of core collected deeper in the borehole, and the overall quality of the core.

Coring equipment and methods will be chosen to maximize recovered core diameter given planned laboratory testing requirements (Section 6.4). The largest feasible core diameter will be selected to maximize core volume for extraction of formation liquids and gases (Mazurek et al. 2011), for geochemical whole-rock assessments, and to provide representative samples for laboratory-based core testing. Oriented core, calibrated with image logs, will allow determination of absolute fracture orientations. To the extent that rotary sidewall coring is used, it will also be planned to meet the needs of the DBFT even though the length and diameter of sidewall core is much smaller than advance core.

6.2.1.1 Core handling

Onsite core handling should be minimized, but will include activities necessary for sample preservation and any immediate examination needed (e.g., for making decisions about drilling, continued coring, and testing). Table 8 lists the types of analyses planned for the collected core. The majority of the core will be cut into lengths suitable for transportation, capped and left in the inner core barrel or sleeve for protection during transport to an off-site laboratory for further core processing, analysis, and storage. Core depths will be marked on the core barrel or sleeve in the field. Coring depths should be carefully confirmed with mud loggers, rig operators, and drilling engineers. Depth marks will be made at locations on the core barrel where the core will be cut into smaller lengths (approximately 0.9 m [3’]) for packaging and shipment. The cut sections will be sealed to stabilize the core and minimize dry-out and biological activity. Depth marking procedures should be systematic and documented in the field test plan. Assumptions used to estimate depths should be documented (e.g., any loss of core was at the bottom of the length of the core and not at the top). Cutting should be done so the core can be unambiguously pieced back together; cores should be “island-cut” instead of a smooth straight-through cut. Correction to core depths will be made using correlation between core and borehole geophysical and image logs.

Coring will be conducted to provide samples for laboratory testing (Sections 6.3 and 6.4). Recovered core will be physically divided up, following a standard custody-tracking protocol for shipment to storage or analysis labs. Special core handling may be required onsite (e.g., refrigeration of cores for fluid extraction), and thus a core handling facility should be available; a climate-controlled trailer with good lighting to protect workers and core from inclement weather.

Any subsampling of core onsite should be carefully documented, including photography and marking of sample depth locations while stabilizing the remaining core. Core will be preserved against drying and biological activity using methods such as sealing in wax, ProtecCore, or using tight endcaps on the core sleeve after the core and sleeve are cut to final length. A combination of preserved core and core in helium-tight canisters will be necessary to obtain the appropriate suite of samples for assessing the hydrogeological, mechanical, and thermal properties of the basement interval and key lower sections of the overburden.

We foresee there will be outside interest in core samples from up to 5 km depth in the CB, for scientific or economic reasons not directly related to the objectives of the DBFT. Depending on the site location, the CB may be the first regional borehole drilled 3 km or more into the crystalline basement, and core samples could be valuable for geologic characterization purposes (e.g., analysis of fluid inclusions and isotopic rock age dating). The DBFT Technical Advisory

Committee will approve any other research uses for the CB or samples (core, cuttings, fluids), according to its charter.

Table 8. Geologic characterization of cores

Core testing	Tests and Motivation	Sampling Requirements
Petrophysical Properties	Rock density, spectral gamma, core photography, and fracture distribution analyses for comparison and correlation with cuttings, rock flour XRD/XRF, geophysical logs and in situ testing intervals	Core preservation to minimize dry-out and inhibit biological activity. Proper core depth marking and handling.
Fracture Characterization	Geological and geomechanical characterization of existing fractures. Fractures are primary sources of hydraulic permeability in crystalline basement	Careful handling and reassembly. Core orientations deduced from image logs.
Hydraulic Properties	Porosity, tortuosity & permeability for comparison with packer testing results. Hydraulic testing should be done at a range of confining pressures, up to the in situ stress state at sampling depth.	Large enough diameter samples for representative testing (i.e., several crystals or grains across). Core preservation to minimize dry-out and inhibit biological activity.
Geologic Characterization	Texture, rock type, mineral makeup, fracture filling materials, fluid inclusions & X-ray diffraction for correlation with physical, hydrogeological, geochemical and geomechanical properties. Scanning electron and optical petrography. Stable isotopes and trace elements in whole rock (including fracture fills) to assist reconstruction of paleohydrogeology and the degree of water-rock interaction.	Representative cores from each major crystalline bedrock formation or lithology encountered. Full diameter core across contact of sedimentary overburden and crystalline basement.
Geochemical Properties	Formation fluid extraction and analysis for construction of geochemical and isotopic profiles, to supplement sampling via packers.	Core preservation (including refrigeration) to minimize dry-out and inhibit biological activity. Noble gas samples require handling in He-tight containers.
Geomechanical Properties	Determine stress-strain relationship, elastic parameters, strength anisotropy, tensile strength, Biot coefficients, frictional strength and ultrasonic velocities. Test mechanical properties at representative pore pressures, temperatures, and fluid compositions. Critical information for borehole stability.	Large enough diameter samples for representative testing and directional subsamples (≥10 grains wide and 2-2.25:1 length:width ratio). Core preservation to minimize dry-out and inhibit biological activity.
Thermal Properties	Thermal conductivity, heat capacity, thermal expansion coefficient, and non-linearity of properties for parameterizing numerical PA models.	Core preservation to minimize dry-out and inhibit biological activity.

6.2.1.2 Core subsamples for Helium-tight canisters

In-situ radiogenic/nucleogenic/cosmogenic noble gas tracers (^{3}He, ^{4}He, ^{39}Ar, ^{81}Kr, and ^{129}Xe) can build up in ancient, isolated groundwater and thereby indicate long residence time. A subsample of core from each core run will be preserved in helium-tight canisters (Osenbrück et al. 1998; Rübel et al. 2002; Heath 2010; Gardner et al. 2012) to allow estimation of noble gas content in core formation fluids. Two sample intervals will be preserved from opposite ends of each per core run. The method involves immediately placing of rinsed subsamples of fresh core, as soon as the core reaches the surface, into stainless steel canisters with helium-tight metal-to-metal seals. The canisters are flushed with ultra-high purity nitrogen gas to remove atmospheric gas and finally the cores are left in a vacuum. The noble gases are then allowed to degas from the core samples for at least several weeks, followed by laboratory noble gas isotopic analysis of the head space in the sample containers. After testing for environmental tracers (including whole-rock analyses), remaining samples should be returned for storage and geologic description with the other cores.

The subsampling approach involving the least disturbance and exposure of the core before placing it in the helium-tight sample container would involve cutting 5- to 7-cm [2 to 3”] long full-diameter samples from the ends of the core run. Samples for preservation could alternatively be subsampled perpendicular to the core axis using a drill, but drilling requires addition of a cooling fluid or the sub-coring process will heat the subsamples up significantly. The main disadvantage of using larger full-diameter subsamples is the requirement for larger-diameter helium-tight canisters, which are more expensive. Since the samples will be allowed to degas into the containers for several weeks or months (i.e., not analyzed immediately), helium-tight canisters for all expected samples must be procured before the first core is collected.

6.3 Laboratory Testing of Fluids Extracted from Cores

Laboratory methods for fluid extraction from cores depend on the type of sample analysis to be conducted. Available methods for fluid extraction include: centrifuge extraction, distillation (only for isotopes), flushing cores with deionized water (good for isotopes and trace elements, but may cause some mineral dissolution and clay swelling), high-pressure destructive squeezing, and “crush and leach.” Destructive methods (squeezing and crushing) may lead to dissolution of minerals not originally present in fluid samples and mobilization of fluids trapped in fluid inclusions, and should only be used if other methods are not viable, or after less destructive methods have already been performed on samples. Fluid extraction methods will require generally subsampling to reduce core sample sizes.

Multiple methods will be tried and compared to determine how best to extract useful and representative quantities of formation fluid from cores. This is one of the topics to be developed and investigated as part of the DBFT, as fluid extraction is not trivial and not all approaches may be successful.

Core samples 0.6 m [2’] in length will be chosen from the ends of each core run for preservation in anticipation of fluid extraction. If core diameter is 10 cm [4”], this is approximately 5 L of rock. Assuming 1% porosity and highly efficient recovery, this would correspond to 50 mL of formation fluid. Contamination from invading drilling fluid, especially during drilling, is the primary concern. The depth of invasion into the core is a function of how intact the core is and its permeability. Rock along the axis of the core would be most isolated from contamination.

Here we discuss primary scientific objectives and possible issues related to collecting and analyzing fluid samples extracted from core samples. Analytes include:

- Major/minor ions and selected trace constituents obtained from cores via:

- Centrifugation of formation fluid samples from sub-cores
- Aqueous leaching of coarsely crushed (then progressively finer crushed) cores

- Aqueous extraction or distillation of fission product species from intact or crushed core

In addition, the solid rock components of cores will be analyzed for geologic characterization and to parameterize geochemical models used to interpret results from formation fluid analysis.

Major/Minor Ions and Trace Elements in Fluids Extracted from Cores – Analysis of major/minor ions and trace elements on very small liquid samples (a few mL) that result from centrifugation, is standard practice in many laboratories. Preserved core samples are sub-cored (either dry or lubricated using iodide-traced water) to produce samples of appropriate size.

- **Quantitation Objective:** These are the same as described for drilling fluid samples, but with the additional challenge of small samples with undiluted volume on the order of 1 mL (e.g., by ICP-MS and multi-analyte ion chromatography). Dilution will facilitate analysis by increasing sample volume. Measurement of pH and alkalinity (any analysis method such as a glass electrode that could contaminate the samples) is impractical, so complete chemical analysis may be impossible (although these components may not be a significant portion of the charge balance in a high ionic strength brine). Centrifugation may not produce sufficient quantities of formation fluid from crystalline rock core samples, in which case aqueous extractions from crushed core would be used.

- **Contamination or Loss Potential:** Preserved core is used to limit dryout and the formation of soluble salt residues on the core surface. Cores should be refrigerated prior to sampling to inhibit microbial growth. Due to the small fluid sample size, contamination is possible from everything that touches the samples: centrifuge tubes, sample containers, filters, pipettes, diluent, etc.

If centrifugation does not produce sufficient sample volume, aqueous leaching of coarsely crushed core will be undertaken to estimate analyte concentrations and ratios (e.g., Ca/Na, Cl/Br, Na/K). Successively finer same-sample crushing and leaching can be used to correct approximately for contributions from concurrently dissolved rock minerals and fluid inclusions.

- **Quantitation Objectives:** These are the same as those identified above for major/minor ions, but interpretation is limited to ratios.

- **Contamination or Loss Potential:** Exposure of liquid samples to crushed rock or dust. Core should be refrigerated prior to sampling to inhibit microbial growth.

Fission Product Species in Fluids Extracted from Cores – The most volatile species (e.g., isotopes of He, Ne, Ar, and C) can be extracted directly by distillation on a vacuum line, which can be heated, and can use either crushed or intact core (Davidson et al. 1995). For inert gases distillation (or even partial distillation) can result in efficient recovery, but for more reactive elements (e.g., carbon) losses may occur from mineral precipitation. For very scare fission product species care should be taken to quantify losses from co-precipitation with mineral or in cold traps, and sorption (e.g., on glass).

Less volatile in situ fission product species (^{36}Cl, ^{129}I) that are not mobilized by vacuum distillation, can be sampled by aqueous extraction from crushed core. Centrifugation of sub-cored samples cannot effectively sample enough rock to produce enough fluid, to analyze for these fission product species (up to 1 L needed). Another option is high-temperature distillation from intact or crushed core, but this is developmental.

Extraction of these scarce nuclides from crushed core may be deferred to a later phase of the DBFT (non-volatile fission product species should be stable in longer term core storage).

- **Quantitation Objective:** Similar to ^{4}He, based on an assumed in situ production rate over a specified interval of time. Simultaneous samples of drilling fluid of sufficient volume for characterizing ^{129}I and ^{36}Cl, are needed to correct for invasion effects especially in samples utilized for future crushed core leaching extractions.

