# SANDIA REPORT

# Deep Borehole Laboratory and Borehole Testing Strategy: Generic Drilling and Testing Plan

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## Abstract

This report presents a generic (i.e., site-independent) preliminary plan for drilling, testing, sampling, and analyzing data for a deep characterization borehole drilled into crystalline basement for the purposes of assessing the suitability of a site for deep borehole disposal (DBD).

This research was performed as part of the deep borehole field test (DBFT). Based on revised U.S. Department of Energy (DOE) priorities in mid-2017, the DBFT and other research related to a DBD option was discontinued; ongoing work and documentation were closed out by the end of fiscal year (FY) 2017. This report was initiated as part of the DBFT and documented as an incomplete draft at the end of FY 2017. The report was finalized by Sandia National Laboratories in FY2018 without DOE funding, subsequent to the termination of the DBFT, and published in FY2019.

This report presents a possible sampling, testing, and analysis campaign that could be carried out as part of a future project to quantify geochemical, geomechanical, geothermal, and geohydrologic conditions encountered at depths up to 5 km in crystalline basement.

# ACKNOWLEDGMENTS

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# NOMENCLATURE

| | | | | |
|---|---|---|---|---|
| AECL | Atomic Energy of Canada Limited | | NMR | nuclear magnetic resonance |
| BHA | bottom hole assembly | | PDC | polycrystalline diamond compact (sometimes cutter) |
| BOP | blow-out preventer | | QA | quality assurance |
| CCSD | China Continental Scientific Drilling project | | QC | quality control |
| CCV | continuing calibration verification | | ROP | rate of penetration |
| | | | RSD | relative standard deviation |
| CEC | cation exchange capacity | | SAFOD | San Andreas Fault Observatory at Depth |
| COC | chain of custody | | SEM | scanning electron microscope |
| CB | characterization borehole (component of the DBFT) | | SNL | Sandia National Laboratories |
| DBD | deep borehole disposal | | SP | streaming potential |
| DOE | US Department of Energy | | TBD | to be determined |
| DBFT | deep borehole field test | | THM | Thermal-hydro-mechanical (also HM, TM and TH) |
| DQO | data quality objectives | | TIMS | thermal ionization mass spectrometry |
| D&TP | drilling and testing plan | | | |
| DRZ | disturbed rock zone | | TD | total depth |
| FFEC | flowing fluid electrical conductivity | | TDS | total dissolved solids |
| | | | TRL | technology readiness level |
| FTB | field test borehole (component of the DBFT) | | UFD | used fuel disposition (DOE Office of Nuclear Energy program) |
| ICP-ES | inductively coupled plasma emission spectrometry | | | |
| | | | US | United States |
| ICP-MS | inductively coupled plasma mass spectrometry | | UV | ultraviolet |
| ICV | initial calibration verification | | VCR | vacuum coupling radiation |
| ID | identification code | | VSP | vertical seismic profile |
| IDDP | Iceland Deep Drilling Project | | XLOT | extended leak-off test |
| KTB | Kontinentale Tiefbohrprogramm der Bundesrepublik Deutschland | | XRD | X-ray diffraction |
| | | | XRF | X-ray fluorescence |

# 1 INTRODUCTION

This document is a generic (i.e., site-independent) drilling and testing plan (D&TP) to drill, complete, and test the smaller-diameter characterization borehole (CB), as part of a Deep Borehole Field Test (DBFT). This material is a synthesis of Sandia reports on the characterization needs of the DBFT (SNL 2016b), with an incomplete draft of D&TP material provided to the U.S. Department of Energy (DOE) by the Battelle, Schlumberger, and SolExperts DBFT team in June 2016.

This research was performed as part of the DBFT. Based on revised DOE priorities in mid-2017, the DBFT and other research related to a deep borehole disposal (DBD) option was discontinued; ongoing work and documentation were closed out by the end of fiscal year (FY) 2017. Further DBFT work, for example, implementation of an engineering demonstration (SNL 2016a), would require resumption of DBD research and development at some future time.

This document is both an outline of a D&TP for a future DBFT CB and represents the state of the sampling and drilling plan at the time the project was stopped. The D&TP prepared by Battelle contained many site-specific and company-specific details, which have largely been removed or simplified, but the generic requirements and proposed methodology are left intact. Some places in the D&TP indicate in what additional site-specific information would be expected in a final D&TP. Once a suitable implementation team and location are found, a final D&TP would need to include both site-specific data and implementation-specific details, which will likely include trade names, and other company-specific details. This generic D&TP (or something derived from it) might make a useful document to guide bidding teams in a future DBFT implementation.

The DBFT was conceived to prove the concept behind DBD, but the significant background of material on DBD or the related design of the larger-diameter field test borehole (FTB) are not presented here in detail. Background material on the DBD concept can be found in previous SNL reports (Brady et al. 2009; Arnold et al. 2011). The concept of DBD is to dispose of radioactive waste in the lower portions of deep vertical boreholes drilled into crystalline basement. The primary goal of the DBFT, and specifically the CB portion of the DBFT, is to demonstrate the ability to drill, construct, conduct tests in, and collect samples from a representative borehole in crystalline basement rock. The goal of the DBFT is not to exhaustively characterize a particular site to the level of rigor possibly demanded by some future DBD regulation, but the DBFT is being designed to improve confidence in the possible future isolation of radioactive waste by this method. Some aspects of borehole construction and testing are not planned as part of the DBFT or are included only in a limited way. Hydraulic packer testing of shallow aquifers in the overburden is not included, as this is believed to be an area with a high technical readiness level. We are focusing the DBFT on improving the technical readiness level of relatively immature technologies or processes needed to characterize deep crystalline boreholes. A wide range of hydraulic and geomechanical tests are proposed for the borehole, but we only propose a relatively small number of repetitions of each test. For example, we propose to core 5% of the total crystalline basement, in hopes of more economically allowing demonstration of the process of collecting deep core in crystalline rock, without coring all or most of the borehole – an expensive endeavor.

The performance assessment (PA) aspects of the deep borehole disposal concept are presented in Freeze et al. (2016; 2019). SNL (2016a) presented the conceptual design report for an FTB component of the DBFT, with considerations on-site handling and emplacement design. The scientific needs of the characterization borehole in the DBFT were presented in SNL (2016b) and forms a basis for some of the content presented in this document.

## 1.1 Design Goals for Characterization Borehole (CB)

The following design criteria used to guide preparation of the D&TP (see Figure 1 for well schematic):

- Safe drilling operations meeting best industry standards and practices;

- Directionality:

    o A highly vertical well bore (i.e., plumbness), and

    o Minimum borehole tortuosity (i.e., dogleg severity);

- Integrity of the overburden (i.e., intermediate) borehole section during coring and testing of the upper basement interface (i.e., before setting casing across all the overburden);

- Isolation of the overburden rocks and pore fluids from the drilling in the open hole crystalline section;

- Drilling fluid system enabling high fidelity logging measurements, including one or more drilling fluid tracers;

- Drilling fluid system that minimally chemically and hydraulically disturbs the crystalline basement rock system, to allow future sampling and testing of the crystalline basement;

- Stability of the wellbore in the crystalline section supporting an extended testing program;

- Assessments of drilling method and drill bit alternatives in the crystalline basement;

- Target rate of penetration (ROP) optimized to meet the above technical and scientific criteria (i.e., not the fastest possible ROP);

- Evaluate sampling and testing methods to determine whether deep groundwater in the crystalline basement is old, saline, and reducing.; and

- Measure *in situ* fluid potential gradients, to measure any vertical gradients along the borehole. This includes effects of fluid pressure, stress, temperature, and chemistry.

Land Surface

≈Water Table

Conductor Borehole
and Casing (no scale)

Surface Borehole
44.5 cm [17½"] diam.
TD ≈460 m [1,500']

Surface Casing
34 cm [13⅜"] diam.

Sedimentary Overburden (≤2 km)

≈Base of Fresh Water

Intermediate Borehole
31.1 cm [12¼"] diam.

Intermediate Casing
24.4 cm [9⅝"] diam.

Top of Crystalline
Basement 2 km
[6,560']

Basement borehole
21.6 cm [8½"] diam.

Crystalline Basement (≥3 km)

Total Depth
5 km [16,400']

**Figure 1. Characterization Borehole (CB) schematic, illustrating typical dimensions (SNL 2016b).**

# 2   BACKGROUND AND SITE INFORMATION

Supporting information will be required to provide evidence for the estimated depth to basement at the site. Of all the possible DBD site selection criteria, the depth to basement is likely the most important to consider during siting and planning, since the overburden and the basement will likely be of very different composition and will required different drilling, completion, and testing strategies. The cost of drilling in the crystalline basement is expected to be higher than in sedimentary overburden. Beyond just the depth to basement, all existing information should be gathered regarding the mechanical competency and characteristics of the upper basement, and possibly how this information changes with depth. If this information is available, it will be especially useful in designing the well completion. All nearby information on the condition and nature of the basement will be useful, including: geology (e.g., rock type, major structure, and location of major faults), hydrogeology (e.g., permeability, porosity, connection between basement and overburden, and presence of regional flow gradients), geochemistry (e.g., basement and basal overburden fluid composition), and geomechanical state (e.g., rock strength and regional stress tensor orientation). These data are expected be from boreholes with limited penetration into the basement. Boreholes with significant penetration into the basement will be of special interest, even if they are not immediately proximal to the proposed drilling site.

## 2.1   Well Offset Data Analysis

The D&TP must provide location (latitude, longitude, total depth, borehole direction, and key formation top depths if available) information in both table (i.e., database or spreadsheet) form and on maps (e.g., structure contour and isopach) including the offset well inventory near the selected DBFT site location. For this and all the subsequent data requirements in this section, the data source should always be referenced.

It is unlikely there will be nearby offset wells drilled significantly into basement, but information will be needed from wells reaching the top of the basement, or even wells that reached the basal unit of the overburden. The appropriate distance to include well offset information will increase with depth. Information from all boreholes and wells will be collected in a small area surrounding the site (providing data on shallow aquifers and irrigation wells on adjacent properties), while deeper sedimentary formations, and wells penetrating basement may be collected from a wider area (because they are expected to be fewer of these data). State- and nation-wide databases may be available, depending on the location. If the site is near a state or national boundary, investigation may need to collect well data and geological information from multiple jurisdictions.

Well offset data analysis would typically include a review the following information for nearby boreholes and wells:

- Drilling reports;
- Cuttings and mud logging records;
- Information regarding drilling method and/or bits used;
- Core or cuttings samples and any associated results from laboratory tests;
- Relevant production information from completed wells, especially in the basement or lower basal units of the overburden (productivity and water chemistry);
- History of any well-related activities, such as groundwater or oil and gas production or brine or other fluid disposal.

Other deep crystalline scientific drilling projects are listed in Appendix A. The lessons learned during these projects are likely relevant to any deep drilling project, even if they are not geographically near a proposed site.

## 2.2 Subsurface Information

To compliment the well and borehole offset data, and to support the siting criteria that would likely be used for a DBD site, the project will identify and describe critical geologic and reservoir information on the crystalline basement and overburden. Depending on the location, this may be a significant amount of information and supporting references, including:

1. Geological information regarding overburden (lithology and formation depths);

2. Location of historical earthquakes and estimates of seismic or tectonic activity for the area;

3. Location of any Quaternary age volcanism or faulting;

4. Confirmed, interpreted, or inferred basement structure, shear zones, fabric, or foliation in the vicinity of site;

5. Estimates of the regional stress state, including stress regime (i.e., strike-slip, normal, or reverse) and orientation of minimum and maximum stresses, including any change in stress orientation with depth;

6. Expected trends (i.e., "gradients") in pore fluid pressure, overburden stress ($\sigma_V$), fracture stress ($\sigma_h$) (i.e., least principle stress), and temperature;

7. Published geologic maps and cross-sections through or near the site, including isopach and structure contour maps;

8. Published hydrological, hydrochemical, and isotopic studies of the overburden and basement formations and fluids (especially numerical models of regional groundwater flow and estimates of pre-development hydrological conditions);

9. Data regarding aquifers and reservoirs overlying or within the basement, including:

   a. freshwater aquifers that may be penetrated during drilling;

   b. formations with current or historic injection wells for oilfield brine or waste;

   c. presence of gases ($CH_4$, $H_2S$, $CO_2$) or liquid hydrocarbons;

   d. abnormal pressure zones (significantly higher or lower than hydrostatic);

   e. regional groundwater flow and geochemistry trends in the overburden, especially in basal units; and

   f. evidence for or against deep circulation of fresh or recent groundwater (e.g., lack of significant topographic relief, published analyses indicating old or saline water at depth).

10. Surface or airborne geophysical surveys in site vicinity, especially those methods that may provide information about the depth to basement or the nature of basement rocks (e.g., aeromagnetic, magnetotelluric, gravity, or seismic); and

11. Location of nearby subsurface activities or known anthropogenic contamination with a potential for interference with the test;

## 2.3 Identification of Applicable Regulations

The D&TP should identify and describe applicable local (e.g., county or city zoning variances), state (e.g., borehole or well drilling permits, drill cuttings disposal, state groundwater quality protection programs), and federal (e.g., National Environmental Policy Act, surface runoff discharge, and archeological survey compliance) regulatory requirements for DBFT drilling, downhole testing, surface

site management, and site decommissioning. For all identified regulations, present a plan and schedule for compliance with the regulations.

# 3 DRILLING AND COMPLETION PLAN

This section presents the plan for the drilling and completion of the CB. The drilling and completion must be done in a manner to ensure meeting the technical demonstration and scientific testing and sampling goals of the project.

Following subsections describe the directional drilling approach, the drilling bit selection, the drilling fluid selection, and the drilling rig type. Although they are presented in separate sections, they are not independent choices. All components of the drilling and completion system must be considered, optimized, and selected simultaneously. This inter-dependency of one system on another should be reflected in the justification of design decisions presented below.

## 3.1 Overall Borehole Construction Operations

The CB will be the primary location for activities to:

- demonstrate ability to characterize and evaluate the site,

- acquire data and generate parameters to populate PA models,

- develop specifications for drilling a larger-diameter borehole, and

- build confidence in the DBD concept.

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

Figure 1 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. 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, including depth-to-basement of less than 2 km.

An important site selection requirement for depth to the crystalline basement is from the fact that the borehole must be 5 km total depth, and 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. The characterization efforts associated with the crystalline basement would also be performed over a longer interval and may introduce more costs (e.g., 5% core across 5 km of basement is 250 m, rather than 150 m of core for 5% of 3 km of basement). 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. Sedimentary basins typically contain approximately two-thirds mudstones, shales, and mudrocks (Garrels & Mackenzie 1969; Blatt 1982), and thus may contain many low-permeability sealing lithologies.

Conductor casing will be set to prevent caving, significant inflow of shallow groundwater, or significant loss of drilling fluids to shallow aquifers. Surface casing will then be set to approximately 460 m [1,510'] (see discussion below). An intermediate liner (a liner is a casing that does not extend to the surface) will then be set across the remainder of the overburden and will penetrate the top of the crystalline basement (up to a few tens of meters), until competent basement rock is encountered. Figure 1 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 accurate 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 1) 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 to 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 (BOP) equipment. The total depth will be as required by governing regulatory agencies for well control (assumed 460 m [1,510']). This casing is cemented to the surface. If required by local regulations, it will have a BOP 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.

The following nominal sequence of operations is based on the above casing and drilling plan.

One possible alternative design would omit the intermediate casing section across the overburden and bring the surface casing and associated larger-diameter borehole down into the top of the crystalline basement. This would provide some flexibility if hole stability problems occurred in the crystalline basement section, which ultimately would require casing sections of the crystalline basement. This section could be cased with the 24.4 cm [9⅝"] liner and the target diameter at total depth (21.6 cm [8½"]) could still be achieved. This alternative design may not be feasible, depending on the conditions in the overburden, since it requires extended sections of the borehole to remain open, and may require multiple passes. One possibility would be to drill the interval at a smaller diameter to perform geophysical logs, wireline packer tests, and collect core at the overburden-to-basement interface, then ream the borehole out to a larger diameter immediately before setting the larger casing diameter. If any portions of the crystalline basement are to be cased, they should be sampled via wireline packer tool, since future characterization of these intervals would be impossible.

### 3.1.1 Pre-Drilling Operational Sequence

D1. Construction of access roads and pads.

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D2. Cellar construction and 50.8 cm [20"] diameter conductor installation.

D3. Rig mobilization to the borehole site.

D4. Perform a rig inspection and audit.

D5. Perform a pre-spud meeting.

### 3.1.2 Overburden Drilling Sequence

D6. Safety and operational meeting.

D7. Rig up and set diverter on 50.8 cm [20"] conductor casing.

D8. Drill surface borehole (44.5 cm [12¼"] diameter) to approximately 275 m [900'] depth while collecting drilling performance information, logging cuttings, and analyzing rock flour by XRD and XRF.

D9. Perform a round-trip and pull out of the hole

D10. 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 constrained from existing geophysics or nearby boreholes, VSP would not be necessary.*

D11. Drill pilot hole with 44.5 cm [12¼"] diameter to within ½ core barrel length (assumed here 18.3 m [60']) of expected top of crystalline basement (nominally 2 km [6,560'] depth) and pull out of the hole.

D12. Rig up coring borehole assembly (BHA) and core across the overburden/basement interface. The length of core for the interface should attempt to capture features near the interface such as differences in fracturing or diagenesis. Obtain approximately 9.14 m [30'] of core immediately above the interface and approximately 27.43 m [90'] of core below the interface. A single 36.58 m [120'] core barrel could be used but consider shorter core barrels as appropriate to obtain high-quality core.

D13. Pull the coring BHA out of the hole.

D14. Geophysically log open borehole. Identify candidate unit of overburden (basal unit if sufficiently permeable) for hydraulic testing.

D15. 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). *It us likely the wireline-based packer tool cannot be set in 44.5 cm [17½"] hole.*

D16. Rig up BHA with 44.5 cm [17½"] bit, enlarging and drilling borehole to casing point – assumed 396 m [1,300'].

D17. 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.

D18. 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.

D19. Depending on competence of crystalline basement rock, drill intermediate borehole deeper into crystalline basement until competent crystalline rock is encountered.

D20. Collect any required rotary sidewall cores via wireline from to-be-cemented intervals of interest identified from geophysical logging.

D21. Perform a conditioning trip.

D22. Install and cement 34 cm [13⅜"] diameter surface casing from the bottom to the surface. *This alternative design differs from that shown in Figure 1 and may allow more flexibility at depth. If there is a need to case off some of the crystalline basement due to poor hole conditions, this can be done, and a 21.6-cm [8½"] diameter hole could still be achieved at 5 km total depth.*

D23. Rig down the diverter and install the casing head.

D24. Install and test BOP as required by local regulations.

D25. Conduct bond log to evaluate cement bond.

### 3.1.3 Crystalline Basement Drilling Sequence

D26. Safety and operational meeting.

D27. Rig up BHA and run in hole 21.6-cm [8½"] BHA to drill out the cement and float collar until reaching the guide shoe.

D28. Conduct extended leak-off test to estimate magnitude of least principal stress at bottom-hole depth.

D29. Switch from the drilling fluid composition used in the overburden, to drilling fluid selected for the crystalline basement interest section. Circulate out all old drilling fluid and begin including tracers in drilling fluid and all subsequent makeup water.

D30. Drill out the guide shoe and drill 3 m [10'] into basement and perform a formation integrity test.

D31. Drill and trip for bit and BHAs as necessary through the crystalline basement section until the next coring point is reached.

D32. Circulate and pull out of hole the BHA.

D33. Run in hole the coring BHA.

D34. Core crystalline basement and pull out of hole the coring assembly.

D35. 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 and XRF analysis on rock flour. *Repeat last 4 steps.*

D36. 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).

D37. Rig up and run in hole sampling and hydraulic fracture tools. Perform hydraulic testing and fluid sampling if sufficient permeability, using the wireline-based hydraulic packer-isolated interval testing tool near the bottom.

D38. Set wireline-based packer tool on a low-permeability interval for hydraulic fracturing stress measurement.

D39. Pull out of hole and rig down sampling and hydraulic fracture tools.

D40. Using imaging tools, log the interval where hydraulic fracture stress measurement was conducted to determine orientation of the induced fracture.

D41. Provide CB data and analysis to support the decision point to move forward with the procurement process associated with drilling the FTB.

D42. 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 performing real-time logging of drilling fluid liquid, dissolved gas, and cuttings and performing XRD and XRF analysis on rock flour. *Repeat 4 steps above.*

D43. Using a suite of geophysical tools log the open part of the borehole (the entire crystalline basement interest section).

D44. 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.

D45. Run a wiper trip to flush cuttings and drilling fluid from borehole. Replace drilling fluid with workover/testing fluid selected to provide long-term chemical stability and well control during subsequent testing.

D46. Based on geophysics, locate and drill any additional intervals with rotary sidewall coring via wireline tool.

D47. Run in hole and place a packer as a temporary plug in 34 cm [13⅜"] diameter casing.

D48. Assemble the wellhead.

D49. Demobilize non-essential drilling rig equipment before workover rig testing.

### 3.1.4 Time and Cost Estimation

The time required to drill and construct the borehole is estimated by combining the times required for each activity in the operational sequence. Time required for most activities are known, and the uncertainty associated with drilling the overburden is low in contrast with drilling and coring in the crystalline basement which present the greatest time uncertainty.

The ROP in stable crystalline basement rock during drilling and coring will be much slower than the expected in the sedimentary section. There may be no significant penetrations of the crystalline basement near the DBFT site to provide reference data; nevertheless, crystalline rock formations have been drilled all over world and these data are available. Based on analyzing drilling data from deep geothermal wells in Europe, Baujard et al. (2017) estimated a likely ROP to be 3 to 6 m/hr between 2 and 3.5 km depth, and 2 to 5 m/hr from 3.5 to 5 km depth.

Given the assumed low, high, and likely ROP in Table 1, and nominal depths associated with the DBFT CB completion (e.g., 2 km to basement), Figure 2 shows an expected range of drilling schedules. Site-specific estimates should be prepared based on the depths at the site and expectations of the drilling team. Related to ROP is bit life; Beswick (2008) and Beswick et al. (2014) give an expected bit life to be in the range of 100 m to 150 m [330' to 492']. Increased bit life will reduce the number of extra trips out of the borehole that are solely for bit changes.

**Table 1. Expected range of drilling penetration rates**

|  | Low rate [m/hr] | High rate [m/hr] | Likely rate [m/hr] |
|---|---|---|---|
| Surface drilling rate | 17.0 | 30.0 | 23.5 |
| Intermediate drilling rate | 13.0 | 30.0 | 21.5 |
| Basement coring rate | 0.50 | 1.00 | 0.75 |
| Basement drilling rate | 0.70 | 4.57 | 2.64 |
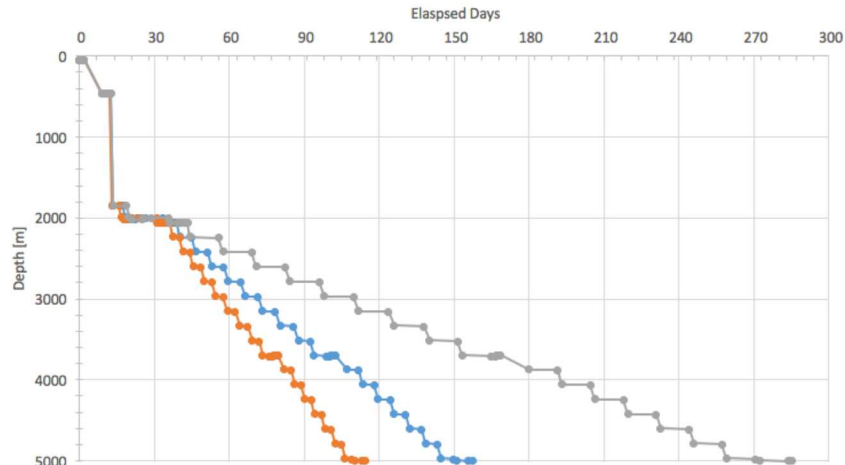
**Figure 2. Example estimated drilling schedule using low, likely, and high drilling penetration rates.**

Cost estimation is clearly related to and is strongly affected by realistic time estimation. The costs should be itemized and presented clearly, both to justify costs and to better weigh possible cost increases associated with different scenarios. For example, different casing schedules will have different costs, and the costs associated with high-risk off-normal events (e.g., lost circulation or stuck drill pipe) should be included in an approximate manner.

## 3.2  Borehole and Casing Design

There may be more than one casing design, to provide a contingency plan if there are poor hole conditions or severe lost circulation problems in the crystalline basement interest section. The primary goals for the CB borehole and casing design are to achieve 21.6-cm [8½"] diameter at planned total depth in the crystalline basement, and to leave as much of the crystalline basement open hole as is feasible. The diameter of the borehole and casing intervals above this should be adjusted to increase the likelihood of achieving full diameter at total depth, and casing should only be installed in the crystalline basement if it is required for borehole integrity and stability.

### 3.2.1  Conductor Casing

The conductor casing will be set and grouted with cement to surface by a contractor. The casing will be designed to withstand the anticipated service loads imposed during installation and throughout the life cycle of the borehole. The main purposes of the conductor are:

- Protect unconsolidated shallow formations from erosion by drilling fluids;

- Provides a structural support for a diverter system that would be used in the event of an unexpected shallow influx;

- Allow the installation of a full drilling fluid circulation system; and

- Minimize shallow lost returns.

### 3.2.2  Surface and Intermediate Casing

The surface and intermediate casings are the main barriers against subsurface drilling problems, so it is critical to set the casing in a way to maximize access to geological information, while minimizing subsurface risks. The pore pressure, fracture pressure, and temperature profile should be estimated based on regional knowledge. Wireline-conveyed packer test will be performed in the intermediate section to estimate pore pressure before setting casing. Another wireline-conveyed packer test will be conducted in

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the crystalline basement study section, to provide information useful for drilling and understanding breakouts.

The primary goals for the casing design to accomplish the objectives of the scientific borehole include:

- comply with applicable regulatory requirements;

- assure borehole integrity from installation through the later packer-based testing campaign;

- isolate the crystalline basement study section from shallow freshwater aquifers and deeper saline aquifers in the sedimentary overburden;

- assure a 21.6-cm [8½"] borehole diameter through the crystalline basement interest section; and

- minimize amount of casing set in crystalline basement, to allow access to the formation for testing.

The site-specific D&TP should state explicitly all assumptions regarding the design of the casing. State all known and assumed static and transient loads used in the design process, which the casing must survive during emplacement, cementing, and service.

### 3.2.3 Load Cases

A load case describes internal pressure, external pressure, and temperature over the length of a casing string through time. The load case describes events during the drilling and completion of the borehole, such as a "kick" or the effects of an extended leak-off test or hydrofracture stress measurement. Some loads are intentionally applied, while others are accidental. Intentional loads will happen with a high degree of certainty, such as pressure tests and loads while running casing. A kick load or tubing leak may not happen and therefore is an accidental load. Intentional and accidental loads must both be considered.

Since one of the objectives is to complete the crystalline basement at a single 21.6-cm [8½"] borehole diameter, the surface or intermediate casing will serve as a sort of production casing. The loads associated with later packer tests will need to be considered as part of the design.

## 3.3 Borehole Stability Analysis

A borehole stability analysis will be conducted with consideration of local lithology, stresses, fractures, and anomalous formation pore pressures. This analysis will be done to predict the stability of the rock and the borehole during drilling operations. The borehole stability analysis considers the design of the casing and incorporates information from any formation integrity tests and extended leak-off tests.

### 3.3.1 Formation Integrity Test

Verification of casing integrity at the casing shoe is required to ensure that no flow path exists to formations above the casing shoe and to establish the pressure containment capability of the borehole during a well control situation while drilling the next hole section; therefore a formation integrity test will be performed to assure that the casing in properly cemented in a competent formation and to verify the capability to safely handle a kick without breaking down the open hole section just below the casing shoe.

### 3.3.2 Extended Leak-Off Test

The leak-off test is like a formation integrity test, but the pressure is increased until failure occurs in the formation below the end of the casing. An extended leak-off test (XLOT) is essentially a mini-frac (a hydraulic fracture stress measurement) and can be used to estimate the magnitude of the least principal stress at depth.

## 3.4 Drilling Rig Selection and Specifications

Goals for the rig sizing and selection include assurance that:

- borehole maintains integrity;
- drilling rig has the capability to pull out the heaviest expected BHA from total depth (TD);
- adequate drilling fluid flow rate is achieved for borehole cleaning;
- proper trilling speed tripping in and out (27 m/min to 37 m/min [90 ft/min to 120 ft/min]);
- adequate drilling fluid flow rate is achieved to improve ROP in hard formations through adjustments in rig hydraulic horsepower per square inch;
- drilling at TD with 80% of top drive continuous torque capacity.

Depending on the site, utilities, and available rigs, the use of diesel generators should be weighed against using a fully electric rig that runs on grid power.

The site-specific D&TP should provide specifications for all the rig's primary systems: the hoisting system, rotating system, substructure capacity, pumping system, accumulator system, mud system, and safety systems. The site-specific D&TP should provide specifications of all major rig consumables and provide specifications of the interface between the rig and any well control system (i.e., diverter and BOP).

## 3.5 Directional Drilling (Plumbness and Straightness)

The DBFT will require drilling a highly vertical borehole. The requirements for directional drilling are partially to maximize the usefulness of the borehole for subsequent testing and packer emplacement (i.e., minimizing hole tortuosity and dogleg severity), and partially to demonstrate that a relatively large-diameter straight and plumb borehole can be completed in crystalline rock. A second borehole (the Field Test Borehole) may be completed on the same site approximately 200 m [650'] away. Having the CB and any follow-on boreholes be straight and properly located reduces the need for an excessively large drill pad to accommodate both wells safely. Drilling straight and vertical borehole in hard crystalline rock is often at odds with drilling quickly (i.e., high ROP).

A modern directional drilling approach (i.e., a type of rotary steerable system) will be used to achieve a straight and plumb borehole. A site-specific D&TP will give the specifications of the directional drilling system, including any required or recommended survey or measurement while drilling. The D&TP will give indications of expected performance of the proposed directional drilling approach with the proposed drill bits in crystalline rock. Alternative drilling methods or drilling bits may be available for testing to increase the ROP without sacrificing a straight and vertical borehole. These drill bits must be compatible with the directional drilling and mud circulation system. Most directional drilling experience in the US is associated with drilling in softer sedimentary rocks, which may not translate directly to the crystalline basement rocks targeted in the DBFT.

A site-specific D&TP should include drilling and data transfer specifications of all proposed steering tools, and any logging while drilling tools or measurement while drilling tools. Again, indication of experience using these tools in crystalline rock should be stated, including their expected performance.

## 3.6 Drilling Bit Selection

It is likely the overburden and the crystalline basement sections will require different drill bit types. A sedimentary overburden sequence may use modern polycrystalline diamond compact (PDC) bits. The crystalline basement section may use more traditional tungsten carbide insert roller-cone bits. Some PDC bits have been developed for hard crystalline formations, but most drilling operator's experience with these bits is limited. Sections of the crystalline basement may be targeted to be drilled with experimental PDC or hybrid bits. Goals for the bit plan include:

- select bits to ensure a highly vertical borehole is drilled with minimal tortuosity;
- drill the surface and intermediate sections in a single run each;

- drill the basement section in a single run between coring points.

The goal would be to use a single drill bit between coring points in the crystalline basement will depend on rock hardness (i.e., silica content), bit type, bit life, and drilling fluid circulation.

It may be possible to drill using a down-the-hole hammer drilling method that utilizes water-based circulations fluid, but there are few operators with experience using this relatively new method, and it may not be compatible with the verticality and straightness requirements.

Any plans to test alternative drilling bit technologies (e.g., hybrid PDC bits) in the crystalline basement section should be planned so that they do not impact the stability or tortuosity of the borehole. One of the purposes of the DBFT is to test and prove new technology, so some use of experimental drilling bits may be warranted. Clearly state when and how any experimental drilling methods will be used, and how they will compare to the drilling methods used for the majority of the borehole.

A site-specific D&TP should specify the bottom hole assembly (BHA) associated with each type of drilling bit used and the directional control system. The team should indicate any experience using these assemblies and bits under similar conditions in hard rock.

## 3.7  Core and Core Handling

Advance coring will target recovery of 50 m [164'] of core per 1,000 m [3,280'] of basement (5% of crystalline basement interval). To the extent practical, coring activities should be coordinated to coincide with bit changes and other activities when drilling is stopped. Core points will be chosen to maximize the ability to interpret environmental tracers and other core data. Most of the core will be collected from the basement rock, with one longer core run targeted at the basal overburden unit and the interface between overburden and crystalline basement.

Similar in philosophy to the packer-based testing program (Section 4), the objective of the coring program is not to completely characterize the entire length of the borehole drilled at the DBFT site, as would likely be required by some future regulator to characterize a site for radioactive waste disposal. The primary objective is a technology demonstration to illustrate the feasibility of the proposed sample collection methods and data interpretation strategies. This is the primary reason behind the target of 5% total core collection. This target should also be seen as an upper limit to be used for financial and logistical planning purposes, rather than as a core recovery target that must be achieved. It is unlikely core recovery will be high in the deep portions of the borehole (i.e., core discing is likely at great depth), and potential coring challenges may result in core recovery amounts lower than 5% of the total borehole drilled. Some of the budget associated with the planned 5% advance coring may be set aside to perform sidewall coring at locations identified only through geophysical logging. Similar to alternative drill bit testing, alternative coring bits or collection approaches may be attempted to improve core recovery at depth, where rock stress may be high, and discing may be severe.

Core may be required from intervals other than those core points initially planned, based on fulfilling the science objectives of the DBFT. Core diameter will be 10.2 cm [4"] in diameter to maximize the volume of rock cored for both extraction of pore water and gases for geochemical assessments and to provide representative rock samples for laboratory-based thermal, hydrologic, and mechanical properties testing. Sidewall core may be collected via wireline tool from intervals of interest that were only identified after geophysical logs were run.

Goals for the core collection system include:

- Core the overburden-basement interface – plan for 75% of the core below the interface, while 25% would be across the basal formation of the overburden, but the planned amount should attempt to capture any anticipated features above, below, and at the interface that may depend on the specific local geology;

- Target recovery of 5% core from the crystalline basement (approximately 15 9.1-m [30'] core runs for 3 km of basement);

- Coring equipment and methodology must be selected to assure core quality (i.e., minimize discing and breaking) and maximize core diameter (i.e., most wireline core types are too small);

- Minimize damage to core and invasion of drilling fluid into core while tripping core out of hole.

After reaching the surface, core handling will include the following requirements:

- Core depths will be marked on the core barrel or sleeve in the field.

- The core shall be cut into smaller lengths (e.g., 0.9 m [3']) for packing and shipment.

- Cuttings shall be done so the core can be unambiguously pieced back together, cuts shall be "island-cut".