- **Contamination or Loss Potential:** Crushing and subsampling should be done in a "clean" rock room, which is accomplished using smaller equipment, cleaned by rinsing and crushing of "clean" materials (e.g., silica sand). Because of the very low concentrations of these tracers, extractions and separations should be done in a clean environment where dust contamination (e.g., containing traces of historical radioactive fallout) can be controlled.

6.4 Laboratory Testing of Cores

Rock components of cores will be tested to geologically characterize and parameterize geochemical, geomechanical, hydrologic, and thermal constitutive models.

6.4.1 Geologic characterization of cores

Here we discuss primary scientific objectives and possible issues related to collecting and analyzing core samples for geologic characteristics and properties. Analysis includes rock and mineral identification through visual examination, thin-section analysis, and scanning electron microscopy. The occurrence of fractures, their characteristics, and orientation will be logged. Fracture filling minerals will be qualitatively identified.

All core collected will be logged by geologist with relevant experience (i.e., Precambrian crystalline rock). Some core will only be logged after those samples are returned from other labs after is complete.

Geologic characterization of cores should be performed at levels permitted by project constraints (i.e., both by analysis complexity and number of samples analyzed), since these data populate the geological model, but would only be used indirectly to parameterize PA models.

- **Quantitation Objective:** Qualitative petrological examination for comparison with cuttings log, thin section, and scanning electron microscope (SEM) studies. Quantitative imagery, XRF analyses, and fracture logs will be compared with wireline logs (borehole image logs, dynamic fluid logging survey, and sonic) and used for selecting intervals for packer tests (flow tests, hydraulic fracture stress measurement tests, and possible future tests such as an in situ heater test).

- **Contamination or Loss Potential:** Core will be split for evaluation, and will desiccate in the process. Examination may introduce biological contamination such as mold spores, etc., so core splits should be re-packaged, and stored in a reasonably low-humidity environment to inhibit biofouling. Orientation of all core fragments will be maintained to the extent practical. Use of cleaners, oils, acids, tap water, etc. on cores should be minimized and documented (e.g., perform acid testing for carbonate on small samples removed from cores and kept separate from other core or discarded).

Laboratory thin-section analyses will be performed on at least one sample from each rock type or fracture fill type encountered to characterize minerals, micro-cracks, crack fillings, fluid inclusions, etc. for the geologic model. Analysis will include point counting of mineral abundances and porosity. Results will include determination of porosity variation and interpretation of the origin and development of porosity and permeability. Point count data will be presented with color photomicrographs and detailed geological descriptions.

- **Quantitation Objective:** Qualitative petrological examination to determine mineral types for comparison with cuttings log, XRF/XRD of rock flour, and SEM studies.

- **Contamination or Loss Potential:** Thin-section sample orientation should be recorded and preserved.

Laboratory SEM and XRD analysis will be performed on at least one sample from each core run, with at least one analysis from each rock type encountered to characterize minerals, trace elements, crack and fracture fillings, fluid inclusions, etc. supplementing optical petrographic analyses of thin sections. XRD analysis will provide semi-quantitative determination of sample mineralogy. The data output will include photographs at varying magnification documenting significant rock constituents, pores, and any fracture-filling minerals, including elemental abundance from EDS analysis.

- **Quantitation Objective:** Qualitative/semi-quantitative petrographic examination for petrologic comparison with cuttings log, XRF/XRD of rock flour, and thin-section analyses.

- **Contamination or Loss Potential:** Exposed faces of natural fractures should be preserved for investigation and should not be abraded during storage and handling.

6.4.2 Geochemical analyses of cores

Here we discuss primary scientific objectives and possible issues related to collecting and analyzing core samples for geochemical analyses. A suite of geochemical analyses of rock samples is needed for the geologic model, and to interpret chemical and isotopic analyses of fluids. Analyses include helium buildup of preserved whole-rock core samples and of quartz crystals.

Helium Buildup Testing of Core Samples – Helium buildup testing of core rocks and core formation fluids (one subsample collected from end of each core run) will be done to understand the balance of diffusive and advective transport rates, balanced against the in situ production rate of ^{4}He from alpha decay of U and Th in the rocks. The subsampling and core preservation methodology required (i.e., sealing in He-tight canisters) is described in Section 6.2.1.2.

- **Quantitation Objective:** Interpret He concentrations as evidence for isolation using in situ He production rates (from abundance of parent nuclides in rock) or accumulation rates (using estimated fluxes) over a specified interval of time (e.g., 1 million years) assuming a closed system or perfect trap. Such a calculation indicates the amounts of gaseous species that can be produced from preserved cores. Invasion of cores by drilling fluid should be quantified from simultaneous sampling and parallel testing of the drilling fluid, by quantitation of iodide tracer residue in the cores and comparison of radiogenic (i.e., generated in situ – ^{4}He, ^{40}Ar, ^{21}Ne, and ^{22}Ne) to non-radiogenic (i.e., atmospheric only and not generated in situ – ^{3}He, ^{39}Ar, and ^{20}Ne) noble gas ratios. The abundances of He and possibly Ar are likely sufficient to obtain useful data from reasonable quantities of core, but the other noble gases (e.g., Ne, Kr and Xe) may be too scarce for a reasonable sampling effort.

- **Contamination or Loss Potential:** Exposure of core samples to air (for more than a few minutes) will cause sample loss and/or contamination of gaseous analytes. Once core is packaged in He-tight metal containers, the containers should not be reopened (except degassing via gas sampling ports) until noble gas sampling is complete.

Helium Content of Quartz Crystals – The He content of quartz crystals will be estimated to better understand the rock component of the water-rock equilibrium for He in the basement rock (Smith et al. 2013). At least one sample from each core run will be analyzed, with at least one analysis from each rock type encountered. The He closure of the system is temperature-dependent, and will likely be exceeded in the subsurface, allowing diffusion between formation fluids and quartz grains. Once brought to the surface, quartz grains should lock in He content until heated to above closure temperature again.

- **Quantitation Objective:** Determine He content of quartz grains from the same whole-rock samples used for He buildup testing. Quartz grains are isolated in the laboratory using classic mineral separation techniques including hydrofluoric acid digestion, and heavy liquids. Quartz fractions are sieved to provide mineral grains of known size.

- **Contamination or Loss Potential:** Quartz grains can lose helium to diffusion. The helium loss rate is a function of grain size, temperature and duration of elevated temperature. For 100 micrometer spherical quartz grains, the temperature should be kept below 200 °C for periods longer than a day during handling, including any sub-coring activities that may generate localized heating.

Whole-Rock Isotope Ratios and Elemental Abundance – The natural whole-rock abundances of U and Th will be determined to calculate production rates for ^{4}He and fission products. Whole-rock isotopic ratios and elemental abundances will be determined for at least one sample from each core run, with at least one analysis from each rock type encountered, for Li (^{6}Li/^{7}Li), Sr (^{86}Sr/^{87}Sr), and U (^{234}U/^{238}U), for comparison with formation fluids. The ^{6}Li/^{7}Li and ^{86}Sr/^{87}Sr ratios can indicate marine or water-rock interaction and origin for the waters, while the ^{234}U/^{238}U ratio can indicate open-system loss of ^{234}U from groundwater transport, and the apparent residence time.

Subsamples should be located near those placed in He-tight canisters for He buildup and quartz crystal He content analyses.

- **Quantitation objective:** Determine abundance to interpretable accuracy of 10% of measured values, or better. Determine isotopic ratios as described for water samples: ^{6}Li/^{7}Li ±1 per mil; ^{86}Sr/^{87}Sr 1 part in 10,000 of direct ratio; ^{234}U/^{238}U approximately

3 ppm of direct ratio or 0.05 increment in activity ratio. If possible, determine $^{234}U/^{238}U$ with at least an order of magnitude better accuracy than this, for comparison to fractionation in formation fluids to quantify residence time on the order of 10^5 years or longer.

- **Contamination or Loss Potential:** The rock room used to for sample crushing and subsampling should be reasonably free of contamination. Chemical separations should be done in a clean trace-metal chemistry environment.

6.4.3 Geomechanical and hydraulic analyses of cores

Here we discuss primary scientific objectives and possible issues related to collecting and analyzing core samples for geomechanical and coupled hydro/mechanical properties. Tests include:

- Compressive strength vs. confinement: Triaxial tests to develop rock strength as a function of confining pressure for breakouts
  - Relatively fast loading strain rates (up to 10^{-4}/sec) to explore rock failure modes during drilling, and
  - slower loading strain rates (down to 10^{-8}/sec or slower) to explore time dependence of rock strength.
- Tensile strength: Brazilian indirect tension tests for drilling induced breakout and tensile strength fracture analysis
- Geomechanical tests with hydraulic/pore-pressure component:
  - Hydrostatic compression with permeability tests, and
  - Pre-existing fracture normal and shear compliance tests
- Anelastic strain recovery analysis of cores (begins onsite)

Determine deformation moduli and strength envelope for at least one sample from each core run in the crystalline basement, with at least one analysis from each rock type encountered. Standard geomechanical tests include uniaxial compression, hydrostatic compression, triaxial compression, and direct shear. Applications of these data include geomechanical analyses near the wellbore, for example borehole breakout analysis.

Strength vs. Confinement – The first objective is to gather data to better understand borehole breakout failure. These tests will construct a strength vs. confining pressure envelope based on testing samples to failure at different values of confining pressure, from almost zero up to the overburden stress. These triaxial tests should be performed at two representative in situ temperatures (50 °C and 100 °C) with compositionally representative brine as formation fluid, holding pore pressure equal to the in situ hydrostatic pressure (20 MPa for top of basement and 50 MPa for bottom of borehole). There will be inter-sample variability, so tests should be replicated, giving at least 20 tests total (a minimum assuming 10 core intervals and two samples per core). Repeated ultrasonic measurements should be made through the cores during testing to detect failure onset behavior and characterize damage. At least one set of directional triaxial tests on oriented samples should be run for each major rock type encountered.

Breakouts are also known to occur days to weeks after drilling, so a subset of the triaxial tests should be conducted at constant loading conditions, while monitoring the accumulation of dilatant volume strain. Test conditions will be adjusted for nominal strain rate of 10^{-7}/sec to 10^{-8}/sec. The lower strain-rate tests could help us understand why we have breakouts, if the series of faster strain-rate tests indicates they should not occur. The goal would be to bound the time dependent weakening behavior, rather than characterize creep over a wide range of strain rates, which should help limit the scope and duration.

Indirect Tensile Strength – A series of Brazilian tests will be performed to provide tensile strength data for interpreting in situ hydraulic fracture stress measurement tests, and for understanding wellbore damage if it occurs. A large number (50 to 100) of these tests is needed because tensile strength is variable, will be tested in multiple orientations (relative to the borehole axis and any fabric observed in samples), and the samples are small (~5.4 cm in diameter – NX core size). These tests can be done dry at room temperature, especially if tensile strength is low enough that fluid and temperature effects are less important.

Fluid Flow and Permeability Measurement During Triaxial Compression – A series of confined compressive strength tests will be performed at low confining pressure, combined with He- or brine-based permeability measurements. Constant flowrate or falling-head flow tests will be repeated during loading. Axial loading rates will be sufficiently slow such that pressure transients will have little to no effect on the mechanical response. Flow test data will be used to determine permeability. For gas permeant measurements (if needed to measure very low permeability) samples will first be dried in a manner so as not to disrupt the microstructure, and sufficient data will be collected to evaluate the Klinkenburg effect (Knudsen slip flow along pore walls at low gas pressures).