- The cut sections will be sealed to stabilize the core and prevent dry-out or biological activity (care will be used to ensure any core sealants are compatible with proposed analysis methods and analytes of interest, and do not lead to biological fouling) – a portion of the core will be preserved with high-quality sealing methods as discussed below.

- A portion of each core run will be preserved under vacuum using helium-tight canisters that utilize metal-to metal seals and are flushed with ultra-high purity nitrogen gas to remove atmospheric gases and to preserve noble gases in core pore fluids.

- Core handling at the surface shall be video recorded.

## 3.8  Drilling Fluid (Mud) System

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). The drilling fluid functions are to cool and lubricate the bit, lubricate the drill string, remove cuttings from the borehole, provide filter cake or fracture plugging to limit sloughing and lost circulation, and control downhole pressure. Typical oilfield drilling fluid contains a suite of additives that control different aspects of the drilling process. For water-based circulation systems, additives are used to control the hydrostatic weight of the drilling fluid in the borehole (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 all proposed drilling fluid additives have on target analytes for *in situ* fluid sampling, coring, drilling fluid tracer, and borehole geophysics should be carefully considered. From the point of view of geochemical sampling, it is better to introduce as few chemicals as possible into the borehole. It is difficult to specify beforehand what chemical and physical interactions will occur between the drilling fluid additives, formation fluids, rock cuttings and flour, and makeup water. Minimizing the complexity of the drilling-fluid system is the preferred overall approach for the DBFT.

The drilling fluid used in the overburden section may be very different from that used in the target crystalline basement section. New mud will be prepared for drilling the 21.6 cm [8½"] diameter borehole. No reuse of mud from the overburden in the interest section is allowed. The mud from the overburden will be discarded and mud containers or pits will be cleaned before the mud for the crystalline basement is prepared. In the section of interest in the crystalline basement, tracers will be used. Tracer concentrations will be maintained through careful monitoring of the composition of the mud onsite.

The goals for the drilling fluid system include:

- produce minimal environmental impact;

- ensure maximum control over drilling progress, quality, and costs;

- ensure the fluid system is compatible for logging operations in each section of the borehole;

- ensure the fluid system is compatible with drilling fluid tracers and tracers to be used in later injection/withdrawal testing activities.

The primary objective of the borehole is to obtain useful high-quality geochemical, geomechanical, and hydrological data. Therefore, the drilling mud will be chosen to be as simple as possible, while still achieving the technical and scientific objectives. There will be some tradeoffs, but they should be clearly stated, and any options weighed.

The key factors affecting drilling mud selection are:

- dealing with any swelling clays or evaporate layers in overburden;

- maintain borehole stability while drilling, before setting casing (especially if there are wireline-based open-hole tests to conduct);

- ensure minimal mud losses will occur;

- the drilling mud (including all additives) must be compatible with the chosen tracer;

- the drilling mud (including all additives) must be compatible with the water chemistry and packer-based sampling and testing to be conducted in the interest section of the crystalline basement;

- reservoir damage is not a factor because this is not a hydrocarbon reservoir, and the interest formation will be fractured crystalline rock (not porous sandstone).

While alternative drilling fluid systems are possible, we propose a drilling fluid similar to that used in the KTB deep borehole. The drilling fluid would be high-viscosity and have shear-thinning characteristics, with minimal chemistry interference. This fluid would be relatively low density, meaning the borehole would either be drilled in an extremely underbalanced manner, or pressure could be increased through addition of NaCl salt. This drilling fluid system could include iodide and fluorescein as tracers.

Alternative drilling fluid systems could be air-based (e.g., as that used with down-the-hole hammer systems) or oil-based drilling fluid systems. SNL has preliminarily rejected these alternative drilling fluids for a simpler water-based system, since later packer-based hydrologic testing, geomechanical testing, tracer testing, and geochemical sampling would be made more difficult through introduction of other phases (e.g., water or oil) into the crystalline basement.

### 3.8.1 Makeup Water

The fresh water system should contain consistent and low levels of the tracers or ions that could complicate the interpretation of tracers prior to adding tracers (e.g., high bromide levels can complicate analyses of iodide). Whenever possible, a single source should be used for water and mineral additives (e.g., NaCl). Mineral additives will be analyzed for bulk composition including minor constituents for characterizing expected drilling fluid composition. The makeup water/NaCl ratio (density) will be documented during drilling, and the identities and masses of any other chemical additions will be logged.

The makeup water should be analyzed regularly during drilling for pH, conductivity, and all major elements (e.g. Na, Cl, Ca, Sr, $HCO_3$, $SO_4$, Sulfide, Si, Br, I) using standard analytical methods. Iodide in the makeup water might be analyzed by specific ion electrode. A one-time measurement of stable isotope composition in the makeup water should be performed (i.e., O, deuterium, C, S, N, and Fe). These analyses should be performed again if the source of the makeup water is changed or adjusted.

The site-specific D&TP should indicate what the source of the makeup water will be and indicate a preliminary compositional understanding of the water source. A single consistent source of water (e.g., a single groundwater well) would be preferred to changing or variable makeup water source. Will the makeup water source be able to supply sufficient quantity and consistent quality water for the expected duration of the project?

### 3.8.2 Solids Control

One of the most significant roles the mud plays is removal of cuttings. The drilling fluid must bring cuttings and rock flour to the surface, but then they must be efficiently removed from the drilling fluid before recirculating. The goal of solids control is to:

- maintain the drilling fluid by minimizing solids content, maintaining fluid density and rheological properties while removing and preparing solid and liquid waste disposal;
- perform testing and maintain auditable records for waste streams to assure they meet disposal requirements; and
- reduce drilling fluid losses and minimize waste volume by minimizing fluid content in the cuttings.

The solid control system comprises shale shakers, desanders (i.e., one or more hydrocyclones), desilters (i.e., multiple hydrocyclones) and centrifuges. The correct connection and setup of this equipment is essential to maximize separation efficiency. The solid control equipment is set up in a descending order, based on the particle size that each remove. Standard shale shaker removes particles 440 microns and larger, desanders remove particles 100 microns and larger, desilters remove particles 15 microns and larger, while centrifuges remove 4 to 8 microns and larger. There are several possible configurations and they depend on the exact drilling fluid system used. For a water-based polymer system, the drilling fluid system is classified as "unweighted drilling fluid".

Shale shakers are separators made of vibrating screens used to remove drill cutting from the drilling fluid, they are the first step in the solids removal chain and therefore the first line of defense against solid accumulation. They are the most important solid-control equipment, since if they do not operate properly all other equipment downstream will be subject to overloading and inefficient operation.

Desanders (cone size inside diameter 30 cm [12"]) and desilters (cone size inside diameter 10 cm [4"]) are "cyclone-type" centrifugal separators. They are fed at high flow rates by centrifugal pumps through a tangential opening into the large end of the funnel-shaped hydrocyclone, when the proper amount of pressure at the drilling fluid inlet is used, the drilling fluid will pass through the equipment expelling wet, higher density solids waste out the open bottom while returning the less dense liquid through the top of the hydrocyclone to the drilling fluid active system.

The decanting centrifuges consist of conical, horizontal steel bowls rotating at a high speed, with a screw-shaped conveyor inside. The conveyor rotates in the same direction as the outer bowl, but at a slightly slower speed. The solids are forced to the inside wall of the bowl and the conveyor pushes them to the end of the discharge.

Dewatering is the final step of the drilling fluid processing system, a dewatering unit is where the drilling fluid is chemically and mechanically treated to remove all the colloid-size solids from the drilling fluid, obtaining a solids waste flow that is discharged for disposal and an optically clear fluid that is ready for testing and final disposal.

A site-specific D&TP should present a detailed specification of the drilling fluid system, including listing of components and diagrams showing how all major components of the solids control system will be assembled on site.

## 3.9  Drilling Parameters Monitoring

Drilling parameters are to be logged and assimilated with the geophysical logs, the formation and fluid samples, and other data acquired during drilling the borehole. They will be used to further constrain the geology and borehole conditions encountered. The goal of drilling parameters monitoring is to:

- identify drilling anomalies in a fast and accurate manner;

- improve drilling efficiency; and

- minimize downtime.

The following drilling parameters (Table 2) are representative of those that will be continuously monitored, as a function of time and depth:

**Table 2. Drilling parameters**

| Hole depth [m] | Total mud volume [m$^3$] | Flowrate [l/min] |
|---|---|---|
| Bit depth [m] | Casing pressure [Pa] | Rotating time [hr] |
| Hook load [N] | Standard pipe pressure [Pa] | Circulating time [hr] |
| Weight on bit [kg] | Tank volume [m$^3$] | Hole azimuth [deg. from north] |
| Rotary speed [rpm] | Pump strokes [strokes/min] | Rate of penetration [m/hr] |
| Drag [N] | Block height [m] | |
| Torque [N-m] | Hole inclination [deg. from vertical] | |

The requirements of the drilling parameters monitoring platform that coordinates drilling parameters monitoring are:

• The acquisition system must be an integrated and customizable platform where all the drilling parameters can be monitored at the same time

• The platform must be able to integrate all the drilling parameters information coming from different sensors involved in the drilling process used by mudlogging, drilling rig, directional, open hole/cased logging and testing services.

- The platform must provide continuous drilling parameters at high frequency.

- Remote access to the platform must be possible from anywhere in the world.

- The platform must allow to stream data to advanced analysis applications.

- The platform must be a secure system where only authorized personnel are able to access.

- The platform must have configurable alarms on any drilling parameter.

A site-specific D&TP should present a detailed listing of the drilling parameters that will be monitored and illustrate how they will be collected and incorporated with other data streams from the borehole.

## 3.10 Cementing and Casing Hardware

The upper portions of the borehole must be cased and cemented to effectively isolate both shallow aquifers and deep saline formations from the open-borehole crystalline basement interest section. The goals for the cementing plan include:

- assure borehole integrity;

- provide isolation between the overburden and the basement; and

- protect and support the well casing and borehole.

The cementing operation will likely use a conventional slurry system, optimized using the results of caliper and other logs after each section is drilled. Cemented sections will have both a lead and a tail slurry formulation. The assumed fracture gradient (i.e., the profile of least principal stress with depth) should be stated for all cement operations. After cementing, a bond log will be run to assure the quality of the cement emplacement. An extended leak-off test (XLOT) will be performed at the shoe of the casing, after emplacing cement. The XLOT will ensure the cement seal is of sufficient quality and will provide information regarding the magnitude of the least principal stress in the formation below the shoe.

A site-specific D&TP will present a detailed listing of all the planned casing hardware, for the primary design and any significant alternative designs. The D&TP must also present detailed cement slurry specifications for each casing string and lead/tail slurry, including the volume, density, yield, and a list of additives to be included and their concentration.

## 3.11 Well Control

In the DBFT, the primary goal of the well control basis of design is to assure borehole integrity. In typical hydrocarbon wells, the operation is more concerned with preventing an influx of liquid or gas into the well from a trapped high-pressure reservoir. The DBFT will comply with any requirements of local regulations related to drilling, but we foresee a mostly hydrostatic pressure gradient in the crystalline basement interest section. For drilling the DBFT, the following well control assumptions seem prudent:

- A diverter will be used to drill the surface section, unless there are nearby offset well data to confirm there are no high-pressure shallow aquifers or hydrocarbon formations.

- Even if no hydrocarbons are expected to be found in the overburden section at the DBFT location, well control equipment selection and procedures will be selected as if the DBFT were a hydrocarbon exploration borehole.

- A BOP stack will be used once the surface casing is set and will be utilized if local regulations require it.

If there are plans to use a diverter when drilling shallow formations, the site-specific D&TP should list the specifications and assumptions related to the diverter. The conditions under which the diverter or BOP will be used need to be explicitly stated, along with related requirements and procedures to follow in these cases. Testing procedures for this safety equipment must be presented and included in the D&TP.

The site-specific D&TP should specify the well control system, including:

- criteria to be used for the selection of well control equipment;

- the minimum requirements for the well control equipment;

- the method of well control; and

- techniques, tools and training to maintain primary well control.

## 3.12 Sampling and Evaluation While Drilling

The goals are focused on accomplishing the science objectives for the CB. The sampling and analysis plan (Section 5) gives more detailed information regarding each analyte. The sampling and testing to be conducted during drilling include:

- running open hole geophysical logs;

- performing on-site mudlogging of the solid, liquid, and gas components of the drilling fluid;

- collecting samples of the drilling fluid before circulation (after addition of all drilling fluid additives) for laboratory analyses;

- collecting samples of the drilling fluid after circulation (before exposure of the drilling fluid to the atmosphere) for laboratory analyses;

- coring of the overburden-basement interface;

- recover 5% of total core from the crystalline basement; and

- perform a wireline-conveyed packer permeability and hydraulic fracture tests.

The site-specific D&TP should indicate the frequency, location, and sampling protocol for each of the required sample types.

### 3.12.1 Mud Logging

Mud logging includes sampling the drilling fluid as it comes to the surface for solid, liquid, and gas composition. Extensive mud logging is planned for the borehole since these data are unique and will be used later to interpret basement fluid and rock composition. Analyses will include both the data required to make real-time adjustments to drilling fluid composition, as required to maintain efficient and safe drilling, and to chronicle and preserve the progress of drilling and the formations encountered.

An on-site drilling fluids specialist will usually perform "mud checks" over the course of their shift. The specialist will collect a whole mud sample from the discharge line (flow line) for testing. This will allow discovering whether anything is occurring downhole that is having a negative impact on fluid properties or the drilling fluid is performing as planned. Their interpretation of those results will determine if any immediate remedial action is needed. This may encompass maintenance treatments to maintain mud properties, adjust treatment concentrations or possibly add additional mud additives. They may, under certain circumstances, collect a sample at the pump suction to obtain mud properties of the fluid headed downhole. This gives the mud specialist a baseline for understanding any changes in mud properties measured on samples collected at flowline.

In addition to the real-time analyses performed on-site by the drilling fluid specialist, samples will also be collected for later laboratory analysis of the analytes of concern in the borehole.

### 3.12.1.1 Drill Cuttings

Standard logging of drill cuttings provides a semi-continuous vertical profile of rock type, stratigraphy, mineralogical and textural characteristics encountered during the drilling process. This information can later be correlated with geophysical logging to calibrate the geophysical signal with geology in the borehole. Drill cuttings samples will be stored for possible future geochemical and petrophysical analysis.

For the basement section, cuttings samples collected at 3-m [10'] intervals, provide a semi-continuous vertical profile of crystalline basement lithology. Basic lithological information from the borehole is central to interpreting the geology and lithology of the site and providing information relevant to groundwater flow and radionuclide transport, such as porosity and sorption characteristics.

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, as done in the larger KTB borehole (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 and 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.

### 3.12.1.2 Drilling Fluid Chemical Properties

During drilling in the crystalline basement interest section and the basal formation of the overburden, the general mineral and general physical properties (e.g., temperature, pH, redox potential, major anions and cations, total dissolved solids) of the liquid component of drilling fluid will be monitored at a high frequency to qualitatively determine inflow and outflow zones, including changes in groundwater geochemistry. Drilling fluid composition will be tested and logged (i.e., mud logging) before it is recirculated with makeup water back into the borehole. Geochemical logging includes monitoring concentration of any added tracers.

### 3.12.1.3 Drilling Fluid Dissolved 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 (e.g., every 100 m [328'] 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.

### 3.12.1.4 Drilling Fluid Tracer (Basement Interest Section Only)

Additional drilling fluid is added to the drilling fluid system to maintain the required mud system volume as cuttings are removed. The chemistry of added makeup fluid will be monitored, and tracers will be added. The quantity and timing of tracer additions to the drilling fluid and makeup water will be logged, to maintain and document a relatively uniform concentration of tracers in the drilling fluid system. Conservative (i.e., non-sorbing and non-reacting) drilling fluid tracers will be used, which will not significantly alter drilling fluid chemistry. The log of the amount of tracer added to the system will help quantify drilling fluid losses in the system. Tracers will also be used to indicate both contamination of formation water samples pumped from higher-permeability crystalline basement portions of the borehole, and fluid invasion and contamination in cores.

Tracers can be added on a continuous basis, but confirmatory analyses should be performed approximately every 4 hours. This schedule is going to be dependent on the variation in the concentrations over time and the time required to perform the analysis. The recommended tracer are potassium iodide and fluorescein. All additions of drilling fluid tracer must be managed to ensure a consistent approach to ensuring uniform tracer concentration.

Potassium iodide is a good tracer but may concentrate over time where circulating rates and flow line temperatures are high. Evaporation rates in this borehole may be significant given that flow line temperatures of at least 77 °C [170 °F] could be expected. Additional samples of tracer concentration should be made at the beginning of each core run to quantify the tracer level in the drilling fluid, which may invade the core during retrieval.

Tracer requirements include:

- The concentration of the tracers must be held within a concentration range fixed by the formation water analysis program objectives.

- The tracers must not strongly adsorb to the rock being drilled under the expected temperature and geochemical conditions.

- The tracers must be stable over relevant time scales in the borehole and must not interfere with drilling fluid properties.

- Tracer testing would be performed throughout the duration of the drilling and coring operations in the crystalline basement interest section.

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- On-site monitoring of the tracer in the drilling fluid is required to ensure consistent concentrations.

- Tracers can be quantitatively measured in recovered waters at levels consistent with 1% filtrate contamination.

The site-specific D&TP should include the final selection of the drilling fluid tracers, should present a protocol for adding and monitoring the drilling fluid tracer. Depending on the drilling fluid system, the tracer, and the planned additives, some preliminary laboratory analyses may be needed to determine if there are any adverse reactions between the drilling fluid tracers and the planned drilling fluid additives.

### 3.12.2 Coring

The objectives are to core the overburden-basement interface and perform intermittent conventional coring which totals 5% of the total basement (nominally 150 m of core out of 3 km of basement). This amount of coring is not a hard requirement of the DBFT but is included more as a target for planning and budgeting. It is expected the recovery of intact core will be more difficult at greater depths (e.g., due to core discing). Any proposed methods for improving core recovery, which do not jeopardize borehole integrity, may be worth testing as part of the DBFT plan to improve the technical readiness level of relevant technologies.

#### 3.12.2.1 Overburden-Basement Interface Coring

The overburden-basement interface, and the upper 30 to 40 m of crystalline basement below this interface, are of special interest to hydrological, mechanical, and thermal assessments, and thus should be cored. The nature of the interface will likely be sharp (i.e., an unconformity), and therefore the choice of core point for optimal characterization should be chosen carefully. The variation of the basement immediately below the interface is of significant technical and scientific interest to the project. It is believed that most of the variability between the overlying sedimentary hydrological system and the crystalline basement hydrological system occurs at the top of the basement. The project hopes to capture core from this interval and perform hydrologic testing and sampling before setting casing into the upper crystalline basement.

One method to pick the coring point for the interface is through inferred prediction of the interface by correlation of lithology. A gamma ray logging-while-drilling tool could be included in the BHA to measure formation lithology while drilling. If a regionally consistent marker unit is known to exist at or immediately above the overburden-basement interface, this type of log may provide enough certainty of the depth to basement. A reference type log should be prepared from nearby offset wells and used as a lithologic guide to the lower portions of the overburden. When the gamma ray tool detects the expected lithology log pattern indicating the lower units of the overburden, drilling will be stopped. The risk in this approach is that the type log will be approximate and the correlation to the measured gamma ray data may be weak, so that drilling may not be stopped prior to the interface.

A more generally applicable method combines gamma ray lithology correlation with a direct acoustic measurement of the interface using a "look-ahead" vertical seismic profile (VSP). In a look-ahead VSP, drilling would be suspended 200 to 300 m above the expected overburden/basement interface. VSP data would then be acquired using a down-hole wireline receiving tool and a surface seismic source. Seismic energy will travel along a direct path to the VSP tool and will be reflected off of the high-contrast basement interface and received into the VSP tool. The acoustic impedance contrast at the interface will be very high, providing a strong seismic reflector. The VSP technique yields accurate velocity data for conversion of travel time to depth, thus predicting the vertical distance to the interface with an expected resolution of 6 to 12 m [20' to 40']. VSP data will be immediately processed and interpreted. Once the depth to the interface has been estimated, drilling may then proceed confidently to a point above the interface where coring will begin.

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The first approach is likely cheaper and may be adequate if there is consistent offset well data in the area of the proposed site. The second approach is likely more expensive but will refine the depth of the interface even if there are no nearby offset wells to constrain the depth to basement. The VSP data will also be useful in interpretation of any seismic surveys are conducted at the site. A site-specific D&TP should weigh the costs and benefits of the VSP to the costs of coring a larger amount of the lower overburden.

Assuming the overburden-basement interface is at 2 km [6,562'] depth, the following plan represents a possible use of VSP to constrain the coring point for the overburden/basement interface.

1) Drill to 1,800 m [5,900'].

2) Perform a conditioning trip and pull out of hole the BHA.

3) Perform a VSP survey to better estimate the top of basement depth.

4) Run in hole the drilling BHA and continue drilling until 9.1 m [30'] before the VSP estimated basement depth, while monitoring the lithology with the near-bit gamma ray sensor.

5) Pull out of hole the drilling BHA.

6) Perform a conditioning trip and start adding tracers to the mud.

7) Run into the hole the coring BHA.

8) Core 36.6 m [120'] (maximum length for coring barrel) across the basement interface and the upper portion of the crystalline basement.

9) Pull out of hole the coring BHA to surface and verify that the interface and an adequate amount of the underlying crystalline basement have been cored.

10) If no crystalline base is encountered, or if not enough of the underlying crystalline basement has been cored, run in hole coring BHA and keep coring.

11) Repeat these two steps until an adequate amount crystalline basement is cored (e.g., 9.1 m [30']).

12) Run geophysical logging tools and log the open hole portion of the borehole.

13) Using wireline-conveyed packer system, perform hydraulic tests and collect samples from permeable basal unit of overburden and at least one interval in the upper crystalline basement.

14) Possibly collect sidewall core from units of interest identified in geophysical logs that were not cored or might have had poor core recovery.

15) Determine from cores, hydraulic testing, and logs if crystalline basement encountered at bottom of hole is competent enough to set bottom of casing.

16) If competent crystalline basement has been encountered, run casing and cement.

17) Perform extended leak-off test (XLOT) to determine the least principle stress in the upper crystalline basement.

The site-specific D&TP should specify how they will ensure the overburden-basement interface will be cored, and the specific protocol that will be followed to capture this core and the core in the upper portion of the crystalline basement interest section.

### 3.12.2.2 Basement Coring

Advance coring will target recovery of 50 m of core per 1 km of basement (5% of crystalline basement interval). Coring activities will be coordinated, to the extent practical, to coincide with bit changes and other activities when drilling is stopped. Core points will be chosen to maximize the ability to interpret environmental tracers and other core data.

Core may be required from intervals other than those initially planned, based on fulfilling the science objectives of the DBFT. Core diameter will be of 10 cm [4"] to maximize the volume of rock cored for both extraction of pore water and gases for geochemical assessments and to provide representative rock samples for laboratory-based thermal, hydrologic, and mechanical properties testing. Measurements will be made of the types and relative orientation of fractures in the cores, and these observations should be considered before disturbing the core for other types of measurements.

The site-specific D&TP will provide the specifications of the coring system (i.e., the bits, core catching system, and coring bottom-hole assembly) to be used for intermittent advance coring of the crystalline basement. The D&TP must specify how the core will be handled, conveyed, and preserved as it comes to the surface and how/where it will be handled at the surface (i.e., in a laydown cradle and in a climate-controlled trailer). Provide a table of the estimated core points across the basement interest section.

### 3.12.2.3 Borehole Logging

There will be several open hole logging events. The logs to be run in each section will be coordinated to maximize understanding of the entire borehole system, while focusing characterization efforts on the interest crystalline basement interval (Table 3). Cased hole logging (i.e., cement bond evaluation) will be performed of previously cased at the same time, when appropriate.

Many standard open-hole tools are limited by borehole diameter (Nekrasov 1990), borehole fluid composition, temperature, and pressure (Hänel 1990). 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 expected to be approximately 150 °C [300 °F]. A field test location is being sought with typical or less-than-typical geothermal gradient, so the maximum downhole temperature is hoped to be less 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.

**Table 3. Proposed Geophysical Logs**

| 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 Log | Interval | Purpose |
| --- | --- | --- |
| Borehole Imaging (Caliper, Formation Micro-Resistivity Imaging, Borehole Televiewer, and Ultrasonic Borehole Imager) | 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. |
| 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. |

| Borehole Log | Interval | Purpose |
|---|---|---|
| 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. |

### 3.12.2.4   Surface Borehole Section

Logging Interval: surface to 460 m [1,500'] depth

- Deviation (azimuth and inclination)
- Borehole Imaging: Formation Micro-Imager (FMI), Borehole Televiewer, and Acoustic Caliper as applicable
- Borehole Caliper (taken from imaging)
- Resistivity
- Spectral Gamma-Ray (Thorium, Potassium & Uranium)
- Spontaneous Potential
- Neutron Porosity
- Bulk Density
- Shear-Wave Anisotropy
- Cement Bond Log in conductor casing

### 3.12.2.5   Intermediate borehole section

Logging Interval: 460 m to 2,060 m [1,500' to 6,760'] depth

- Deviation (azimuth and inclination)
- Vertical Seismic Profile
- Borehole Imaging: Formation Micro-Imager (FMI), Borehole Televiewer, and Acoustic Caliper as applicable
- Borehole Caliper (taken from imaging)
- Spectral Gamma-Ray (Thorium, Potassium & Uranium)
- Resistivity
- Spontaneous Potential
- Induced Polarization
- Photoelectric Factor
- Nuclear Magnetic Resonance
- Neutron Porosity
- Bulk Density

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- High-Resolution Temperature Survey

- Full Waveform Sonic (including Shear Wave Anisotropy)

- Cement Bond Log in surface 34-cm [13⅜"] casing

### 3.12.2.6  Crystalline Basement Upper Half

Logging Interval: 2,060 to 3,500 m [6,760' to 11,480'] depth

- Deviation (azimuth and inclination)

- Borehole Imaging: Formation Micro-Imager (FMI), Borehole Televiewer, and Acoustic Caliper as applicable. Especially image potential location for mini-frac near bottom of hole.

- Borehole Caliper (taken from imaging)

- Spectral Gamma Ray (Thorium, Potassium, Uranium Yields)

- Resistivity

- Spontaneous Potential

- Induced Polarization

- Photoelectric Factor

- Nuclear Magnetic Resonance

- Neutron Porosity

- Bulk Density

- Full Waveform Sonic (including Shear Wave Anisotropy)

- High-Resolution Temperature Survey

- Cement Bond Log in intermediate 24.4-cm [9⅝"] casing

### 3.12.2.7  Crystalline Basement Lower Half

Logging Interval: 3,500 m to 5,000 m [11,480' to 16,400'] depth

- Deviation (azimuth and inclination)

- Borehole Imaging: Formation Micro-Imager (FMI), Borehole Televiewer, and Acoustic Caliper as applicable. Image orientation of any induced fractures from mini-frac.

- Borehole Caliper (taken from imaging)

- Spectral Gamma Ray (Thorium, Potassium & Uranium)

- Resistivity

- Spontaneous Potential

- Induced Polarization

- Photoelectric Factor

- Nuclear Magnetic Resonance

- Neutron Porosity

- Bulk Density

- Shear Wave Anisotropy

- High-Resolution Temperature Survey

The site-specific D&TP will provide specifications for each of the downhole tools that will be used to perform the logging. Each tool should be appropriately selected and sized for the borehole diameter, drilling fluid, and pressures, and temperatures expected in each section of the borehole. The D&TP will provide estimates of logging rates and total logging times for each type of log.

### 3.12.3 Wireline-Based Downhole Hydraulic and Mechanical Testing

Hydraulic testing will be conducted using a wireline-conveyed packer system or equivalent. Hydraulic testing and water sampling will be done in sufficiently high-permeability intervals as the equipment allows.

Hydraulic packer tests are planned for the basal unit of the overburden and at least one interval in the upper crystalline basement that will be cased off. It is expected there will be a sharp geologic transition between the overburden and the crystalline basement, so this testing is to assess whether the hydraulic properties and the water chemistry also changes significantly across this boundary, and into the upper reaches of the crystalline basement.

Hydraulic fracturing (i.e., mini-frac) packer tests are planned in lower-permeability rock, for example approximately the midpoint depth through the crystalline basement (3,500 m [11,480'] depth). This will provide information on the least principal stress, which can be used during drilling the lower portion of the crystalline basement, and to provide early information that may inform decisions about the feasibility of nearby follow-on boreholes. The

Section 5 provides more information on the sampling and analyses associated with the wireline-based packer testing. The site-specific D&TP should give specific protocols for the execution of the planned tests. Special consideration should be given to the stability of the open-hole sections of the overburden, which will not yet be cased, while performing tests on the lower portions of the sedimentary overburden and upper portions of the crystalline basement. One possible approach is to drill the lower portions of the overburden and upper portions of the basement initially at a smaller diameter. The diameter of this initial pass would depend on the capabilities of the wireline-based packer system. After testing is complete, this region would be reamed out to its final diameter immediately before setting casing at its final diameter.

## 3.13 Wellhead

Although the DBFT is not a typical hydrocarbon production well, it may have a wellhead installed to accommodate any well control requirements given by local laws. If needed, the wellhead will

- assure and provide well integrity;

- isolate annuli among the various casing sections;

- provide support for the BOP;

- provide a sealed connection and support for each casing section; and

- perform well testing while maintaining well integrity.

The site-specific D&TP will specify the equipment that will be involved in the wellhead and include drawings of the wellhead design. A master valve will be placed to allow possible rigless operation after completion.

# 4 OPEN HOLE TESTING VIA TUBING-DEPLOYED PACKERS

This section describes the approach for conducting hydraulic, geomechanical, geochemical, and other tests to obtain the critical data needed to meet the six primary CB science objectives, including the following tests:

- multiple low-permeability hydraulic tests (e.g., packer pulse tests) to characterize the hydraulic properties of the non-fractured crystalline rock;

- a high-permeability hydraulic test (pumping test or other appropriate test) in a porous and permeable formation at/near the base of overburden, while drilling, to characterize hydraulic properties of the formation and to collect water samples for chemical analysis;

- multiple high-permeability hydraulic tests (pumping test or other appropriate test) in fractured intervals in the crystalline rock to characterize hydraulic properties of the fracture intervals and to collect water samples for chemical analysis;

- an open borehole fluid logging test across the entire open borehole crystalline rock section to identify fractured intervals for subsequent hydraulic testing;

- multiple hydraulic fracturing stress measurement tests (i.e., mini-frac) to characterize the stress regime through the crystalline rock section, in addition to one test in the upper portion of the crystalline rock while drilling;

- two push-pull tracer tests in the crystalline rock, including one in the upper portion and another near the bottom of the crystalline rock.

The goals of the packer-testing program in the DBFT are to conduct a technology readiness demonstration, rather than to exhaustively characterize the entire length of the borehole for the disposal of radioactive waste at a particular site. Stemming from this motivation, a relatively small number of tests repetitions are proposed, of various different types, to assess the efficacy of different testing methods under relevant conditions. The specific conditions in the DBFT that will require demonstration are: testing and sampling at the end of a long tubing string (i.e., 3 to 5 km), under elevated hydrostatic pressure (i.e., 30 to 60 MPa [4,300 to 8,700 psi]), under elevated temperature (i.e., up to 150 °C [300 °F]), and in a possibly highly-stressed rock with extensive borehole breakouts. The end result of the DBFT will be a recommended path forward for future characterization projects at other sites, rather than an in-depth characterization of the appropriateness of a particular site for future deep borehole disposal of radioactive waste.

The packer-based testing program must plan for the presence of borehole breakouts. Some breakouts may be avoided by picking testing intervals that contain fewer breakouts. In lower portions of the borehole, breakouts may be unavoidable. The testing plan should develop and possibly test contingency plans for situations where borehole breakouts exist across much of the borehole. This is one of the areas where developments or testing DBFT hopes to inform future deep crystalline drilling and testing programs. Methods for dealing with breakouts should minimally affect the long-term condition of the borehole. Leaving stuck tools or cement in the borehole should be avoided, if possible.

The following summarizes a possible sequence for *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.

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

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- 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.
    - Before pumping, monitor transient pressure response in packer interval to estimate static formation pressure.
    - 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.
    - 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.
    - Collect large-volume fluid samples at surface for water quality testing and collect small-volume down-hole pressurized samples.
    - Monitor recovery of interval pressure, temperature and packer inflation after end of testing to further constrain formation hydraulic properties and estimate static formation pressure.
    - Retrieve packers and pressurized fluid sample (replacing pressurized fluid sample containers) before moving packer tool to next high-permeability test interval
- 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).
    - Before perturbing interval pressure, monitor transient pressure response in packer interval to estimate static formation pressure.
    - 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.
    - Monitor recovery of interval pressure, temperature and packer inflation after end of testing to further constrain formation hydraulic properties and estimate static formation pressure.
    - Move packers directly to next low-permeability test interval.
- 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, if possible.
    - Before pumping, monitor transient pressure response in packer interval to estimate static formation pressure.
    - 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.

- 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 fully mixed, regularly monitoring fluid temperature, and sample mixed fluids for laboratory analysis.

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

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

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

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

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

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

- 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).

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

- 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.

- 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.

- 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.

- Move hydraulic fracture stress measurement testing packer system to next interval.

- Demobilize testing equipment (i.e., workover rig) from borehole.
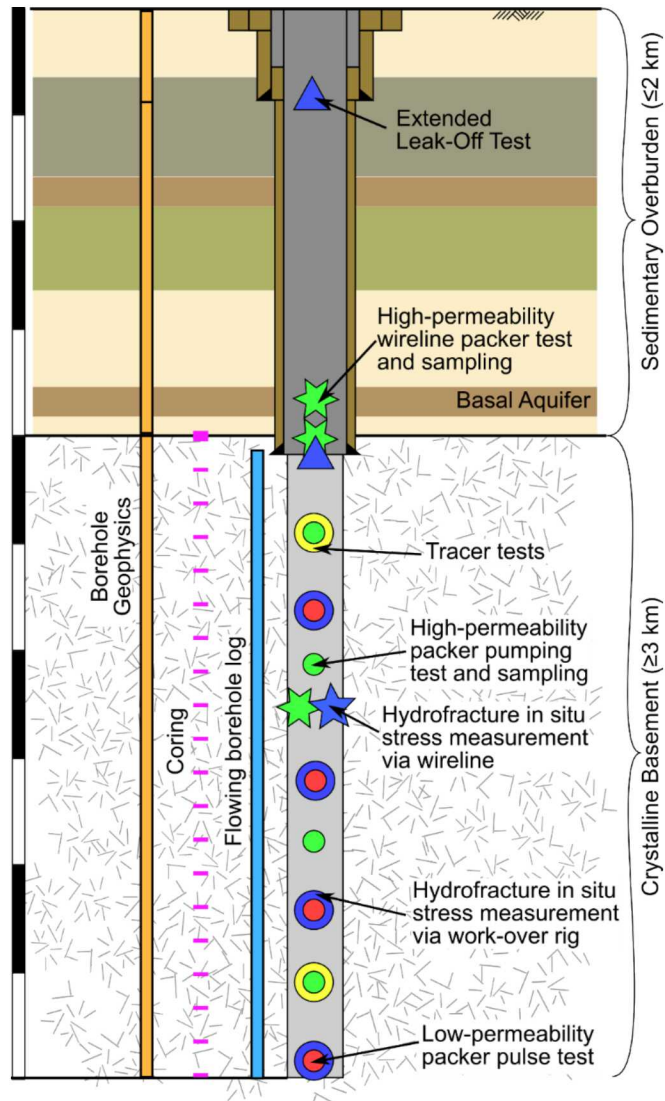
**Figure 3. CB schematic with nominally located tests and samples. Polygons represent tests conducted during drilling, circles represent tests via tubing-deployed packer system (SNL 2016b).**

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.