Normal and Shear Compliance of Pre-existing Fractures – Large core samples (0.5 m [1.6’] in length) will be preserved that have potentially significant fractures (e.g., open, and mineralized or with evidence of shearing). Fracture normal and shear compliance will be determined on 2 to 5 natural fractures obtained from cores. These parameters will be determined for loads representing the in situ stress conditions acting on the fractures. Test results will be used in geomechanical analyses. Compressive and shear wave measurements made during fracture compliance determinations will be important indications of deformation.

- **Quantitation objectives (all laboratory geomechanical tests):** Determine moduli and strength parameters directionally with measurement uncertainty less than between-sample variability of replicate samples, or 10% RSD (relative standard deviation for repeated measurements) for repeated measurements, whichever is smaller. Laboratory methods should have low enough measurement uncertainty to quantify natural sample variability.

- **Contamination or Loss Potential (all laboratory geomechanical tests):** Some lab tests will be performed on full diameter core, so core for lab tests should be reserved prior to any core splitting. Core sample diameter should be at least 10 times the grains size to limit grain-scale size effect, and the length/diameter ratio should be 2 to 2.25. Directional samples should follow the same size and aspect-ratio rules. Any formation fluids used in testing should be compositionally similar to native fluids, as estimated from analysis of in situ water sample or fluids extracted from core. Elevated temperature and high ionic strength brines may be incompatible with test equipment.

Anelastic Strain Recovery – Intact core is instrumented with directional strain or displacement gages immediately after coming to the surface (Voight 1968; Teufel 1983). Core can additionally be instrumented in a similar manner later in laboratory to monitor strain recovery after cutting core (residual strain recovery). The method is non-destructive.

- **Quantitation objectives:** Core is allowed to equilibrate while being monitored for several weeks. Estimates of principal directions of strain on core can be related to principal directions of in situ stress, if the core is oriented using image logs.

- **Contamination or Loss Potential:** Temperature of instrumented core should be carefully controlled and monitored to minimize thermal expansion and contraction. Core should be instrumented as soon as possible after being cut (including time for tripping out of borehole). This method best targets sub-cores from bottom of a core run, which have spent the least amount of time in core barrel before coming to the surface.

6.4.4 Hydrologic and thermal analyses of cores

Here we discuss primary scientific objectives and possible issues related to measuring hydraulic flow and transport and thermal conduction properties on core samples. Analyses include:

- Hydraulic flow and transport properties:
  - Pore size distribution (mercury porosimetry and NMR)
  - Diffusion, tortuosity and formation factor coefficient estimation
- Hydraulic/mechanical coupling (Biot coefficients) estimation:
  - Thermal properties:
  - Thermal conductivity and heat capacity (including temperature-dependence)
  - Thermal/mechanical coupling (expansion coefficient) estimation

Determine rock fluid flow properties (porosity, grain density, and directional permeability), rock transport properties (diffusion coefficients, tortuosity, and sorption coefficients), thermal conductivity properties (thermal conductivity, heat capacity), hydromechanical coupling (Biot coefficients), and thermal expansion coefficients for at least one sample from each rock type encountered, for use in process models supporting PA.

Nuclear magnetic resonance (NMR) analysis and mercury porosimetry will be used to estimate sample porosity distribution (Hg injection is destructive and can be conducted on small sample fragments).

Tortuosity and formation factor are important for interpreting electrical geophysical logs. They are related to the effective diffusion coefficient, which is an important property in numerical flow and solute transport modeling studies. While free-water diffusion coefficients are well-known for most dissolved species of interest, the effective diffusion coefficient in a porous medium is less well constrained. These parameters can be estimated from monitoring breakthrough of conservative tracers (via diffusion) across thin disc-shaped samples. Porosity and formation factor can also be estimated by measuring the bulk resistivity of a small sample saturated with different fluids covering a range of salinity.

Thermal conductivity of fluid-saturated samples (using formation fluid of representative composition) is important for simulating heat conduction in numerical models. Whereas thermal conductivity can be measured wet, heat capacity should be measured dry. The thermal conductivity and heat capacity of crystalline rocks are typically slightly temperature dependent (lower thermal conductivity and higher heat capacity at higher temperatures; Vosteen and Schellschmidt 2003) so these thermal material properties should be measured across a range of temperatures relevant to radioactive waste disposal applications.

The coefficient of thermal volume expansion should also be measured as a function of temperature. While thermal expansion of rock is less than that of the brine, this coefficient plays a significant role in thermomechanical modeling.

The hydromechanical coupling coefficients (Biot coefficients) should be estimated as functions of confining pressure. These coefficients are related to how the rock is impacted by pore pressure. A typical assumption in soils (sometimes called the Terzaghi effective stress; Wang 2000) is the Biot coefficient is approximately unity. It has been shown the Biot coefficient can be much less than unity for competent, low-porosity, low-permeability crystalline rocks, and may actually decrease significantly with increasing confining stress (Zangerl 2003). Measuring these coefficients is equivalent to estimating the bulk modulus (K) and Poisson ratio (ν) under both drained and undrained conditions.

- **Quantitation objective (all thermal and hydraulic tests):** determine sample permeability to ±10% RSD, and physical and thermal properties to 5% RSD.

- **Contamination or Loss Potential (all thermal and hydraulic tests):** Some lab tests will be performed on full-diameter core, so core for lab tests should be reserved prior to any core splitting. Any water-based formation fluids used in testing should be compositionally similar to native fluids, as estimated from analysis of in situ liquid samples or formation fluids extracted from core.

6.5 Wireline-Based Packer Testing

Wireline-conveyed packer testing will be done to obtain three critical pieces of information on the host formation: formation static fluid pressure, formation bulk permeability, and in situ formation fluid geochemistry. Wireline packer testing equipment consists of a packer or tool to isolate a section of the borehole, down-hole pressure sensor, flow control valves that can be controlled from the surface, and a pump which brings fluids to the surface along with possible down-hole pressurized sampling devices.

Extended packer-based testing will be conducted after drilling using a set of at least two packers to isolate an interval, and will utilize a workover rig. Testing and sampling via wireline-conveyed packer testing will be limited to higher-permeability intervals that will eventually be cased or cemented as part of the completion of the borehole; they will not be available for later testing via workover rig.

Wireline-based packer intervals will generally involve:

1. Estimating shut-in/static formation pressure (i.e., identification of any under- and overpressure zones that deviate significantly from hydrostatic pressure);
2. Slug, pulse, or constant-head hydraulic testing to estimate permeability and storage properties of fracture zones and the near-borehole region;
3. Pumping an interval to obtain representative in situ fluid samples; and
4. Monitoring enough recovery to improve estimates of static formation pressure.

This sequence of testing is conceptually similar to that conducted via workover rig (Section 6.9), but workover rig testing may include multiple packers, will allow testing lower-permeability intervals, be of longer duration, and will include tracer testing components. Wireline-conveyed packer testing is used as a modern alternative to traditional drill-stem testing, which should be sufficient in higher-permeability intervals. Low-permeability intervals may take extended time to equilibrate and are not the focus of testing during drilling. Low-permeability and low-porosity intervals are typically not well-suited to testing via wireline-conveyed packer systems.

Depending on the availability of nearby shallow wells and the uncertainty associated with the local geology overlying the crystalline basement, wireline-conveyed packer testing may be performed on lower portions of the overburden before setting casing or liner, to better characterize the flow system. For example, if the overburden formation immediately above the basement is a poorly characterized brackish reservoir, sampling and testing that formation via wireline-conveyed packer tool may be warranted. Aquifers that can be tested and sampled from nearby wells (possibly constructed as part of the DBFT for water supply) would not warrant wireline-based sampling in the CB, due to the existence of data or ready access otherwise.

6.5.1 Shut-in testing

The system will be shut-in to allow equilibration of fluid pressure within the tubing and the formation. Formation fluid pressure will be monitored downhole until it stabilizes. Fluid pressure is altered during and after drilling, and the equilibration process should allow such anomalous pressures to dissipate. The static formation pressure will be estimated from both this pre-test pressure equilibration and the recovery portion of the hydraulic test.

Accurate estimates of ambient formation pressure are necessary to determine vertical hydraulic gradients in the system and to develop an overall hydrologic conceptual model. Vertical profiles of fluid pressure and factors that affect fluid density (primarily temperature and salinity) are used to calculate the overall fluid potential. Vertical fluid potential gradients are the driving forces for fluid movement in the deep crystalline basement system.

6.5.2 Hydraulic testing

Both pumping and slug tests will be used to estimate the geohydrologic properties of crystalline basement and near-borehole DRZ. In typical tests, the packer-isolated interval is shut-in and monitored while fluid is removed from the tubing above the shut-in tool. After a steady pressure trend is established, the shut-in valve is opened for a period of time to allow flow out of the isolated zone. The shut-in- tool is then closed and the shut-in recovery pressure is observed and analyzed.

The formation properties that will be estimated from the hydraulic tests include formation permeability, rock and matrix compressibility (i.e., storage properties), and possibly any spatial variability or anisotropy of these properties vertically along the borehole or radially away from the borehole (e.g., borehole damage or skin).

In higher-permeability intervals, hydraulic testing will include multiple pulses or applied stresses (both positive and negative pressure changes), to allow assessment of the impact fluid pressure has on any interpreted results. To minimize wellbore storage effects, specified head tests will be conducted (at multiple imposed heads), rather than at a specified flowrate. Recovery data collected after any imposed hydraulic perturbation (slug, pulse, or pumping) will also be used to estimate the static formation pressure.

6.5.3 Fluid sampling

If intervals isolated with the wireline-conveyed packer system are sufficiently permeable, samples will be collected using a downhole pump bringing formation fluids to the surface, and also through pressurized liquid sample containers filled at depth. Formation fluid samples will be tested for similar analytes as are planned for workover rig packer-testing (Section 6.9) and drilling fluid sampling (Section 6.1.2). Wireline-conveyed packer sampling will be performed sooner than packer-based workover rig testing, before the drilling fluid has had weeks or months to invade the formation and contaminate formation fluids, but without the luxury of extended sampling time, which is available after drilling when using the workover rig.

Wireline-conveyed packer-based sampling will be conducted to compare against drilling-fluid sampling and later against any nearby workover-rig based packer sampling. Wireline-conveyed packer sampling is critical for any sample intervals that will not be available later because they are cemented, cased, or lined.

6.6 Hydraulic Fracture Stress Measurements

Hydraulic fracturing stress measurement tests will be performed in the crystalline basement interval while drilling to estimate the horizontal principal stresses, and to evaluate the variation of in situ stresses with depth. They will be used in conjunction with geophysics and observations of borehole breakouts and drilling-induced tensile fractures (e.g., formation micro-resistivity image log, borehole televiewer, and anisotropic shear wave velocity log) to describe the orientation and magnitude of stress through the entire basement interval.

Hydraulic fracture stress measurements are a common diagnostic tool in geomechanical testing (Haimson 1978). Although based on the same principal as hydrofracture well stimulation used by the oil and gas industry, hydraulic fracture stress measurements are only performed to determine the properties of the rock and in situ stress, not to create a large stimulated volume of rock. Hydrofracture well stimulation is a high-flowrate, high-pressure, high-volume method that includes a mixture of chemicals and proppant (i.e., sand) to maximize subsequent production from the stimulated region. Hydraulic fracture stress measurements are high-pressure, low-flowrate, low-volume tests run with a small pump and only use water. The types of tests planned for the CB are often called “mini-fracs” when performed in the oilfield to estimate in situ stress.

Extended leak-off tests will be conducted after surface and intermediate casing annuli have been cemented. The borehole is drilled deeper (typically 3 to 6 m [10-20’]) and the open borehole is pressurized to the point of hydraulic fracture, allowing estimation of the least principal stress.

For hydraulic fracture stress measurement tests during drilling, a wireline-conveyed packer tool will be placed in a relatively unfractured interval near the bottom of the borehole. Pressure within and outside the isolated interval will be monitored while fluid pressure and flowrate are controlled and monitored to hydraulically fracture the rock. Data will be collected from at least two repetitions of the hydraulic fracturing cycle, to collect information on the formation breakdown pressure, the fracture propagation pressure, the instantaneous shut-in pressure, and the fracture closure pressure.