The site-specific D&TP should include a preliminary design of these experiments, including engineering drawings of all plumbing and pre-test numerical modeling to illustrate the expected range of behaviors. Analysis methods must accommodate the presence of possibly high-temperature, high-salinity fluids, and must incorporate the observed pressure history in the borehole as part of the analysis. Analysis of low-permeability intervals (and likely high-permeability intervals too) requires careful testing and analyses methods. Borehole pressure histories should be recorded at a high frequency in the borehole, and in any tested intervals before, during, and after all hydraulic testing. Interpretation approaches should consider successful methods, such as those used in low-permeability sedimentary rocks in Canada (Intera 2011; Beauheim et al. 2014).

It will be important to begin sampling and testing intervals in the borehole as quickly as possible, to minimize contamination, but the urgency in proper scheduling of the tubing-based packer testing program will not be as high as the drilling and wireline-based testing program.

## 4.1 Open-Hole Fluid Logging Test

Before any intervals are picked for tubing-deployed packer testing, an open-hole fluid logging test will be conducted to ensure the highest-permeability zones in the borehole are identified without requiring exhaustive packer testing of the entire open borehole interval.

This section provides a technical discussion and considerations for the design, performance and analysis of Flowing Fluid Electrical Conductivity (FFEC) logging surveys within the open crystalline basement interest section (i.e., nominally from 2 to 5 km depth). The primary objective of performing the FFEC surveys is to provide a rapid means of determining the permeability profile distribution over large open borehole basement sections within the CB, particularly where the crystalline basement section's permeability is localized by relatively widely-spaced, fluid-conducting, discrete fracture systems that collectively possess a composite borehole transmissivity of $10^{-5}$ m$^2$/sec, or less. For these environmental conditions, standard dynamic flowmeter surveys that are commonly used for reconnaissance-level, open borehole permeability profile characterization are not feasible due to either associated low-flow, borehole velocity conditions (i.e., velocity resolution limitations for conventional spinner, full-bore velocity flowmeters) or anticipated testing conditions exceeding instrument operational capabilities (e.g., heat-pulse flowmeters).

Because of these performance limitations presented by standard, commercially-available flowmeter logging, the FFEC survey characterization method was developed initially as a collaborative effort in the late 1980's and early 1990's between Nagra and the U.S. DOE for the purpose of rapidly determining the permeability/depth profile over large open borehole sections (i.e., ~1,000 m) in deep Nagra boreholes drilled in support of Swiss nuclear repository characterization studies. Examples of the collaborative effort in development of the FFEC characterization method include: Hale and Tsang (1988), Tsang and Hufschmied (1988), and Tsang, et al. (1990). In Europe, deep borehole characterization examples (i.e., for boreholes >700 m depths) generally demonstrate that the FFEC method compares favorably with other detailed hydrologic characterization test results (e.g., packer tests, flowmeter surveys). These comparisons are provided in: Tsang et al. (1990), Kelley et al. (1991), Guyonnet et al. (1993), Adams and Wyss (1994) in Switzerland; Tsang et al. (2016), Doughty et al. (2017) in Sweden; and Sharma et al. (2016) in Finland. Similar comparative results have also been demonstrated for the FFEC characterization method for more shallow borehole depths (i.e., ≤500 m) and include: Pedler et al. (1990), Paillet and Pedler (1996), Doughty and Tsang (2005), Beauheim and Pedler (2007), and Doughty et al. (2005, 2013).

Briefly stated, the FFEC logging characterization method is implemented by first emplacing a uniform and contrasting fluid salinity profile (i.e., in comparison to fracture fluid salinity) within the open borehole interval. In most deep borehole applications where the crystalline basement rocks contain elevated formation fluid salinities, a low-salinity borehole emplacement water (e.g., 60 to 300 μS/cm) is commonly utilized. Following emplacement of the contrasting borehole fluid, the ambient, pre-test fluid electrical conductivity and fluid temperature vs. depth profile characteristics within the borehole are determined utilizing a commercially-available FEC and fluid temperature wireline probe/recording systems. Following completion of the ambient, pre-test logging surveys, the FFEC test is initiated by removing fluid from the borehole at a low and constant rate (e.g., 2 to 20 L/min). Borehole fluid removal during FFEC testing is usually accomplished by utilizing a submersible pump installed at a depth commonly ≤ 250 m below static fluid level conditions. To facilitate analytical considerations and minimize test uncertainties, multiple constant-rate pumping steps (e.g. 2 to 3) are utilized during performance of the FFEC test, with a combined pumping test period duration ranging between 1 and 7 days. FFEC wireline logging is accomplished utilizing an access tube (e.g., oil-field "Y-tool") to by-pass the set submersible pump within the borehole.

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The FFEC characterization method has exhibited some developmental refinements pertaining to its implementation and analysis approaches from what was originally reported in Tsang and Hufschmied (1988) and Tsang et al. (1990). The most current and complete summaries on implementing FFEC surveys within deep boreholes are contained in Tsang et al. (2016), Dobson et al. (2016), and Doughty et al. (2017).

Briefly stated, the FFEC logging characterization method is implemented first by emplacing a uniform and contrasting fluid salinity profile (i.e., in comparison to fracture fluid salinity) within the open borehole interval. To minimize incursion of non-formational emplacement water into surrounding intersecting fracture systems, the emplacement fluid is administered near the base of the test interval at a prescribed low injection rate, while simultaneously removing fluid from the well at the same rate near the top of the fluid column (Figure 4a). The simultaneous injection of emplacement fluid (at the base of the test interval) and removal of well water from near the top of the fluid column using the same rates, minimizes borehole pressure buildup and incursion of non-formation well fluid into permeable fractures. The incursion of non-formational borehole fluid into surrounding hydraulically-conductive fractures complicate analysis of the FFEC profiles that evolve during the dynamic pumping phase of the test. In most deep borehole applications where the crystalline basement rocks contain elevated formation fluid salinities, a low-salinity borehole emplacement water (e.g., 60 to 300 μS/cm) is commonly utilized.
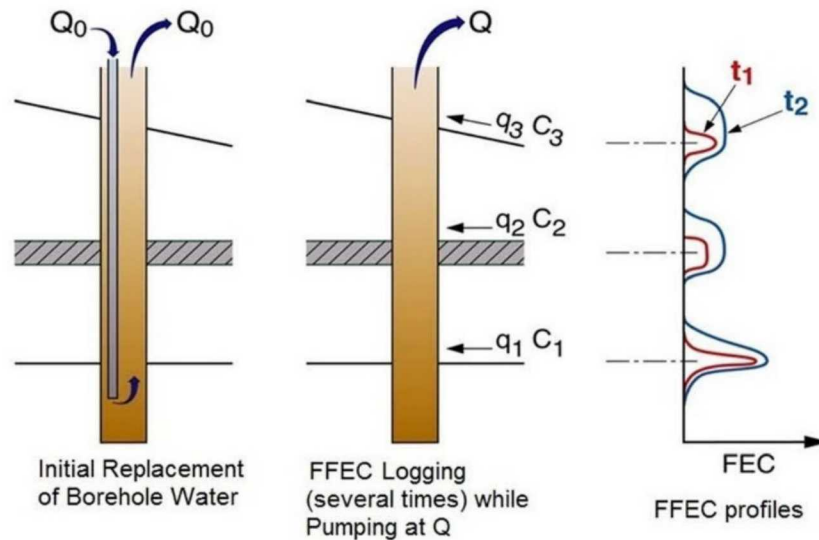


**Figure 4. Schematic of FFEC Logging Survey (Doughty et al. 2017).**

Following emplacement of the contrasting borehole fluid, the ambient, pre-test fluid electrical conductivity (FEC) and fluid temperature vs. depth profile characteristics within the borehole are determined utilizing a commercially-available fluid electrical conductivity and temperature wireline probe/recording systems. The FFEC profile surveys are commonly logged using a stacked, multi-probe assembly system that includes sensors for not only measuring FEC and temperature, but also for fluid pressure, and formational depth indicators (e.g., gamma ray).

It should be noted that FEC is only an indicator of fluid salinity concentration and is influenced not only by the dissolved solid content, but also by the effects of temperature. FFEC measurement profiles collected over an extended borehole length can exhibit significant temperature variation, and therefore, need to be corrected to a standard reference temperature value (e.g., 20 or 25 °C). This is accomplished by interpolative use of electrical conductivity vs. temperature calibration relationships established in the laboratory for the specific sensor used in the FFEC surveys or through use of empirical, scientifically-established electrical conductivity vs. temperature relationships.

Following completion of the ambient, pre-test logging surveys, the dynamic phase of the FFEC test is initiated by removing fluid from the borehole at a low and constant rate (e.g., 2 to 20 L/min). The constant extraction of water from the well causes the composite hydraulic head within the well to decline with time, which induces fluid flow from hydraulically-conductive fractures (having higher hydraulic head) to the well (Figure 4b). Borehole fluid removal during FFEC testing is usually accomplished by utilizing an electrical submersible pump installed at a well depth commonly ≤ 250 m below static fluid level conditions. To facilitate analytical considerations and minimize test uncertainties, multiple constant-rate pumping steps (e.g. 2 to 3) are utilized during performance of the FFEC test, with a combined pumping test period duration generally ranging between 1 and 7 days. FFEC wireline logging is accomplished utilizing an access tube (e.g., oil-field "Y-tool") to by-pass the set submersible pump within the well.

As an alternative to fluid extraction using a submersible, air-lift/evacuation pumping can be utilized where compressed air is administered via a conductor pipe (usually through a centrally-installed injection tubing), and fluid removed/evacuated from the well using the existing well casing, along with a surface wellhead enclosure to divert well flow. FFEC wireline logging in this case is conducted through the central injection tubing using a surface stuffing box or wellhead lubricator mounted on the top of the injection tubing. Multiple-pumping rates can be implemented by lowering the injection tubing to greater depths, which will impose greater drawdown in the well and a higher subsequent well discharge rate.

During the pumping or dynamic "flowing" period, multiple FFEC profile surveys are logged (2 to 5 up/down FEC logging passes per each individual constant-rate pumping step) across the selected open borehole characterization section. The comparison of repeated logging results obtained progressively during the pumping period establishes changes to the FFEC depth profile within the borehole over time. The inflow of fluid from hydraulically conductive fractures (which have significantly different salinities from the initially emplaced, pre-test borehole fluid) generate discernable FFEC peak patterns that evolve and expand over time within the borehole depth interval during the FFEC test period. Analysis of the evolving FFEC patterns provides a wide-spectrum of information for hydraulically-conductive fractures intersected by the borehole, including:

- Precise inflow/outflow location depths

- Inflow rates and fracture fluid salinity

- Fracture hydraulic head conditions

Fracture inflow location depths are delineated by the FFEC peak locations and relative skewness of the profile pattern. Fracture inflow rates and fluid salinities are determined analytically or numerically (e.g., BORE II; Doughty and Tsang, 2002) through analysis of repetitive FFEC profile runs. Fracture hydraulic head relationships are discerned by comparing the analysis results for repetitive FFEC profile runs with similar comparisons derived during multiple pumping steps. FFEC-derived analysis results obtained for $q_i$ and $h_i$ are then used with standard transient and steady-state analytical equation relationships to determine discrete fracture transmissivity and hydraulic conductivity.

The site-specific D&TP should include a design for the open-hole logging test that accommodates the depth, diameter, and expected conditions of the crystalline basement interest section. Fluid electrical conductivity logging tools with sufficient resolution for the expected conditions should be identified. Alternative approaches using temperature as a tracer, and using distributed fiber optic sensing systems, may be proposed and even compared to the more traditional FFEC logging method.

## 4.2 Low-Permeability Interval Packer Tests

Lower-permeability intervals will not support significant pumping or sampling and will only be hydraulically tested using pulse, slug, or multi-step constant head withdrawal 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.

This section describes the data objectives of the low-permeability hydraulic tests. To achieve the CB primary science objectives, several hydraulic parameters must be quantified. The key parameters are those that characterize:

- the ability of the bulk rock to transmit water (transmissivity, hydraulic conductivity, and permeability);

- the capacity of the rock to store water (storativity and pore or fracture compressibility);

- the direction and magnitude of the hydraulic gradient, which is the driving force for water movement (static pressure profile);

- the size and hydraulic properties of the disturbed rock zone (DRZ) surrounding the borehole that could be a preferential pathway for water migration (skin thickness, hydraulic conductivity and storativity); enhanced;

- the effective size of the flow system (test radius of influence, boundaries).

Approximately five low-permeability zones in the crystalline rock will be tested. The test intervals will be selected after investigation of the cores and the borehole logging results. The intervals including intact rock (matrix) or non-fractured zones would be suitable intervals for low-permeability testing. In addition, the borehole section must be appropriate to be isolated by the packer elements. This means, the borehole diameter must be consistent and appropriate to the maximum sealing diameter of the chosen packer elements which is also dependent on the inflation pressure of the packers. The existence of open breakouts or spalled regions at the sealing sections will increase risk of damage and failure of the packer elements. The existence of a highly developed DRZ could lead to packer by-pass through the formation and preclude proper test interval isolation. To choose suitable test intervals, image logs, caliper logs, and any available core will be inspected.

## 4.3 High-Permeability Interval Packer Tests

Packer-based pumping tests will be conducted to estimate formation permeability and storage or compressibility properties. The pumping tests will be conducted in any 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 and 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 (Section 5.11). 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.

The high-permeability hydraulic (pumping) tests in the crystalline basement will use a tubing-deployed straddle-packer tool, a pump that brings samples to the surface, and other associated equipment. Although formation water samples will be conducted in conjunction with the high-permeability hydraulic tests, the approach for collecting formation-water samples from the high-permeability zones is described in Section 5.11. The testing approach described in this section could also be used to characterize the hydraulic and geochemical properties of the porous and permeable formation at/near the base of overburden; however, testing/sampling of the overburden zone will be performed while the drilling rig is present and will use a wireline-conveyed packer system. This approach is described in the sampling and analysis plan Section 5.11.3.

This section describes the data objectives of the high-permeability hydraulic tests. To achieve the CB primary science objectives, several hydraulic parameters must be quantified. The key parameters are those that characterize:

- the ability of the bulk rock to transmit water (transmissivity, hydraulic conductivity, and permeability);

- the capacity of the rock to store water (storativity and pore or fracture compressibility);

- the direction and magnitude of the hydraulic gradient, which is the driving force for water movement (static pressure profile);

- the size and hydraulic properties of the DRZ surrounding the borehole that could be a preferential pathway for water migration (skin thickness, hydraulic conductivity and storativity);

- effective size of the flow system (test radius of influence, boundaries).

## 4.4 Hydraulic Fracture Stress Measurements

Geophysical logs (i.e., anisotropic shear log), wireline-based hydraulic fracturing stress measurements (i.e., mini-fracs) and extended leak-off tests will be performed in the crystalline basement interval before reaching total depth to estimate the horizontal principal stresses, and to evaluate the variation of *in situ* stresses with depth. They will be used in conjunction with observations of borehole breakouts and drilling-induced tensile fractures (e.g., formation micro-resistivity image log, borehole televiewer) 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 and geothermal industries, 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 (Xie et al. 2015). Hydrofracture well stimulation is a high-flowrate, high-pressure, high-volume method that includes a mixture of chemicals and proppant (e.g., 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 called "mini-fracs" when performed in the oilfield to estimate *in situ* stress.

At least one wireline-based hydraulic fracture stress measurement will be made before reaching total depth. Extended leak-off tests will be conducted after setting casing strings. Further hydrofracture stress measurements will be made after drilling is complete, including both standard hydrofracture stress measurements made on unfractured intervals, and re-opening tests conducted on pre-existing fractures of various orientations. 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.

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.

Tubing-deployed packer hydraulic fracturing stress measurements will be conducted in relatively low-permeability rock (degree of fracturing may be confirmed by coring and borehole televiewer). 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.

During hydraulic fracturing stress measurements, intact rock formation is exposed to an overpressure until the initiation of a tensile fracture at the borehole wall. Initiated fractures develop perpendicular to the minimum horizontal principal stress if the vertical principle stress is not the least principle stress. The orientation of the induced or stimulated fractures in deep boreholes is usually determined with ultra-sonic or electrical imaging devices. Thus, the magnitude and direction of the *in-situ* stress regime can be estimated.

Hydraulic testing of pre-existing fractures is performed in borehole sections with pre-existing fractures with different orientations with respect to the orientation of the principal stresses. By fluid injection into a sealed-off borehole interval containing such a fracture, the fracture will open as soon as the fluid pressure exceeds the normal stress acting across the (arbitrarily oriented) fracture plane. Together with data on the orientation of the stimulated fractures, the *in-situ* stress tensor can be estimated through an inversion technique.

Although the method of hydraulic fracturing has successfully been applied in thousands of boreholes, the database on hydraulic fracturing campaigns in very deep boreholes of more than 2 km depth still is limited. Thus, the conduction of hydraulic fracturing tests during the DBFT contributes essentially to the understanding of tectonics at greater depths. However, due to the challenging conditions at great depth, the equipment needs to be specifically designed to meet the requirements of high temperatures and ambient pressures. The careful prediction of the *in-situ* conditions and the selection of proper materials, tools and testing the equipment under similar conditions prior to *in situ* testing minimizes risks during the field campaign.

## 4.5 Push-Pull 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, identify any possibly reactive fracture fill or alteration materials, 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, and with different mineral components of the rock, will lead to preferential retention via sorption or ion exchange processes that may have 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 (with possible fracture infill or alteration products) and microfractures in the rock matrix play in solute transport through the borehole DRZ.

Before each test, preparations 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 push-pull part of the test starts with a pulse-type injection of a tracer solution (push) followed by extraction (pull) of water/tracer mixture from the same interval (Istok et al. 1997). This method is used in geothermal boreholes especially during the exploration phase of geothermal heat to study the energy reservoir (Pauwels et al. 1992). The advantage of single-well tracer tests is that they provide flow reversibility, which may be argued to be an advantage for the identification and quantification of time-dependent processes such as matrix diffusion or sorption.

The constant flowrate injection is followed by injection of non-traced formation water (chaser) at same constant flowrate. The chaser injection aims to push the tracer into the formation instead of injecting larger volumes of tracer solution to overcome the tubing and interval dead volume. Nordqvist et al. (2012) suggest the use of chaser to obtain more complete breakthrough curves. Hebig et al. (2015) studied the effect of the chaser in push-pull tracer tests injection. Neither the shape of the tailing nor the tracer mass balance is negatively affected by the application of a chaser (Hebig et al. 2015).

A rest period (no pumping or injection) will follow the chaser 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. to displace formation fluid with tracer;

3. to chase tracer with formation fluid; and

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.

The disadvantage of the push-pull test is the rather small radius of investigation and thus a reduced fracture volume of the test. Besides, the use of a chaser in a push-pull test would lower the main peak breakthrough due to mixing of the two fluids and dispersion/dilution among them (Hebig et al. 2015). In addition, by using a chaser, the shape of the tracer plume within the aquifer is shaped more like a donut (Hall et al., 1991) instead of a cylinder form.

Examples for single-well tracer tests can be found in Nordqvist & Gustaffson (2002) or in the work of Pauwels et al. (1992), Pauwels (1997) from the geothermal hot dry rock project in Soultz. The testing method is described in Istok et al. (1997). Schroth et al. (2001) propose an *in-situ* evaluation of solute retardation using a push-pull test.

# 5   SAMPLING AND ANALYSIS PLAN

This section presents a sampling and analysis plan for the collection and analysis of rock, fluid, and gas samples that will provide useful physical or geochemical information from drilling activities performed during the DBFT. This sampling and analysis plan describes the objectives of sampling activities, and sample collection methods and sample analysis procedures. The sampling and analysis plan also describes project management, quality assurance/quality control (QA/QC) assessment and oversight of the project, and QA/QC protocols necessary to achieve project objectives.

The purpose of the activities at this DBFT project site is to conduct rock, fluid, and gas sampling necessary to demonstrate a methodology for characterizing the geology and hydrogeology of the borehole to determine the feasibility of long-term radioactive waste storage. In addition, testing will be performed on the borehole to obtain hydrologic and geologic information near the borehole. Many of the samples will be collected in the crystalline rock formations encountered with the borehole, but testing will also be performed in the unconsolidated overburden.

**Table 4. Sample Analyses Summary**

| Matrix | Analyses |
|---|---|
| Basal Unit of Overburden Formation Water | Anions |
| | Cosmogenic/Anthropogenic Isotopes |
| | Isotopic Ratios |
| | Metals |
| | Noble Gases |
| | Stable Isotopes |
| | Trace Elements |
| | Water Quality Parameters |
| High Permeability Zone Water | Anions |
| | Cosmogenic/Anthropogenic Isotopes |
| | Isotopic Ratios |
| | Metals |
| | Noble Gases |
| | Stable Isotopes |
| | Trace Elements |
| | Water Quality Parameters |
| Drill Cuttings | Weight-% of 10 major and minor element conc., and trace element conc. |
| | XRD Spectral Images |
| Rock Flour | Weight-% of 10 major and minor element conc., and trace element conc. |
| | XRD Spectral Images |
| Drilling Fluid | Anions |
| | Metals |
| | Stable Isotopes |
| | Trace Elements |
| | Water Quality Parameters |
| Drilling Fluid Gases | Gases |
| Drilling Fluid Tracers | Tracers |
| Drilling Fluid Makeup Water | Water Quality Parameters |
| Drilling Fluid Tank/Pit Water | Anions |
| | Metals |

| Matrix | Analyses |
|---|---|
| | Stable Isotopes |
| | Trace Elements |
| | Dynamic and Static Poisson's Ratio |
| | Uniaxial Compressive Strength |
| | Average Crystal (grain) sizes of 10 possible mineral constituents |
| | Average Modal Percentages of 10 possible mineral constituents |
| | Bulk Density |
| | Bulk Modulus |
| | Compressional Velocity |
| | Diffusivity |
| | Dynamic and Static Young's Modulus |
| | Energy-Dispersive X-Ray Spectra of elements |
| | Fracture Fillings for Mineralogical and Isotopic Compositions |
| | Grain Density (g/cm$^3$) |
| | Heat Capacity |
| | Liquid Permeability (mD) |
| | Hydrostatic Compressive Strength |
| | Lithium 6/7 isotope ratio |
| | Lithium total concentration |
| | Lithologic Classification |
| | Modal Porosity Percentage |
| | Oxide wt-% of 10 major and minor element conc., trace element conc. |
| Core Samples | Photomicrographs |
| | Pore Radius |
| | Pore Space Fraction |
| | Pore Volume |
| | Porosity (%) |
| | Porosity Description |
| | Quartz Helium 3/4 isotope ratio |
| | Quartz inclusions |
| | Range of Crystal (grain) sizes |
| | Rock Fabric |
| | Shear Modulus |
| | Shear Velocity |
| | Strontium 86/87 isotope ratio |
| | Thorium total concentration |
| | Thermal Conductivity |
| | Thermal Expansion |
| | Triaxial Compressive Strength |
| | Uranium 234/238 isotope ratio |
| | Uranium total concentration |
| | XRD Spectral Image |
| | Anions |
| | Fission Products Isotopes |
| Core Porewater | Radiogenic/Nucleogenic Noble Gas Tracers |
| | Trace Elements |

## 5.1 Sample Identification

A consistent identification system must be created for all samples collected as part of the project, to allow tracking and reference. Samples should have consistent labels that help to ensure all proper fields and metadata are acquired and saved. A consistent depth scale should be used for all depth-specific samples. Measurements (e.g., depths) should be rounded consistently, and all depths should reference the same source (depth below land surface vs. depth below kelly bushing), or the depth datum should be stated explicitly. Dates and times should be written in a consistent and unambiguous format (e.g., 24-hour time format). Field duplicates and trip blanks will be identified with "FD" or "TB" appended to the end of the identification (ID) number. Subsamples should be indicated in a manner to trace them back to their parent sample. Samples from a depth range (i.e., packer-isolated intervals or cores) should indicate the entire range in their depth, not just the top or bottom.

Each sample should have a unique identifier, that is consistent across all data collected for the project, encodes key metadata in the sample id (e.g., sample depth and date/time), and facilitates identification of the data in an electronic database.

## 5.2 Sample Packaging, Shipment, and Chain of Custody

After samples are collected in the appropriate containers and labeled, each fluid sample will be placed in re-sealable plastic bags and then placed into a sample cooler (containing ice, if required). All glass sample containers will be protected with bubble wrap to minimize the chance of breakage. Canisters or tubes with gas samples will be placed in a sunlight-protected environment after attaching labels to individual canisters with pertinent information.

## 5.3 Sample Custody

Samples will be recorded on chain-of-custody (COC) forms using the sample ID scheme described above. COC forms will be completed using permanent ink so that entries are legible. Any errors made by the individual completing the COC form shall be crossed out with a single line, initialed, and dated. The COC form serves as the legal documentation of the sample custody because it records the transfer of custody of the samples from personnel collecting the samples to the field and analytical laboratories.

Each sample is considered in the field personnel's custody if any of the following are true:

- The sample is in the person's physical possession.
- The sample is in view of the person after that person has taken possession.
- The sample is secured so that no one can tamper with the sample.
- The sample is secured in an area that is restricted to authorized personnel.

The COC form will be signed by the individual responsible for custody of the sample containers, and the original will accompany the samples to the laboratory. One copy of the COC form will be kept by the project manager and/or the quality assurance officer and included in the project files. Information to be recorded on the COC form should include the following:

- Sample matrix
- Sample collector's name
- Dates/times of sample collection
- Sample IDs (following a uniform convention)
- Number and type of containers for each sample aliquot
- Type of preservation

- Laboratory QC sample designation
- Analysis method
- Special handling instructions
- Destination of samples
- Name, date, time, and signature of each individual releasing the shipping container.

For gas matrix COCs, the beginning and ending canister pressure, if applicable, will be recorded in the field logbook and on the COC form. Beginning pressure will be measured immediately before the start of sampling.

### 5.3.1 Analytical Laboratory Receipt and Custody

The laboratory will designate a sample custodian. Upon receipt, the laboratory sample custodian is responsible for inspecting the sample shipment and verifying the correctness of the COC forms. The sample custodian will accept the samples by signing the COC form and noting the condition of the samples in the space provided on the COC form and on the laboratory's sample receipt form. In case of breakage or discrepancies between the COC form, sample ID numbers, or requested analysis, the sample custodian will notify the quality assurance officer as soon as possible. All discrepancies associated with COC forms or sample breakage will be relayed to the quality assurance officer within 24 hours so that corrective action can be implemented appropriately.

Samples received by the laboratory will be entered into a laboratory information management system, which must include the following:

- laboratory sample number;
- field sample designation;
- analytical batch numbers; and
- list of analyses requested for each sample container.

Immediately after receipt, the samples will be stored in an appropriate secure storage area. The laboratory will maintain custody of the samples as required by the contract. The analytical laboratory will maintain written records showing the chronology of sample handling during the analysis process.

## 5.4 Drill Cuttings and Rock Flour

This section describes the sampling and analysis procedures for the drill cuttings and rock flour samples collected during drilling of the deep characterization borehole. High-frequency sampling and analysis of drill cuttings and rock flour will provide a semi-continuous lithologic profile of the sedimentary overburden and crystalline basement that can be correlated to geophysical log data, intermittent core data, and stratigraphy.

While drilling through the overburden section of the borehole, drill cutting samples will be collected every 3 m [10'] of borehole drilled for visual inspection and lithologic characterization. Beginning at the interface between the sedimentary overburden and the crystalline basement, drill cuttings will be sampled every 3 m [10'] of drilling for standard lithologic logging, or description, of rock type, mineralogy, and textural features. In addition, rock flour will be centrifuged from drilling fluid every 9.1 m [30'] to undergo on-site geochemical and mineralogical analysis via X-ray fluorescence (XRF) and X-ray diffraction (XRD). Information from drill cuttings and rock flour samples will help to quantify lithologic variations/transitions observed with depth during the drilling process.

## 5.4.1 Data Quality Objectives

The data quality objectives (DQOs) defined for drill cuttings and rock flour samples are provided in Table 5, including sample frequency, analysis type, and data QA/QC requirements. Table 5 also provides key information about the intended application/purpose of cuttings and rock flour analysis, potential sources of sample contamination and loss, and provides guidance for minimizing sample/data degradation to ensure the resulting dataset is aligned with lithologic characterization objectives.

A qualitative (visual inspection/characterization) logging of lithologic characteristics will be performed on drill cuttings collected every 3 m [10'] during drilling of the sedimentary overburden and crystalline basement. Gross mineralogy, rock textures, and lithologic transition zones will be examined and recorded in sufficient detail to develop a semi-continuous vertical profile of the geology encountered during drilling.

Combined XRD and XRF analysis will be conducted on rock flour sieved and potentially centrifuged from drilling fluids every 9.1 m [30'] of drilling to facilitate mineralogical phase identification along with measurement of whole-rock major, minor, and trace element composition (such as Si, Al, Na, Ca, K, Mg, Mn, etc.). Rock flour will undergo cleaning with de-ionized water to remove drilling fluid signals from the samples prior to analysis. Background noise and preferred mineral orientation will be minimized during sample analysis to generate XRD patterns that can be used to identify and quantify the major mineralogy of complex, multi-component rocks (e.g., igneous and metamorphic rocks) to ±1.5%. Results will be plotted to examine the bulk-rock mineralogy and geochemistry encountered during drilling operations.

**Table 5. Cuttings and Rock Flour Analyses**

| Sample Type | Target Analysis/ Analytes | Analysis Location | Frequency | Analytical Technique | Purpose | Data Quality Objective | Potential Contamination or Sample Loss |
|---|---|---|---|---|---|---|---|
| Drill Cuttings | Qualitative lithologic characteristics, mineralogy, and rock classification | On-site | Once per every 10 feet drilled | Standard lithologic mud logging | Provide a semi-continuous lithologic profile of the sedimentary overburden and crystalline basement for use in the geologic model, and correlation to geophysical log data, intermittent core data, and stratigraphy | Qualitatively identify lithology and major mineralogy with reasonable confidence. Identify transitions with depth, and any anomalies encountered | Undissolved thickening agents, loss of circulation materials, and weighting agents added to drilling fluid may contaminate cuttings. |
| Rock Flour | Whole-rock major, minor, and trace-element geochemistry | On-site | Once per every 30 feet drilled | X-Ray Fluorescence (XRF) | Measure major (e.g., Si, Al, Na, Ca, K, Mg), minor (e.g., Mn, Fe), and trace element concentrations (metals and esp. actinides U, Th). | Quantify elemental abundances within ±1 to 3 parts per million (ppm); typical XRF limits of detection | Undissolved thickening agents, loss of circulation materials, and weighting agents added to drilling fluid may contaminate rock flour. Rock flour will likely require multiple washes with de-ionized water to remove brine signal prior to XRF. |
| Rock Flour | Bulk Mineralogy | On-site | Once per every 30 feet drilled | X-Ray Diffraction (XRD) | Identify and quantify weight percentages of major and minor minerals, and fracture/crack fillings. | Quantify mineral abundance to ±1.5% | Undissolved thickening agents, loss of circulation materials, and weighting agents added to drilling fluid may contaminate cuttings. Samples may require multiple washes with de-ionized water to remove brine signal prior to XRD. |

## 5.4.2 Sample Collection Procedures

Samples of the drill cuttings and rock flour will be collected from the drilling fluid stream on a regular basis to characterize the lithology and mineralogy of the formations encountered during the drilling of the borehole. This section describes the methods that will be used to collect the samples and the procedures that will be followed during the preparation of the samples.

### 5.4.2.1    Field Sampling Procedures

Samples of the drill cuttings will be collected by the mudlogger at 3-m [10'] intervals. Samples will be collected at the shale shakers in the mud-circulation system to gain a composite of the cuttings for the entire 3-m [10'] interval by allowing the cuttings to pile on a board under the shaker prior to collecting the sample. The cuttings pile will be mixed to evenly distribute the cuttings before a 1-liter sample is collected from the pile. Samples will then be sieved and washed either at the shakers or in the mudlogging lab trailer. Cuttings trapped between the #4 (4.74 mm) and #10 (2.00 mm) sieves will be used for visual description of the sample. The flour, which passes through the #200 (0.074 mm) mesh sieve, will be collected every 9.1 m [30'] of borehole drilled and used for the rock flour analysis using XRD and XRF. Emmermann & Lauterjung (1990) define rock flour as grain sizes < 63 microns. Centrifugation will be necessary to separate the rock flour solids from the liquids that pass through the #200 mesh.

### 5.4.2.2    Sampling Equipment Cleaning/Decontamination

Between each sample, the sieves will be washed by running water from the bottom of the sieve to the top of the sieve to remove any particles trapped on the sieve from the previous sample.

### 5.4.2.3    Sample Containers, Preservation, and Holding Times

All analyses will be performed on location; therefore, no sample containers will be needed. Preservatives and holding times do not apply to the drill cuttings and rock flour samples. While there are no known holding times for the cuttings or rock flour analyses, the samples will be analyzed within hours of collection.

### 5.4.2.4    Sampling Packaging, Shipment, and Chain of Custody

Each sample of the drill cuttings and rock flour will be collected in cotton sample bags with the appropriate sample IDs prior to processing and analysis and will be provided to the mud logger/on-site analyst in the bags. After the samples have been processed and analyzed, multiple splits of each sample will be collected in small envelopes and labeled with the proper ID code and saved for any future use.

### 5.4.2.5    Sample Documentation Requirements

The sampler's name, sample IDs, sample collection depths, sample descriptions, and other pertinent information will be recorded in the field log book. In addition, details of the drill cuttings and rock flour sample collection and analysis will be part of the mudlog. All information will be stored both in hard copy and electronic formats.

## 5.4.3 Drill Cuttings Visual Description

Throughout the drilling process (both overburden and crystalline basement), drill cuttings will be sampled in the field during every 3 m [10'] of drilling. A qualified designated field geologist will record the observed mineralogy, textural features, and associated rock type for lithologic characterization of the sedimentary overburden and crystalline basement that can be correlated to geophysical log data, intermittent core data, and stratigraphy. The field geologist logging the cuttings in the sedimentary overburden may be different from the geologist logging the cutting in the crystalline basement section, depending on relevant experience logging the types of rocks and lithologic units that will be encountered.

Qualitative visual descriptions of lithologic characteristics will be recorded for drill cuttings collected every 3 m [10'] during drilling of the sedimentary overburden and crystalline basement. The designated field geologist will log the gross mineralogy, textural features, and lithology observed in drill cuttings at each depth interval in detail sufficient to identify lithologic transition zones and develop a semi-continuous vertical profile of the geology.

### 5.4.4 Rock Flour Analysis Program

XRF and XRD analysis of rock flour samples will be conducted on site. The portable XRD/XRF instrument will include XRD methods (crystallographic analysis) with XRF (elemental analysis) on powdered samples. Approximately 15 mg of rock flour is required for analysis.

Qualitative XRF scans of the sample will be used to identify elements, while the XRD spectra are compared to a database of spectra for standard minerals. This combination of mineral and elemental analyses will fill in gaps between cored regions and will be compared against the results of geophysical logging.

## 5.5 Drilling Fluids

Throughout the drilling of the borehole (both the lower overburden and crystalline formations), samples of the drilling fluids will be collected from the drilling fluid stream to chemically characterize the drilling system. The analytical results will be a primary source of information regarding changes in formation chemistry (both rock and fluids), some of which may be producing or taking on water, may indicate fractured zones, and will provide total abundances of the elements that will be measured for isotopic composition.

The drilling fluid sampled at the surface will be an integrated response of the formation at the bottom of the borehole, and all the formations open to the borehole. The integrated drilling fluid responses will not provide discrete compositional information about any one region of the borehole, but it will provide valuable information regarding how the drilling fluid changes with time as new formations and fracture zones are encountered, or as drilling fluid pressure changes and zones higher up in the borehole possibly change from gaining to losing. The drilling fluid compositional information may not be used to make on-site decisions regarding the drilling, but the information will be a critical component during the later synthesis of all information collected in the borehole.

Liquid samples will be collected of drilling fluid prior to injection into the borehole (from the stock or mixing tanks, including all the drilling fluid additives being used at that point in the drilling) and after the fluid has passed through the borehole (at or before the shale shakers, before prolonged exposure the atmosphere) to identify changes in the drilling fluid chemistry due to the entire integrated drilling process. Samples will be taken of drilling fluid to allow a limited on-site analysis of the samples on a near-real-time basis in the field or at a nearby laboratory. On-site analysis will allow possible decisions to be made about the drilling fluid program, as needed. Samples will also be collected for less frequent, but more exhaustive testing in an off-site laboratory. Off-site laboratory analyses will involve more processing and will remove the extensive solid fraction from the drilling fluid (both drilling fluid additives and rock flour) through filtration and centrifugation.

In addition to the samples collected for detailed chemical analysis, samples of the drilling fluid will also be collected by the mudlogger for more routine analysis of field and drilling parameters that will be used to guide the drilling process and to make modifications to the drilling fluids.

### 5.5.1 Data Quality Objectives

The DQOs for the drilling fluid samples are presented in Table 6. These samples will be analyzed for major cations, major anions, trace elements, and stable isotopes, and the analytical data will provide information regarding the chemical characteristics of the formations being drilled through and formations

or fracture zones that may be contributing water or taking drilling fluid to/from the borehole. The laboratory analyses of the liquid fraction of the drilling mud will show effects of:

- Formation fluid flowing into the borehole near the bit, and along its length;

- Evaporation of water from the drilling fluid;

- Dissolution of some mineral components of the rock flour and cuttings during circulation;

- Dissolution of some drilling additives in the liquid part of the drilling fluid;

- Minor reaction of the drilling fluid with the drilling bit, bottom-hole assembly, drilling pipe, and other components of the drilling fluid circulation system;

- Incorporation of drilling fluid tracers; and

- Interactions between all these solids and liquids (formation fluid, rock flour, drilling fluid additives, drilling fluid tracers).

In contrast to these analyses, a subset of the analyses will be done near-real-time on samples only filtered a limited amount to assist in the decision making during the drilling of the borehole.

The samples for cation/anion analyses will be performed for total concentrations within ±0.1% of the total abundance. Filtering will be performed to remove the solid fraction of the drilling mud from the samples. Samples will be filtered to remove larger particles, then centrifuged to remove rock flour, and filtered again before analyzing the liquid fraction. In addition to the major anions and cations, the concentrations of trace elements (metals) will also be measured on the drilling fluids samples using inductively coupled plasma - mass spectrometry (ICP-MS) or thermal ionization mass spectrometry (TIMS). The elements to be analyzed as part of the trace metal analyses are: Al, Sb, As, Ba, Be, Cd, Cr, Co, Pb, Mn, Hg, Li, Mo, Ni, Se, Ag, Sr, Sn, and U. Target reporting limits for trace metals are between 0.01 and 0.1 mg/L.

Samples can be analyzed for pH 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* pCO2 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.

Stable isotope data for water (O-18 and deuterium) provide information for the origins of the recharge water (i.e., climate conditions when precipitated – Sharp 2007; IAEA 2013) and can also be used essentially as drilling fluid tracers, since the stable isotope compositions of drilling fluid makeup water will be very different from expected formation waters. These samples will be analyzed using cavity ring-down spectrometry to measure differences of 1.0 per mil in the sample.

Analysis of other stable isotopes (carbon, sulfur, nitrogen, and iron) will also be conducted to better quantify the contribution of these elements in the water composition from sources besides deep groundwater. Many components of the drilling fluid (e.g., additives or the makeup water itself) may have very different isotopic composition compared to deep, isolated groundwater. Multiple processes can lead to fractionation of these isotopes (e.g., ancient geological sources, metabolic processes), and it is not the goal here to understand the exact mechanisms causing the different isotopes to fractionate (Cravotta 1995; Sharp 2007; Thomazo et al. 2009). The primary objective is to assess the usefulness of these isotopic ratios for distinguishing between deep and shallow (i.e., contamination) sources of these elements in the other analyses. Depending on the results of the drilling fluid isotopic analyses, isotopic ratios of C, S, N, and Fe in the rock contained in preserved samples of cuttings and flour may be analyzed later.

**Table 6. Drilling Fluids Analyses**

| Target Analysis / Analytes | Frequency | Analytical Technique | Purpose | Data Quality Objective | Potential Contamination or Sample Loss |
|---|---|---|---|---|---|
| Major Cations (Na, Ca, K, Mg, Si, Fe total) | At least one sample per interval tested | ICP-ES | Major cations, in combination with the major anions and trace metals, analyses provide geochemical characterization information for the test zone. Complete chemical analysis (charge balanced to <5%). 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 is assumed here. Undiluted sample reporting limits for metals (using ICP-ES): Na (100 mg/L), Ca (100 mg/L), K (100 mg/L), Mg (100 mg/L), Fe total (5 mg/L). These are likely to be at less than 1% of total abundance except for K, Mg, and Fe. Improvement may be achieved by optimizing dilutions, or by using alternative methods such as atomic absorption for metals. | Residues from pumping equipment. |
| Major Anions (Bromide, fluoride, iodide, sulfate, nitrate + nitrite) | At least one sample per interval tested | Ion Chromatography | Major anions, in combination with the major cations and trace metals, analyses provide geochemical characterization information for the test zone. 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 is assumed here. Undiluted sample reporting limits for non-metals (ion chromatography): chloride (2 mg/L), bromide (1 mg/L), fluoride (10 mg/L), iodide (1 mg/L), sulfate (2 mg/L), nitrate + nitrite (1 mg/L). These are likely to be at less than 1% of total abundance except for fluoride. Iodide is estimated for dilution of 1:9. Improvement may be achieved by optimizing dilutions. | Residues from pumping equipment. |
| Trace elements (Al, Sb, As, Be, Cd, Cr, Co, Pb, Mn, Hg, Mo, Ni, Se, and Ag. Ba, Li, Sn and Sr, U. Total abundance) | At least one sample per interval tested | ICP-MS | Trace element analyses will be used to control isotopic measurements with total abundance at appropriate accuracy (objectives: Li at ±1 ppb; U at ±0.05 ppb). Drilling fluid tracer should be determined at better than ±1% of the applied concentration. Also, trace element analyses can detect local elemental anomalies at ppb-level. | 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 between 0.01 and 0.1 mg/L can be obtained for Al, Sb, As, Be, Cd, Cr, Co, Pb, Mn, Hg, Mo, Ni, Se, and Ag. Higher reporting limits of approx. 10 mg/L can be obtained for Ba, Li, Sn and Sr using ICP-MS, although lower limits may be obtained by atomic absorption. U can be analyzed by ICP-MS with an undiluted reporting limit of 0.03 mg/L, but this could be readily improved using isotope dilution, chemical separation and ICP-MS or TIMS. | Exposure to crushed rock, residues or leakage from pumping equipment, filtration equipment, etc. Use ultra-high purity acid to treat samples for storage. |
| Stable water isotopes (O and deuterium) | At least one sample per interval tested | Cavity ring-down spectroscopy | Stable water isotopes provide data for interpreting recharge water provenance (e.g., climate conditions when precipitated) or origin other than meteoric (e.g., marine). Also serves as a secondary drilling fluid tracer. | Precision of 0.1 per mil for O-18 and D samples can be achieved using vaporization or diffusion processes to extract pure $H_2O$ from brine without significant fractionation. Quantitation objective: resolve and accurately discriminate sample differences as small as 1 per mil O-18 or D. Cavity ring-down spectroscopy is a commercialized desktop method that can achieve this performance. | Prolonged exposure to air (more than a few minutes); residual fluids from pumping equipment. |
| Stable isotopes (C, N, S, Fe) | At least one sample per interval tested | Mass spectrometry | Stable isotopic ratios will be analyzed for C, N, S, and Fe to quantify any biochemical transformations of these elements and to further quantify contamination from drilling fluid in formation water samples. The isotopic ratios 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. | 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 (C 13/12, N 15/14, S 34/32, Fe 56/54) in gases (e.g., $CO_2$, $N_2$, and $SO_2$) generated from combustion of sample material | Samples should minimize unnecessary exposure to carbon, nitrogen, sulfur, and iron-bearing compounds during sample collection and preservation. Assuming the concentrations of dissolved C, N, S, and Fe species are high enough, the samples should not require isolation from the atmosphere. Contamination is possible from residual drilling fluid from overburden section. |

### 5.5.2  Sampling Procedures

Samples of the drilling fluids will be collected during the drilling of the overburden and crystalline basement portions of the borehole. In the crystalline basement, drilling fluid will be sampled every 36.6 m [100'] of borehole drilled for cations, anions, trace elements, and stable isotopes. In the overburden sampling will be done less frequently. Samples will be collected every 9.1 m [30'] for at least 36.6 m [100'] above and below the overburden/basement interface, to better characterize the expected sharp contrast in geological and hydrological systems.

### 5.5.2.1  Sample Collection Procedure

Samples of the drilling fluid stream will be collected by the driller after the drilling fluid has been circulated from the borehole (at or before the shale shakers). The after-circulation drilling fluid samples will be collected at least every 36.6 m [100'] of borehole drilled in the crystalline basement. The pre-injection samples will be collected at similar frequencies during drilling, or at any time the drilling fluids are changed. Samples will be collected from a dedicated sampling port on the drilling fluid discharge before the shale shaker, allowing samples to be collected before they are significantly exposed to the atmosphere, and before they mix with other drilling fluid in the stock or mixing tank. Approximately 4-liter samples will be collected for laboratory analysis in sample containers with minimal head space and preserved with the required preservatives.

### 5.5.2.2  Sampling Equipment Cleaning/Decontamination Procedure

New sample collection bottles will be used for each sample, so there will not be a need to rinse the collection bottles before sampling.

### 5.5.2.3  Sample Containers, Preservation, and Holding Times

Table 7 presents the methods for each set of analyses and the containers, sample volumes, and preparation/preservation required for each sample suite. While minimum volumes are listed in Table 7, there should be no problem collecting the requested sample volumes from the drilling fluid stream. The metals and trace elements (cations) samples will be collected in a 1.5-liter polyethylene bottle that contains 2% nitric acid, and the bottle will be filled completely to minimize headspace. The samples for anion analyses will be collected in a 1-liter polyethylene bottle with no preservative, and the stable isotope samples will be collected in a 50-mL amber glass bottle. The stable isotope sample does not require any preservative, but the bottle should be filled so there is no headspace. Liquid samples should be filtered, centrifuged, and filtered again before any required analyte-specific preservation steps.

**Table 7. Drilling Fluid Sample Details**

| Analyte | Instrument / Method | Container Volume | Minimum Volume | Preparation / Preservation |
|---|---|---|---|---|
| Cations and trace elements: Na, Ca, K, Mg, Si, Fe (total), Al, Sb, As, Be, Cd, Cr, Co, Pb, Mn, Hg, Mo, Ni, Se, Ag Ba, Li, Sn, Sr, U | 200.8 | 1.5 L Poly | 1.0 mL | Filter out cuttings, centrifuge out rock flour and clays. 2% $H_2NO_3$ Zero Headspace |
| Anions: Bromide, fluoride, iodide, sulfate, nitrate + nitrite | E300 | 1 L Poly | 1.0 mL | Filter out cuttings, centrifuge out rock flour and clays. No Preservative |
| Stable water isotopes: O-18 and D | Cavity Ring- down Spectroscopy | Amber Glass 50 mL | 1.0 mL | Filter out cuttings, centrifuge out rock flour and clays. Zero Headspace |
| Stable isotopes: C, N, S, Fe | Mass spectrometry | 1 L Poly | Depends on concentration of species of interest | Filter out cuttings, centrifuge out rock flour and clays. Preserve to 0.5 vol-% HCl. |

### 5.5.2.4    Sample Packaging, Shipment, and Chain of Custody

If the samples are analyzed on site, no sample packaging would be required; however, a COC form would be filled out with the sample ID numbers, the analyses to be performed, the numbers of bottles for each sample, and any other pertinent information. If a local laboratory is performing the analyses, shipping likely will not be required because one of the field staff would drive the samples to the laboratory on a regular basis shortly after the samples are collected, and the analyses would be performed on a near real-time basis. A COC form would need to be completed for drilling fluid samples submitted to a local laboratory for analyses.

### 5.5.3  Sample Analysis Program

Drilling fluids will be analyzed at laboratories for major cations, major anions, trace elements (metals) and stable isotopes.

### 5.5.3.1    Laboratory Instrument Calibration

Analytical instruments will be calibrated in accordance with the analytical methods. All analytes reported, except as noted by the laboratory, will be present in the initial and continuing calibrations, and will meet the specified acceptance criteria (Table 8). All reported results will be within the calibration range.

Records of standard preparation and instrument calibration will be maintained. Records will unambiguously trace the preparation of standards and their use in calibration and quantitation of sample results.

**Table 8. Drilling Fluid Sample Calibration**

| Analyte | Method/ Instrument | Calibration Acceptance Criteria | Reporting Limits |
|---|---|---|---|
| pH | pH meter | ±0.2 standard units of pH buffer | 0.1 pH units relative, but will be difficult to get absolute accuracy with high TDS. |
| Conductivity | Conductivity Meter | ±5% of standard value | 1 µs/cm |
| Viscosity | Viscometer | To be determined (TBD) | 1 P |
| Salinity | Multimeter | TBD | 1 practical salinity unit (PSU) |
| Total Dissolved Solids | 2540C | TBD | 1 mg/L |
| Specific Gravity | D1429 | TBD | 0.1 g/cm3 |
| Sodium, Calcium, Potassium, Magnesium, Iron | 200.8 | Linear 5-point calibration, RSD ≤20%, $R^2$≥0.99 ICV ±10% CCV ±10% | Sodium = 100 mg/L, Calcium= 100 mg/L, Potassium= 100 mg/L, Magnesium = 100 mg/L, Iron = 5 mg/L |
| Silica | 307.1 | TBD | TBD |
| Chloride, Bromide, Fluoride, Iodide, Sulfate, Nitrate-Nitrate | E300 | Linear 5-point calibration, RSD ≤20%, $R^2$≥0.99 ICV ±10% CCV ±10% | Chloride = 2 mg/L Bromide = 1 mg/L Fluoride = 10 mg/L Iodide = 1 mg/L Sulfate = 2 mg/L Nitrate-Nitrate = 1 mg/L |
| Aluminum, Antimony, Arsenic, Barium, Beryllium, Cadmium, Chromium, Cobalt, Lead, Lithium, Manganese, Mercury, Molybdenum, Nickel, Selenium, Strontium, Silver, Tin | 200.8 | Linear 5-point calibration, RSD ≤20%, $R^2$≥0.99 ICV ±10% CCV ±10% | RLs between 0.01 and 0.1 mg/L can be obtained for Al, Sb, As, Be, Cd, Cr, Co, Pb, Mn, Hg, Mo, Ni, Se, and Ag. Higher reporting limits of approx. 10 mg/L can be obtained for Ba, Li, Sn and Sr. U has an undiluted reporting limit of 0.03 mg/L |
| Stable water isotopes: O-18, Deuterium | TBD | Linear 5-point calibration, RSD ≤20%, $R^2$≥0.99 ICV ±10% CCV ±10% | TBD |
| Stable isotopes: C, N, S, Fe | TBD | TBD | Report ratios of major isotopes |

### 5.5.3.2    Laboratory Quality Control

Laboratory QC samples will be analyzed in accordance with the analytical methods and may include tune blanks, method blanks, matrix spikes, laboratory control samples and laboratory sample duplicates. QC sample results must meet the criteria outlined in the analytical method or Laboratory Quality Assurance Plan. Laboratory QC samples will be analyzed in accordance with the analytical methods and must meet the applicable method acceptance criteria.

## 5.6  Drilling Fluid Gas

Gases evolving out of the drilling fluids will be captured at the surface on a semi-continuous basis for analysis of atmospheric, petroleum, and noble gases. The concentrations of these gases will be used in conjunction with other analytical measurements and drilling operational data to identify potential higher-permeability or flow zones in the borehole as it is being drilled, and as part of the overall synthesis of data

after drilling is complete. Analysis of the drilling fluid gases will also be used for determining the distribution of naturally-occurring tracers (i.e., noble gases) in the borehole.

## 5.6.1 Data Quality Objectives

Table 9 presents the DQOs for the drilling fluid gas analyses. A sample of the gases evolved from the drilling fluid will be analyzed on site every 90 seconds throughout the drilling of the bore using a field mass spectrometer. The gas will be analyzed for its major components, which would be expected to include: noble gases (He, Ar, Ne, and Kr); atmospheric gases ($N_2$, $O_2$, $H_2$, and $CO_2$); and light hydrocarbon gases ($C_1$-$C_6$). Not all these gases may be present at measurable levels in the system at all times. If any other gases beyond these listed are found at significant and field-detectable levels, they should be added to the list of gases to monitor.

**Table 9. Drilling Fluid Gases Analyses**

| Sample Analysis | Frequency | Analytical Technique | Purpose | Data Quality Objective | Potential Contamination or Sample Loss |
|---|---|---|---|---|---|
| On-site analysis of noble gases (He, Ar, Ne, Kr); atmospheric gases ($N_2$, $O_2$, $H_2$, $CO_2$); petroleum gases ($C_1$-$C_6$) | Once every 90 seconds during drilling. | Field mass spectrometer | Drilling fluid gas analyses will later be correlated with inflow and outflow zones, and to track naturally occurring tracers. | Reporting limit will be 1 ppmv using a mass spectrometer | The mass spectrometer will be connected to the mud outflow to minimize sample loss or fractionation. Exposure of the drilling to the atmosphere before and within the mud agitator should be minimized. |

## 5.6.2 Sample Collection Procedures

Samples will be collected for both field and laboratory analyses of the target gases. The field analyses do not require true sample collection because the gas samples will be conveyed directly from a sampling port on the drilling fluid system to the analytical instrument. The samples for laboratory analyses, however, will be collected in cylinders that will be delivered to the laboratory. Field samples will be collected every 90 seconds during drilling, while samples for laboratory analyses will be collected every 100 m [328'] of borehole drilled in the crystalline rock interest section, with at least one sample approximately 100 m before the overburden/basement contact.

### 5.6.2.1    Field Sampling Procedure

A portion of the drilling fluid gases will be collected from the flowline trap located between the end of the flowline and the shale shakers where a mud agitator liberates the gas from the drilling fluid stream. The mud agitator should be connected to the system in a way to minimize exposure of the samples to the atmosphere, which would allow loss of some gases, and incorporation of atmospheric gases into the gas samples. The gas stream will be pumped directly via a polyethylene tubing from the mud agitator to the mud logger's trailer where it will be analyzed for its $N_2$, $O_2$, $H_2$, $CO_2$, Ar, He, Ne, Kr, and light hydrocarbons ($C_1$-$C_6$) using a mass spectrometer. A full suite of analyses (including additional gases to those listed above) will be performed with the mass spectrometer every 90 seconds during drilling. The chromatograph output data will then be used to determine the concentrations of the target gases on a 1.0 part per million by volume (ppmv) basis.

A lag calculation will be created using mud pump strokes per 100 feet of borehole and mud pump strokes per minute to determine the time required for the drilling fluid to be pumped from the bottom of the borehole to the ground surface. The lag calculation will be used to "correct" the analytical data for the proper sampling depth. The concentrations of the target gases will be reported at the appropriate depth in the borehole on the mud log.

In addition to the analyses performed on site, samples of the drilling fluid gases will be collected and submitted for laboratory analyses. These samples will serve as confirmatory analyses performed on site, and will be analyzed to determine the major components (expected to include: $N_2$, $O_2$, $H_2$, $CO_2$, Ar, He, Ne, Kr, and light hydrocarbons $C_1$-$C_6$). The samples for laboratory analysis will be collected from a port located in the delivery line between the drilling rig and mud logger's trailer. The samples will be collected by connecting a polished and evacuated 250-mL, stainless steel sampling cylinder to the sampling port and opening the valve of the cylinder nearest the connection. The sample will immediately fill the sampling cylinder, but the valve should be left open and the cylinder should be left connected to the sampling port for 30 seconds to ensure a proper sample volume is collected. After 30 seconds, the valve should be closed, the cylinder should be removed from the sampling port, and prepared for shipment. The samples will be collected every 100 m [328'] of crystalline rock drilled, beginning near the base of the overburden for a total of approximately 40 samples over the lower portion of the borehole. These samples are collected for confirmatory analyses of the field measurements and to determine concentration of any secondary gases; therefore, no duplicate samples are planned for these samples.

### 5.6.2.2    Sample Equipment Cleaning and Decontamination

The gas analytical system is a continuous flow-through system and naturally purges itself on a continuous basis; therefore, no decontamination in required unless fluid is inadvertently introduced to the system. If fluid enters the system, the mass spectrometer will need to be disassembled and cleaned/dried per the manufacturer's recommendations. Also, the mass spectrometer routinely burns off any residue that builds up in the system by increasing the temperatures inside the analytical instrument.

The sampling cylinders used for laboratory analyses are one-time-use devices, so no field cleaning will be required for the sampling cylinders.

### 5.6.2.3    Sample Containers, Preservation, and Holding Times

The field measurements of the drilling fluid gases will be performed with a continuous flow-through system; therefore, no sampling containers or preservation will be required. Also, holding times are not applicable to these real-time analyses. The gas stream will, however, flow through a liquid trap and dehydrating agent to prevent moisture from entering the analytical instrument.

The laboratory analyses will be performed with a gas chromatograph/mass spectrometer (GC/MS). All analyses (atmospheric, noble, and petroleum gases) will be performed from the same 250-mL sample cylinder; these samples will not require any preservation or preparation following the sample collection.

### 5.6.2.4    Sample Packing, Shipment, and Chain of Custody

The samples collected for field analyses will be pumped directly from the mud system to the mud logger's analytical trailer on location. Therefore, no sample packing, shipment, or COC form will be required for these samples.

The samples collected for laboratory analyses will be in pressure-rated cylinders, and these cylinders should be wrapped in a protective material, such as bubble wrap, to prevent damage during shipment. The samples should then be placed in a hard case to further prevent damage and loss of sample. The address of the laboratory should be written on the outside of the hard case, and the samples should be shipped directly to the laboratory. The shipping case should also include the completed COC form which provides the sample ID number, the required analyses, the pressures of the sample vessels.

### 5.6.3  Field Sample Analysis Program

Each of the analyte groups (atmospheric, noble, and light hydrocarbon gases) will be analyzed using the same mass spectrometer instrument on a near-real-time basis. This system has a detection limit of 0.01 ppmv for all gas component molecular weights from 1 to 140. The system should be calibrated on a daily basis using atmospheric gas; therefore, no other calibration gases are used. Periodic checks of the system performance will be completed by allowing the system to collect a sample of atmospheric gas and

confirming the system reads $N_2$, $O_2$, and $CO_2$ at the appropriate concentrations. In addition, these checks will be used to confirm that no petroleum hydrocarbon contaminants are being trapped in the system.

### 5.6.4 Laboratory Sample Analysis Program

Drilling fluid gases will be analyzed $N_2$, $O_2$, $H_2$, $CO_2$, Ar, He, Ne, Kr, and light hydrocarbons ($C_1$-$C_6$). Sample vessel pressure before subsampling for testing will be recorded on the COC.

#### 5.6.4.1 Laboratory Instrument Calibration

Analytical instruments will be calibrated in accordance with the analytical methods. All analytes reported, except as noted by the laboratory, will be present in the initial and continuing calibrations, and will meet the standard acceptance criteria. All reported results will be within the calibration range.

Records of standard preparation and instrument calibration will be maintained.

#### 5.6.4.2 Laboratory Quality Control

Laboratory QC samples will be analyzed in accordance with the analytical methods and may include tune blanks, method blanks, matrix spikes, laboratory control samples and laboratory sample duplicates. QC sample results must meet the criteria outlined in the analytical method. Laboratory QC samples will be analyzed in accordance with the analytical methods and must meet industry method acceptance criteria.

## 5.7 Drilling Fluid Tracers

During the drilling of the crystalline basement interest section, tracer(s) will be introduced into the drilling fluid to facilitate two objectives. First, to provide a means for determining the extent of drilling fluid contamination of collected formation samples (i.e., core) and formation water samples. Second, to provide a secondary check for water gains or losses which could indicate the presence of geologic discontinuities such as fractures or faults, while drilling the crystalline basement section. Two proposed tracers to be added and monitored are iodide and fluorescein, and these will be added at levels that are easily detected without interference with naturally-occurring chemical species. The selected tracers cannot interfere with other testing being performed in the borehole. This section of the sampling and analysis plan only includes details for the sampling and analysis procedures for the tracers; the detailed approach for the overall tracer testing is provided in Section 3.8.

### 5.7.1 Data Quality Objectives

Table 10 presents the DQOs for the tracer samples. Each sample will be analyzed on site for fluorescein and iodide using hand-held meters. The meters will be calibrated for concentrations of the tracers that will be added to the system, which will likely be in the 1 mg/L-range concentrations. Fouling of the electrodes and sensors represent a potential problem with the field meter, and therefore, a routine maintenance schedule should be followed for these meters.

**Table 10. Drilling Fluid Tracer Analyses**

| Sample Analysis | Frequency | Analytical Technique | Data Quality Objective | Potential Contamination or Sample Loss |
|---|---|---|---|---|
| On-site analysis of fluorescein and iodide tracer to inform changes to tracer conc. Fluorescein and Iodide can be quantified at 1 mg/L in drilling fluid using an ion field instruments, if the bromide concentration is less than 1000 mg/L (bromide interference if Br/I > 1000). | Each 9.1 m [30'] drilled or at any changes in drilling mud system. | Hand-held meter for fluorescein. Either hand-held meter or on-site Ion Chromatograph for iodide analyses. | Quantification objective: determine fluorescein and iodide concentrations at 1 mg/L. Added iodide concentration in drilling fluid should be at least 20 mg/L, or greater if bromide concentration exceeds 1000 mg/L (or is expected to exceed). Assume NaCl added to drilling fluid will be of evaporate origin with Cl/Br on the order of 3000, and maximum concentration of ~5 M (saturated NaCl or Na/Ca brine). Formation fluid with the same chloride concentration and Cl/Br on the order of 100 would have to displace about 13% of the drilling fluid for bromide concentration to exceed 1000 mg/L (limit for interference with the iodide specific ion electrode at 1 mg/L). Field measurements will be checked by ion chromatograph. | Potential for electrode malfunction due to fouling, plating, etc. |

### 5.7.2  Sampling Collection Procedures

Throughout the drilling of the crystalline basement interest section, samples of the drilling fluid will be collected for quantification of the tracer concentrations. Every 9.1 m [30'] of crystalline basement drilled will be tested for drilling fluid tracers (assumed fluorescein and iodide).

### 5.7.2.1  Sample Collection Procedure

Samples of the drilling fluid stream will be collected by the mudlogger before and after the drilling fluid has been circulated from the borehole. The samples collected before the fluid has been pumped into the borehole will be collected from the mixing or reserve pits after the tracers have been added to the drilling fluid, and the post-injection samples will be collected at the shale shakers. As indicated in Table 10 the samples will be collected every 9.1 m [30'] of borehole drilled. Sample collection will be performed by dipping the sampling ladle into the mixing pits or under the fluid stream at the shakers and filling a sample collection bottle with approximately 100 mL of sample.

### 5.7.2.2  Sampling Equipment Cleaning/Decontamination Procedure

Prior to collecting the sample, the sampling ladle will be dipped or run through the sample stream at least three times to rinse any remnants of the previously collected sample from the sampling ladle. New sample collection bottles will be used for each sample, so there will not be a need to rinse the collection bottles before sampling.

### 5.7.2.3  Sample Containers, Preservation, and Holding Times

The sample collection bottle will only be used to carry the sample from the sampling location at the drilling rig to the field analytical trailer. The tracer testing and analysis will be performed in real time, and therefore holding times are not applicable to these samples. Also, no preservation will be required for the tracer samples.

### 5.7.3  Sample Analysis Program

The field analyses for the tracer test will focus on the tracers that have been added to the drilling fluid (assumed here to be fluorescein and iodide) to quantify amount of formation fluid that has entered the

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borehole during drilling, and to clearly mark the drilling fluid for assessment of contamination levels in cores and packer-based formation fluid samples. Hand-held meters will be used to determine the concentrations of the tracers in the drilling fluid after the fluid has been filtered to remove particulate matter. A hand-held fluorometer will be used to detect fluorescein and an iodide-specific electrode will be used to measure the iodide concentration. There is a possibility that the iodide analysis may be performed with an ion chromatograph (IC) or an ICP-MS that is used to analyze other components in the drilling fluid.

A single set of detailed laboratory analyses will be conducted on the makeup water source (once for each change in makeup water source). This set of analyses will be conducted on the drilling fluid makeup water before any additives are introduced, or before it is transported to the site. If a single source of drilling fluid makeup water is used for the entire drilling, only one set of samples will be needed.

### 5.7.3.1 Field Instrument Calibration

Field instruments will be calibrated following the manufacturer's user manual. Calibration will be performed on a daily basis prior to use. The field instruments will be calibrated using a two- or three-point calibration to cover the expected range of concentrations to be added to the drilling fluids.

### 5.7.3.2 Field Quality Control

Duplicate samples for the tracer analyses will be collected at a rate of 10% of the actual samples. These samples will be prepared and analyzed using the same methods as the true tracer samples. In addition, distilled water will be analyzed on a 2% rate to confirm the absence of the tracers in these blank samples. The drilling fluid samples (Section 5.5) can also be analyzed in the laboratory for tracer content as a means of confirming field estimates of tracer content.

## 5.8 Drilling Fluid Makeup Water

Throughout the drilling operations, the makeup water will be frequently sampled and analyzed for field water-quality parameters (pH, electrical conductivity, and temperature) to understand the source of any changes observed to be occurring in the samples of drilling fluid collected before circulation. These samples will be collected from tanks or trucks prior to mixing the additives drilling fluids. These compositional changes will then be used to identify fluctuations in the source water, to provide "baseline" chemical conditions of drilling fluids, and to determine chemical reactions that may be occurring during the drilling of the borehole. To monitor these changes in real time, the more frequent field analyses will be performed on site. One set of exhaustive laboratory tests (similar to the set of tests required for drinking water sources, along with isotopic analyses of stable water and C, N, S, and Fe isotopes) will be conducted on the drilling fluid makeup water source every other week, to help quantify the changes to the system that may be attributable to the makeup water (as opposed to the drilling fluid additives).

### 5.8.1 Data Quality Objectives

The DQOs for the makeup water samples are presented in Table 11. These samples will be analyzed for water-quality parameters, and the analytical data will provide information regarding the chemical characteristics of the water that is being used to produce the drilling fluid. Essentially, these analytical data will provide the background concentrations of the analytes prior to mixing the drilling fluid and circulating the fluid through the borehole.

**Table 11. Drilling Fluid Makeup Water Analyses**

| Target Analysis/ Analytes | Frequency | Analytical Technique | Purpose | Data Quality Objective |
|---|---|---|---|---|
| Field Analyses (pH, electrical conductivity, temperature, and density) | Once per week or if the source of the water changes | Field Instrument | Quantitation objective: simple check on consistency of water source. Field electrodes are simple and only accurate enough to indicate stability or change in source water. | Tanker truck or on-site frac tanks should be clean of any oilfield hydrocarbon/brine residue (steam-clean truck or use water-only equipment). |
| Stable isotopes, both stable water (O, D) and C, N, S, Fe | Once for each makeup water source. | Laboratory | Quantify the isotopic makeup of drilling fluid makeup water before addition of any drilling fluid additives. | Collect sample of makeup water at source, before transport by pipeline or tanker truck. |
| Major ions and trace metals | Once for each makeup water source. | Laboratory | Quantify the bulk composition of the drilling fluid makeup water source before addition of any drilling fluid additives. | Collect sample of makeup water at source, before transport by pipeline or tanker truck. |

### 5.8.2  Sampling Equipment Cleaning/Decontamination Procedure

The 5-gallon sample collection buckets should be rinsed with distilled or deionized water between the collection of individual samples. In addition, approximately 20 liters [5 gal] of water should be flushed from the port on the storage tank prior to collecting the sample. Following the measurement with the field probe, the probes on the meter should be rinsed with distilled water and returned to the storage container between uses. Additionally, the storage container should be filled with the manufacturer's recommended solution to prevent damage to the meter's probes.

#### 5.8.2.1  Sample Containers, Preservation, and Holding Times

The field analyses will be performed at the drilling location; therefore, holding times and preservatives are not applicable for these analyses. The 500 mL samples for pH, temperature, total dissolved solids, electrical conductivity, and specific gravity will not require any filtering because the water is likely to be from a municipal source.

Samples for laboratory analyses will be the same as the requirements used for these types of analyses for drilling fluid samples (Section 5.5).

### 5.8.3  Sample Analysis Program

The flow cell provided with the meter or a beaker should be filled to sufficient size to submerge the probes of the meter in the sampled water (typically this would require approximately 500 mL). No filtering should be required for water originating from a municipal water source. Field measurements should be performed for pH, electrical conductivity, temperature and specific gravity. The readings will be allowed to stabilize prior to making the measurements for the desired parameters, and the measurement data will then be recorded in the field logbook and the data sheet for the makeup water quality.