Packer-based hydraulic fracturing stress measurements will be conducted in relatively low-permeability rock (degree of fracturing may be confirmed by coring, borehole televiewer, etc.). Rock quality is important to avoid opening a pre-existing fracture instead of creating a new one, and to limit fluid leakage during interval pressurization. To ensure proper seating of the packers, borehole breakouts and drilling induced tensile fractures cannot be significant in the test interval. Cored intervals may have less drilling-induced damage than drilled intervals, and may have a more uniform surface to set packers. Image logs will be collected before and after hydraulic fracturing to both locate the testing interval and determine the orientation of the induced fracture.

6.7 Borehole Geophysics

Borehole geophysical characterization methods measure characteristics of the drilling-fluid filled borehole, the rock formations intersected by the borehole, and the formation fluids saturating the DRZ and far-field rock. They will be relied upon extensively to provide vertically continuous data about the stratigraphy and lithology in the CB for the DBFT. Some geophysical tools and methods may not be effective in the large-diameter FTB (43.2 cm [17”]), and are therefore planned for the smaller-diameter CB (21.6 cm [8½”]). The choices of wireline logs and logging tools are also constrained by borehole temperatures.

There are three basic types of borehole geophysical methods: cross-hole testing, surface-to-borehole methods, and in-hole methods. During and right after drilling of the CB, only the latter two methods are applicable and in-hole testing (geophysical logging) is the primary means of acquisition for most types of data. In-hole logging can either be traditional wireline deployed or “logging while drilling” with sensors built into the drilling collar. Cross-hole testing and surface-to-borehole testing are common for seismic data acquisition (e.g., VSP, check-shot or velocity surveys) used to characterize geophysical properties away from a single borehole or between two boreholes. VSP is particularly useful for imaging faults and fracture zones and abrupt changes in mechanical properties tens to hundreds of meters away from the borehole, albeit the estimated properties are at lower resolution than those estimated using in-hole methods of features that intersect the borehole. VSP may be performed when drilling has progressed to near the bottom of the overburden, to better constrain the overburden/basement interface, if existing depth-to-basement data are unavailable or uncertain.

A suite of wireline geophysical logs will be obtained after the CB reaches total depth, as summarized in Table 9 (also see Tables 1 through 5 for indication of how geophysical methods will be used for characterization). Most of this same geophysical log suite will also be obtained at intermediate depth to characterize the overburden rock prior to emplacement of the surface and intermediate casings/liners. A description of the data to be collected from the suite of geophysical logs is given after Table 9.

Information gained during wireline logging, wireline-conveyed packer testing, and the flowing borehole log is critical to the success of the later workover rig packer test program (Section 6.9).

Table 9. Borehole geophysical methods

Borehole Log	Interval	Purpose
Deviation Survey	Entire borehole	Borehole azimuth and inclination measurements complement continuous downhole measurements during drilling and help ensure the hole is kept within design limits.
Borehole Imaging (Caliper, Formation Micro-Resistivity Imaging, Borehole Televiewer, and Acoustic Caliper)	Entire borehole	Determine horizontal stress orientations from breakouts or drilling-induced tensile fractures and newly created fractures when run after hydraulic fracturing. Determine location, orientation and spacing, of fractures, faults, bedding, fabric, and foliation. 3D visualization of borehole. Essential for calibration and interpretation of many wireline logs (providing directionality). Provides map of fractures for orienting cores, and can be used to select locations for setting packers and sidewall cores.
Gamma-Ray	Entire borehole	Identify lithology, can operate through casing and cement (often run with other wireline logs to assist in depth correction for cable stretch).
Spectral Gamma-Ray	Entire borehole	Identify lithology and discern radioactive sources (K, Th & U) for quantifying sources of ^{4}He in rock.
Resistivity	Entire borehole	Input for interpretation of lithology, hydrothermal alteration, permeability, and calculation of formation fluid salinity (using formation factor). Downhole drilling fluid resistivity measurements while drilling can locate fluid inflow zones.
Spontaneous Potential	Entire borehole	Identify lithology, mineralization, and formation fluid salinity.
Nuclear Magnetic Resonance	Basement portion of borehole	Estimate formation porosity and tortuosity, which can be used to infer permeability. Sensitive to formation fluid geochemistry. May be less useful in very low porosity rock.
Induced Polarization	Basement portion of borehole	Estimate formation chargeability, a function of the solid-liquid interface that can be related to permeability. Sensitive to formation fluid geochemistry.
Photoelectric Factor	Entire borehole	Lithological input based on mineral composition for constructing advanced lithology logs.
Gravity	Entire borehole	Estimate density and therefore porosity at lower resolution but over larger volumes than neutron porosity. Also use to corroborate overburden stress estimates based on gamma density logs. Requires gravity model for interpretation.
Neutron Porosity	Entire borehole	Estimate water or hydrocarbon content and therefore porosity at high resolution over smaller volumes than gravity. Best used with gamma density log.
Temperature	Entire borehole	Estimate geothermal gradient and provide temperature corrections for other logs.

Borehole Log	Interval	Purpose
High-Resolution Temperature	Basement and lower sedimentary portions of borehole	In conjunction with borehole imaging, locate groundwater inflow and outflow features from small-scale variations in borehole fluid temperature. Downhole measurements while drilling can identify inflow zones.
Gamma Density	Entire borehole	Estimate formation bulk density and porosity. Input for design of VSP survey.
Full Waveform Sonic	Entire borehole	Estimate porosity and rock hydromechanical properties from compressional seismic waves. Useful for interpreting VSP data and constructing synthetic seismograms, Needed for building velocity models for seismic modeling. Estimate horizontal stress anisotropy from shear-mode seismic waves.
Borehole Radar Polarimetry	Basement portion of borehole	Estimate depth and extent of borehole breakouts and near-borehole fractures (both natural and drilling induced).

Many standard open-hole tools are limited by borehole diameter (Nekrasov 1990), borehole fluid composition, temperature, and pressure. Maximum hole size is typically determined by tool signal strength and diameter of caliper arms and centralizers.

Most standard wireline logs are rated to approximately 175 °C [350 °F] and 140 MPa [20,000 psi]. Some tools, such as standard neutron porosity tools, need substitution in high temperature, high pressure environments by special sensors. Many standard wireline tools can be upgraded to withstand temperatures to 260 °C [500 °F] by installing sensitive electronics in a special housing (e.g., a dewar flask). On long tool strings, these flasks can cause problems with additional weight on cables. Most logging tools have a reduced operating time in high temperature boreholes. Temperatures above 175 °C also affect packer testing applications (i.e., temperature limits of downhole electronics and packer materials) and wireline pressure tools. Logging tool failure is common and logging companies should have backup tools available.

Given an average geothermal gradient of 25 °C/km [23.5 °F/100'] depth, the ambient temperature at 5 km depth is approximately 150 °C [300 °F]. A field test location is being sought with typical or less-than-typical geothermal gradient (DOE 2015; 2016), so the maximum downhole temperature is not expected to be significantly higher than this value. If conditions encountered are much hotter than expected at depth, testing will likely be conducted only to the maximum depth and temperature possible in the borehole, rather than switching to more expensive and specialized high-temperature logs and equipment. Although it would be possible to conduct these high-temperature logs and tests, they would likely not be representative of future DBD sites.

6.7.1 Spectral gamma-ray

Gamma-ray logs measures naturally occurring gamma radiation, which varies by lithology. The most common emitters of gamma radiation are ^{40}K, ^{232}Th, ^{238}U, and their daughter products. A spectral gamma-ray log will determine the relative abundance of Th and U, which are typically of sufficient concentration to be important sources of ^{4}He, a key component in the geochemical profile. Standard and spectral gamma-ray logs can be conducted in both open borehole and through steel casing and annular cement, though the steel and cement will absorb much of the gamma radiation and reduce logging rates (to obtain comparable resolution). Standard and spectral gamma-ray logs can be run in dry or fluid-filled holes, operating up to 260 °C and 25,000 psi in boreholes up to 51 cm [20”] in diameter.

6.7.2 Resistivity

Resistivity is a fundamental material property that represents how strongly a material impedes the flow of electrical current. Most rock materials are essentially insulators, while saline formation fluids are conductors. Resistivity logs measure electrical current flow in the formation, produced by electrodes spaced along a sonde (e.g., normal or lateral arrays), or by induction coils (e.g., laterolog tools). The induction tools use coils and magnetic fields to develop currents in the formation whose intensity is proportional to the conductivity of the formation. In contrast to resistivity tools, induction devices provide resistivity measurements regardless of whether the drilling fluid in the borehole is air, bentonite mud, oil, or water, and are therefore most generally applicable Microlaterologs do not work in oil-based drilling fluids; the electrode arrays and contacting electrode tools rely on an electrically conductive borehole drilling fluid to facilitate current injection and voltage measurement. Standard tools can operate to 175 °C, in boreholes up to 51 cm [20”] in diameter. Deep-formation resistivity logs can be run in cased sections.

Drilling fluid resistivity logging can also be done during drilling (Section 6.1.3) to identify fresher or saltier formation fluids flowing into the borehole.

6.7.3 Spontaneous potential

Spontaneous or “self” potential logs measure the difference in electrical potential between two electrodes in the absence of an applied current. One electrode is grounded at the surface and the other is set at the target location in the borehole. When drilling fluids and the natural formation fluid come into contact, they set up an electrical potential. These spontaneous potentials arise from the different access that different formations provide for ions in the borehole and formation fluids. Spontaneous-potential (SP) logs provide information on lithology, the presence of high permeability beds or features, the volume of shale in permeable beds, the formation fluid resistivity, and formation water quality (e.g., salinity, ionic concentration). Water-saturated rock and electrically conductive liquid-filled boreholes are required to conduct the current between the electrodes (i.e., the method does not work with oil, air, or fresh-water drilling fluid systems). The SP log is not constrained by hole size.

6.7.4 Induced polarization

Induced polarization logs pass a low-frequency alternating current through the formation in one set of electrodes, while observing the variation in observed voltage from another set of electrodes. The frequency-dependent resistivity (i.e., complex resistivity) of the formation can be estimated from the log, which is an indication of the rock-surface/fluid interactions in fractures and pores. The results of the induced polarization log can be related to formation clay content, composition of formation fluids, and rock matrix permeability using petrophysical assumptions. Induced polarization logging can be performed both in water or oil-based drilling fluids, but generally available tools are restricted to borehole diameters less than 41 cm [16”].

6.7.5 Neutron porosity

Neutron porosity tools consist of a fast neutron source and sensors for detecting thermal or epithermal neutrons. Fast neutrons emitted by the radioactive source in the tool interact with the nuclei of surrounding materials via elastic collisions and lose energy at a thermal level and are then detected by the sensor. Fast neutrons are converted to thermal (or epithermal) neutrons most efficiently by collisions with hydrogen nuclei. The neutron porosity tool thus effectively measures the hydrogen concentration, or formation fluid content, within about 20 cm [8”] of the borehole wall.

Porosity estimates will be corrected for effects from borehole diameter, drilling fluid characteristics, rock type, salinity of the formation fluid, and presence of casing material. Neutron porosity logging is useful for estimating the porosity of the crystalline basement in conjunction with borehole imaging. Neutron porosity logs can be run in open or cased holes, but generally available tools are limited to boreholes diameters less than 41 cm [16”].

6.7.6 Gamma density

The gamma density log uses a decentralizing arm to place a radioactive source against the borehole wall, emitting gamma rays into the formation. These are scattered and measured in the tool’s detector, also placed against the borehole wall. The formation’s electron density and composition control the observed response; the observed response is then related to the formation bulk density and ultimately porosity. Generally available gamma density tools can operate up to 260 °C and 140 MPa [20,000 psi], and in boreholes up to 41cm [16”] in diameter (due to limitations of the decentralizing arm).

6.7.7 Photoelectric effect

The photoelectric effect log measures a rock’s ability to adsorb gamma rays, and varies with lithology. This is a pad contact tool, which is part of the density tool (sharing both detectors and radioactive sources). Both density and photoelectric effect are sensitive to borehole rugosity and washouts. The tool provides a strong indicator of lithology, some indication of mineral composition, and is a critical input for computing more accurate, advanced lithology logs. Measurements are not valid in drilling fluid containing barite, and because of the decentralizing arm on generally available tools, hole size is limited to less than 41 cm [16”].

6.7.8 Full-waveform sonic

The sonic log is often integrated with dipole shear logging. Sonic logging determines the formation’s acoustic travel time over a fixed distance. The compressional velocity is a function of bulk modulus and density and varies with lithology and other rock properties such as fractures, porosity and fluid content. There are two types of sonic tools: the compensated sonic and the full waveform sonic. The full waveform sonic acquires waveforms that can be used to determine both compressional- and shear-mode velocities, and is therefore potentially more useful to the DBFT. Shear velocities are used to estimate mechanical properties and acoustic anisotropy, which are often related to the intensity of fracturing. Attenuation of shear mode (pseudo-Rayleigh) and tube waves can also be used to identify open fractures and permeability. Full-depth coverage by full-waveform sonic logs will be used to constrain interpretation for other seismic methods such as VSP. Acoustic tools require liquid-filled boreholes, and borehole diameters are limited to 50 cm [20”] for generally available tools.

Dipole shear-wave velocity log measures the velocity of circumferentially polarized shear waves that travel axially along the borehole wall, as a function of azimuthal direction to the travel path. Anisotropy in the shear-wave velocity can be related to differential horizontal stress, rock fabric orientation (e.g., bedding or foliation), and fracture orientations. Rock micro-fractures oriented parallel to the maximum horizontal compressive stress tend to be more open than micro-fractures parallel to the minimum horizontal stress. Shear wave velocity tends to be greater when the direction of particle motion corresponds with the direction of maximum horizontal stress. Interpretation of the anisotropic shear-wave velocity log can provide an estimate of the directions of maximum and minimum in situ horizontal stress as a function of depth, even in the absence of macroscopic indicators such as borehole breakouts and drilling-induced tensile fractures. Generally available dipole shear wave tools are limited to borehole diameters less than 35 cm [14”].

6.7.9 Borehole imaging

Multiple methods are available and in common use for imaging the borehole wall. Most borehole geophysical logs are omnidirectional (an integrated response without directionality), but borehole imaging methods give information about azimuthal variation in the borehole wall. These methods allow determination of borehole diameter and shape due to breakouts, washouts, and tensile fractures, and can be used in analysis of existing rock fabric, layers, and fractures. Because of the importance of good borehole imaging data to the characterization of the borehole, and the complementary nature of the methods (borehole televiewer measurements are more influenced by rock properties, while micro-resistivity imaging is more sensitive to fluid properties), all possible approaches should be used where hole conditions are appropriate (Davatzes & Hickman 2010).

6.7.9.1 Formation micro-resistivity imaging

Formation micro-resistivity imaging uses small-scale surface resistivity measurements to construct an oriented image of the electrical surface resistance of the rock exposed on the borehole wall. Measurements are made with multiple electrode pads pressed against the borehole wall in a borehole filled with conductive drilling fluid (oil-based drilling fluid micro-resistivity image logging tools are available). The tool is self-centralizing, and the arms holding each pad also serve as calipers.

The tool produces a strip-like image where each pad traverses the borehole wall; typically, four strips spaced at 90° around the borehole are acquired with a single logging run. The resulting imagery can be used to determine dip and dip azimuth of any planar feature that crosses the borehole. It can resolve strike and dip of stratigraphic contacts and through-going fractures, fracture filling and aperture, and rock foliation. Borehole breakouts will typically capture one or two arms of the tool, resulting in no imagery but tracking the breakout orientation. The images also record rock texture that may include grain size, brecciation, fault displacement, and drag folds. Natural and drilling-induced tensile fractures can usually be distinguished from one another on formation micro-resistivity image logs. The tool is affected by hole rugosity and washout, and is limited to hole size diameters less than 55 cm [22”].

6.7.9.2 Borehole televiewer

Acoustic or ultrasonic televiewers scan the borehole wall with a focused ultrasound beam, resulting in a continuous 360^{o} image of the borehole wall. Both amplitude and travel time are recorded. The amplitude log indicates the borehole wall roughness, while the travel-time log indicates borehole diameter changes and is sensitive to breakouts and open fractures. This type of borehole log can be conducted in a borehole with water or oil-based drilling fluid. The borehole televiewer must be centralized in the borehole. This borehole log is typically used in shallow borehole applications, and generally available tools may have depth and temperature limitations that restrict its use for the DBFT.

6.7.9.3 Borehole caliper

Borehole caliper tools measure the diameter of the borehole using multiple arms. They record several diameters on the same horizontal plane (in a vertical borehole) simultaneously, thus physically measuring the irregularity of the borehole. Borehole caliper logging is fast and will be used to determine the integrity of the borehole and to confirm borehole imaging (i.e., identifying larger fractures).

6.7.9.4 Acoustic caliper

Sonic or acoustic logging tools can be used to estimate the shape of the borehole, in a manner similar to the borehole televiewer. The acoustic caliper log is better suited to pressure and temperature conditions expected at significant depth than the borehole televiewer. The method can also be used to inspect quality of casing and cement (i.e., a bond log), depending on the frequency of the acoustic signal used.

6.7.10 Borehole radar polarimetry

Borehole-based ground-penetrating radar is the electromagnetic analog of sonic tools. Antennas send and receive high-frequency electromagnetic signals that reflect and image the rock around the borehole. The tools can detect and to some extent image fractures and lithology changes with favorable orientation. Radar can be especially useful when interpreted in conjunction with sonic, since the two methods are analogous but sensitive to different material properties (electromagnetic waves are more sensitive to formation fluid salinity). Due to geometrical constraints of a long narrow borehole, it can be difficult to get directional results from borehole radar systems. Polarimetry monitors the phase and amplitude of multiple polarized electromagnetic waves, which can be used to deduce the orientation of reflectors in the host rock (Slob et al. 2010).

The presence of borehole breakouts and drilling-induced tensile fractures will likely dominate the radar signal, but even imaging the extent and nature of these into the rock will be useful for both locating intervals for placing packers during in situ testing and providing data to understand the variation in rock strength and in situ stress with depth in the borehole. Borehole radar works in a liquid- or air-filled borehole, but does not work with steel casing. The wavelengths of the radar antennas should be chosen to get the required information.

Most available borehole radar units are designed for slim holes (≤15 cm [5.9”] diameter) and shallow depths, which may prohibit their use in the DBFT.

6.7.11 Borehole gravity

Borehole gravity logs measure gravitational acceleration as a function of depth in the borehole. Tiny differences in the Earth’s gravitational field are used to calculate the average density of the rock formation surrounding the borehole. Borehole gravity logging determines the average density of the formation over a relatively large volume and is sensitive to density for distances of tens of meters into the rock. In combination with information on rock grain density, borehole geometry, and fluid density (i.e., an earth model), borehole gravity logging results can be used to estimate total porosity, averaged over a similarly large volume. Rock grain density can be measured on core samples, while fluid density would be determined from groundwater samples and resistivity logging.

Estimates of porosity from borehole gravity logs apply further into the rock formation than those from neutron, sonic, or gamma density logs. Borehole gravity logs are not constrained by borehole size, fluid composition or casing, but are relatively expensive and can be difficult to interpret, requiring an inverse solution using a model of rock density distribution around the borehole.

6.7.12 Nuclear magnetic resonance

Nuclear magnetic resonance (NMR) logs can be used to estimate both the water content (absolute value of response) and the distribution of free water in the porosity surrounding the borehole (t_2 relaxation time). In water-saturated rock in the CB, the NMR response to hydrogen should be proportional to water content. When using oil-based drilling fluid, interpretation must account for the effects of hydrocarbons. Similar to neutron porosity logs, the absolute NMR response can be used to estimate rock porosity, assuming a fluid saturation. The relaxation time distribution can be used to estimate the in situ tortuosity (i.e., mean free path of water molecules).

These two components can be related to permeability using petrophysical assumptions. The NMR log may not be useful in very low-porosity rock. It would be prudent to only run the NMR log after the porosity log, and then run the NMR log only in intervals with sufficient porosity. This log works in water- or oil-based drilling fluids and generally available tools are limited to boreholes less than 50 cm [20”] in diameter.

6.7.13 Vertical seismic profile

Vertical seismic profiling (VSP) is a surface-to-borehole seismic method that is typically used to correlate with surface seismic data (i.e., reflection or refraction). In the most common type of VSP geophones or accelerometers are deployed in the borehole to record seismic energy that originates from a surface source and interacts with stratigraphic or structural features located proximal to the borehole. Multicomponent surveys collect both shear (S) and compressional (P) modes with the same sensors. VSP surveys include zero-offset and walk-away VSP. A walk-away VSP produces short 2D seismic lines that have much higher resolution than do surface surveys, and would be important for detecting fault and fracture zones and risk-factors in the subsurface geology between the CB and the FTB. A zero offset VSP provides a high-resolution map of the seismic-sensitive rock properties along the length of the borehole.

6.7.14 High-resolution temperature

Temperature logs record fluctuations in borehole fluid temperature with depth. Temperature data are usually acquired after drilling, but downhole measurements during drilling are also possible. If the borehole (or portions of it above installed packers) is allowed to equilibrate thermally after completion, periodically repeated temperature logs can be recorded to observe the decay of the temperature perturbations caused by drilling and construction activities (Freifeld & Finsterle 2010).

Temperature logs in boreholes are used to characterize subsurface conditions for a number of purposes in petroleum production, groundwater studies, geothermal exploration, and other geoscientific studies. Temperature data will be used to estimate fluid viscosity and density, and apply thermal corrections to other geophysical logs. High-resolution temperature logs via wireline sensor or distributed fiber-optic sensor can be used to identify zones of inflow and outflow from the borehole and identify any intra-borehole flow.

High-resolution temperature logging can be used to estimate inflow locations when used in conjunction with borehole imaging. These inflow locations can also be correlated with specific fractures, and the orientation of those features is related to whether they are flowing (Barton et al. 1995, Ito & Zoback 2000).

6.7.15 Fluid density or downhole pressure

Vertical profiles of fluid pressure or differential pressure are related to the fluid density in the borehole. These measurements can be used to correct formation pressure measurements and identify inflow, outflow, or changes in salinity within the borehole. A piezometric pressure tool is the most accurate method for profiling fluid pressure, and such a profile can be readily processed to yield a log of fluid density.

6.8 Production Profile

The production profile is an important survey for locating high-permeability inflow or outflow intervals for packer testing. The production profile tests the entire open borehole, or sections of the open borehole, in an integrative manner.

The open crystalline basement portion of the CB will be tested via a flowing or pumping log to identify higher-permeability features. The method relies on repeated surveys using one or more methods: 1) salinity logging, 2) high-resolution temperature logging, and/or 3) on-station high-resolution measurements of axial flow. Modern high-resolution flow meter tools are based on solute dilution or heat-pulse time-of-flight principles (Paillet et al. 2010).

Fluid flows into and out of the borehole through permeable features, under natural head conditions (driven by differences in pressure head between the formation and the borehole). Simply logging the borehole may reveal temperature or salinity anomalies that indicate inflow and outflow. These anomalies can be further investigated using a calibrated borehole flow meter to make point measurements of axial flow. For better resolution, the borehole can first be flushed with fluid that is colder or less saline, or both, to set up a transient condition that is monitored by repeated logging, as it is modified by inflow and outflow. Finally, the borehole can be pumped during repeated logging to increase the strength of temperature or salinity transients, and to produce flow from additional features of the host formation.