## 5.9  Cores

This section describes the sampling and analysis procedures for the whole cores of the crystalline basement and overburden. Cores will be recovered from the borehole using standard coring methods (as opposed to wireline retrieval) and brought to the surface under normal atmospheric conditions. The coring

program should target 5% coring for budgeting purposes. Assuming approximately 3 km [9,840'] of crystalline basement is drilled, approximately 150 m [490'] of core will be collected during drilling the crystalline basement, corresponding to 14 evenly-spaced coring events. The planned core intervals are highlighted on a schematic of the deep characterization borehole shown in Table 12. The core samples will be used to facilitate analysis of petrologic, geochemical, petrophysical, geomechanical, and thermal properties of the host rock in the deep characterization borehole.

**Table 12. Nominal Coring Program**

| Lithology | Core Run # | Top of Core Run [m bgs] | Target Core Length [m] | Core Diameter [in.] | Number of Subsamples of Total Core | | |
|---|---|---|---|---|---|---|---|
| | | | | | 30-cm Samples[a] | 61-cm Samples[b] | 91-cm Samples[b] |
| Overburden-Basement Interface | 1 | 1,990.9 | 36.58 | 5.25 | 8 | 56 | 0 |
| Crystalline Basement | 2 | 2,246.9 | 9.14 | 4 | 2 | 2 | 8 |
| | 3 | 2,475.6 | 9.14 | 4 | 2 | 2 | 8 |
| | 4 | 2,704.3 | 9.14 | 4 | 2 | 2 | 8 |
| | 5 | 2,932.9 | 9.14 | 4 | 2 | 2 | 8 |
| | 6 | 3,161.6 | 9.14 | 4 | 2 | 2 | 8 |
| | 7 | 3,390.3 | 9.14 | 4 | 2 | 2 | 8 |
| | 8 | 3,618.9 | 9.14 | 4 | 2 | 2 | 8 |
| | 9 | 3,847.6 | 9.14 | 4 | 2 | 2 | 8 |
| | 10 | 4,076.2 | 9.14 | 4 | 2 | 2 | 8 |
| | 11 | 4,304.9 | 9.14 | 4 | 2 | 2 | 8 |
| | 12 | 4,533.6 | 9.14 | 4 | 2 | 2 | 8 |
| | 13 | 4,762.2 | 9.14 | 4 | 2 | 2 | 8 |
| | 14 | 4,990.9 | 9.14 | 4 | 2 | 2 | 8 |
| **Total** | **16** | **-** | **155.5** | **-** | **30** | **87** | **122** |

(a) In the field, 30-cm [1'] samples will be placed in a helium-tight stainless-steel container for preservation.
(b) In the field, 61-cm [2'] and 91-cm [3'] samples will be left in their core sleeves and placed in aluminum transport tubes for preservation.

The use of alternative drilling or coring approaches or methods are possible if they do not jeopardize the success of the overall project. These methods might be attempted to improve core recovery at depth (i.e., minimize core discing). Testing and demonstration of alternative approaches fits with the philosophical approach of the DBFT.

For successful control of breakout in the DBFT research borehole, understanding of constitutive behavior and the potential for threshold effects, and measurement of *in situ* stress, are needed *early* during the drilling phase to inform breakout mitigation (see modeling and discussion in Appendix B). Constitutive models should be calibrated to laboratory tests conducted on some of the first crystalline basement cores retrieved from the borehole. The types of laboratory tests should evaluate strength development response, friction and dilation, and permeability changes vs. accumulated shear or volume strain (or other indicators).

Additional modeling sensitivity studies are needed using site-specific information on stress conditions and rock characteristics. More advanced simulations should incorporate longer simulation periods, parameter sensitivity studies, other constitutive mechanical models, grid refinement, and alternative codes.

### 5.9.1  Data Quality Objectives

The DQOs defined for core samples are provided in Table 13, including sample types, targeted analytes, analytical techniques, and data QA/QC requirements. Table 13 also provides key information about the

intended application/purpose of each analysis, potential sources of sample contamination and loss, and provides guidance for minimizing sample/data degradation. The DQO components for cores will guide sample collection and analysis activities to ensure resulting data are of sufficient quantity and quality for achieving the scientific objectives of the deep characterization borehole.
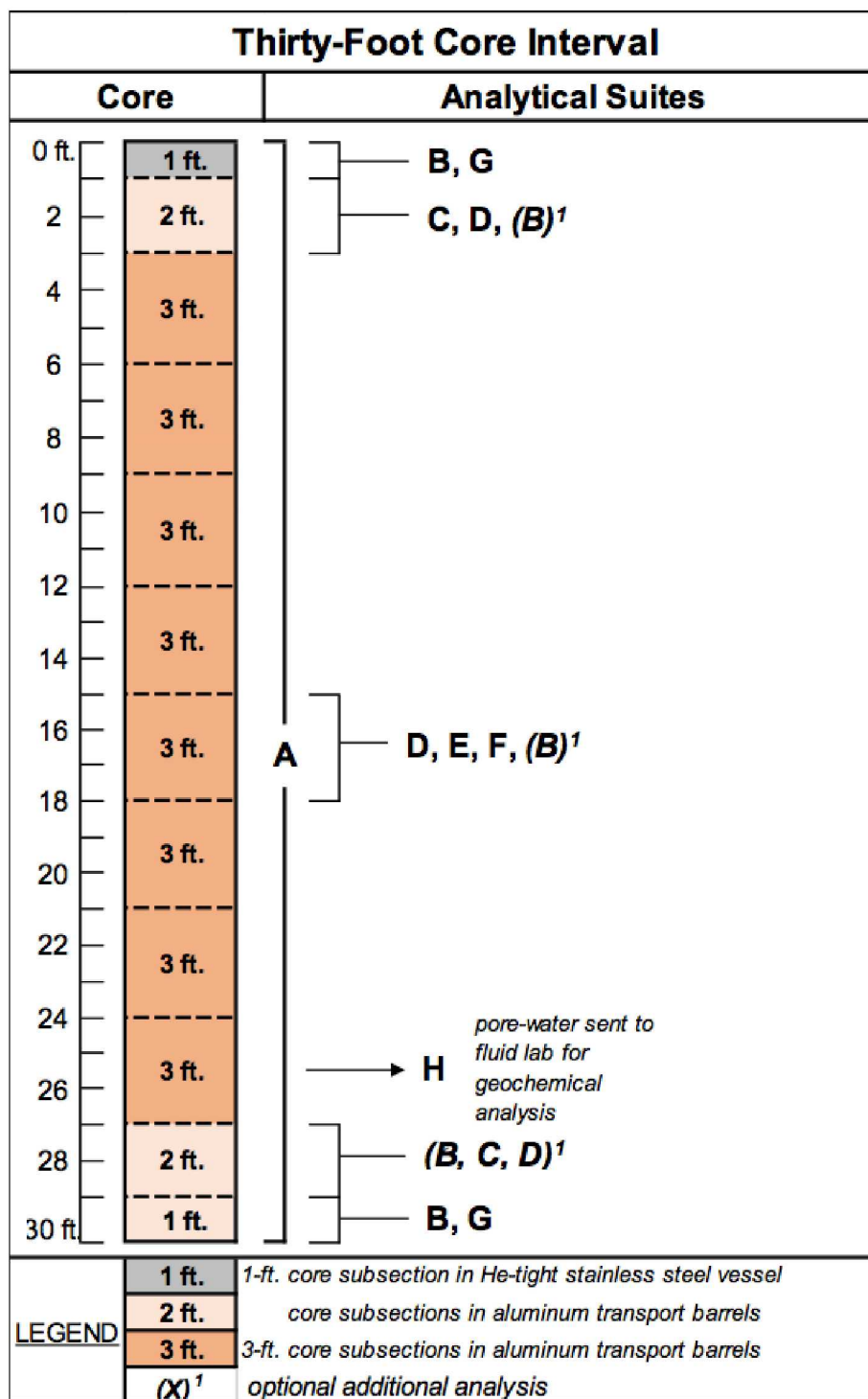
**Figure 5. Distribution of Core Subsections in a 30-ft Core Run.**

All recovered whole cores will undergo qualitative petrologic examination via core photography and written descriptions to document gross lithologic and textural features such as major mineral constituents and occurrence of fractures. These general observations will be used to supplement more detailed,

quantitative and semi-quantitative petrologic analysis, such as thin-section petrography, scanning electron microscopy (SEM), XRD and XRF analysis with one analysis of each type conducted on at least one subsection (30, 61, or 91 cm [1, 2, or 91-cm]) from each core run (e.g., Figure 5). Data from this suite of petrologic analyses will be used to determine the origin, composition, classification, and evolution of the crystalline basement, which will serve as the foundation for interpreting results from assessments from geochemical, petrophysical, geomechanical, and thermal analyses. Preserved in He-tight stainless-steel containers, the 30-cm [1'] subsections from both ends of each core run will be used to provide constraints on water-rock equilibrium conditions and fluid residence times via analysis of He-content (He-3 and He-4 isotopes) in quartz inclusions based on He-partitioning coefficients and crystal closure temperatures (Lehmann et al., 2003; Smith et al., 2013). These 30-cm [1'] subsections will also be used for the collection and analysis of pore fluids for geochemical parameters.

Geochemical analysis of whole-rock Li, Sr, U, and Th concentrations (total and isotope ratios) are to be conducted on the 61-cm [2'] and/or 91-cm [3'] subsection(s) stored in conventional aluminum core barrels from each core run. The analyses will be compared with results from He-in-quartz and geochemical water analyses to assess water-rock interaction origins and characterize radiogenic markers in the crystalline basement. The 61-cm [2'] and/or 91-cm [3'] subsection(s) will also be used for routine petrophysical analysis (ambient porosity, permeability, grain density) and advanced core tests, such as hydraulic permeability, porosity distribution, geomechanical analysis (e.g., deformation moduli, strength tests), and thermal analysis (e.g., conductivity, thermogravimetry). Information from these physiothermal datasets will be used to evaluate hydraulic regimes, conduct breakout analyses, and develop process and performance models that will be key for establishing the safety profile of the deep borehole environment. Cores acquired from the overburden-basement interface during the first core run will also be an important component of geomechanical and hydrologic assessments.

**Table 13. Core Analyses**

| Core Type | Sample Type | Target Analysis/ Analytes | Analysis Location | Frequency | Analytical Technique | Analysis Description/Purpose | Data Quality Objective | Potential Contamination or Sample Loss |
|---|---|---|---|---|---|---|---|---|
| All Whole Core | Whole Core | Core orientation and depth | Off-site Laboratory | All core collected | FMI/sonic imager logs | Cores will not be collected oriented. Core will be oriented afterwards through comparison with borehole imaging logs of fractures and lithology | Orientation and depth-correction of all core to the degree necessary to establish subsurface representations of the *in situ* core | |
| All Whole Core | Whole Core | Gamma ray, and U, Th, & K spectra | Off-site Laboratory | All core collected | Spectral Gamma-Ray Core Logging | Characterize gamma ray signatures and proportions of radioactive components U, Th, and K in the whole core | Measurements suitable to use in qualitative petrologic assessments | |
| All Whole Core | Whole Core | General Petrologic Features and Rock Description | On-site and Off-site Laboratory | All core collected | Core Photography | Image documentation of visual core characteristics such as; textures, orientation, fabric, major mineral constituents, and the occurrence and orientation of fractures | Imaging of all notable gross core characteristics to conduct qualitative sample characterization, petrologic examination, and identification of fracture fillings, and to enable comparison with cuttings, thin sections, and SEM studies. | Core desiccation and contamination may occur during opening of the core barrel for imaging. Cores should be re-packaged using open packaging and stored in a reasonably low-humidity environment to inhibit fouling. Orientation of all cores and core fragments should be maintained. The use of cleaners, oils, acids, tap water, etc. on cores is prohibited. |
| All Whole Core | Whole Core | General Petrologic Features and Rock Description | On-site and Off-site Laboratory | All core collected | Report of qualitative written descriptions | Written documentation of core characteristics, such as rock type, textures, fabric, orientation, major mineral constituents, and the occurrence and orientation of fractures. Qualitatively identify the presence of any fracture fillings. Fractures should be characterized and classified as induced or natural. Fracture surfaces should be examined to obtain data on shear-sense indications if present. | Detailed written record of all notable gross core characteristics to conduct qualitative sample characterization, petrologic examination, and identification of fracture fillings, and to enable comparison with cuttings, thin sections, and SEM studies. | Core desiccation and contamination may occur during opening of the core barrel for examination. Cores should be re-packaged using open packaging, and stored in a reasonably low-humidity environment to inhibit fouling. Orientation of all cores and core fragments should be maintained. The use of cleaners, oils, acids, tap water, etc. on cores should be minimized or eliminated. |
| 30-cm Subsection(s) | Thin-section | Microscopic sample mineralogy and textures | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered | Thin-sectioning & petrographic microscopy | Examine sample mineralogy, textures, reaction/alteration features, pores, microcracks, crack fillings, and fluid inclusions - with emphasis on quartz inclusions, for input in the geologic model. | Petrographic detail sufficient to identify inclusion-rich samples, characterize micropores/fractures, and determine modal amounts of major, minor, and trace minerals to enable rock classification and comparison with cuttings and SEM studies. | Sample desiccation and contamination may occur during splitting, processing, and preparation of the sample for thin-section examination. Care should be taken to minimize abrasion of exposed natural fracture faces during thin-section preparation. Sample orientation should be maintained/noted on the thin-section. |
| 30-cm Subsection(s) | Billet/ Thin-section | Microscopic sample mineralogy, high-resolution textural features | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | SEM | Conduct high-resolution imaging and qualitative chemical analysis of sample mineralogy, textures, reaction/alteration features, pores, microcracks, crack fillings, and fluid inclusions - with emphasis on quartz inclusions, to supplement thin-section analysis | Petrographic detail sufficient to identify inclusion-rich samples, characterize micropores/fractures, and determine modal amounts of major, minor, and trace minerals to enable rock classification and comparison with cuttings and thin-section studies. | Sample desiccation and contamination may occur during splitting, processing, and preparation of the sample for thin-section examination. Care should be taken to minimize abrasion of exposed natural fracture faces during thin-section preparation and coating (e.g. carbon-coating) for analysis. Sample orientation should be maintained/noted on the thin-section. |
| 30-cm Subsection(s) | Powder | Bulk Mineralogy | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | XRD | Quantitatively identify major and minor minerals, fracture/crack fillings for sample classification and input for the geologic model. | Quantification of weight percentages of major and minor minerals to within ±3-5% to enable lithologic classification, identify mineralogical variations with depth, and positively identify crystalline phases filling fractures. | Sample desiccation and contamination can occur during processing and preparation for XRD analysis. Care should be taken to reduce exposure time and contamination potential during sample crushing, sieving, and transfer. |
| 30-cm Subsection(s) | Powder | Whole-Rock Geochemistry | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | XRF | Measure whole-rock concentrations of major elements (e.g. Si, Al, Na, Ca, K, Mg), minor elements (e.g. Mn, Fe), and trace elements (metals & esp. actinides U, Th). | Quantification of whole-rock major, minor, and trace element geochemistry to within 5% of measured values to enable geochemical characterization and identify variations with depth. | Sample desiccation and contamination can occur during processing and preparation for XRF analysis. Care should be taken to reduce contamination potential during sample crushing, sieving, and transfer. Volatiles will be lost during if heating/ignition is employed. |

**Table 13. Core Analyses (continued)**

| Core Type | Sample Type | Target Analysis/ Analytes | Analysis Location | Frequency | Analytical Technique | Analysis Description/Purpose | Data Quality Objective | Potential Contamination or Sample Loss |
|---|---|---|---|---|---|---|---|---|
| 61-cm Subsection (conventional) | Crushed digested core | Total Lithium Concentration | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Mass Spectrometry (TIMS, ICP-MS) | Measure total whole-rock abundance and aid in isotopic analyses. | Determine total abundance to ±5% of measured values | Sample contamination and volatilization/loss of analytes can occur during processing and preparation for analysis. Care should be taken to minimize sample exposure and holding time. The rock room used for sample crushing and sub-sampling should be reasonably free of contamination sources. Chemical separations should be done in a clean trace-metal chemistry laboratory. |
| 61-cm Subsection (conventional) | Crushed digested core | Lithium 6/7 Isotope Ratio | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Mass Spectrometry (TIMS, ICP-MS) | Measure whole-rock isotope ratios for comparison with fluid samples, to determine marine or rock-water interaction origin of the waters. | Measurement of Li 6/7 isotopic ratios to ±1 per mil. | Sample contamination and volatilization/loss of analytes can occur during processing and preparation for analysis. Care should be taken to minimize sample exposure and holding time. The rock room used for sample crushing and sub-sampling should be reasonably free of contamination sources. Chemical separations should be done in a clean trace-metal chemistry laboratory. |
| 61-cm Subsection (conventional) | Crushed digested core | Strontium 87/86 Isotope Ratio | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Mass Spectrometry (TIMS, ICP-MS) | Measure whole-rock isotope ratios for comparison with fluid samples, to determine marine or rock-water interaction origin of the waters. Total Sr abundance may also be obtained as byproduct to supplement/aid isotopic analysis. | Measurement of Sr 87/96 isotope ratios to 1 part in 10,000 of direct ratio | Sample contamination and loss of analyte volume can occur during processing and preparation for analysis. Care should be taken to minimize sample exposure and holding time. The rock room used for sample crushing and sub-sampling should be reasonably free of contamination sources. Chemical separations should be done in a clean trace-metal chemistry laboratory. |
| 61-cm Subsection (conventional) | Crushed digested core | Total Uranium Concentration | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Mass Spectrometry (TIMS, ICP-MS) or XRF | Measure total whole-rock abundance in order to calculate production rates for He-4 and fission products, and aid in U 234, 238 isotopic analyses. | Determine total abundance to ±5% of measured values | Sample contamination can occur during processing and preparation for analysis. The rock room used for sample crushing and sub-sampling should be reasonably free of contamination sources. Chemical separations should be done in a clean trace-metal chemistry laboratory. |
| 61-cm Subsection (conventional) | Crushed digested core | Uranium 234/238 Isotope Ratio | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Mass Spectrometry (TIMS, ICP-MS) | Measure whole-rock isotope ratios for comparison with fluid samples and determine marine or rock-water interaction origin of the waters. | Measurement of U 234/238 isotopes to approximately 3 ppm of direct ratio, or 0.05 increment in activity ratio | Sample contamination can occur during processing and preparation for analysis. The rock room used for sample crushing and sub-sampling should be reasonably free of contamination sources. Chemical separations should be done in a clean trace-metal chemistry laboratory. |
| 61-cm Subsection (conventional) | Crushed digested core | Total Thorium Concentration | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Mass Spectrometry (TIMS, ICP-MS) or XRF | Measure total whole-rock abundance to calculate production rates for He-4 and fission products. | Determine total abundance to ±5% of measured values | Sample contamination can occur during processing and preparation for analysis. The rock room used for sample crushing and sub-sampling should be reasonably free of contamination sources. Chemical separations should be done in a clean trace-metal chemistry laboratory. |
| 61-cm Subsection (conventional) | Plug | Porosity | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Porosimetry (e.g. He-gas, Hg) | Quantify percentage of pore space to supplement flow tests and characterization of physical rock properties for use in process models. | Determine sample porosity to ±5% RSD | Sample contamination and analysis interference may occur if He-porosimetry is used on same samples undergoing geochemical analysis (U, Th) to determine He-4 production rates. Different subsamples of the same core subsection can be used to avoid this. |
| 61-cm Subsection (conventional) | Plug | Fluid Saturation | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Dean Stark - Soxhlet Extraction | Quantify water and oil saturation percentages. | Determine fluid saturation to ±5% RSD | Sample degradation and volume loss can occur during exposure to heat and solvent during the distillation and refluxing processes. Sample mineralogy and susceptibility should be considered prior to analysis to determine if preservation of native-state sample conditions is needed. |
| 91-cm Subsection (conventional) | Whole core or Plug | Hydraulic Permeability | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Fluid Permeametry | Measure permeability to facilitate flow testing and characterization of physical rock properties for use in process models, including stress-sensitivity of permeability. | Determine sample permeability to ±10% RSD | Some lab tests will be performed on the full size 4" core, so core for lab tests should be reserved prior to core subsampling (splitting, plugging, crushing, etc.) |
| 61 or 91-cm Subsection (conventional) | Plug | Porosity Distribution | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Hg-Porosimetry, or NMR | Quantify pore-size distribution and percentages to supplement flow tests and characterize physical rock properties for use in process models. Directional porosimetry with jacketed samples can be considered. | Determine sample pore distributions to ±5% RSD | |

**Table 13. Core Analyses (continued)**

| Core Type | Sample Type | Target Analysis/ Analytes | Analysis Location | Frequency | Analytical Technique | Analysis Description/Purpose | Data Quality Objective | Potential Contamination or Sample Loss |
|---|---|---|---|---|---|---|---|---|
| 61 or 91-cm Subsection (conventional) | Plug | Fluid Saturation | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Dean Stark - Soxhlet Extraction | Quantify water and oil saturation percentages. | Determine fluid saturation to ±5% RSD | Sample degradation and volume loss can occur during exposure to heat and solvent during the distillation and refluxing processes. Sample mineralogy and susceptibility should be considered prior to analysis to determine if preservation of native-state sample conditions is needed. |
| 61 or 91-cm Subsection (conventional) | Plug | Grain density | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Pycnometry | Measure the density of the solid mineral matrix in the rock for use in process models. | Determine sample grain densities to ±5% RSD | Sample contamination and analysis interference may occur if He-pycnometry is used on same samples undergoing geochemical analysis (U, Th) to determine He-4 production rates. Different subsamples of the same core subsection can be used to avoid this. |
| 61 or 91-cm Subsection (conventional) | Whole Core or Plug | Thermal Conductivity & Diffusivity | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Laser Flash Analysis | Measure the conductive properties and diffusion boundaries of the rock for use in process models. | Determine thermal conductivity and diffusivity of the sample to ±5% RSD | Some lab tests will be performed on the full size 4-inch core and will be destructive. A systematic plan for reservation and distribution of core material should be developed prior to subsampling. |
| 61 or 91-cm Subsection (conventional) | Whole Core or Plug | Thermal Expansion | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Dilatometer | Measure the fractional change in size of the rock in response to temperature changes for use in process models. | Determine thermal expansion of the sample to ±5% RSD | Some lab tests will be performed on the full size 4-inch core and will be destructive. A systematic plan for reservation and distribution of core material should be developed prior to subsampling. |
| 61 or 91-cm Subsection (conventional) | Whole Core or Plug | Thermal Heat Capacitance | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Thermo - gravimetry | Measure the thermal response of the rock and ability to store/release heat for use in process models. | Determine heat capacitance of the sample to ±5% RSD | Some lab tests will be performed on the full size 4-inch core and will be destructive. A systematic plan for reservation and distribution of core material should be developed prior to subsampling. |
| 61 or 91-cm Subsection (conventional) | Whole Core or Plug | Uniaxial Compressive strength | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Uniaxial compressive strength test[1] | Measure uniaxial compressive strength of rock for use in the geologic model and breakout analysis | Measurement uncertainty should be less than between-sample variability of replicate samples, or 10% RSD for repeated measurements, whichever is smaller. Laboratory methods should have low enough measurement uncertainty to quantify natural sample variability. | Some lab tests will be performed on the full size 4-inch core and will be destructive. A systematic plan for reservation and distribution of core material should be developed prior to subsampling. Analytical results may be compromised if samples are not analyzed at reservoir temperatures and native-state fluid saturation conditions. |
| 61 or 91-cm Subsection (conventional) | Whole Core or Plug | Hydrostatic Compression Parameters | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Hydrostatic compression test[1] | Measure hydrostatic compression parameters of rock for use in geologic models and breakout analysis | Measurement uncertainty should be less than between-sample variability of replicate samples, or 10% RSD for repeated measurements, whichever is smaller. Laboratory methods should have low enough measurement uncertainty to quantify natural sample variability. | Some lab tests will be performed on the full size 4-inch core and will be destructive. A systematic plan for reservation and distribution of core material should be developed prior to subsampling. |
| 61 or 91-cm Subsection (conventional) | Whole Core or Plug | Strength Envelope & Static Elastic Moduli | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Triaxial compressive strength test[1] | Measure strength envelope and static deformation moduli of rock for use in geologic models and breakout analysis | Measurement uncertainty should be less than between-sample variability of replicate samples, or 10% RSD for repeated measurements, whichever is smaller. Laboratory methods should have low enough measurement uncertainty to quantify natural sample variability. | Some lab tests will be performed on the full size 4-inch core and will be destructive. A systematic plan for reservation and distribution of core material should be developed prior to subsampling. |
| 61 or 91-cm Subsection (conventional) | Whole Core or Plug | Dynamic Elastic Moduli | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Ultrasonic Tests[1] | Measure dynamic deformation moduli and acoustic properties of the rock for use in geologic models and breakout analysis | Measurement uncertainty should be less than between-sample variability of replicate samples, or 10% RSD for repeated measurements, whichever is smaller. Laboratory methods should have low enough measurement uncertainty to quantify natural sample variability. | Some lab tests will be performed on the full size 4-inch core and will be destructive. A systematic plan for reservation and distribution of core material should be developed prior to subsampling. |

**Table 13. Core Analyses (continued)**

| Core Type | Sample Type | Target Analysis/ Analytes | Analysis Location | Frequency | Analytical Technique | Analysis Description/Purpose | Data Quality Objective | Potential Contamination or Sample Loss |
|---|---|---|---|---|---|---|---|---|
| 61 or 91-cm Subsection (conventional) | Whole Core or Plug | Mechanical Creep parameters | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Creep Tests[1] | Measure the creep parameters and deformation rate of the rock under stress/strain conditions for use in geologic models and breakout analysis | Measurement uncertainty should be less than between-sample variability of replicate samples, or 10% RSD for repeated measurements, whichever is smaller. Laboratory methods should have low enough measurement uncertainty to quantify natural sample variability | Some lab tests will be performed on the full size 4-inch core and will be destructive. A systematic plan for reservation and distribution of core material should be developed prior to subsampling. |
| 30-cm Subsections (He-Tight Containers) | Quartz Grain Aliquots | Helium 3/4 isotope concentration in quartz | Off-site Laboratory | One analysis from each core run, with at least one analysis from each rock type encountered. | Mass Spectrometer (Magnetic Sector Field Linear; Static) | Measure He isotope content of quartz crystals to assess equilibration with pore fluids. The He closure of the system is temperature dependent, and will likely be exceeded in the subsurface, allowing diffusion between pore fluids and quartz grains. Once brought to the surface, quartz should lock in He content until heated to above closure temperature again. | Quantitation objective: determine He content of quartz grains from same samples used to estimate He content of rock porewaters. Determine concentrations of He 4 to an uncertainty of $\pm5\%$ (1s) cc STP/$g_{qz}$, and concentrations of He 3/4 ratios to an uncertainty of $\pm2\%$ for values $\sim10^{-6}$, and $\pm20\%$ for values $\sim10^{-8}$. | Loss of He from the sample can occur during processing and preparation for analysis. Care should be taken to minimize breakage and fracture of inclusion-bearing crystals during mineral separation. Invasion of atmospheric gases into the sample chamber can obscure measurement of sample He-content. A proxy analyte for atmospheric gases, such as Ne-20, should also be measured during analysis to quantify/correct for atmospheric He. |

The sequence of analyses and the use and distribution of core subsections for multiple analyses will largely be determined by the analytical procedures and requirements defined by individual core laboratories, such as: required sample volumes, analytical limits of detection, analyte loss/preservation, sample preparation, the use of destructive techniques, etc. These considerations, along with the DQO guidelines, are used to develop a systematic plan for the preservation, subsampling, distribution, and analysis of core material.

## 5.9.2 Sample Collection Procedure

Advanced coring will be conducted intermittently in coordination with planned drilling hiatuses to target recovery of approximately 5% of the basement interval drilled. Coring runs will consist of one 36.6-m [120'] interval followed by evenly-spaced 9.1-m [30'] intervals until 5% recovery is achieved. Coring will begin in the transition zone between the sedimentary overburden and the crystalline basement, as indicated by drill cuttings and regional geologic trends, to begin the first 36.6-m [120'] core run approximately 6.1-m [20'] above the overburden-basement interface. Assuming 3 km of crystalline basement, a total of 150 m [492'] of core will be targeted for recovery during 14 coring events as outlined in Table 12, with the majority of cores recovered from the crystalline basement. A secondary goal will be to collect core from each major rock type drilled through in the crystalline basement. Sidewall coring may be used as a contingency, to collect small cores from regions not initially cored. These regions may only be identified from cuttings or even after geophysical logging.

### 5.9.2.1 Field Sampling Procedure

Core handling and processing will be minimized and performed on site. At the surface, each 9.1-m [30'] section of core will be cut into 30-, 61-, and 91-cm [1', 2', and 3'] subsections in the field to optimize core handling and processing operations while maintaining maximum, intact sample volumes for designated laboratory tests. Each subsection of core will then be placed in preservation-transport tubes, packaged, and shipped to designated off-site laboratories for analysis.

Field personnel involved in core handling will be fully trained in relevant health, safety, and environment standards and practices and will carry the necessary certifications. Pre-core review meetings will be conducted in advance of the actual coring operation to ensure all staff are familiar with the core handling and processing procedures. A three-person crew will be used to conduct the core handling operations. Responsibilities of the core-handling crew will be as follows:

- Two crew members will be responsible for marking, cutting, orientation, preservation, inventory, packing, and shipping;

- One crew member will be responsible for documenting core handling operation via field forms, videography, and photography.

- The core-handling crew will provide all ancillary equipment and materials needed to transfer the core from the core barrel in which it is brought to surface to the containers in which it will be shipped to the laboratory.

The first core run will consist of one 36.6-m [120'] interval of 13.3-cm [5¼"] diameter core from the interface between the sedimentary overburden and underlying basement (approximately 2 km depth). Subsequent core runs will consist of thirteen 9.1-m [30'] intervals of 10.2-cm [4"] diameter.

At the surface, the first 120-ft interval of core will be cut into eight 30-cm [1'] subsections and fifty-six 61-cm [2'] subsections to reduce the weight and impact on field personnel assigned to the processing and handling of the 13.3-cm [5¼"] diameter core. Each 9.1-m [30'] section of core will be cut into two 30-cm [1'] subsections, two 61-cm [2'] subsections, and the remaining interval will be cut into 91-cm [3'] subsections. It is assumed that the 36.6-m [120'] core run across the overburden- basement interface will capture at least 9.1-m [30'] of crystalline basement that will be processed and handled in the same manner as the 9.1-m [30'] core intervals acquired during subsequent runs. Each subsection of core will then be

placed in designated preservation/transport tubes, packaged, and shipped to designated off- site laboratories for analysis.

The handling procedure for core will include the following steps:

1) As the core surfaces, the coring company will record times and depths.

2) If a mid-catch was taken, it will be collected by a technician and stored in a zip-lock bag, and the empty mid-catch will be returned to the inner barrel once the barrel is on the catwalk or working area. A mid-catch is a section of core that may be fractured/broken or rubbleized between the lower and upper core barrels; it can also be any core that is protruding from the core catcher or from the upper barrel.

3) The core will be laid down in 9.1-m [30'] sections with the top depth noted on the inner barrel. Once the inner barrel is laid down and positioned in a safe working area, it will be wiped down and the actual top of the core will be located using a tape measure inserted into the liner to find the top of the core. This top of core depth will then be marked on the outside of the inner barrel as "Top of C#1". From this point down, the distance will be marked to the bottom of the core in 30-cm [1'] increments.

4) At this point, the core depths will be verified against the depths received from the coring company.

5) Prior to cutting the core into subsections, orientation marks must be applied to the barrel so that the uphole and downhole directions are always known. The industry-standard way marking of the core is with red and black stripes. The red stripe indicates the uphole direction when on the right-hand side of the black stripe.

6) A half-moon (split liner) inner barrel will be used for the coring sleeve. The split liner is recommended because it is galvanized and will minimize interactions between the drilling fluids, the aluminum preservation vessel, and the liner which over time may hinder the removal of the liner with core from the aluminum transport vessel.

7) The coring company representative will mark the depths for preservation samples. These will be the 30-cm [1'] core subsections that will be placed immediately in helium-tight stainless-steel canisters for shipment to the designated laboratory.

8) The core will be video recorded for inventory control purposes as each section comes out of the hole and is handled. Photos and videos will be recorded after the core is clearly marked and before it is cut.

9) While still in the split liner, the core and liner will be cut using an "island cut" technique made with a hand-held saw. The core will be cut into 91-cm [3'] sections for subsequent transfer to aluminum transport tubes, and also into 30-cm [1'] sections for the stainless-steel canisters (i.e., the preserved samples). Island cuts are critical to maintain azimuthal orientation and to help reconstruct the core during later steps at the laboratory.

10) All cut subsections will be marked and numbered on the outside of the sleeve. For example, Core #1 Section 8 or Tube 8 would be labeled "C1-T8". This information is also entered onto field inventory sheets.

### 5.9.2.2    Sampling Equipment Cleaning/Decontamination Procedure

The core-handling crew will provide all ancillary equipment and materials needed to transfer the core from the core barrel in which it is brought to the surface to the containers in which it will be shipped to the laboratory. All of the equipment that is used for sampling or comes in contact with the core samples will be cleaned by rinsing with water prior to each use to prevent potential cross contamination between core samples. In addition, the use of disposable sampling equipment will be utilized to the extent possible to avoid cross contamination. Standard equipment includes:

- Personal protective equipment

- Core inventory forms
- Abundance of rags
- Hammer and chisel
- Tape measures
- Paint markers (black, red, white and yellow)
- Plastic zip-lock bags
- Field record keeping notebook
- Water-proof pen(s)
- Chop saw (gas or pneumatic) or equivalent for cutting core barrel liner
- Portable lighting
- Tape/hose clamps
- 30-cm [1'] helium-tight stainless-steel canisters for packaging cores
- 91-cm [3'] aluminum preservation transport tubes with metal end caps
- Gas-sample containers
- Vacuum pump, tubing, fittings, gauges, valves
- Grade 5 nitrogen cylinder, gauges, regulator, valves, tubing, fittings
- Sample labels for helium-tight stainless-steel canisters and aluminum preservation transport tubes, water bottles, gas-sample containers
- Ice chests (cooler) for shipping water-sample bottles and gas-sample containers
- Core bins for shipping core, including ratcheting straps
- COC forms
- COC seals

### 5.9.2.3    Sample Containers, Preservation, and Holding Times

After each of the 14 core intervals have been measured, marked, and cut into subsections, the cores will be transferred by field personnel to containers specially designed for preservation and protection against damage, fluid loss, and biologic activity. The cores will remain in these containers until removed for analysis at an off-site core laboratory.