Flow survey methods are common in shallower groundwater investigations, typically involving fluids with much lower salinity than expected for crystalline basement brine (e.g., §3 Dobson et al. 2016). Also, the open-borehole depth interval investigated is typically much less than the 3 km planned for the CB. Accordingly, some published methods may fail in the CB if inflows and outflows are strong, and mixing occurs more rapidly in the borehole than can be observed by logging a long interval. In this case a shorter interval of the CB can be investigated by setting a packer and performing the survey above it.

The thermal approach can be performed using chilled borehole fluid and does not involve changing the fluid composition, which is preferred to changing the salinity (which could affect the composition of formation fluid samples to be pumped from high-permeability zones). However, thermal diffusion is much faster than solute diffusion in free liquid, and even faster in the crystalline rock formation, so thermal transients from inflow and outflow may be short-lived compared to the time needed to log the open interval. Using both the high-resolution temperature and salinity logs may allow interpretation of small salinity effects even after temperature effects are attenuated by diffusion.

The production profile survey in the CB will begin with repeated logging of the open interval with high-resolution temperature, pressure, and salinity tools. Logging speed will be reduced to limit mixing, and logging will be performed on the trip in rather than the trip out. Repeat logs over several days will establish a baseline. It is expected that differences in the fluid density-depth profiles in the borehole vs. the formation will generate significant pressure differences that drive flow. Fluid pressure log data will be used with temperature and salinity data to discriminate dynamic pressure effects associated with axial flow, which may be possible if the flow is large enough, driven by pressure differences with the formation.

The temperature and salinity logs will be compared with imaging logs to identify permeable fractures and zones. Once a baseline is established, the borehole fluid will be circulated and cooled for up to 24 hours, and repeated logging will resume. If rigid tubing is used then the time to trip out from total depth (5 km) will be approximately 10 to 20 hours, during which time much of the thermal transient from flushing the borehole will be lost to mixing and thermal diffusion. If coiled tubing is used, withdrawal of the tubing could be done in 1 to 2 hours, comparable to tripping the wireline tools.

Finally, the entire CB (or an isolated section) will be pumped at one or more constant flow rates, while logging continuously up and down the interval (or a sub-interval containing features of interest). The borehole may be flushed (with fluid that is colder or less saline, or both) prior to this pumping phase. The initial pumping rate will be small (selected from baseline surveys of axial flow in the borehole), and if useful data are obtained, then the pumping rate will be increased immediately, followed by re-logging, and so on until the borehole fluid has been mixed and temperature or salinity transients are no longer interpretable.

If one or more high-permeability intervals of the CB dominates flow into or out of the borehole, the production logs may not be sensitive to minor flows through less permeable features. If required, the tests may be re-run after isolating high-permeability intervals with packers to better resolve the presence of intermediate-permeability zones in the borehole.

The production profile survey will conceptually take the place of a much more resource intensive program of longer-duration tests in many intervals isolated by packers. For example, in the 3-km open interval 100 adjacent hydraulic tests could be performed using a 30-m packer tool, roughly doubling the overall duration of testing in the CB. The objective of the production profile survey is to identify higher-permeability zones for further packer testing, geochemical sampling, and tracer testing.

6.9 Borehole Packer Testing via Workover Rig

Borehole packer testing with a workover rig will be similar to wireline-conveyed packer testing (Section 6.5), but with tools deployed on strings of rigid tubing. Packer testing involves setting packers above and below the target interval. A straddle packer system can be used or a "bridge plug" packer can be set at the bottom of the test interval and a single packer system set at the top of the interval. Guard packers may be used to ensure isolation. Packer testing via workover rig allows more accurate determination of the thermophysical and geochemical conditions than the short-term tests possible with wireline-conveyed packer tools and geophysical logs.

The production profile survey (Section 6.8) may be used to select several intervals for testing via packers. Cored intervals of the borehole may also be targeted for packer testing. Packers can be reliably set only where the borehole wall is in good condition, with limited damage from breakouts, tensile cracks, etc. Formation micro-imaging, borehole televiewer, acoustic caliper, and multi-arm caliper logging (Section 6.7.9) can provide information on the condition of the borehole.

Packer testing should introduce limited quantities of foreign water into testing intervals to reduce the possibility of compromising future samples. Previously produced formation water could be saved to be used when filling tubing or chasing tracers during tracer testing (Section 6.9.6).

6.9.1 Zonal isolation

A packer testing tool isolates an interval between packers or sets of packers (in the case of guard zones on each end of a straddle interval). Zonal isolation in the open borehole environment requires packer systems that seal against the rough wall, including breakouts, that may remain after drilling. The ideal packer for sealing and retrievability in open intervals is an external casing packer (ECP), which allows for the use of gland elements that can be up to 6 m [19.7'] long. Either mechanical or inflatable ECPs can be fabricated with deformable metal backing slats that aid survivability of the gland element when set against voids and breakouts. ECP may be retrieved reliably using several methods.

Limitations and potential problems with ECP deployments (Gai & Elliot 1997) require careful design and operation. Consideration should be given to: 1) deployment of redundant gland systems at each isolation interval, 2) utilizing long seal glands with metal reinforcement, 3) use of permanent set valve bodies for inflation, and 4) an inflation fluid less prone to leaking than water. Tradeoffs in ECP design should also be considered. Use of a permanent set valve body will require the destruction of the gland element within the packer with a perforation charge, in which case the packer will be single-use only. While ECPs are normally fabricated on tubular mandrels similar to tubing strings, instrumentation using control lines requires the use of mandrels incorporating pass-throughs to allow required control lines. Given a projected 21.6 cm [8½"] drill bit size for the open-hole portion of the CB, an ECP string can be run-in-hole using a 7.3 cm [2⅞"] tubing string. A typical run-in diameter for such an ECP would be 19.4 cm [7⅝"]. The ECP can be built on a custom mandrel with pass-throughs for numerous control lines to provide flexibility in instrumentation options.

Packer inflation in uncased boreholes requires special attention at great depths (Dreesen et al. 1988). Packer inflation procedures and the proper sizing of lines and pumps should consider the significant depth required for some crystalline basement tests. The packer inflation pressure must be sufficient to expand the packer gland against the borehole wall.

If successful packer seals cannot be set in the borehole at the required locations due to significant breakouts, alternative designs will be considered. Packers may be constructed of more compliant or swelling material to allow sealing against large breakouts, or the packer may be set inside a perforated pipe, which is set using annular cement. Any approaches that permanently change the borehole conditions (i.e., cementing or use of non-retrievable packers) will be considered carefully before execution.

Packer length and the length of intervals between packers used in testing are controlled by the equipment available and the borehole conditions. Longer packer elements could be more tolerant of damage at the borehole wall. Longer packers are more expensive and take longer to procure, especially for large borehole diameters. The length of the interval between packers should be chosen to test a representative portion of the borehole. Stress measurements by hydraulic fracture of opening of pre-existing fractures will require smaller intervals than hydraulic flow testing, since stress measurements typically target specific fractures or unfractured intervals.

6.9.2 Packer pulse testing

Lower-permeability intervals will not support significant pumping or sampling and will only be hydraulically tested using pulse, slug, or multi-step constant head injection tests. The most reliable method for acquiring geochemical samples from lower-permeability intervals may be extraction of formation fluids from cores.

The monitoring system for packer tests will consist of downhole tools and measurement instrumentation. Downhole tooling includes the tubular elements, packers, and valves that facilitate the isolation and access to different testing zones. Downhole tools also allow application of a mechanical pulse (i.e., slug) or specified pumping rate to the interval, depending on its permeability. Instrumentation will monitor flowrate or volume changes (if any), downhole fluid pressure, and fluid temperature. Instrument signals can be multiplexed on the same cable to the surface, simplifying the cable and tubing assembly that controls various types of tests.

After inflating the packers across a test interval the static formation pressure will be monitored for a long enough period to establish long-term trends. After the monitoring period both positive and negative slug/pulse tests will be performed. These tests monitor the decay or buildup in pressure after a hydraulic pressure pulse is applied to the formation fluid in the isolated interval.

Four low-permeability intervals will be identified from geophysical logs, borehole image logs, and the production profile survey. Testing will be performed to: 1) estimate the range of crystalline basement permeability, rock compressibility, and static formation pressure, and 2) explore the efficacy of different testing approaches. Exhaustive testing (i.e., coverage of a significant portion of the open borehole) is not planned, since the DBFT objective is to demonstrate methods of investigation, rather than to fully characterization the selected site.

6.9.3 Packer pumping tests and sampling

Packer pumping tests for both fluid sample collection and hydraulic property characterization will be performed in selected higher-permeability borehole intervals, identified by the production profile survey (Section 6.8).

The borehole monitoring system described under packer pulse testing (Section 6.9.2) will be used for pumping tests on more permeable intervals, but additionally downhole flowrate will be monitored and samples will be collected. The packer system must have adequate flow-through capacity for the expected pumping rates.

Pumping tests will be conducted to estimate formation permeability and storage/compressibility properties. The pumping tests will be conducted in zones with higher permeability (as identified in the production profile), but the ability of the system to test very transmissive regions (e.g., fracture or shear zones) may be constrained by the downhole flow control tools (e.g., rate and pressure output limit of pump, friction losses in the supply line).

During pumping, geochemical parameters will be monitored downhole or at the surface (e.g., fluid resistivity and drilling fluid tracer concentration) to identify changes that indicate when fluids being produced are representative of the formation or if drilling fluid is still being produced.

After inflating the packers on a relatively high-permeability test interval the static formation pressure will be monitored for a long enough period to establish long-term trends. Then a discharge test will be conducted by pumping fluid from the isolated interval at a series of constant rates, and monitoring the interval pressure.

At the end of each packer pumping test, samples of formation fluid will be collected for laboratory analyses. Collecting representative environmental tracer samples of sufficient volume is a key component of the DBFT project, and formation fluids pumped from higher permeability zones are the best samples possible for analyses that require large sample volume (e.g., fission products from spontaneous fission). Some of these tracers have specific sampling requirements, which must be considered when determining whether samples are representative of the formation water, or are still contaminated by drilling fluid and atmospheric air.

Each pumping test and sampling event will be followed by monitored recovery, long enough to estimate static formation pressure.

6.9.4 Onsite water quality analysis objectives

Here we discuss primary scientific objectives and possible issues related to collecting and analyzing pumped formation fluid samples onsite. Analytes include drilling fluid tracer (Section 6.1.2.6), pH, temperature, Eh, specific gravity, and TDS. These onsite samples are primarily used to determine when pristine laboratory-analyzed samples can be taken (when pumping downhole intervals). They are also needed to evaluate the quality of formation fluid samples acquired for other analyses, and to interpret sample provenance and water-rock interaction.

Temperature of formation fluids should be a relatively constant temperature, and changes in temperature coming up the borehole should be relatively constant with time. Temperature could also be measured downhole in the packer interval to understand transient thermal losses related to coming up the borehole and >2 km of tubing.

- **Quantification Objective:** Temperature can be accurately and repeatedly measured to ±2 °C at field conditions. Chemical processes such as mineral solubility, gas solubility, etc. are not so sensitive to temperature that additional accuracy would be useful, given other sources of uncertainty in reaction path calculations (e.g., analyzed concentrations).

- **Contamination or Loss Potential:** Insufficient flow through the measurement cell. Extreme weather may shift the measured temperature.

pH of the formation fluids should also be relatively constant, since the pH of drilling fluid may be different from that in the formation.