The two 30-cm [1'] subsections located at the ends of each core interval will be transferred from their inner sleeves to helium-tight, stainless steel containers to reduce core contamination and loss of volatiles/analytes required for analysis of fluid-rock equilibrium and fluid residence times in the deep borehole environment. The larger subsections of core, contained in conventional split-liner aluminum sleeves, will be placed into outer aluminum transport tubes for shipment to the receiving laboratories where they will undergo a broad range of petrologic, geochemical, petrophysical, geomechanical, and thermal analyses. Cores will be shipped to the designated core analysis laboratory immediately following each coring event. Core samples will not be stored on site.

### 5.9.2.4    Sample Packaging, Shipment, and Chain of Custody

The **standard 61-cm [2'] and 91-cm [3'] core subsections** will be packaged for shipment per the procedure as discussed below.

1) Place 91-cm section of core or 61-cm section of core (while still inside sleeve) directly into 91-cm [3'] long aluminum preservation transport tube.

2) Secure the end flange of the tube;

3) Label the outside of the tube

4) Each transport-preservation tube ID will be recorded on the core inventory sheet.

5) Each container will then be placed into a shipping bin for shipment to the laboratory

One of the **30-cm [1'] core subsections** will be transferred to 15.2-cm [6"] diameter helium-tight stainless-steel canisters per the procedure discussed below. After evacuating and flushing the core headspace, the sample will be sent to a laboratory that can analyze noble gas content (especially the He-3/He-4 ratio). The noble gas analyses are non-destructive but will be require several weeks or months of degassing before the analyses can be performed, and the samples can be returned to the core handling facility for additional analyses. The other **30-cm [1'] core subsection** will be subsampled and analyzed for other geological characteristics.

1. Prior to placing the 30-cm [1'] subsection of core into the stainless-steel canister, the cores will be removed from their sleeve (de-tubed).

2. Once removed, the core will be marked with orientation and depth marks.

3. After marking the core, it will be placed into the specially designed stainless steel, helium tight canisters with metal-to-metal sealing surfaces.

4. Once the core has been placed inside the canister, the sealing flange will be aligned and secured by following an appropriate bolt-tightening sequence, and the bolts will be checked with a torque wrench.

5. The stainless-steel helium-tight canisters will be flooded with $N_2$ gas, purged with a vacuum, and sealed using a piping and valve system that has metal-to-metal seals and gaskets that seal against helium—this is a "purge-and-pump" procedure. The exact purge-and-pump procedure should be determined beforehand using calculations that incorporate the volume of the preservation canister and the flow rate of the vacuum pump used to pull a vacuum on the canister. The calculations are to determine the number of purges and pump-downs to achieve an amount of remaining gases that is several times below the detection limits of the laboratory methods for analysis of the noble and other gases. We provide general guidance below, which assumes that an appropriate piping system is attached to the vacuum, the canister, and the nitrogen tank. Fittings of the piping system and valves should have metal-to-metal seals.

    a) Connect vacuum pump to Swagelok VCR Metal Gasket via and pull a vacuum of 6.7 kPa [2" Hg] (the vacuum reached may depend on the pump and the fact that wet samples will limit the vacuum that can be achieved) for approximately 30 seconds; close the valve to the vacuum.

    b) Open the valve to ultra-high purity Grade 5 (99.999%) $N_2$ tank and regulator with gauge to Swagelok VCR Metal Gasket on canister. The regulator should be preset to 13.8 kPa above atmospheric pressure [2 psig]. Flood the canister with Grade 5 $N_2$.

    c) Close valve to nitrogen tank and open valve to the vacuum pump and pull a vacuum of ~ 6.7 kPa [2" Hg] for approximately 30 seconds or until a reasonably low vacuum is achieved. Close the valve and remove vacuum assembly.

    d) The purge-and-pump needs to be enough times to get levels of atmospheric gases in the head space down low enough to allow accurate estimation of noble gas levels that evolve from the core. Three purge-and-pump downs will probably be necessary.

    e) Sample weight and pressures achieved during each step of the purge-and-pump process are to be recorded.

6. Once purged, the stainless-steel helium-tight canister will be labeled on the outside by the following method:

   a) The canister IDs will be recorded on the core inventory sheet; and

   b) Each container will then be placed into a shipping bin for shipment to the laboratory.

Except for the coring event across the overburden-basement interface, each conventional coring event will yield 9.1-m [30'] of core, including eight 91-cm [3'] aluminum preservation-transport tubes, two 61-cm [2'] aluminum preservation-transport tubes, and two 30-cm [1'] helium-tight stainless-steel containers. The interface coring event will yield many more aluminum preservation-transport tubes, depending on how much overburden and crystalline basement are cored, and how much core is recovered.

Core contained in the 0.9-m [3'] aluminum preservation-transport tubes will be placed into special core shipping containers for shipment to the core laboratory. The vessels will be isolated using foam rubber. Each shipping container can hold approximately 30.5 m [100'] of 10.2-cm [4"] core so, except for the interface coring event, all core produced from each coring event can be contained within a single shipping container. Cores contained in the helium-tight stainless-steel containers will be shipped in ice chests (cooler) similar to water and gas samples. All 30-cm [3'] aluminum preservation-transport tubes and helium-tight stainless-steel containers will have previously been labeled using water-proof labels containing pertinent sample information (sample ID, date and time collected, sampler name, sampler(s) contact information, etc.).

For each shipping container and cooler to be shipped to an off-site laboratory, a COC form will be completed in triplicate that lists the core transport tubes or stainless-steel containers contained inside and the original copy of the COC form with one carbon copy attached to be placed inside the shipping container or cooler. The sampling representative will be responsible for retaining the other carbon copy of the COC form. The shipping containers and cooler(s) will be sealed with tape and COC seals to deter/detect unauthorized opening.

Upon arrival at the designated core laboratory, the containers will be opened and inventoried on the enclosed COC form/carbon copy. The laboratory will retain one copy of the COC form and send the other copy to the DBFT sample manager.

### 5.9.2.5    Sampling Documentation Requirements

In addition to core inventory forms provided in the field, all samples will be recorded on COC forms using the sample ID described above. COC forms will be completed using indelible ink so entries are legible. Any errors made by the individual completing the COC form shall be crossed out with a single line, initialed, and dated. The COC form serves as the legal documentation of the sample custody because it records the transfer of custody of the samples from field personnel to the laboratory. Pre-printed sample labels should be provided with the unique sample ID number and the sample collector's name.

### 5.9.3  Sample Analysis Program

The laboratory analyses planned for core samples can be grouped into eight main analytical suites based on the following characterization efforts: (A) general geologic, (B) petrologic, (C) geochemical, (D) petrophysical, (E) thermal, (F) geomechanical, (G) noble gas/radiogenic signatures, (H) pore water extraction (Table 14). Except for the helium-tight stainless-steel canisters, the core samples will arrive in their transport/preservations tubes at a designated central core processing laboratory where the majority of core subsampling, sample preparation, and analyses will be conducted. Specialized, advanced analyses (i.e., He-in-quartz, thermal tests) may be performed at a different laboratory than the central core laboratory, and this specialized laboratory may elect to process the core samples for these analyses. If the specialized laboratories are not equipped to handle and process the whole core subsections, the processing may take place at the central core laboratory and the processed/prepared samples will be subsequently shipped to the specialized laboratory.

All recovered whole core will undergo the general analyses grouped into Analysis Suite A, including whole core gamma (spectral U, Th and K levels), photography and qualitative written descriptions (Table 14). To minimize loss of noble gases and other volatile analytes, the 30-cm [1'] core subsections not preserved in the helium-tight canister from each core run will first be sent to the designated central core processing laboratory to undergo subsampling and preparation for analysis of He-in-quartz content and core-pore water extraction (Table 14). If necessary, the central core processing facility will subsample a portion of the whole core and package/ship to a noble gas analysis laboratory for He isotope measurements on quartz-grain aliquots, taking care to reduce core exposure time. The core pore-water sample may also be collected by the central core processing laboratory which would send the water sample to a fluid analytical lab for geochemical testing.

The 61-cm [2'] core subsections located next to the 30-cm [1'] subsections at the end of the core run could then be subsampled for whole-rock Li, Sr, U, and Th analysis (Analysis Suite C), and routine petrophysical analyses such as grain density and ambient porosity and permeability (Analysis Suite D). To ensure core material is retained from a subsection after subsampling for destructive analyses, at least one 91-cm [3'] subsection located near the center of each core run may be used for thermal and geomechanical analyses grouped into Analysis Suite E and F, respectively (Figure 8). The lower 91-cm [3'] section (closest to the helium-tight stainless-steel preserved sample) would be used to produce core pore water samples for further geochemical analyses. The core subsampling and distribution plan described above and shown in Figure 6, Figure 7, and Figure 8 would provide complimentary datasets that could be used to augment interpretation and integration of results for better characterization of each core interval. Table 15 provides a preliminary overview/summary of the limits of detection, sample types, and approximate sample volumes required for each suite of core analysis.

**Table 14. Core Analyses Grouped by Suite**

| Analysis Suite | Core Type | Min. Sample No.[1] | Analysis | Technique |
|---|---|---|---|---|
| **A (General)** | All whole core | All core | Gamma-Ray, U, Th, K | Spectral Gamma |
| | | All core | Core Photography | White & UV Light whole-core photography |
| | | All core | Core Description | Report of qualitative written descriptions |
| **B (Petrologic)** | 30-cm subsection s (per run) | 30 | Thin-Section Preparation | Standard slide thin-sectioning |
| | | 30 | Thin-Section Petrography | Petrographic microscopy & reporting |
| | | 30 | Thin-Section Photomicrographs | Petrographic Microscopy |
| | | 30 | Scanning Electron Microscopy | Scanning Electron Microscopy (SEM-EDS) |
| | | 30 | Bulk Mineralogy | X-Ray Diffraction (XRD) |
| | | 30 | Whole-Rock Geochemistry | X-Ray Fluorescence (XRF) |
| **C (Geochemical)** | 61-cm. subsection (per run) | 15 | Lithium Total Concentration | TIMS, ICP-MS |
| | | 15 | Lithium 6/7 Isotope Ratio | TIMS, ICP-MS |
| | | 15 | Strontium 87/86 Isotope Ratio | TIMS, ICP-MS |
| | | 15 | Uranium Total Concentration | TIMS, ICP-MS or XRF |
| | | 15 | Uranium 234/238 Isotope Ratio | TIMS, ICP-MS |
| | | 15 | Thorium Total Concentration | TIMS, ICP-MS or XRF |
| | | 15 | Estimates alteration products, via testing cation exchange capacity of crushed samples. | Batch CEC analyses |

**Table 14. Core Analyses Grouped by Suite (continued)**

| Analysis Suite | Core Type | Min. Sample No.[1] | Analysis | Technique |
|---|---|---|---|---|
| **D**<br>**(Petrophysical)** | One 61 or 91-cm. subsection (per run) | 15 | Hydraulic Permeability | Fluid Permeametry |
| | | 15 | Porosity | Porosimetry (e.g. He-gas, Hg) |
| | | 15 | Porosity Distribution | Hg-Porosimetry, or NMR |
| | | 15 | Fluid Saturation | Dean Stark-Soxhlet Extraction |
| | | 15 | Grain density | Pycnometry |
| **E**<br>**(Thermal)** | 91-cm. subsection (per run) | 15 | Thermal Conductivity & Diffusivity | Laser Flash Analysis |
| | | 15 | Thermal Expansion | Dilatometer |
| | | 15 | Thermal Heat Capacitance | Thermogravimetry |
| **F**<br>**(Geomechanical)** | 91-cm. subsection (per run) | 15 | Uniaxial Compressive strength | Uniaxial compressive strength test |
| | | 15 | Hydrostatic Compression Parameters | Hydrostatic compression test |
| | | 15 | Strength Envelope & Static Elastic Moduli | Triaxial compressive strength test |
| | | 15 | Dynamic Elastic Moduli | Ultrasonic Tests |
| | | 15 | Mechanical Creep parameters | Creep Tests |
| **G**<br>**(Specialized)** | 30-cm. subsection (per run) | 15 | Mineral Separation (Quartz) | Microscopic, manual picking |
| | | 15 | He-Content of Quartz | Mass Spectrometer (Magnetic Sector; Static) |
| | | 15 | He-degassing of core | Headspace of degassed core sampled for He 3/4 isotope ratio |
| **H**<br>**(Pore Water)** | 91-cm. subsection (per run) | 15 | Core Pore-water Extraction | Centrifugation, Piston Flow, Aqueous Leaching |

[1.] Approximate, minimum sample numbers
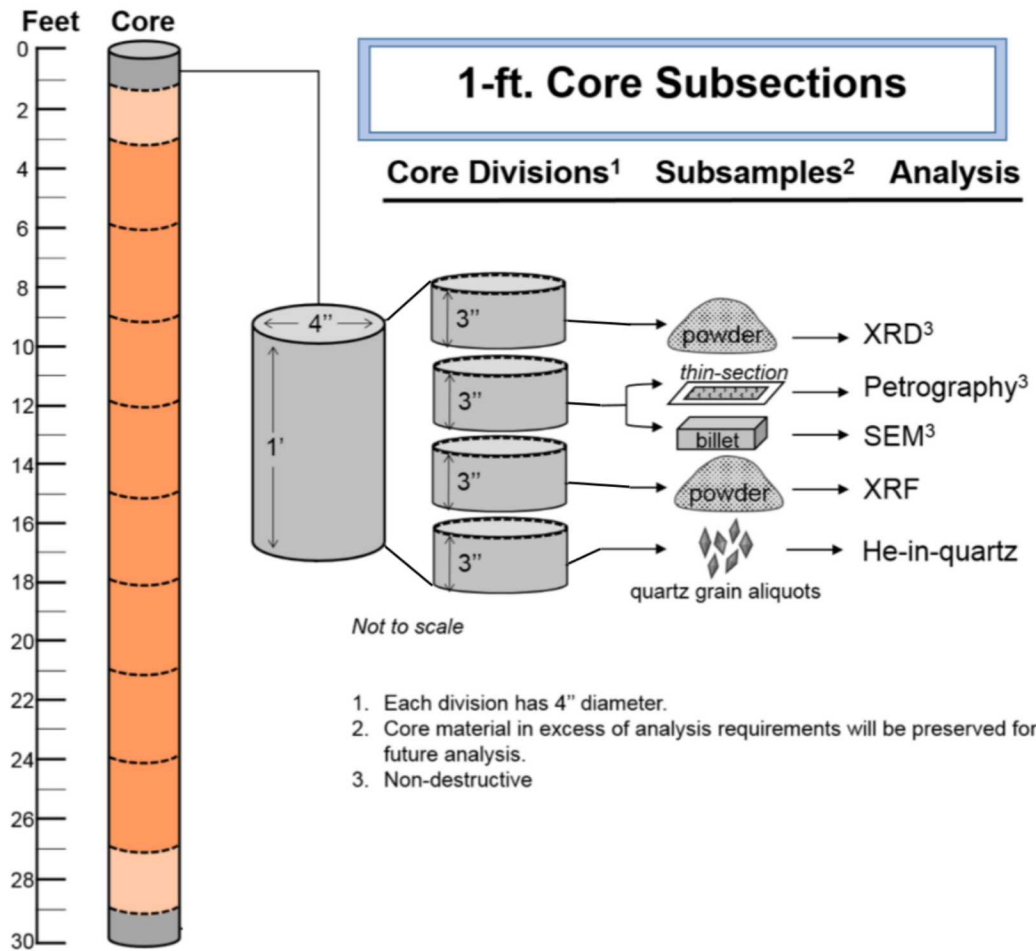
**Figure 6. Subdivision of 30-cm Core Subsections.**
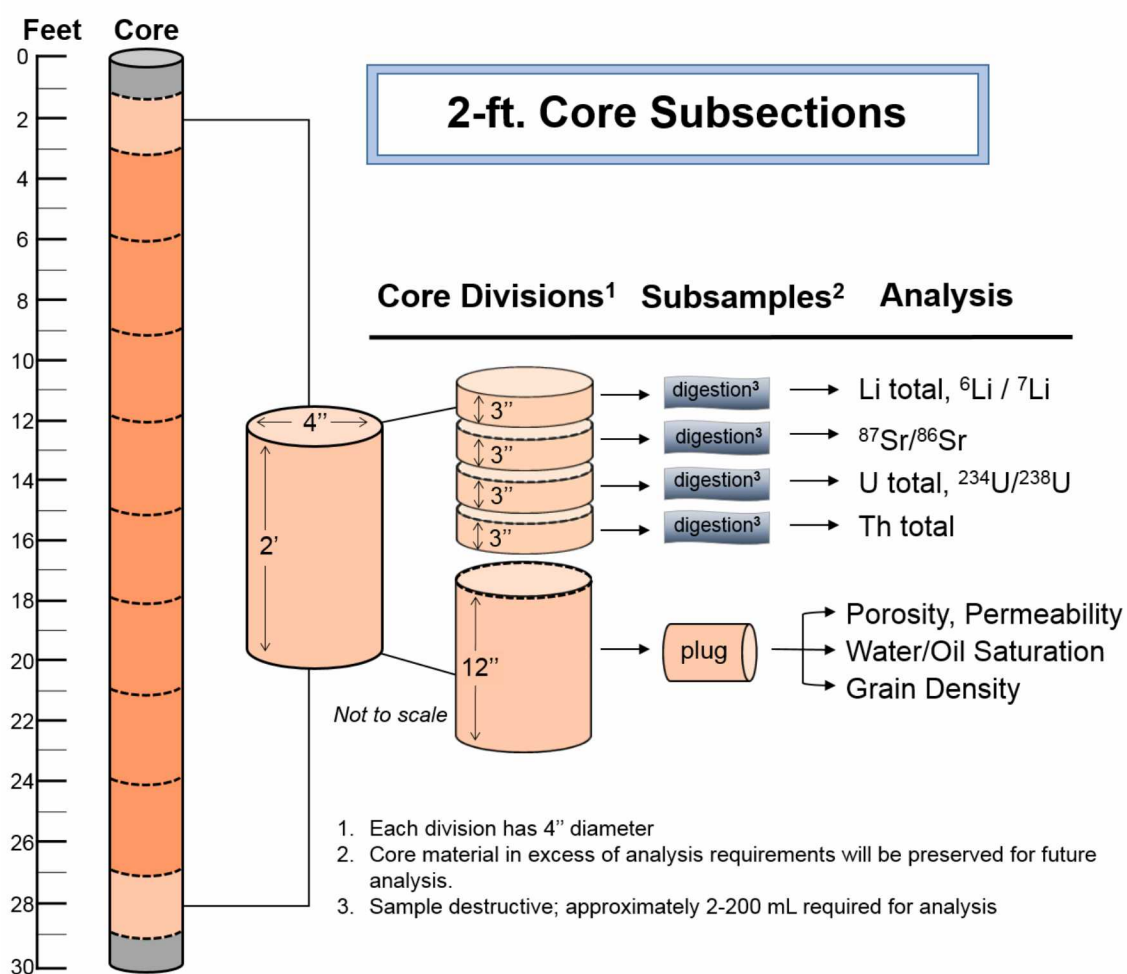
**Figure 7. Subdivision of 61-cm Core Subsections.**
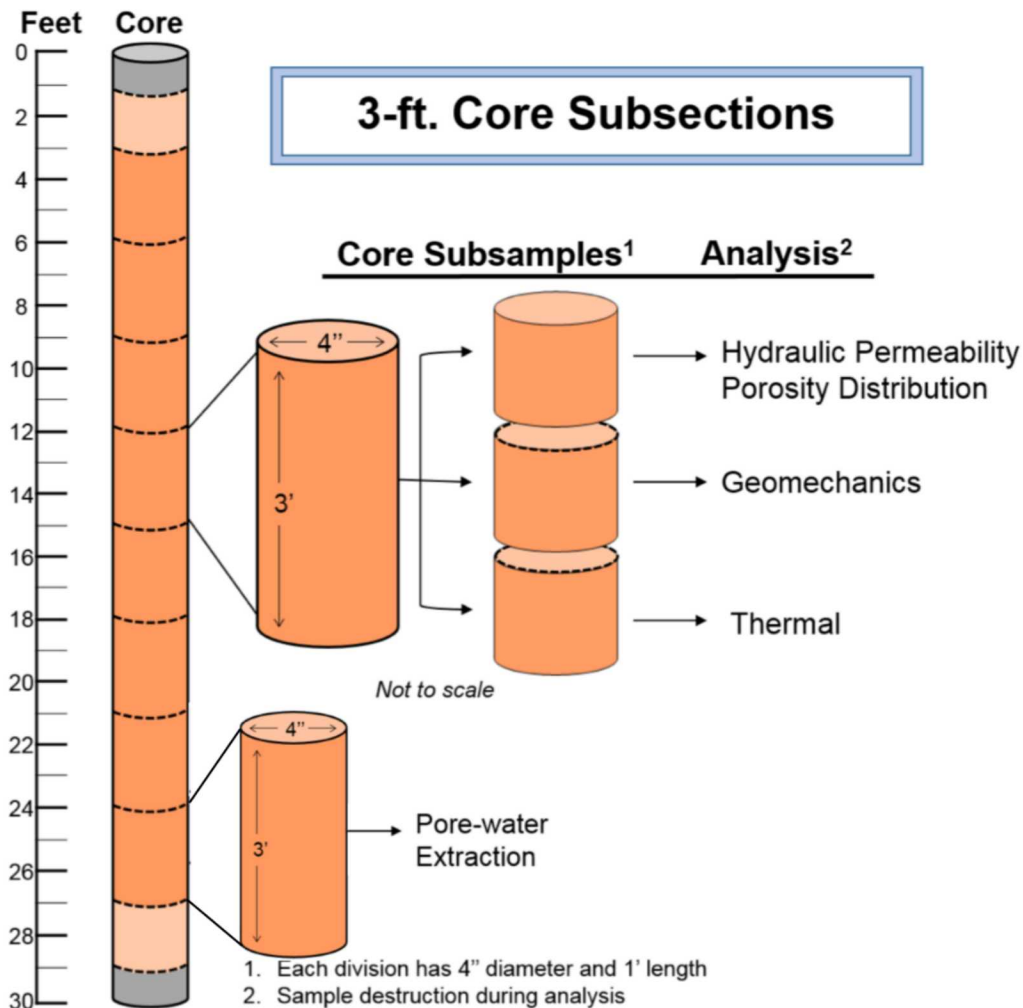
**Figure 8. Subdivision of 91-cm Core Subsections.**

### 5.9.3.1 General Geological Analyses (Suite A)

General geologic analysis (Analysis Suite A) and core subsampling will occur at the central core processing facility. The entire length of whole core (with the exception of the 30-cm core sealed in the He-tight container) from each coring run will undergo spectral gamma analysis to derive U, Th, and K concentrations (wt-%, standard resolution) and conduct depth verification/correction. The spectral gamma logging will be performed with a stationary, automated logging instrument, where the core will be positioned on the instrument, and the instrument moves the core past the detector and records the depth simultaneously.

Portions of the core that will be further sampled will be slabbed into 1/3 and 2/3 sections. Most of the core will not be slabbed, to allow larger samples to be taken for possible additional geomechanical and hydrological tests at a later time from the cores. All core will be photographed using high-resolution digital photography in natural (white) light and ultraviolet (UV) light to provide visual documentation of the textural, mineralogical, and structural features of the core. The whole core images will be supplemented by detailed written descriptions of the rock types, mineral assemblages, and textures observed in the core with depth to provide a lithologic profile of the crystalline basement in the borehole. Notation of specific sample candidates for petrologic, geochemical, and petrophysical analyses will also be included in the descriptions of core subsections designated for that associated analysis. If whole core

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processing is needed prior to arriving at a specialized laboratory, the 30-cm [1'] subsections of core will be immediately subsampled, packaged, and shipped from the central core facility to the noble gas and fluid analytical labs to minimize sample exposure and loss of volatile analytes. In this scenario, the 30-cm [1'] subsections of core may be split into two samples, with one sample processed for noble gas and pore-water analyses, and the other subsampled for petrologic analysis via thin-section petrography, SEM, XRD and XRF analysis (e.g. Figure 6).

### 5.9.3.2 Petrologic Analyses (Suite B)

Sufficient core material will be available to enable petrologic analyses to be performed on at least one 30-cm [1'] section from each coring run. Petrologic analyses include petrographic microscopy, scanning electron microscopy (SEM), X-ray diffraction (XRD), and X-ray fluorescence (XRF), and would likely be performed at the central core laboratory.

Four discs of core, each 7.6-cm [3"] long, may be cut from the 30-cm [1'] subsections to provide samples for the petrologic analyses (Figure 6). Two of the discs could be disaggregated into powders for XRD analysis to identify the mineral phases present in the rock. The two discs would be combined in a mixer mill for crushing, powdered with a mortar and pestle, and sieved to a grain size of approximately 10 to 50 microns to derive a representative 6- to 10-gram sample aliquot for XRD. The remaining powder may be used for analysis via XRF spectrometry to determine bulk-rock elemental concentrations of the core subsections, including major elements (as oxide wt-%) $SiO_2$, $TiO_2$, $Al_2O_3$, $Fe_2O_3$, MnO, MgO, CaO, $Na_2O$, $K_2O$, $P_2O_5$, and trace elements V, Cr, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Mo, Ba, Hf, Pb, Th, and U (in parts per million by weight). The third disc of core may be processed into a billet and thin section for petrographic microscopy and SEM analysis with energy dispersive X-ray spectrometry (EDX/EDS).

Thin-sections will be imaged and observed in plane-polarized and cross-polarized light using an optical petrographic microscope with a digital imaging system. Petrographic reports and photomicrographs will be used to record the petrographic features of each sample, including optical properties (birefringence, extinction angles), textural phase relations, and mineral distribution/occurrence. The sample billet used in thin-sectioning can then be coated with carbon (to prevent damage to the analyzed surface and surface charging) and placed in an SEM for secondary–electron and back-scatter electron imaging and qualitative elemental mapping. Results of thin-section and SEM microscopy will help to determine mineral paragenesis, sample equilibrium, compositional zoning profiles, and fracture and inclusion assemblages.

### 5.9.3.3 Geochemical Analyses (Suite C)

The 61 cm [2'] cores collected near the 30 cm [1'] sections at the ends of each core interval may be used for geochemical analyses and routine petrophysical analysis (Figure 7). Four 7.6 cm [3"] long pieces could be cut from the 61 cm [2'] section to perform the Li, Sr, U, and Th analyses, and each 7.6 cm [3"] piece will be used for the analysis of the four different elements and their isotopes. Prior to analysis, each 7.6 cm [3"] piece will be crushed to a powder and then digested using a combination of hydrofluoric and hydrochloric acid in pre- washed Teflon bombs at ~400 °C. The digested material will be dried, re-digested in 10% nitric acid, and diluted using ultra-pure deionized water to a total dilution of approximately 200 times. The concentration or abundance of Li, U, and Th in the digested fluids will be measured via inductively coupled plasma mass spectrometry (ICP-MS) or inductively coupled plasma optical emission spectrometry (ICP-OES).

Measurements of isotopes for Li (Li-6/Li-7), Sr (Sr-87/Sr-86), and the activity ratio of U (U-234/U-238) will be analyzed using thermal ionization mass spectrometry (TIMS). Measured isotope ratios will be corrected for instrumental biases and mass fractionation.

Water-rock interactions with typical crystalline basement will increase the salinity of the porewater and will lead to precipitation of key minerals, including laumonite and chlorite. While the presence of these minerals can be estimated from microscopic analyses of thin sections, a cation exchange capacity (CEC)

analysis can also be conducted on crushed samples, since these minerals should have much higher CEC than the primary granite minerals quartz and feldspar. Rock samples will be disaggregated, and batch tests will be conducted on samples from every core run. To better interpret these results, comparisons will be made against CEC studies on standard known amounts of laumonite, chlorite, quartz, feldspars, and other major rock-forming minerals.

### 5.9.3.4    Petrophysical Analyses (Suite D)

Analyses of petrophysical properties, including permeability, porosity, pore distribution, fluid saturation, and grain density may be performed on portions of the 7.6-cm [3"] and/or 91-cm [3'] sections of core. The ambient porosity and permeability measurements will be performed on ~2.5-cm [1"] diameter plugs cut from the core subsections (Figure 7). The plugs will represent the full diameter of the core and will be collected after the core has been slabbed for visual inspection. The permeability and porosity will be determined using He-gas permeametry and porosimetry. Additional porosity measurements and pore size distribution will be made using nuclear magnetic resonance (NMR) or mercury porosimetry methods (non-destructive). These techniques will be performed on the full diameter of the remaining whole core material.

### 5.9.3.5    Thermal Analyses (Suite E)

The thermal properties of the rock samples (i.e., thermal conductivity and diffusivity, thermal expansion, and thermal heat capacitance) may be measured using a smaller sample removed from a three-foot section of core (Figure 8). The thermal conductivity and diffusivity could be measured on a subsection or plug from the whole core subsection. These analyses will be performed at confining pressures and the sample will be subjected to a step-wise increase of pressure from 35° to 200° C. The end temperatures of these tests can be adjusted depending on the temperatures expected from the depth that the core is collected. A heater will be used on one side of the plug to apply a temperature gradient across the sample while the temperature on both ends of the sample and the side/edges are measured throughout the test.

A plug may also be collected from the same core subsection for the thermal expansion testing. The plug is placed in a pressure vessel with heaters surrounding it, and the temperature is measured at the mid-point of the plug. The test is typically performed at four different temperature steps from 50° to 200° C (experimental range and incremental adjustments can be varied), and the sample is measured for axial and radial expansion at each step.

Thermal Heat Capacitance will be measured on a crushed/disaggregated and dried sample weighing >100 g collected from a subsection of core. The dried sample is placed in an aluminum holder with a heater. Thermocouples are positioned to measure the temperature of the heater and the holder after reaching a stable specified temperature. A measured power input is added to the sample/holder, and the increase in temperature is measured to calculate the specific heat. The heat capacity is typically measured at three or four temperatures between 35° to 200°C, with the range and temperature steps adjusted depending on the expected temperatures at the sample collection depths.

### 5.9.3.6    Geomechanical Analyses (Suite F)

Samples for the geomechanical testing may also be cut from a core subsection with an inert mineral oil to minimize any chemical changes, and the ends of the test samples will be machine-ground to achieve parallel end surfaces necessary for compression testing. The samples are prepared with a length/diameter ratio of two (2) or more to minimize end-effects. Photographs and computed tomography CT images of the samples before and after the testing will be for QA/QC of the testing.

In an unconfined (uniaxial) compression test, a cylindrical core sample is compressed along the long axis, with no confinement (lateral support), until failure occurs. Conceptually, the peak value of the axial stress is taken as the unconfined compressive strength of the sample. Axial stress is monitored with a load cell. Axial and radial strains are measured using cantilever type strain transducers. In addition to axial stress,

axial and radial strains may be monitored during this test, to determine elastic constants (Young's Modulus, E, and Poisson's ratio). In view of the variability of rock properties, when adequate samples are available, repeat testing may be merited to determine average values.

Experimental results are represented as stress-strain curves, and tabulated values of elastic constants and strength. The stress-strain data are used in determining the compressive strength and elastic constants. In a brittle or elastic-perfectly plastic or strain softening material, unconfined compressive strength is taken as the maximum axial stress accommodated by the sample. When strain hardening occurs, other criteria are adopted. Elastic constants are determined over linear sections of the stress- strain curves, often in the range of 20 to 70% of the maximum applied axial stress. Generally, this, or a similar stress range, ensures that the calculated static elastic properties are obtained from a linear portion of the stress-strain curves.

The confining pressure is increased from the reference condition of effective mean *in situ* stress (determined from estimates of the three *in situ* principal stress gradients and the formation pressure gradient) to the desired confining pressure target value (e.g., 70 MPa) and reduced at the same rate to the reference *in situ* stress condition. Pore pressure is drained to atmospheric conditions. The stress-strain data collected during the course of the test are used to evaluate the bulk compressibility of the material.

In the triaxial compression test, a cylindrical core sample is compressed along the long axis while the confining pressure (along the sides of the core) are held at a constant pressure. The peak value of the axial stress is taken as the confined compressive strength of the sample. In addition to axial stress, axial and radial strains may be monitored during this test, to determine basic elastic constants (Young's modulus and Poisson's ratio). Combining triaxial testing at several confining pressures, along with the 3-sample multi-stress path testing suite, unconfined compression and tensile test data, a representative failure locus can be constructed (i.e., Mohr-Coulomb failure envelope). The selected confining pressures for triaxial testing are generally spread over a range from very low to beyond the maximum anticipated *in situ* effective stress conditions. Alternatively, a multi-stage triaxial test can be performed on a single sample. The sample is loaded at different confining stresses but is unloaded prior to failure. Only the last cycle in the sequence is taken to failure.

During a triaxial compressive strength test, the axial stress is monitored with a load cell. Confining pressure and pore pressure are monitored with conventional pressure transducers, and axial and radial strains are measured using cantilever type strain transducers. The geomechanical tests for this project will be performed at a range of relevant temperatures. Experimental results are represented as stress-strain curves, and tabulated values of elastic constants and strength. The stress-strain data are used in determining the compressive strength and elastic constants.

### 5.9.3.7     He in Quartz and Pore Water Chemistry Analyses (Suite G)

One of the 3-inch pieces from 30-cm [1'] sections will be used to measure the He-content (3/4 isotopes) in quartz grains present the samples. Quartz grains will be analyzed via the methodology described by Smith et al. (2013) after careful disaggregation and separation from the bulk core sample. The sample will be sieved after disaggregation, and the fraction from the 42 to 150 sieves will be retained for analysis.

The quartz fraction separated from the bulk sample will be placed in a 63.5 mm [¼"] diameter refrigeration grade Cu tubing that had one end silver soldered shut and a frit enclosing the other end. The tubing will be evacuated using a deep vacuum (<25 in Hg) and heated to 290⁰ C to release the He from the quartz grains and the headspace in the tubing will be analyzed using a mass spectrometer to determine the He and He 3/4 isotope concentrations. Helium concentrations will be corrected for any leakage into the tubing through Ne isotope concentrations in the samples and from analysis of impregnated quartz samples.

### 5.9.3.8     Core Pore Water Sampling (Suite H)

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 will contribute fluids trapped in fluid inclusions and should only be used after other less destructive methods have been performed on samples. Fluid extraction methods will require some type of subsampling to reduce core sample sizes (e.g., centrifuge will have a relatively small maximum sample volume/mass).

Multiple methods will be tried and compared to determine what sequence of methods can best be used 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. Porewater extraction was recently discussed as part of the Canadian repository program, and recent reports by Intera (2011), Mazurek et al. (2013), and Eichinger & Waber (2013) discuss the feasibility of different approaches.

Core samples 61 cm [2'] in length will be chosen from the ends of each core run for preservation in anticipation of fluid extraction. If core diameter is 10.2 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.

Whenever possible, subcores will be collected to obtain the largest possible fluid sample with the least possible contamination from drilling fluid. When possible, liquid samples extracted from cores will be tested for drilling fluid tracer concentration, to quantify the contamination of drilling fluid into the core subsamples.