- **Quantification Objective:** pH can be measured in concentrated NaCl solutions using a double-junction Ag/AgCl reference with a filling solution matching the brine electrolyte composition, and by calibrating in high-strength buffers. The typical ±0.1 pH unit repeatability should not be interpreted as accuracy in brines because of the K_w shift (e.g., maximum at ~0.6 M NaCl, 10^{-16} at 5 M NaCl). Acid-indicator alkalinity titration, together with pH measurement, allows calculation of in situ pCO_2 at an accuracy of 1 to 2 significant figures. Alkalinity titration performed on water samples will be used to interpret the carbonate system, and must be performed onsite.

- **Contamination or Loss Potential:** Degassing and temperature changes can shift measured pH. These can be caused by insufficient flow through the measurement cell. Checking pH at the surface should be done while minimizing exposure to atmosphere (e.g., 1 minute or less).

Eh is a measure of the redox state of the fluid, which would likely be different for reducing isolated groundwater and drilling fluid which has been in recent contact with the atmosphere.

- **Quantification Objective:** Eh can be measured using the Pt-referenced Calomel electrode method, on filtered samples, with suitable filling solution (e.g., 4M KCl), and temperature correction. Field measurements may be affected by drift (e.g., from aging or poisoning of electrodes) limiting accuracy to ±25 mV. This encompasses typically achievable repeatability (±10 mV) and along with pH, allows interpretation of redox equilibria (e.g., discernment of stability fields in systems such as Fe-O-H_2O).

- **Contamination or Loss Potential:** Exposure to atmosphere and temperature changes can shift measured Eh. Measurement electrodes may foul or acquire a patina produced from the sample formation fluids.

Total dissolved solids (TDS) is typically estimated from electrical conductivity measurements, which should indicate an overall stability in the chemical composition of the produced formation fluids.

- **Quantification Objective:** TDS in electrolyte dominated solutions such as formation fluid and drilling fluid, can be estimated from conductance (reciprocal resistivity). The limit of accuracy is generally proportional to conductance, up to a limit determined by the precision of voltage measurement possible. Downhole tools may be designed to resolve a specific range of conductance. Thus, ±2% accuracy may be readily achievable with a range of multiple instruments. Several ranges of instrument should be available or included in downhole measurements.

- **Contamination or Loss Potential:** Fouling of conductance cell electrodes (e.g., by H_2S) can shift TDS measurements.

Specific gravity is measured to check density of the fluid, which is related to the total dissolved solids or electrical conductivity at constant temperature.

- **Quantification Objective:** Specific gravity is measured in a graduated cylinder with a hydrometer. Multiple ranges of hydrometers should be available to most accurately capture the expected density range of the sample fluids.

- **Contamination or Loss Potential:** Specific gravity estimates will be temperature compensated. Significant degassing can lead to bubbles sticking to the hygrometer.

6.9.5 Off-site water quality analysis objectives

Extensive off-site analyses will be conducted on formation fluid samples pumped from packer-isolated intervals. Depending on the flowrate, a gas-water separator will be included at the surface to allow sampling of dissolved gases (Probst et al. 2007; Purtschert et al. 2013). Intervals will be pumped continuously until measurement readings at the surface (drilling fluid tracer concentration, pH, Eh, temperature, and TDS) are stable, before samples are taken for off-site analysis. The same constituents tested in drilling fluid (major/minor ions, trace elements, stable water isotopes, noble gases, and Sr, Li, U isotopes; Section 6.1.2.5) will be analyzed on collected samples from pumped intervals, with the addition of cosmogenic and anthropogenic tracers discussed below.

Cosmogenic and anthropogenic tracers (^{4}He, tritium, ^{21}Ne, ^{36}Cl, ^{81}Kr, ^{85}Kr and ^{129}I) will be analyzed for in situ produced fluid samples (e.g., Kietäväinen et al. 2014). These results will be compared with atmospheric values, drilling fluid, and samples from rock core, to detect contamination and interpret provenance (apparent age and origin) of formation waters.

- **Quantification Objective:** Reporting limits should be 1% to 10% of atmospheric or modern groundwater background levels, for correcting and interpreting in situ water composition. The presence of nuclear-age isotopes or cosmogenic isotopes could be used to interpret sample contamination or young groundwater. Exceptions are species that are also radiogenic in situ (e.g., ^{36}Cl and ^{81}Kr), which may indicate build-up in ancient groundwater. Also, cosmogenic radioactive isotopes may be significant in their absence, indicating groundwater aging in situ. The objective is therefore quantitation of tracer concentrations in brine at a fraction (e.g., 10% or better) of the corresponding atmospheric or meteoric levels. These species will be very scarce, so formation fluid samples on the order of tens to hundreds of liters of water will be needed for certain analytes. Quantitation may be unsuccessful depending on the productivity of the permeable zones and contamination from drilling fluid, workover fluid, or atmospheric air.

- **Contamination or Loss Potential:** Possible contamination due to exposure of formation fluid samples to air (for more than a few seconds) will cause sample loss and/or contamination of gaseous analytes. Two promising quality-control tracers (besides the iodide in drilling fluid) are tritium and ^{85}Kr, which will likely be present in the drilling or workover fluid makeup of water, and could indicate leakage into sample waters (since they have short half-lives they are not expected in natural waters). Leaching recently crushed rock in the borehole, and residues or leakage from or into pumping and, filtration equipment, etc. could also contribute. Sample ^{36}Cl is likely to be overwhelmed by chloride (drilling and workover fluids, and formation fluid, will likely be chloride brines) and may not be analyzable.

6.9.6 Injection-withdrawal tracer test

Tracer injection/withdrawal (push/pull) tests will be conducted across identified high-permeability fracture zones to help estimate the density and spatial distributions of fractures, and interrogate fracture surface area. The use of suites of geochemically reactive and conservative tracers can provide insight into changes in the exposed reactive fracture surface area, and the surface area of rock matrix porosity, in fractured rock systems. The interaction of tracers with newly exposed surfaces will lead to preferential retention via sorption or ion exchange processes that may have complex kinetics, scale dependence, and long-tail behavior (Haggerty et al. 2000; Dai et al. 2009; 2012). Hence, analysis of pumped flow-back formation fluids promises to yield useful information on the type and magnitude of new exposed surfaces.

Two of the high-permeability intervals used for hydraulic testing and sampling will be used to perform injection-withdrawal tracer tests. This involves pumping fluid from a packer-isolated interval, then injecting traced water into the interval, a rest period, and finally a pumping phase with both downhole and surface fluid sampling for added tracer constituents. These tests will inform the roles that primary fractures and microfractures in the rock matrix play in solute transport through the borehole DRZ.

Each test will begin by producing fluid from the packer-isolated interval to the surface, and diverting produced formation fluid to a surface mixing container. It is also possible to use fluids produced from previous packer test and in situ water sampling on the same interval.

Tracers will be added to the produced formation fluid. There are many potentially useful tracers including uranine, fluorinated benzoic acids, amino-G acid, and cesium salts. The suite of tracers should include at least one conservative tracer, one sorbing tracer (cesium would likely sorb onto clays present in fracture zones), and possibly a chemically or thermally reactive tracer. Amino-G has been shown to break down at higher temperatures to a stable daughter product, allowing use in geothermal systems to estimate the temperature along flowpaths (Rose & Clausen 2015). Potential interactions between tracers should be considered. Mixed and traced formation fluid will be sampled for laboratory analysis and to ensure that its composition is stable during the entire tracer injection period. Surface handling should ensure the tracer does not become contaminated or allow microbial growth during the injection period.

The mixed and traced solution will be injected at a constant flowrate into the packed-off interval, followed by injection of non-traced formation water (chaser) at same constant flowrate. A rest period (no pumping or injection) will then be held for at least one day, before the packed-off interval is pumped at a constant flowrate. During pumping, samples will be collected at regular intervals at the surface and several pressurized down-hole samples will be collected, as permitted by logistics and the design of the downhole test equipment. Collected samples will be analyzed off-site for introduced tracers and samples will be preserved for more extensive future analysis, if deemed necessary.

The final pumping phase will continue until a decrease in relative conservative tracer concentrations of at least two orders of magnitude is observed (compared to peak tracer concentration observed during pumping). If this is not achievable, pumping will continue as long as possible to allow analysis of long-tail behavior in the response (Haggerty et al. 2000).

The packers and pressurized fluid samples will be retrieved (replacing pressurized fluid sample containers) before moving to the next high-permeability tracer test interval.

The plumbing of the tracer testing tool should be designed to minimize the volume of fluid stored in the packed-off section, and in the tubing string between the surface and the downhole tool. Unnecessary fluid volume in the packer interval or tubing will dilute the signal from the formation with fluid that must be removed, and lengthen the period of pumping required to inject traced fluid into the formation, and bring produced fluid to the surface. System volume should be as small as possible because the tubing and packer interval will be flushed several times during the tracer test: 1) at the beginning to replace drilling/workover fluid with formation fluid, 2) again to displace formation fluid with tracer, 3) again to chase tracer with formation fluid, and finally 4) to replace chaser with traced formation fluid. The packer interval should have the minimum length, the interval volume should be minimized, and small-diameter tubing should be used to minimize storage capacity between the surface and the tested interval.

6.9.7 Hydromechanical test

A hydromechanical test will be conducted to explore the role of the DRZ in flow up the borehole, and the effect of applying normal stress to the borehole wall (with a middle packer, simulating the effects of a plugging material with swelling properties). A three-packer hydromechanical test will be conducted, with the middle packer inflation pressure controlled separately from the outer two packers. This test will perform and observe pulse flow tests between two adjacent packed-off intervals, with the inflation of the intermediate packer changing during between repetitions of the test.

A pulse hydraulic test will first be performed before inflating the middle packer, using both intervals together as a single interval. Additional tests will be conducted in both intervals, as pressure is increased stepwise in the middle packer (keeping the packer inflation of the outer two packers constant). Pulse testing will be done from the upper interval, observing in the bottom interval, and vice-versa. After stepping up the middle packer inflation pressure beyond the packer inflation of the outer two packers (up to the potential swelling pressure of bentonite, 20 MPa above the borehole fluid pressure, if equipment allows), the inflation pressure will be decreased on the middle packer in a stepwise manner while repeating pulse testing and observation in both test intervals.

This test will explore the hydromechanical coupling in situ and will possibly obtain data for characterization of strain-permeability constitutive models. Independent measurement of mechanical strain in the borehole (rather than just packer inflation pressure) during testing would provide data useful for interpreting the test results. The tool should have minimal storage in the testing interval, to increase the tool’s sensitivity to the storage properties of the formation. The hydraulic testing should be able to discern a positive or negative wellbore skin that may exist in the packer interval, and how this changes with packer inflation pressure. A coupled hydro-mechanical numerical model will be used to interpret the test results.

6.9.8 Hydraulic fracture stress measurements

Hydraulic fracturing tests similar to those performed during the drilling phase will be performed during the testing phase of the CB investigations to quantify the magnitudes and directions of horizontal principal stresses at depth.

A packer tool will be deployed from a workover rig, at multiple locations in the borehole. Pressure within and outside the packed off interval will be monitored while fluid pressure and flowrate are controlled and monitored, following standard hydraulic fracture stress measurement procedures (Haimson 1978). Data will be collected from at least two repetitions of the hydraulic fracturing cycle, to collect information on the formation breakdown pressure, fracture propagation pressure, instantaneous shut-in pressure, and fracture closure pressure.

Hydraulic fracturing stress measurements will be conducted in relatively low-permeability rock (degree of fracturing may be confirmed by coring, borehole televiewer, etc.) so fluid pressure build-up can reach the breakdown pressure. To ensure proper seating of the packers, borehole damage (e.g., breakouts) should be limited in the test interval. Image logs will be collected before and after hydraulic fracturing to both locate the testing interval and determine the orientation of the induced fracture.