**Table 15. Summary of Core Analyses**

| Target Analysis / Analytes | Analytical Technique | Limits of Detection (LOD) | Approximate Sample Volumes | Sample type | DQO Requirement |
|---|---|---|---|---|---|
| Core orientation and depth | FMI/sonic imager logs | - | - | Whole core | Orientation and depth-correction of all core to the degree necessary to establish subsurface representations of the in-situ core |
| Gamma ray, and U, Th, & K spectra | Spectral Gamma-Ray Core Logging | - | Whole core | Whole core | Measurements suitable to use in qualitative petrologic assessments |
| Microscopic sample mineralogy and textures | Petrographic microscopy | - | >1 cc | Thin-section | Petrographic detail sufficient to identify inclusion-rich samples, characterize micropores/ fractures, and determine modal amounts of major, minor, and trace minerals to enable rock classification and comparison with cuttings and SEM studies. |
| Microscopic sample mineralogy, high-resolution textures | SEM | ~50 nm | >1cc, <40cc | Billet | Petrographic detail sufficient to identify inclusion-rich samples, characterize micropores/ fractures, and determine modal amounts of major, minor, and trace minerals to enable rock classification and comparison with cuttings and thin-section studies. |
| Bulk Mineralogy | XRD | ~2% of sample | ≥ 6 g | Crushed core, powder | ±3-5 wt-% |
| Whole-Rock Geochemistry | XRF | 1-3 ppm | ≥ 10g | Crushed core, powder | ±5% of measured values |
| Total Lithium Concentration | TIMS, ICP-MS | 0.1 ppm | 2 g; 2-200 mL | Powdered, digested core | ±5% of measured values |
| Lithium 6/7 Isotope Ratio | TIMS, ICP-MS | - | 2 g; 2-200 mL | Powdered, digested core | ±1 per mil. |
| Strontium 87/86 Isotope Ratio | TIMS, ICP-MS | - | 2 g; 2-200 mL | Powdered, digested core | 1 part in 10,000 of direct ratio |

**Table 15. Summary of Core Analyses (continued)**

| Target Analysis / Analytes | Analytical Technique | Limits of Detection (LOD) | Approximate Sample Volumes | Sample type | DQO Requirement |
|---|---|---|---|---|---|
| Total Uranium Concentration | TIMS, ICP-MS, XRF | 0.02 ppm | 2 g; 2-200 mL | Powdered, digested core | ±5% of measured values |
| Uranium 234/238 Isotope Ratio | TIMS, ICP-MS | - | 2 g; 2-200 mL | Powdered, digested core | 3 ppm of direct ratio, or 0.05 increment in activity ratio |
| Total Thorium Concentration | TIMS, ICP-MS, XRF | 0.02 ppm | 2 g; 2-200 mL | Powdered, digested core | ±5% of measured values |
| Hydraulic Permeability | Fluid Permeametry | - | - | Whole Core | ±10% RSD |
| Porosity | Gas Porosimetry | - | 2 cm × 5 cm plug | Core plug | ±5% RSD |
| Porosity Distribution | Hg-Porosimetry, NMR | - | 2 cm × 5 cm plug | Core plug | ±5% RSD |
| Fluid Saturation | Dean Stark - Soxhlet Extraction | - | 2 cm × 5 cm plug | Core plug | ±5% RSD |
| Grain density | Pycnometry | - | 2 cm × 5 cm plug | Core plug | ±5% RSD |
| Thermal Conductivity & Diffusivity | Laser Flash Analysis | - | - | Whole core or core plug | ±5% RSD |
| Thermal Expansion | Dilatometer | - | - | Whole core or core plug | ±5% RSD |
| Thermal Heat Capacitance | Thermo-gravimetry | - | - | Whole core | ±5% RSD |
| Uniaxial Compressive strength | Uniaxial compressive strength test | - | - | Whole core or core plug | less than between-sample variability of replicate samples, or 10% RSD |
| Hydrostatic Compression Parameters | Hydrostatic compression test | - | - | Whole core or core plug | less than between-sample variability of replicate samples, or 10% RSD |

**Table 15. Summary of Core Analyses (continued)**

| Target Analysis /Analytes | Analytical Technique | Limits of Detection (LOD) | Approximate Sample Volumes | Sample type | DQO Requirement |
|---|---|---|---|---|---|
| Strength Envelope & Static Elastic Moduli | Triaxial compressive strength test | - | - | Whole core or core plug | less than between-sample variability of replicate samples, or 10% RSD |
| Dynamic Elastic Moduli | Ultrasonic Tests | - | - | Whole core or core plug | less than between-sample variability of replicate samples, or 10% RSD |
| Mechanical Creep parameters | Creep Tests | - | - | Whole core or core plug | less than between-sample variability of replicate samples, or 10% RSD |
| Helium 3/4 isotope concentration in quartz | Magnetic Sector Field-Linear MS; Static MS | - | ~100g crushed core | Quartz grain aliquots | He-4 to an uncertainty of ±5% (1 σ) cc STP/gqz, and concentrations of He 3/4 ratios to an uncertainty of ±2% for values ~$10^{-6}$., and ±20% for values ~$10^{-8}$. |

# 5.10 Core Pore Water

This section describes the sampling and analysis procedures for the core porewater extracted from cores. Porewater will extracted from cores to facilitate analysis of *in situ* radiogenic and nucleogenic noble gas tracers, non-volatile fission products, and major, minor, and trace element concentrations in low-permeability regions of the borehole that cannot be sampled using packer-based pumping.

## 5.10.1 Data Quality Objectives

Laboratory analyses on the porewater from the core samples includes suites for major cations, major anions, trace elements, stable isotopes, noble gases, cosmogenic and anthropogenic tracers, and strontium, lithium, and uranium isotopes. Each suite provides specific information regarding the geochemical conditions of the core porewater and interactions between the porewater and the rock matrix. The samples for cation analyses will be analyzed for sodium, calcium, potassium, magnesium, and iron. All of these analyses will be performed for total concentrations within ±1% of the total abundance; therefore, these samples will not be filtered with fine filters during the sampling process. Also, if dilution with high-purity water occurs there should be a limited concentration of fine materials in the sample. It also should be noted that contamination of the sample could potentially occur as a result of the sample coming in contact with any piece of equipment due to the very small sample size. All laboratory equipment should be properly cleaned prior to handling the porewater samples.

In addition to the major metals, the concentrations of trace elements (metals) will also be measured on the core porewater using ICP-MS or TIMS. The elements that will be analyzed as part of the trace metal analyses are: Al, Sb, As, Ba, Be, Cd, Cr, Co, Pb, Mn, Hg, Li, Mo, Ni, Se, Ag, Sr, Sn, and U. Target reporting limits for trace metals are between 0.01 and 0.1 mg/L. As with the cation analyses, these samples will not be filtered. Dilution may be required to obtain enough sample volume for the required analyses.

Analysis for major anions will also be performed on the drilling fluid samples. Specifically, these samples will be analyzed for bromide, fluoride, iodide, sulfate and nitrate/nitrite. The objective is to measure the anions at ±1% of the total abundance with reporting limits in the low mg/L concentrations.

Noble gas analyses include the total abundance of He, Ne, Ar, and Xe, and these analyses will be used to interpret the age and provenance of the formation fluids. The data for noble gas concentrations in the formation fluids will be compared to the noble gas data from the rock samples to confirm the origin of the fluid/rock and determine interactions between the two media. Samples will be carefully handled to minimize exposure to the atmosphere during the sample collection, processing, and analysis, with the objective of limiting atmospheric contamination to less than 10% of the total noble gas concentration.

The concentrations of *in situ* radiogenic/nucleogenic tracers (He-3, He-4, Ar-39, Kr-81, and Xe-129) will be measured in the headspace over the core inside helium-tight core holders. The relative noble gas composition of the headspace will be used to estimate the apparent age of the fluid and detect any contamination of the fluid samples by atmospheric gases or non-native waters. Due to potential contamination issues by other fluids or gases, care must be taken to prevent exposure to the atmosphere and sampling equipment during the sampling process. The feasibility of performing these analyses may be limited as a result of the low concentrations of these species in the water samples.

Less volatile *in situ* fission product species (Cl-36 and I-129) will be sampled from crushed core samples. It is believed that simple centrifugation will not produce the required sample volume needed for the analysis. All rock preparation and water collection must be performed in a clean laboratory to avoid contamination of the samples.

**Table 16. Core Porewater Analyses**

| Target Analysis/ Analytes | Frequency | Purpose | Data Quality Objective | Potential Contamination, Sample Loss, or Sample Size Issues |
|---|---|---|---|---|
| Major Cations (Na, Ca, K, Mg, Fe total | Two sample intervals (each with nearby duplicates) from ends of each core run | Major cations, in combination with the major anions and trace metals, analyses provide geochemical characterization information for the core sample. Complete chemical analysis (charge balanced to <5%). 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 is assumed here. Undiluted sample reporting limits for metals (using ICP-ES): Na (100 mg/L), Ca (100 mg/L), K (100 mg/L), Mg (100 mg/L), Fe total (5 mg/L). These are likely to be at less than 1% of total abundance except for K, Mg, and Fe. Improvement may be achieved by optimizing dilutions, or by using alternative methods such as atomic absorption for metals. | May recover only small sample volumes, Dilution with high-purity water could "increase" sample size. |
| Major Anions (Bromide, fluoride, iodide, sulfate, nitrate + nitrite) | Two sample intervals (each with nearby duplicates) from ends of each core run | Major anions, in combination with the major cations and trace metals, analyses provide geochemical characterization information for the core sample. 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 is assumed here. Undiluted sample reporting limits for non-metals (ion chromatography): chloride (2 mg/L), bromide (1 mg/L), fluoride (10 mg/L), iodide (1 mg/L), sulfate (2 mg/L), nitrate + nitrite (1 mg/L). These are likely to be at less than 1% of total abundance except for fluoride. Iodide is estimated for dilution of 1:9. Improvement may be achieved by optimizing dilutions. | May recover only small sample volumes, Dilution with high-purity water could "increase" sample size. |

**Table 16. Core Porewater Analyses (continued)**

| Target Analysis/ Analytes | Frequency | Purpose | Data Quality Objective | Potential Contamination, Sample Loss, or Sample Size Issues |
|---|---|---|---|---|
| Radiogenic/ Nucleogenic Noble Gas Tracers | One sample from the end of each core run | He-3, He-4, Ar-39, Kr-81, and Xe-129 can build up in ancient, isolated groundwater and thereby indicate long residence time. Analyses performed off-site. Headspace of He-tight sample containers is tested for ratios of noble gas isotopes. Samples may be heated to accelerate diffusion of noble gases from pore water and rock into sample container head space. | Quantitation objectives are determined from *in situ* production rates (using abundance of parent nuclides in rock) or accumulation rates (using estimated fluxes) over as specified interval of time (e.g., 1 Myr) 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 must be quantified from simultaneous sampling of the fluid, and if significant noble gas content is found, by quantitation of iodide tracer residue in the cores (see below). The abundances of He-4 and possibly Ar-39 are likely sufficient to obtain useful data from reasonable quantities of core, but the other nuclides may be too scarce for a reasonable sampling effort. | 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 subsampling through gas ports) until noble gas sampling is complete. |
| Less Volatile *in situ* Fission Product Species (Cl-36, I-129) | Two samples from the end of each core run | Long-lived radioactive isotopes are generated *in situ* through at well-known rates. Comparison is made between I-129 and its decay product Xe-129, or between Cl-36 and its sources (Cl-35, K-39, and Ca-40). These analyses may be deferred to later times, using preserved samples. | Quantitation objectives have the same basis as described above for noble gases, based on hypothetical *in situ* production over a specified interval of time. Simultaneous samples of drilling fluid of sufficient volume for characterizing I-129 and Cl-36, are needed to correct for invasion effects especially in (future) crushed core leaching extractions. | Crushing and sub-sampling must 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 must be done in a "clean" environment where dust contamination (e.g., containing traces of historical radioactive fallout) can be controlled. |

## 5.10.2 Sample Collection Procedures

The samples of porewater will be obtained from core. The sections of core marked for pore-fluid extraction will be shipped to a laboratory for further processing to extract the fluids from the core sections.

Some specialized analyses to be performed on the porewater (noble gases and the fission product species) from the core samples may require relatively large volumes of water, however, obtaining even small amounts of water from core may be extremely difficult, and the methods described in this plan for extracting fluids are not guaranteed to generate the desired volumes of water needed for accurate analysis. In addition, the extraction process may require multiple steps to recover the needed volumes.

A non-destructive centrifugation method will be attempted first to remove the native waters from the core sample. In addition, this method is less likely to lead to contamination of any water recovered from the core. For this method, the core or smaller plugs of the core will be placed in a centrifuge and spun up to 10,000 rpm to force the water from the core sample. Typical core analytical laboratories are only capable of working with small volume/mass samples (3.8-cm [1.5"] diameter by 5-cm [2"] long), and this limitation may require additional processing of the whole core sample with a greater possibility of contamination. Specialized centrifugation may need to be performed in centrifuges larger than those used for core plug analyses. Sample chambers on the centrifuge are sealed during the extraction process to minimize the opportunity for contamination of the extracted fluid by atmospheric gases. After the sample has been centrifuged for a minimum of 24 hours, the core plug will be removed from the centrifuge and a pipet will be used to collect any water that has separated from the core.

If no fluid is recovered from the core samples using the centrifuge, other non-destructive methods will be attempted. These include diffusion methods, submerging unconfined samples into deionized water or confining samples and forcing deionized water into them at high pressure. In addition to non-destructive methods, the core will be crushed, and an aqueous extraction method will be used to recover native water from the samples. The core or plug samples used in the centrifugation method will be crushed using a jaw-crusher to produce coarse (~¼"-diameter) particles of the sample. These particles will be rinsed with high-purity water with known values for the targeted analytes. The leachate from this process will be collected in polyethylene containers and will immediately be analyzed.

Multiple methods will be tried and compared to determine what sequence of methods can best be used 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. Porewater extraction was recently discussed as part of the Canadian repository program, and recent reports by Intera (2011), Mazurek et al. (2013), and Eichinger & Waber (2013) discuss the feasibility of different approaches.

## 5.10.3 Sample Analysis Program

Core porewater will be analyzed for *in situ* radiogenic nucleogenic gases, Cl-36, I-129, major cations, major anions, metals, thorium and uranium. Core water consists of porewater recovered from core samples of the crystalline rock. The cores will likely produce very limited volumes of fluid sample, and the sample that is recovered may contain a certain percentage of drilling fluid that has infiltrated the core sample during the collection of the core. Therefore, it is extremely important that the laboratory is prepared to analyze the required parameters on very limited volumes of sample, and can account for the drilling fluids present

### 5.10.3.1 Laboratory Instrument Calibration

Analytical instruments will be calibrated in accordance with the analytical methods. All analytes reported, except as noted by the laboratory, will be present in the initial and continuing calibrations, and will meet the specified acceptance criteria (Table 17). All reported results will be within the calibration range.

Records of standard preparation and instrument calibration will be maintained.

**Table 17. Core Porewater Instrumentation**

| Parameter/Analyte | Method/ Instrument | Acceptance Criteria | Reporting Limits |
|---|---|---|---|
| *In situ* radiogenic nucleogenic gases: He-3, He-4, Ar-39, Kr-81, Xe-129 | TIMS, ICP-MS | Linear 5-point calibration, RSD ≤20%, $r^2$≥0.99 ICV ±10% | TBD |
| Less volatile in-site fission product species: Chlorine-36, Iodine-129 | TIMS, ICP-MS | Linear 5-point calibration, RSD ≤20%, $r^2$≥0.99 ICV ±10% | TBD |
| Cations: Sodium, Calcium, Potassium, Magnesium, Iron | 200.8 | Linear 5-point calibration, RSD ≤20%, $r^2$≥0.99 ICV ±10% CCV ±10% | Sodium = 100 mg/L, Calcium= 100 mg/L, Potassium= 100 mg/L, Magnesium = 100 mg/L, Iron = 5 mg/L |
| Anions: Chloride, Bromide, Fluoride, Iodide, Sulfate, Nitrate-Nitrate | E300 | Linear 5-point calibration, RSD ≤20%, $r^2$≥0.99 ICV ±10% CCV ±10% | Chloride = 2 mg/L Bromide = 1 mg/L Fluoride = 10 mg/L Iodide = 1 mg/L Sulfate = 2 mg/L Nitrate-Nitrate = 1 mg/L |
| Trace Elements: Aluminum, Antimony, Arsenic, Barium, Beryllium, Cadmium, Chromium, Cobalt, Lead, Lithium, Manganese, Mercury, Molybdenum, Nickel, Selenium, Strontium, Silver, Tin | 200.8 | Linear 5-point calibration, RSD ≤20%, $r^2$≥0.99 ICV ±10% CCV ±10% | RLs between 0.01 and 0.1 mg/L can be obtained for Al, Sb, As, Be, Cd, Cr, Co, Pb, Mn, Hg, Mo, Ni, Se, and Ag. Higher reporting limits of approx. 10 mg/L can be obtained for Ba, Li, Sn and Sr. U has an undiluted reporting limit |
| Thorium, Uranium | TIMS, ICP-MS | Linear 5-point calibration, RSD ≤20%, $r^2$≥0.99 ICV ±10% | TBD |

### 5.10.3.2   Laboratory Quality Control

Laboratory QC samples will be analyzed in accordance with the analytical methods and may include tune blanks, method blanks, matrix spikes, laboratory control samples and laboratory sample duplicates. QC sample results must meet the criteria outlined in the analytical method. Laboratory QC samples will be analyzed in accordance with the analytical methods and must meet the method acceptance criteria

## 5.11 Formation Fluid from High-Permeability Zones

Samples will be collected from at least one zone in the basal overburden formation and from four zones within the crystalline basement, these samples will be collected in conjunction with testing to determine the hydraulic properties of the formations. Sampling and testing of the unconsolidated formation above the crystalline rock will be performed during the drilling of the borehole prior to setting the intermediate casing, while the sampling and testing of the crystalline formation will be performed after the borehole has been drilled to total depth. Two testing/sampling approaches are proposed for the different formations: a wireline-deployed tool for the unconsolidated formation; and a tubing-deployed straddle packer system with a downhole pump in the crystalline basement. Both methods will be capable of producing unpressurized (collected under atmospheric pressures) and pressurized (collected at formation pressures) samples.

### 5.11.1 Data Quality Objectives

Table 19 presents the DQOs for the samples collected from both the unconsolidated formation and the higher-permeability zones in the crystalline formation. In preparation for sample collection, water will be purged from the test zones to remove any drilling or non-native fluids from the formations. This purge water will be routinely monitored on site for water-quality parameters (pH, temperature, Eh, TDS, iodide and fluorescein). The exact frequency of the field monitoring will be determined during the testing because the yield of the formations is currently uncertain.

Laboratory analyses include suites for major cations, major anions, trace elements, stable isotopes, noble gases, cosmogenic and anthropogenic tracers, and strontium, lithium, and uranium isotopes. Each suite provides specific information regarding the geochemical conditions of the test zone and will be performed on each water sample collected from the higher permeability formations/zones. The samples for cation analyses will be analyzed for sodium, calcium, potassium, magnesium, and iron. All of these analyses will be performed for total concentrations within ±1% of the total abundance; therefore, these samples will not be filtered with fine filters during the sampling process. However, some filtering may need to be performed to remove the drilling mud from the samples. Currently, the TDS concentrations are not known, and the samples may need to be diluted in order to analyze the samples within the normal operating conditions of the analytical instruments.

In addition to the major metals, the concentrations of trace elements (metals) will also be measured on the drilling fluids samples using ICP-MS or TIMS. The elements that will be analyzed as part of the trace metal analyses are: Al, Sb, As, Ba, Be, Cd, Cr, Co, Pb, Mn, Hg, Li, Mo, Ni, Se, Ag, Sr, Sn, and U. Target reporting limits for trace metals are between 0.01 and 0.1 mg/L. As with the cation analyses, these samples may require some filtering to remove the drilling fluids.

Analysis for major anions will also be performed on the drilling fluid samples. Specifically, these samples will be analyzed for bromide, fluoride, iodide, sulfate and nitrate/nitrite. The objective is to measure the anions at ±1% of the total abundance with reporting limits in the low mg/L concentrations.

Stable isotope data for water (O-18 and deuterium) provide information for the origins of the recharge water (i.e., climate conditions when precipitated – Sharp 2007; IAEA 2013). These samples will be analyzed using cavity ring-down spectrometry to measure differences of 1.0 per mil in the samples.

Noble gas analyses include the total abundance of He, Ne, Ar, and Xe, and these analyses will be used to interpret the age and provenance of the formation fluids. The data for Noble gas concentrations in the formation fluids will be compared to the Noble gas data from the rock samples to confirm the origin of the fluid/rock and determine interactions between the two media. Samples will be carefully handled to minimize exposure to the atmosphere during the sample collection, processing, and analysis, with the objective of limiting atmospheric contamination to less than 10% of the total Noble gas concentration.

The concentrations of cosmogenic and anthropogenic tracers (tritium, Ne-21, Cl-36, Kr-85, and I-129) will be measured in the fluid samples and compared to concentrations in the atmosphere and/or the hydrosphere to calculate the apparent age of the fluid and detect any contamination of the fluid samples by atmospheric gases or non-native waters (IAEA 2013). Due to potential contamination issues by other fluids or gases, care must be taken to prevent exposure during the sampling process, and efforts will be made to limit contamination to less than 10% of the total concentration of the species. The feasibility of performing these analyses may be limited as a result of the low concentrations of these species in the water samples. This may also result in the need for relatively large sample volumes.

The isotope ratios of strontium (Sr-87/Sr-86), lithium (Li-6/Li-7), and uranium (U-234/U-238) will be used to measure the apparent age of the mineral assemblages and to evaluate the rock/water interactions.

Measurements will be made to quantify the ratios of the Sr isotopes to within 0.1 per mil, and the Li isotope ratio within 1.0 per mil. Uranium quantitation objective is to determine within 5% of total content

and the direct content to within 3.0 ppm (activity ratio difference of 0.05). These samples could be contaminated as a result of exposure to other rock material or sampling equipment.

**Table 18. Core Porewater Analyses**

| Target Analysis/ Analytes | Analysis Location | Frequency | Analytical Technique | Purpose | Data Quality Objective | Potential Contamination or Sample Loss |
|---|---|---|---|---|---|---|
| Alkalinity | On-Site | At least once per each interval tested | Titration | Acid-indicator alkalinity titration, together with pH measurement, allows calculation of *in situ* pCO2. | Acid-indicator alkalinity titration, together with pH measurement, allows calculation of *in situ* pCO2 at an accuracy of 1 to 2 significant figures. Alkalinity titration performed on samples of water is used to interpret the carbonate system and must be performed on-site. | None |
| Temperature | On-Site | Multiple times during purging and once when samples for off-site analysis are being collected | Thermometer | Temperature, along with, pH, Eh, and TDS are used to determine when pristine samples can be taken (for downhole pumped intervals). They are also needed to evaluate the quality of water samples for other analyses, and to interpret sample provenance and water-rock interaction. | Temperature can be accurately and consistently 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). | Insufficient flow through the measurement cell, in extreme weather, may shift the measured temperature. For wireline-conveyed packer sampling, the *in situ* temperature is recorded (along with pH, CO2, resistivity, and other factors). |
| pH | On-Site | Multiple times during purging and once when samples for off-site analysis are being collected | pH meter | pH, along with, temperature, Eh, and TDS are used to determine when pristine samples can be taken (for downhole pumped intervals). They are also needed to evaluate the quality of water samples acquired for other analyses, and to interpret sample provenance and water-rock interaction. | 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 Kw shift (e.g., maximum at ~0.6 M NaCl, $10^{-16}$ at 5 M). | Degassing and temperature changes can shift measured pH. These can be caused by insufficient flow through the measurement cell. For wireline-conveyed packer sampled waters, *in situ* pH can be measured with the *In situ* Fluid Analyzer. Checking this pH at the surface should be done while minimizing exposure to atmosphere (e.g., 1 minute or less). |
| Eh | On-Site | Multiple times during purging and once when samples for off-site analysis are being collected | Electrode | Eh, along with, pH, temperature, and TDS are used to determine when pristine samples can be taken (for downhole pumped intervals). They are also needed to evaluate the quality of water samples acquired for other analyses, and to interpret sample provenance and water-rock interaction. | Eh can also 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- $H_2O$). | Exposure to atmosphere and temperature changes can shift measured Eh. Measurement electrodes may foul or acquire a patina of produced from the sample water. |
| Total Dissolved Solids (TDS) (calculated from conductivity) | On-Site | Multiple times during purging and once when samples for off-site analysis are being collected | conductivity meter | TDS, along with, pH, temperature, and Eh are used to determine when pristine samples can be taken (for downhole pumped intervals). They are also needed to evaluate the quality of water samples acquired for other analyses, and to interpret sample provenance and water-rock interaction. | 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 low, rather than high conductance. Thus, ±2% accuracy may be readily achievable with dilute waters but ±20% may result with concentrated brines. | Fouling of conductance cell electrodes (e.g., by $H_2S$) can shift TDS measurement to lower or higher values. |
| Iodide | On-Site | Multiple times during purging and once when samples for off-site analysis are being collected | Ion-specific electrode, | Iodide is added to the drilling fluid as a tracer and is used to determine when pristine samples can be taken (for downhole pumped intervals). | | |

Table 18. Core Porewater Analyses (continued)

| Target Analysis/ Analytes | Analysis Location | Frequency | Analytical Technique | Purpose | Data Quality Objective | Potential Contamination or Sample Loss |
|---|---|---|---|---|---|---|
| Fluorescein | On-site | Multiple times during purging and once when samples for off-site analysis are being collected | Fluorometer | Fluorescein is added to the drilling fluid and is used to determine when pristine samples can be taken (for downhole pumped intervals). | | |
| pH and TDS (calculated from conductivity) | Laboratory | At least one sample per interval tested | pH meter and conductivity meter | pH and TDS will be performed on samples of the higher permeability formation water to confirm the measurements made in on-site. | If significant off gassing occurs with the samples during transport, the pH measurements could be different between the on-site and laboratory. | |
| Major Cations (Na, Ca, K, Mg, Fe total | Laboratory | At least one sample per interval tested | ICP-ES | Major cations, in combination with the major anions and trace metals, analyses provide geochemical characterization information for the test zone. Complete chemical analysis (charge balanced to <5%). 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 is assumed here. Undiluted sample reporting limits for metals (using ICP-ES): Na (100 mg/L), Ca (100 mg/L), K (100 mg/L), Mg (100 mg/L), Fe total (5 mg/L). These are likely to be at less than 1% of total abundance except for K, Mg, and Fe. Improvement may be achieved by optimizing dilutions, or by using alternative methods such as atomic absorption for metals. | Residues from pumping equipment. |
| Major Anions (Bromide, fluoride, iodide, sulfate, nitrate + nitrite) | Laboratory | At least one sample per interval tested | ICP-ES | Major anions, in combination with the major cations and trace metals, analyses provide geochemical characterization information for the test zone. 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 is assumed here. Undiluted sample reporting limits for non-metals (ion chromatography): chloride (2 mg/L), bromide (1 mg/L), fluoride (10 mg/L), iodide (1 mg/L), sulfate (2 mg/L), nitrate + nitrite (1 mg/L). These are likely to be at less than 1% of total abundance except for fluoride. Iodide is estimated for dilution of 1:9. Improvement may be achieved by optimizing dilutions. | Residues from pumping equipment. |
| Trace elements: Al, Sb, As, Be, Cd, Cr, Co, Pb, Mn, Hg, Mo, Ni, Se, and Ag. Ba, Li, Sn and Sr, U. Total abundance | Laboratory | At least one sample per interval tested | ICP-MS | Trace element analyses will be used to control isotopic measurements with total abundance at appropriate accuracy (objectives: Li at ±1 ppb; U at ± 0.05 ppb). Drilling fluid tracer should be determined at better than ±1% of the applied concentration. Also, trace element analyses can detect local elemental anomalies at ppb-level. | 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 between 0.01 and 0.1 mg/L can be obtained for Al, Sb, As, Be, Cd, Cr, Co, Pb, Mn, Hg, Mo, Ni, Se, and Ag. Higher reporting limits of approx. 10 mg/L can be obtained for Ba, Li, Sn and Sr using ICP-MS, although lower limits may be obtained by atomic absorption. U can be analyzed by ICP-MS with an undiluted reporting limit of 0.03 mg/L, but this could be readily improved using isotope dilution, chemical separation and ICP-MS or TIMS. | Exposure to crushed rock, residues or leakage from pumping equipment, filtration equipment, etc. Use ultra-high purity acid to treat samples for storage. |
| Stable isotopes: O-18 and D | Laboratory | At least one sample per interval tested | Cavity ring-down spectroscopy | Stable water isotopes provide data for interpreting recharge water provenance (e.g., climate conditions when precipitated) or origin other than meteoric (e.g., marine). | Precision of 0.1 per mil for O-18 and D samples can be achieved using vaporization or diffusion processes to extract pure $H_2O$ from brine without significant fractionation. Quantitation objective: resolve and accurately discriminate sample differences as small as 1 per mil O-18 or D. Cavity ring-down spectroscopy is a commercialized desktop method that can achieve this performance. | Prolonged exposure to air (more than a few minutes); residual fluids from pumping equipment. |

**Table 18. Core Porewater Analyses (continued)**

| Target Analysis/ Analytes | Analysis Location | Frequency | Analytical Technique | Purpose | Data Quality Objective | Potential Contamination or Sample Loss |
|---|---|---|---|---|---|---|
| Noble gases - He, Ne, Ar, Xe total abundance | Laboratory | At least one sample per interval tested | Diffusion sampler | Noble gases - Use He, Ne, Ar, and Xe total abundance to interpret sample age and provenance, and to check on noble gas isotopic analyses. Objective: <<10% contamination/loss of noble gases from/to the atmosphere. Analyses performed off-site. | Noble gas abundance measurements are relative in that losses to drilling and borehole circulation cannot be readily quantified. However, depth series can be interpreted, and inter-relationships between noble gas abundances can be compared to *in situ* rock composition to interpret consistency of origin. Contamination from modern water (e.g., drilling fluid makeup water) can be detected using the iodide tracer in drilling fluid, and possibly stable water isotopes and tritium. Some noble gases (Ne, Xe) may be very scarce so that quantitation is unsuccessful. | Exposure to air (more than a few seconds). |
| Cosmogenic and anthropogenic tracers (tritium, Ne-21, Kr-85) and Less volatile *in situ* fission product species (Cl-36 and I-129) | Laboratory | At least one sample per interval tested | | Cosmogenic and anthropogenic tracers (tritium, Ne-21, Cl-36, Kr-85 and I-129) can be compared with atmosphere or hydrosphere abundance to directly calculate apparent age, and/or to detect contamination of *in situ* samples. Quantitation objectives are determined from atmospheric or modern groundwater background levels and should be 1% to 10% of these levels for interpreting or correcting subsurface groundwater 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., Cl-36), which may indicate build-up in ancient groundwater. Also, cosmogenic radioactive isotopes may be significant by their absence, indicating groundwater aging *in situ*. The objective is therefore quantitation of tracer concentrations in brine at a fraction (e.g., 10%) of the corresponding atmospheric or meteoric levels. These species will be very scarce, so that large water samples could be needed, and quantitation may be unsuccessful. The most promising quality-control tracer (besides the iodide drilling fluid tracer) is tritium, if nuclear-age concentrations are found in the drilling fluid makeup water. | Exposure of water samples to air (for more than a few seconds) will cause sample loss and/or contamination of gaseous analytes. Leaching recently crushed rock, residues or leakage from pumping equipment, filtration equipment, etc. could also contribute. Sample Cl-36 is likely to be overwhelmed by drilling fluid chloride and may not be analyzable. |
| Strontium isotopes (Sr 87/86) | Laboratory | At least one sample per interval tested | TIMS | Sr isotopes (Sr-87/Sr-86) are used to interpret apparent age of mineral assemblages and interacting waters. | Quantitation objective: determine the direct ratio of isotopes to better than 1 part in 10,000, with brine samples containing approx. 1 to 10 mg total Sr. | Exposure to crushed rock, residues or leakage from pumping equipment, filtration equipment, etc. Use ultra-high purity acid to treat samples for storage, and Teflon-distilled water for chemical separations. |
| Li 6/7 isotope ratio | Laboratory | At least one sample per interval tested | | The Li-6/Li-7 isotope ratio is compared with whole rock ratios to determine marine or rock-water interaction origin. Analyses performed off-site. | Quantitation objective: Determine abundance to 5% of content, and stable isotope ratio to ±1 per mil, with brine samples containing approx. 10 to 100 ug total Li. | Exposure to crushed rock, residues or leakage from pumping equipment, filtration equipment, etc. Use ultra-high purity acid to treat samples for storage, and Teflon-distilled water for chemical separations. |
| U 234/238 activity ratio | Laboratory | At least one sample per interval tested | Gamma Spectroscopy? | The U-234/U-238 activity ratio is compared with whole-rock ratios to interpret residence time. Isotope dilution, chemical separation, and TIMS analyses performed off site. | Quantitation objective: Determine abundance to 5% of content, and the direct ratio of 234 to 238 isotopes to better than 3 ppm (activity ratio difference of 0.05), with brine samples containing approx. 0.1 to 1 ug total U. | Exposure to crushed rock, residues or leakage from pumping equipment, filtration equipment, etc. Use ultra-high purity acid to treat samples for storage, and Teflon-distilled water for chemical separations. |

## 5.11.2 Sample Collection Procedures for Tubing-Deployed Packers

### 5.11.2.1 Field and Laboratory Sampling Procedures

During the drilling and characterization of the borehole, at least four zones within the crystalline rock with suspected higher permeability will be identified, and four of those identified zones will be selected for sampling and testing. Once a zone has been selected, a tubing-mounted straddle packer system with a downhole pump will be used to isolate the test/sampling zone and to produce fluids from each test location. The system should include a pump able to move water to the surface from the interval isolated between the straddle packers to obtain water samples. The downhole pump will be used to purge water from the test zone. Samples will be collected both at the surface and using a downhole sampling device. However, field analyses will be performed on the purged fluids during pumping to ensure pristine formation fluids are being recovered. Samples for general geochemical parameters (cations, anions, and trace elements), and any analytes that require large sample volumes (but not at reservoir pressure) will be collected at the surface during the purging/pumping process.

The purge water monitoring technique will depend on the volumes of water produced during the pumping process. If the packer-isolated interval of the crystalline basement yields enough fluid to fill the tubing string to surface and continues to produce fluid, geochemical parameters of the pumped water (pH, conductivity, redox potential, iodide tracer, and fluorescein tracer) will be monitored at the surface during the pumping to determine when the residual drilling fluid has been removed from the test zone and pristine formation fluid is present. This monitoring of the purge water will be performed with analyte-specific downhole instruments. The system should minimize fluids coming in contact with the atmosphere during the pumping before sampling. Although the specific geochemical parameters will be monitored during pumping, the test zone will likely be adequately purged if the formation yields enough volume that fluid reaches the surface. Using 7.3-cm [2⅞"] inch tubing to convey fluid from the test zone to the surface would require approximately 29 barrels to fill every 1,500 m [5,000'] of tubing.