The hydraulic fracture stress measurement test sequence will be repeated in at least four depth ranges in the borehole. If practical, measurements will be replicated within each depth range. Each location tested will be selected to limit the influence of existing fractures (for formation breakdown tests). If resources permit, additional intervals will be selected with discrete fractures at different orientations, so that opening pressures for pre-existing fractures in multiple orientations can be used to corroborate estimates of the maximum horizontal principal stress.

7. DBFT PROJECT DATA REQUIREMENTS

There are many types of tests that could be conducted and data that could be collected in the CB, as discussed in the previous sections. Informal quantitation objectives were presented for many field and laboratory tests in Section 6. Data quality objectives (DQOs) will be developed in detail in the Drilling and Testing Plan, which will indicate critical data types, qualities, and quantities which should be required to consider the data collection phase of the DBFT in the CB a success.

The data discussed in the previous sections are grouped according to a combination of likelihood for success and importance associated with each data type for a DBD safety case.

7.1 Objectives for Data

Data indicating and supporting long residence time of formation fluids at depth in the crystalline basement and isolation from shallow groundwater, are central to the DBD concept. Demonstrating methods for collecting such data is represented by one set of objectives for the DBFT (middle box Figure 1). These types of data are summarized below. Of the geochemical methods available to indicate long residence time of formation fluid, we plan to rely principally on those that can be applied to small-volume samples, especially gases and fluids extracted from cores. It will be more challenging to acquire representative (i.e., uncontaminated with drilling fluid) in situ formation fluid samples from crystalline basement rocks, because of the additional downhole equipment needed, and especially if the host rock has few permeable fractures or fracture zones. Accordingly, methods that require larger formation fluid sample volumes will be considered secondary or confirmatory.

Some investigations will be done to evaluate the efficacy of selected methods of investigation, as input to refining the characterization programs for potential future DBD sites. Success for the DBFT will rely on obtaining high-quality depth profiles of geochemical and isotopic indicators. However, the measured data need not show that formation fluids are ancient, for the DBFT to achieve success as a demonstration of characterization technologies. Also, the DBFT will include other investigations, such as the engineering demonstration (lower left in Figure 1).

7.1.1 Data required for success

For a successful DBFT the testing and data collection should obtain:

- Representative profiles of formation fluid composition,
- Mud chemistry sampling for off-site analysis (both before and after circulation) and onsite monitoring (e.g., drilling mud tracer and exsolved gas content),
- Good quality core, adequately preserved (core handling procedures in Section 6.2.1),
- Quality geophysical borehole logs,
- Repeatable hydraulic fracture stress measurements, and
- Hydraulic packer testing is of high quality (requiring adequate packer seals and leak-free testing system performance).

More specifically, we will collect high-quality data profiles for the following constituents and conditions to build a safety case for the DBD concept:

- Helium-4 will be analyzed from core subsamples preserved in He-tight canisters (Section 6.2.1.1). Since He is generated in the crust (especially in granites with high U and Th content), it is expected to be at elevated concentrations in an isolated system in the crystalline basement (possibly up to $10^4\times$ enriched) allowing small sample sizes. Helium profiles from both water and rock samples will provide information on the capability of the crystalline basement rock formation to retain He (a very small and inert molecule) over geologic time scales, and may allow quantification of the rate at which constituents are leaving the isolated system (diffusion vs. advection).

- Stable water isotopes (e.g., ^{2}H [deuterium], ^{3}H [tritium], and ^{18}O) only require small sample sizes, because 1) they are isotopes of the constituents in water and therefore ubiquitous in the environment and 2) analytical methods (i.e., cavity ring-down spectroscopy) have advanced to allow testing of small sample sizes. Profiles of these isotopes can give information about the origin/provenance of water at depth, including the conditions and timing of groundwater recharge. The stable water isotopes and C, N, and S isotopes may also serve to quantify contamination from drilling fluid, since makeup water will likely come from a very different source and will have different composition compared to deep crystalline basement fluids.

- Major anion/cation concentrations and solute isotope ratios in formation fluids will be compared with rock/mineral composition in cores. We are interested in the origin of deep brines, which may contain components of: 1) ancient seawater, 2) salt derived from evaporite dissolution, 3) crystal fluid inclusions, and 4) evidence of in situ water-rock interactions. The Cl/Br and $^{6}Li/^{7}Li$ ratios will be used to identify seawater and evaporite dissolution components (Bottomley et al. 2003). The K/Na ratio is indicative of cation exchange associated with water-rock interactions in most crystalline rocks (Yardley & Bonar 2014). The degree of fluid-rock equilibration is affected by the duration of water-rock reaction, the degree of isolation from advective flux supplying disequilibrium fluids, and the physiochemical conditions (e.g., pressure, temperature) at depth. In addition, drilling-fluid logs (both downhole and at the surface) can be used to support core mineralogy and formation fluid compositions, and may provide supporting information regarding the relationships between depths and changes in formation fluid geochemistry.

- Open hole production logs will be conducted to characterize regions of significant permeability. In shallower boreholes of smaller diameter and fresher formation fluids, these methods have been successful locating fractures and estimating their transmissivity (Paillet et al. 2010; Dobson et al. 2016). Adapting the approach to work in the larger-diameter, deeper, and more saline CB is a goal for the project.

- Borehole physical/mechanical conditions, including natural and induced fractures and breakouts will be measured and analyzed. Borehole geophysical imaging techniques (i.e., caliper logs, formation micro-resistivity imaging, borehole televiewer, and full-waveform sonic logging) will be used to reconstruct both natural fracture sets and fracture zones and drilling-induced breakouts and tensile fractures where they occur. Understanding the conditions of occurrence for both the natural and induced features is important for characterizing the in situ stress state, interpreting geophysical logs, determining the orientation of permeable fractures, orienting and locating core, and mapping geologic contacts.

- Borehole geophysical surveys will include: 1) standard electromagnetic logs and surveys (i.e., resistivity, spontaneous potential, induced polarization, borehole radar, and NMR), 2) nuclear logs (i.e., neutron porosity, gamma density, and natural gamma), 3) borehole gravity, and 4) seismic-based logs and surveys (i.e., full-waveform sonic, dipole shear-wave velocity, and VSP). The data from these logs will be used jointly with results from laboratory tests on core, and packer-based in situ testing, to understand the variation of geological, lithological, geochemical, physical, and geomechanical properties with depth.

- In-situ stress measurements (including extended leak-off tests) will be made at multiple depths in the crystalline basement and at the transition between the crystalline basement and the overburden. Tests will be repeated at several depths, and replicated at each depth (resources permitting) to characterize the in situ state of stress and its variation, and to help plan for drilling the larger-diameter FTB.

- Bulk permeability and static formation pressure will be determined from packer tests. These model parameters will be estimated from data collected during pulse tests in low-permeability intervals, and from pumping/flow tests conducted in higher-permeability intervals. Permeability is an important parameter in flow models used for PA, and static formation pressure will be used to assess whether formation fluid in the crystalline basement is overpressured or underpressured. Static formation pressure will also be used to estimate the extent of contamination of formation fluid samples due to invasion by borehole fluids.

- Laboratory tests on rock flour, cuttings, and cores will determine properties for model parameterization. These tests include petrophysical (e.g., lithology, mineralogy, fractures, and grain size), hydraulic, geochemical, geomechanical, and thermal rock properties.

7.1.2 Additional data

Additional types of data could further support the DBD safety case, and test the efficacy of alternative characterization methods. For the DBFT, these are generally methods that involve sampling or testing with a lower likelihood of success. Although not critical to the success of the project, successful collection of these data may represent an advancement in available characterization methodologies for future projects, including DBD.

- Geochemical and isotopic analyses requiring larger sample sizes. These profiles would require in situ sampling from packer-based intervals, which may be difficult to obtain in a reasonable time period (i.e., less than a few weeks per sample interval) free of contamination from drilling fluid.
  - Noble gases other than He (i.e., Ne, Ar, Kr, and Xe).

- Isotopic tracers that originate from cosmogenic or nuclear-age anthropogenic processes, or in situ spontaneous fission (e.g., ^{36}Cl, ^{39}Ar, ^{81}Kr, ^{85}Kr, ^{129}I, and ^{129}Xe).
- Uranium and strontium isotopic ratios for in situ formation fluids (samples sizes of tens to hundreds of mL may be needed depending on elemental concentrations).

- Geochemical data for in situ formation fluids that will be challenging to collect without contamination or interference:
  - Redox potential (Eh): Large amounts of metal and air-saturated fluid will be introduced to the borehole environment during drilling. Formation fluid samples from high-permeability zones will be pumped through >2 km of metal tubing to the surface. Also, any drilling fluid additives that are redox-active (e.g., biocides) could further interfere with Eh measurements.
  - pH: Drilling fluid may alter the pH of the formation fluid near the borehole. Some common drilling fluid additives (e.g., caustic soda) are specifically used to control pH. Also, elevated temperature and the presence of concentrated chloride brines cause shifts in water dissociation behavior that complicate the interpretation of in situ pH.

- In-situ injection-withdrawal tracer testing may be difficult at several kilometers depth in low-permeability crystalline basement rock. The greatest risk is that wellbore damage (breakouts or tensile cracks, which may not always be recognizable from borehole imagery) may allow bypass around packers. The primary flow path may be along the borehole wall, due to poor sealing of the packers. The primary focus of testing will be the flow and transport properties of the DRZ, which could be difficult to discriminate from bypass behavior. Testing is planned for borehole intervals in good condition, but prevalent wellbore damage could degrade test results.

- Hydromechanical pulse testing will explore the in situ geomechanical/hydraulic coupling in the DRZ, but depending on formation responses, results may not be interpretable as formation properties due to the compliance and design of the packer tool itself.

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APPENDIX E
FCT DOCUMENT COVER SHEET [1]

Name/Title of Deliverable/Milestone/Revision No.	Deep Borehole Field Test Laboratory and Borehole Testing Strategy
Work Package Title and Number	Site Characterization – SNL, FT-16SN08030807
Work Package WBS Number	1.02.08.03.08
Responsible Work Package Manager	Kristopher L. Kuhlman (Name/Signature)
Date Submitted	

Quality Rigor Level for Deliverable/Milestone[2]	☒ QRL-3	☐ QRL-2	☐ QRL-1 Nuclear Data	☐ Lab/Participant QA Program (no additional FCT QA requirements)

This deliverable was prepared in accordance with Sandia National Laboratories
(Participant/National Laboratory Name)

QA program which meets the requirements of

☒ DOE Order 414.1 ☐ NQA-1-2000 ☐ Other

This Deliverable was subjected to:

☒ Technical Review	☐ Peer Review
Technical Review (TR)	**Peer Review (PR)**
Review Documentation Provided	**Review Documentation Provided**
☐ Signed TR Report or,	☐ Signed PR Report or,
☐ Signed TR Concurrence Sheet or,	☐ Signed PR Concurrence Sheet or,
☒ Signature of TR Reviewer(s) below	☐ Signature of PR Reviewer(s) below

Name and Signature of Reviewers

Ernest Hardin

NOTE 1: *Appendix E should be filled out and submitted with the deliverable. Or, if the PICS:NE system permits, completely enter all applicable information in the PICS:NE Deliverable Form. The requirement is to ensure that all applicable information is entered either in the PICS:NE system or by using the FCT Document Cover Sheet.*

NOTE 2: *In some cases there may be a milestone where an item is being fabricated, maintenance is being performed on a facility, or a document is being issued through a formal document control process where it specifically calls out a formal review of the document. In these cases, documentation (e.g., inspection report, maintenance request, work planning package documentation or the documented review of the issued document through the document control process) of the completion of the activity, along with the Document Cover Sheet, is sufficient to demonstrate achieving the milestone. If QRL 1, 2, or 3 is not assigned, then the Lab / Participant QA Program (no additional FCT QA requirements) box must be checked, and the work is understood to be performed and any deliverable developed in conformance with the respective National Laboratory / Participant, DOE or NNSA-approved QA Program.*