Once pristine formation fluid is considered to have been recovered through the stabilization of the general geochemical parameters and the absence of tracers, samples of formation fluid will be collected for the final field (water quality parameters) analyses. In addition, samples can also be collected for non-critical measurements and for chemical species that are not easily affected when exposed to the atmosphere and standard pressures. Smaller-volume samples for analytes that require strict isolation from the atmosphere and reservoir pressure will be collected using a downhole sampling system.

If the formation does not yield enough fluid to be pumped to the surface, the timing for the sample collection will be more dependent on the purged volume as opposed to the geochemical conditions of the purged water. At a minimum, efforts will be made to pump at least three test-zone volumes prior to collecting the samples. The test-zone volume is defined as the volume of the borehole (in liters) between the straddle packers, and the pumped volume will be determined by monitoring the fluid level (hydrostatic pressure) in the tubing string. Once at least three test-zone volumes have been pumped into the tubing, the downhole pressurized sampling device will be lowered to the top of the test zone via slackline to collect a sample of the fluid at this depth. At surface, the sample will be analyzed for the presence of the tracers (iodide and fluorescein), and if neither of the tracers is present in the sample, samples for laboratory analyses will be collected. If either of the tracers are present in the sample, further action will be decided by project managers and the technical leads. If the tracers are not present, the downhole sampler will again be lowered through the tubing to the test zone to collect the samples for laboratory analyses.

Independent of whether fluid can be pumped to surface, a pressurized sample of the fluid will be collected from the test zone for laboratory analyses. Once the test zone has been purged free of drilling fluids, the pump will be removed from the tubing and the downhole sampler will be lowered to the test zone via slackline to collect samples under *in situ* pressure conditions. The sampling device should contain a timer-activated valves to initiate sample collection. The clock will be set with enough time to allow the sampler

to be run to the desired depth prior to operating the valves for sample collection. The sampler will be capable of collecting a 600-mL sample with each sampling run. Although one sampling run will be sufficient to collect the minimum volume necessary to perform all of the analyses, at least three samples will be collected from each test zone with the downhole sampler.

Following the collection and retrieval of the pressurized fluid in the downhole sampler, these samples will be transferred to pressure-rated containers for shipment to the laboratory under pressure. A sample transfer system will be used to transfer the sample from the sampler to the pressure- rated container without losing pressure or exposing the fluid to the atmosphere. To the extent possible, enough formation fluid samples will be collected to perform all of the required analyses, and individual pressure cylinders will be filled to send to the laboratories contracted to perform the analyses.

The transfer method will likely prohibit the ability to filter or preserve the samples in the pressure cylinders that will be shipped to the laboratories. However, volatilization, precipitation, and other chemical changes to the sample should be minimized by preventing the exposure of the sample to the air during the transfer and by maintaining the borehole pressure in the sample containers during transfer and shipping.

### 5.11.2.2   Sampling Equipment Cleaning/Decontamination Procedure

Specific cleaning and decontamination of the sampling equipment will not be performed following the collection of the samples at each test location. The addition of chemicals or solvents (including water) may introduce chemical contamination to the sampling equipment. Rather, the sampling equipment will be flushed with water from each new sampling zone to remove and dilute any residual water or chemical species remaining from the previous sampling location.

### 5.11.2.3   Sample Containers and Preservation

All samples will be provided to the laboratory in the pressurized sample bottle that will be shipped under formation pressure conditions. Therefore, no filtering or preservation will be performed on the samples. If filtering is required, this will need to be performed at the laboratory just prior to analysis. Table 19 also includes sample containers and preparation/preservation methods for the required analyses if any non-pressurized sample is collected.

**Table 19. Pumped Water Sample Analytes**

| Analyte | Method | Container/Volume | Minimum Volume | Preparation/ Preservation |
|---|---|---|---|---|
| Total Dissolved Solids | M2540C | Pressurized Sample Bottle/1 L Poly[a] | 1.0 mL | None |
| pH | M4500-H+ B | Pressurized Sample Bottle/1 L Poly[a] | 20 mL | None |
| Cations: Na, Ca, K, Mg, Si, Fe (total), Al, Sb, As, Be, Cd, Cr, Co, Pb, Mn, Hg, Mo, Ni, Se, Ag Ba, Li, Sn, Sr, U | 200.8 | Pressurized Sample Bottle/1.5 L Poly[b] | 1.0 mL | 2% $H_2NO_3$ Zero Headspace |
| Anions: Bromide, fluoride, iodide, sulfate, nitrate + nitrite | E300 | Pressurized Sample Bottle/1 L Poly[a] | 1.0 mL | No Preservative |
| Stable isotopes: O-18 and D | | Pressurized Sample Bottle/Amber Glass 50 mL | 1.0 mL | Zero Headspace |
| Noble gases - He, Ne, Ar, Xe | TBD | Pressurized Sample Bottle/50-mL Stainless Cylinder or Clamped Copper Tubing[c] | 2.5 mL | None |
| Cosmogenic and anthropogenic tracers: tritium, Ne-21, Cl-36, Kr-85 and I-129 | TBD | Pressurized Sample Bottle/50-mL Stainless Cylinder or Clamped Copper Tubing[c] | 2.5 mL | None |
| Strontium isotopes: Sr-87/Sr-86 | TIMS | Pressurized Sample Bottle/50 mL Teflon bottle[d] | 10 mL | 2% $H_2NO_3$ Zero Headspace |
| Li 6/7 isotope ratio | TIMS | Pressurized Sample Bottle/50 mL Teflon bottle[d] | 10 mL | 2% $H_2NO_3$ Zero Headspace |
| U 234/238 activity ratio | TIMS | Pressurized Sample Bottle/50 mL Teflon bottle[d] | 10 mL | 2% $H_2NO_3$ Zero Headspace |

a – TDS, pH, and the anions will be collected in the same 1-Liter container
b – Metals and trace elements will be collected in the same 1.5-Liter container
c – Noble gases and cosmogenic/anthropogenic tracers will be collected in the same container
d – Sr, I, and U isotopes will be collected in the same 50-mL bottle

### 5.11.3 Sample Collection Procedures for Wireline-Conveyed Packers

After the borehole has been drilled through the higher permeability zone above the crystalline formation, samples will be collected from this zone using a wireline-conveyed packer tool that is equipped with packing elements and a pump to isolate and purge test zones, respectively.

The wireline-conveyed packer system will be lowered into the borehole to proper depth and the packer elements for the chosen extraction module will be sealed to isolate the test/sample zone. A pre-sampling pumping test will be performed to confirm the feasibility of sampling the selected zone. If sample collection is confirmed to be feasible, the zone will be purged to remove residual drilling fluids. The effectiveness, or completeness of the purging process will be monitored using downhole sensors.

When a successful pre-sampling test is complete, an unpressurized sample will be collected to determine the quality of the pressurized samples that will be collected. Pumping fluid from the formation will begin with a rate of approximately 5 mL/min, and the differential pressure will be monitored. If the differential pressure exceeds 2.4 MPa [350 psi], the pump rate should be maintained or reduced to prevent pulling sediment into the sampler. Pumping will continue until the monitored parameters have stabilized and there is no indication of fluorescein in the purge water. Unpressurized samples will be collected and returned to surface and will be analyzed for water quality parameters to confirm pristine formation samples have been produced. Pressurized samples will be collected when it has been determined that pristine samples can be collected.

Upon retrieval at the surface, an opening pressure measurement is taken on the pressurized sample to verify the sample was captured and the pressure maintained as planned. The sample bottles are then removed from tool and prepared for shipment to the analytical laboratory.

### 5.11.4 Field Sample Analysis Program

The water pumped from the test zone will be monitored at the surface for water quality parameters (pH, conductivity, redox potential, iodide tracer, and fluorescein tracer) to determine when pristine water has been recovered from the zone. At a minimum, the produced water will be analyzed using the in-line monitoring instruments every borehole volume of the test zone; however, the frequency for the analysis of the fluids will be dependent upon the water production capacity of the test zone in either total volume produced or flowrate. If the test zone is productive (producing more than 3.8 L/min [1 gpm] and is capable of producing approximately 1,000 L total), the water will be analyzed every test borehole volume. However, if the test zone has less than this production capacity, the water will be analyzed every 10% of the borehole volume produced.

The available field analysis equipment consists of online sensors for chemical-physical parameters such as temperature, pH, oxygen concentration, and electrical conductivity. In addition, the concentration of fluorescein and iodide tracers will also be measured online during each withdrawal phase.

#### 5.11.4.1 Field Instrument Calibration and Quality Control

Field instruments will be field-calibrated on a daily basis, or as recommended by the manufacturer. If possible, a two-point calibration will be performed over the range of expected concentrations/value for each analysis.

### 5.11.5 Laboratory Sample Analysis Program

High permeability crystalline rock formation fluid will be analyzed at laboratories for *in situ* radiogenic nucleogenic gases, Cl-36, I-129, major cations, major anions, metals, thorium, uranium, noble gases, cosmogenic and anthropogenic tracers, and radioisotopes (Strontium-87/86, Lithium-6/7 and Uranium-234/238).

#### 5.11.5.1 Laboratory Instrument Calibration and Quality Control

Analytical instruments will be calibrated in accordance with the analytical methods. All analytes reported, except as noted by the laboratory, will be present in the initial and continuing calibrations, and will meet the specified acceptance criteria. All reported results will be within the calibration range.

Records of standard preparation and instrument calibration will be maintained.

Laboratory QC samples will be analyzed in accordance with the analytical methods and may include tune blanks, method blanks, matrix spikes, laboratory control samples and laboratory sample duplicates. QC sample results must meet the criteria outlined in the analytical method. Laboratory QC samples will be analyzed in accordance with the analytical methods and must meet the method acceptance criteria.

## 5.12 Field Documentation

Project-specific data collection forms and field logbooks will be used to provide daily records of significant events, observations, and measurements. Logbooks will contain detailed information regarding site activities including dates, times, personnel names, activities conducted, equipment used, weather conditions, etc. Field logbooks are used by a variety of different field personnel and are part of the project file. Alternately, forms may be used to document activities and should be contained in a three-ring binder.

The following items are examples of information that may be included in a field logbook:

- Name, date, and time of entry
- Names of field crew members
- Names of any site visitors
- Descriptions of field procedures, and any problems encountered
- Number of samples collected
- Details of sampling location, including installed depth of all relevant packers in system
- Sample identification numbers
- Date and time of sample collection
- Sample collector
- Sample collection method
- Decontamination procedures
- Field instrument calibration
- Field measurements and general observations
- Other events and observations such as subcontractor activities or deviations from procedures, including the reason for the deviation

### 5.12.1 Field Documentation Procedures

The following techniques should be used for recording data in the field logbook and on forms.

- Record everything in ink
- Do not remove pages from the logbook
- Do not use loose paper and copy into the field logbook later
- Record enough information to completely document field activities
- Entries should be neat and legible
- Do not erase or scratch out any entry. Changes should be made by crossing out the entry with a single line and initialing the change.
- Initial and date each page

# 6  DATA MANAGEMENT PLAN

The DBFT will generate a large amount of diverse geochemical, petrological, geophysical, and other field and laboratory analytical data. In order to manage these data into coherent information products that can be used to answer key scientific questions, there needs to be a single, integrated, and scientifically defensible repository of the data.

The purpose of the data management plan is to establish procedures for the efficient movement of data generated in the DBFT, effective management of the central data repository, and streamlined dissemination of data and information. A site-specific data management plan will describe all required data workflow activities that comprise the DBFT data management system, including field collection, laboratory analyses, data validation, data repository operations, and distribution to project users. It will address functional requirements for data ownership, data encoding, data reporting, field, laboratory, and validation data handling, sensor data handling, data verification, aggregation of data into the database, unstructured data handling, links between unstructured and structured data, data change management, data distribution, and documentation. A site-specific data management plan will also define expectations for quality assurance/quality control (QA/QC) methods that may be pertinent to managing the data.

The DBFT project will depend on the ability of data managers to manage and disseminate a large amount of data and information collected from and disseminated to project personnel. Project data users (subject matter experts and project managers) need access to the data, and with sufficient quality, to develop data-driven models that allow for meaningful scientific interpretation. Data and information should be tracked from the point of the field observation/analysis or sample collection through laboratory analysis, quality review, validation, and data distribution. Chain of custody (COC) should be documented from collection through long term storage or archiving and eventual disposal for a large number of samples that will be collected and shipped to various laboratories for processing. Data and information resulting from the program must be made available to SMEs and project management in meaningful and reliable forms and in compliance with strict quality assurance (QA) standards.

The specific objectives of the data management system are:

- To manage all raw, processed, and synthesis data and information.
- To manage both structured and unstructured data and maintain the linkages between them.
- To maintain only one authoritative data repository for project data.
- To enforce rules on all data generators (laboratory and field) to deliver complete, error free data.
- To provide sample tracking.
- To facilitate efficient data quality control and data validation of all analytical data.
- To provide fast access to fully qualified data to project data users.
- To facilitate data reduction and analysis by project SMEs.
- To provide final data archive.

A data management plan component of a site-specific D&TP will present the technical details of how data will be entered into the database, how it will be stored in the database (i.e., a schema), and how it will be preserved via access control and backups. Key team members should have remote access to the database over the internet. At the end of the project, the database will be turned over to DOE for long-term preservation and dissemination.

All data will be owned by the Department of Energy and must be made publically available in a reasonable time period.

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# 7 CONCLUSIONS

This document is both an outline of a D&TP for a future DBFT CB and represents the state of the sampling and drilling plan at the time the project was stopped. The D&TP prepared by Battelle contained the required many site-specific and company-specific details, which have largely been removed or simplified, but the generic requirements and proposed methodology are left intact. Many places in the D&TP indicate in what additional site-specific information would be expected in a final D&TP. Once a suitable implementation team and location are found, a final D&TP would need to include both site-specific data and implementation-specific details, which will likely include trade names, and other company-specific details. This generic D&TP (or something derived from it) might make a useful document to guide bidding teams in a future DBFT implementation.

This research was performed as part of the DBFT. Based on revised DOE priorities in mid-2017, the DBFT and other research related to a DBD option was discontinued; ongoing work and documentation were closed out by the end of FY2017. This report was initiated as part of the DBFT and documented as an incomplete draft at the end of FY 2017. The report was finalized by Sandia National Laboratories in FY2018 without DOE funding, subsequent to the termination of the DBFT, and published in FY2019. Further DBFT work, for example, Implementation of an engineering demonstration (SNL 2016a), would require resumption of DBD research and development at some future time.

# 8  REFERENCES

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# Appendix A

# Deep Crystalline Drilling Projects

One of the goals of the DBD concept is to use existing off-the-shelf methodologies, technologies, and hardware from oilfield and geothermal as much as possible; but drilling a straight large-diameter deep hole into crystalline basement rocks is difficult. Previous scientific deep crystalline drilling projects are being used to guide expectations for drilling, sampling, and testing conditions in 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; Xie et al. 2015; Gleeson & Ingebritsen 2016; Baujard et al. 2017). Table 20 summarizes a few statistics from a few major deep (>3 km [9,840'] total depth) drilling (as opposed to coring only) projects mentioned in the following subsections.

Table 21, Table 22, and Table 23 are cross-walks between the DBFT and the KTB, Soultz, and Cajon Pass drilling projects. These tables list references for the primary characterization methods proposed in the CB as part of the DBFT. There are many more references not listed in these crosswalks, or associated with other projects, but these tables provide a few references of previous characterization approaches (from three well-documented deep crystalline drilling projects).

**Table 20. Notable deep (>3 km) 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 | East 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 |
| IDDP-2 | Iceland | 2016-2017 | 0 | 4.7 | 6 | Geothermal |

\* borehole diameter at total depth

## A-1.  Summaries of Deep Crystalline Drilling Projects

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.

## A-2. 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 entire borehole. There was 53% core recovery above 4,600 m [15,100']; below this depth high stresses lead to discing or complete disintegration of the core. This discing problem led to jamming of the core barrel and very poor recovery rates (~6%). A new core recovery tool was tested, this tool featured partial reverse circulation to help feed the core into the chamber increasing the recovery percentage up to 40% (Bodén & Eriksson 1988).

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 significant "firsts" in deep scientific drilling, but many details of the Kola borehole and other deep boreholes in the former Soviet Union (e.g., Pevzner et al. 1992; NEDRA 1992) are unavailable in English-language publications.

## A-3. 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']. A massive hydraulic fracture reservoir stimulation effort 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 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). GeothermEx (1998) presents a tabular summary of the downhole tests and hydraulic stimulations performed at the Fenton Hill site.

## A-4. 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).

## A-5. 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 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).

## A-6. 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 the 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 & James 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). See Table 23 for more specific references to tests and characterization efforts at the Cajon Pass borehole site.

## A-7. 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 core to 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). Drilling began on the main borehole 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) 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 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) and a special issue of *Geofluids* (Erzinger & Stober 2005). See Table 21 for more specific references to tests and characterization efforts in both KTB boreholes.

## A-8. 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 the Upper Rhine graben of 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). Baujard et al. (2017) summarize the rates of penetration achieved during drilling three of these deep wells. Scientific and technical findings from the project are featured in the edited volume by Bresee (1992), a 2006 special issue of *Geothermics* (Volume 35, Issue 5), and a 2010 special issue of *Comptes Rendus Geoscience* (Volume 342, Issue 7-8). See Table 22 for more specific references to tests and characterization efforts at the Soultz geothermal site.

## A-9. SAFOD

The San Andreas Fault Zone Observatory at Depth (SAFOD) project included drilling a 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 crystalline 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 (Henyey et al. 2011). Installed instrumentation only lasted a few weeks.

## A-10. 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. Baujard et al. (2017) summarize the rate of penetration data collected during drilling this deep borehole, comparing it to data from other European geothermal projects. 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; 2016).

## A-11. 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 two deep boreholes are summarized in the book Wang et al. (2015). Xu et al. (2017) gives a recent summary of this and other related exploratory drilling projects in China, performed in the last 15 years as part of the CCSD project.

## A-12. IDDP-2

In 2017, the Iceland Deep Drilling Project (IDDP) finished deepening an existing borehole to a final depth of 4,659 m [15,285'] to explore the viability of producing supercritical geothermal water for energy

production purposes (http://www.iddp.is; Friðleifsson et al. 2017). The goals of the project were to collect cores from depth, measure the temperature and determine if rock permeability would be sufficient to support geothermal energy production. The bottom-hole temperature was measured at 427 °C [801°F], with fluid pressure of 34 MPa [4,930 psi]. Despite these extreme conditions, drill cores were successfully retrieved near total depth, and the formation appears permeable enough at depth to support economical geothermal energy production.

# A-13. DBFT Characterization Reference Crosswalk

Amongst the deep crystalline drilling projects mentioned in the previous sections, the research efforts associated with the KTB, Soultz, and Cajon Pass projects provided considerable information on their characterization programs in the open literature. The following table provides a summary of a literature search on the characterization research performed in the KRB, Soultz, and Cajon Pass boreholes cross-walked to the planned characterization activities for the CB portion of the DBFT.

**Table 21. Crosswalk of Proposed DBFT Characterization Activities to KTB Project**

| Method | KTB Comment and References |
|---|---|
| Laboratory Core Testing | Petrophysical measurements conducted on cores and cuttings include density, radioactive elements, radiogenic heat production rate, ultrasonic wave velocity, thermal conductivity, electrical resistivity, natural magnetization, magnetic susceptibility stress release, porosity, permeability, and internal surface area. (Rauen & Winter 1995) |
| | Ore minerals and fluid inclusions were examined in core samples. The observed temperature-dependent transformation of pyrrhotite and the reaching of its Curie isotherm within the Earth's crust are amongst the striking results of the KTB deep drilling project. (Kontny et al. 1997) |
| | Geomechanical testing of core samples from KTB-HB including uniaxial compression tests and tensile tests, showing a wide range of variation. Massive metabasites have high to very high uniaxial compressive strengths. Gneiss samples with moderate dip angles of 60° show low uniaxial compressive strengths in contrast to steeply or low dipping gneisses which show increased compressive strength. (Roechkel & Nateu 1995) |
| Borehole Imaging and Caliper Logs | Calipers, resistivity imaging tools and acoustic imaging tools were used to calculate the stress direction through the analysis of shear failure (breakouts) and drilling induced tensile failures. (Bram et al. 1995) |
| High and Low-k Packer Tests | Hydraulic testing including packer tests were performed in KTB-HB. A draw down test confirmed communication between KTB-HB and KTB-VB. In addition, the observation of very rapid pressure transmission suggests the presence of a fracture system connecting both boreholes. (Kessels 1991) |
| Vertical Seismic Profile (VSP) | A newly developed high-pressure/high-temperature borehole geophone was used in the KTB-HB that was capable of withstanding temperatures and pressures up to 260°C and 140 MPa, respectively. The seismic properties of the crust *in situ*, particularly within and around the deep fault zone between 7 and 8.5 km, were determined. (Rabbel et al. 2004) |
| | Pronounced P-wave reflections, accompanied by P- to S-wave conversions and a lack of S-wave reflections, occur in the lower depth range only (3 to 6 km) and correlate with fluid-filled fracture systems. Lithological contrasts (gneiss-amphibolite) play a minor role in generating reflections. (Luschen et al. 1996) |
| Gamma Density Log | Gamma density logs were obtained as part of the integrated well log program at the KTB site. In general, the massive metabasite units consisting of amphibolites and metagabbros are characterized by lower gamma activity and higher density than the rocks in the paragneissic section. (Pechnig et al. 1997) |
| Full-Waveform Sonic Log | P and S wave velocity sonic logs together with the density, gamma, and caliper logs were analyzed using nonparametric error estimation to investigate the spectral properties of these logs. Coherence between the gamma and physical logs is weak to absent indicating that the observed velocity and density fluctuations are dominated by the physical state of the rocks rather than by their composition. (Jones & Holliger 1997) |

| Method | KTB Comment and References |
|---|---|
| Spontaneous Potential (SP) Log | Anomalies detected in the SP log are attributed to the presence of graphite in several fracture zones observed in the KTB-HB borehole. (ELEKTB Group 1997) |
| Hi-Res Temperature Log | *In situ* temperature measurements made in KTB-VB clearly exceeded the temperature range predicted by the predrilling geothermal site investigation. This was caused by an increase in the vertical component of the temperature gradient from the surface to about 1.6 km. (Clauser et al. 1997) |
| Neutron Porosity Log | Neutron porosity logs were obtained as part of the integrated well log program at the KTB site. In general, enhanced porosity is restricted to discrete zones of faulting and fracturing, and neutron response in undisturbed sections is predominantly a result of the water content bound in minerals like phyllosilicates or amphibole. (Pechnig et al. 1997) |
| Borehole Gravity Log | A combination of a closely spaced surface gravity survey with a high-resolution helicopter aeromagnetic survey and borehole gravity and magnetometer measurements were utilized to build a detailed three-dimensional (3D) model of anomalies at the KTB drill site. (Bosum et al. 1997) |
| Induced Polarization Log | Performed in both KTB-VB and KTB-HB; showed the presence of conductive pathways likely the result of veins of graphite and/or sulfides. (Bram et al. 1995) |
| Photoelectric Effect Log | Photoelectric effect logs were obtained as part of the integrated well log program at the KTB site. (Pechnig et al. 1997) |
| NMR Log | No reference discussing NMR logging in the KTB boreholes has been located. |
| Fluid Density or Downhole Pressure Log | Formation pressure as a function of depth was measured in both KTB-VB and KTB-HB. (Huenges et al. 1995, 5, 17-21)<br><br>Hydraulic testing over short packed-off (i.e. with downhole sealing elements to separate) borehole sections reduce the shut-in volume to a few cubic meters, whereas surface-operated open hole tests include shut-in volumes of the order of several hundred cubic meters. (Huenges et al. 1997, 102, 18255-18265) |
| Hydraulic Fracturing Tests | Almost 400 microearthquakes were induced at an average depth of 8.8 km by injection of KBr/KCl brine into a 70-m open hole section near the bottom of the KTB-HB borehole. (Zoback & Harjes 1997)<br><br>A continuous profile of the magnitudes and orientations of three principal stresses has been estimated using data from hydraulic fracturing tests. This was achieved by hydraulic fracturing tests at 1 to 3 km, estimates of the magnitude of least principal stress provided by modified hydraulic fracturing experiments at 6 and 9 km depths and analysis of compressional and tensile failures of the borehole wall over nearly the entire depth of the KTB-HB borehole. (Brudy 1997)<br><br>A technique for estimating permeability using the spatio-temporal distribution of the fluid-injection-induced seismic emission was developed. Estimates of the hydraulic diffusivity support the previously calculated value for the upper crust, which is on the order of 1 $m^2/s$. However, this estimate now relates to the depth range 7.5 to 9 km. (Shapiro et al. 1997) |
| Resistivity Log | Analyses of a large number of borehole resistivity measurements were used to develop models for the electrical resistivity of upper and middle crust near the KTB boreholes. (ELEKTB Group 1997) |
| Open Borehole Dynamic Fluid Logging | In order to obtain *in situ* fluids and hydraulic data, six different types of experiments were carried out in both boreholes. All experiments took notice of abrupt changes in mud pressure (i.e. the borehole pressure). Tests included (1) build up pressure drill stem tests (small shut-in volume); (2) build up test-open hole (large shut-in volume); (3) long-term pumping test; (4) injection open hole tests (large shut-in volumes); (5) injection drill stem tests (small shut-in volumes); (6) mud level observation. (Huenges et al. 1997, 102, 18255-18265) |
| Drilling Parameters | A considerable amount of information (in German) is present on drilling parameters throughout the drilling activities in both KTB-VB and KTB-HB. (Engeser 1996)<br><br>Some details of the drilling parameters and measured rock properties are provided in English. (Emmerman & Lauterjung 1997) |

| Method | KTB Comment and References |
|---|---|
| Spectral Gamma-Ray Log | Natural and induced gamma-ray measurements were made as part of the integrated well log program at the KTB site. (Pechnig et al. 1997) |
| Production Profile Survey | No reference discussing production profile surveys in the KTB boreholes has been located. |
| Drilling fluid logging, sampling and analysis at the surface | Continuous analyses of drilling fluids including monitoring of several ions (including Na, Ca, Sr, and Cl), pH and gases ($N_2$, $O_2$, Ar, $CO_2$, $CH_4$ $H_2$, and He) were performed in KTB HB. (Machon 1996)<br><br>Double X-Ray analysis is a technique which utilizes x-ray powder diffraction in combination with x-ray fluorescence to analyze the both the mineralogy and composition of cuttings and rock flour samples from the KTB wells. The technique allows for the reconstruction of rock lithologies in the uncored segments of the KTB wells. (Emmerman & Lauterjung 1990)<br><br>All gas concentrations and isotopic signatures, except for Rn-222, showed constancy during a 12-month production test. This, in combination with large fluid flow rates at a moderate water table drawdown, imply an almost infinite fluid reservoir at 4000 m depth in KTB-VB. (Lippmann et al. 2005) |
| Packer Tracer Tests | A tracer testing campaign comprised single-well push-pull tracer tests, as well as single-well and inter-well tracer tests in crystalline (KTB, Urach) and sedimentary (Horstberg) formations in ~4 km depth; these tests helped understand processes associated with fluid transport in the deep crust, and also to assist in evaluating the effect of hydraulic stimulation measures. (Ghergut et al. 2007) |
| Drill Cuttings and Rock Flour Lithology Log | A detailed lithology log in KTB-HB from 0 to 9,101 m has been developed based on petrographic analyses of cores and cuttings. The lithological profile is composed of three main units: paragneisses, metabasic rocks (amphibolite, metagabbro and metaultramafite) and alternating series (paragneiss, hornblende gneiss, amphibolite, subordinate calc-silicate and marble. Locally dikes of granitic aplite, pegmatite, (monzo)-diorite, and calcalkaline lamprophyre cross cut the metamorphic rocks. (Duyster et al. 1996) |
| On-site water quality analyses | An on-site, real-time system for fluid monitoring over the duration of the year-long pump test in KTB-VB is described. I-129/I ratios are between $1,700\times10^{15}$ and $4,100\times10^{15}$ are above the pre-anthropogenic ratio of $1,500\times10^{15}$. The relatively high I (and Br) concentrations suggest the fluids have derived their halogens from formations with high organic content, perhaps sedimentary rocks of marine origin. (Erzinger & Stober 2005)<br><br>Water temperature, specific electrical conductivity, pH, redox potential, dissolved oxygen, and $HCO_3^-$ (titration with 0.1 N HCl) were measured on-site in KTB-VB. The KTB-VB 4 km fluid can be related to either Mesozoic seawater or formation water from Permo-Carboniferous sedimentary rocks of the Weiden embayment. (Möller et al. 2005) |
| Off-site water quality analyses | A detailed interpretation of the studies of aqueous and gaseous fluid inclusions stable isotopes in rocks and minerals from cataclastic zones as well as radiogenic, nucleogenic and fissiogenic noble gas isotopes, all as a function of depth in the KTB boreholes is presented. (Möller et al. 1997)<br><br>Analyses of I-129 and Cl-36 in the fluids indicates that anthropogenic components are absent and that their ratios reflect an addition from crustal sources. The results also suggest fluid source ages exceed 30 Ma and residence times of 10 Ma or more for the fluids in the KTB deep crustal rocks. (Fehn & Snyder 2005)<br><br>Interpretation of the O, H, C isotopic data indicates fluid evolution in a closed system during slow cooling and that the fluids are completely equilibrated with respect to the surrounding rocks and have lost their primary isotopic composition. (Simon & Hoefs 1993) |

**Table 22. Crosswalk of Proposed DBFT Characterization Activities to Soultz Project**

| Method | Soultz Comment and References |
| --- | --- |
| Laboratory Core Testing | Continuous coring of borehole EPS-1 began at 930 m, continuing to the bottom with core diameters of 78 mm (930 to 1,996 m) and 57 mm (1,997 to 2,227 m), providing 810 m of granite core for structural analysis and petrographic examination. (Genter & Traineau 1992) |
| | An exhaustive analysis of 3,000 macroscopic fractures encountered in the geothermal borehole EPS-I was done on a continuous core section over a depth interval from 1,420 to 2,230 m: 97% of the macroscopic structures were successfully reoriented with a good degree of confidence by comparison between core and acoustic borehole imagery. (Genter & Traineau 1996) |
| Borehole Imaging and Caliper Logs | Attributes of several thousand fractures were collected in three boreholes of 2.2, 3.6, and 3.8 km depth, penetrating the Soultz HDR reservoir. The fractures were sampled from cores and from several high-resolution imaging techniques such as BoreHole TeleViewer (BHTV), ultrasonic borehole imager (UBI), formation microscanner (FMS), formation microimager (FMI), and azimuthal resistivity imaging (ARI). (Genter et al. 1997, 15419-15431) |
| | Fractures were identified in the Soultz granite using borehole imagery and analyzed using the Schlumberger Formation Image Examiner. Fracture geometry was determined by both electrical Formation Microscanner (FMS) and sonic BHTV. (Genter et al. 1991) |
| | Caliper measurements were made in EPS1, GPK1, and GPK2 in conjunction with sonic and gamma ray to determine the type and distribution of petrographic facies in the borehole rock. (Genter et al. 1997) |
| Low and High-k Packer Tests | Hydraulic tests and hydraulic fracturing experiments were carried out in borehole GPK-1 at a depth of 1,420 to 2,000 m to investigate the site-specific hydromechanical conditions. Tests included open hole and packer experiments. (Jung 1991) |
| Vertical Seismic Profile (VSP) | A database of geological data, well logs, microseismicity recordings and vertical seismic profiling (VSP) results were compiled and combined to build a new 3D model of the Soultz-sous-Forets fractured reservoir. (Sausse et al. 2010) |
| Gamma Density Log | Formation density logging was performed in EPS1 over a depth range of 1,420 to 2,000 m. Similarly, over a depth range of 1,420 to 2,000 m and 2,000 to 3,600 m in GPK1. (Genter et al. 1997) |
| Full-Waveform Sonic Log | Sonic logging performed over a depth range of 1,420 to 2,000 m in EPS1. GPK1 was logged using a Digital Sonic Array Tool and a Dipole Sonic Shear Imager tool. Sonic logging was performed in GPK2 over a depth of 2,135 to 3,800 m and revealed four distinct rock sections. (Genter et al. 1997) |
| Spontaneous Potential (SP) Log | SP logging was performed in performed over a depth range of 1,420 to 2,000 m in EPS1 and over a depth range of 1,420 to 3,600 m GPK1. (Genter et al. 1997) |
| Hi-Res Temperature Log | Temperature was logged from 1,410 to 3,878 m in borehole GPK2, ranging from ~95 to 165 °C, over the measured interval. (Genter et al. 1995) |
| | An indirect electromagnetic geothermometer was used for the deep temperature estimations in GPK2 using magnetotelluric (MT) sounding data. Validation of the temperature assessment using MT data is fulfilled by comparison of the forecasted temperature profile with real temperature logs from GPK2 geothermal borehole for two depth ranges 2,000 to 3,878 m and 3,878 to 5,046 m. Finally, a deep temperature forecast using MT data is provided for GPK2 up to a depth 8,175 m. (Spichak et al. 2010) |
| Neutron Porosity Log | Neutron porosity logging was performed in performed over a depth range of 1.8 to 2.2 km in EPS1 and over a depth range of 2 to 3.6 km GPK1. These measurements also provide information on the distribution of fracture zones within the intervals logged. (Genter et al. 1997) |
| Borehole Gravity Log | No references discussing borehole gravity logging in the Soultz boreholes have been located. |
| Induced Polarization Log | No references discussing induced polarization logging in the Soultz boreholes have been located. |

| Method | Soultz Comment and References |
|---|---|
| Photoelectric Effect Log | Photoelectric logging was performed in EPS1 and GPK1 and was used, along with several other logging methods, to define petrographic facies observed downhole. (Genter et al. 1997)<br><br>Gamma ray spectral logs and other geophysical logs (caliper, bulk density, P-wave slowness, and photoelectric factor) revealed some petrographical variations within the Soultz massive granite, as well as altered/fractured zones that act as preferential pathways for fluid flow as indicated by flow logs. (Sausse et al. 2006) |
| NMR Log | No references discussing NMR logging in the Soultz boreholes have been located. |
| Fluid Density or Downhole Pressure Log | The availability of reliable downhole pressure data during hydraulic tests is of crucial importance for interpreting the behavior of the underground system. Especially in the case of EGS systems the high pressure and temperature conditions make downhole measurements rather a challenge. With the new numerical borehole tool HEX-B the downhole pressure data taken during the stimulation test of GPK3 in May 2003 has been corrected and completed. (Mégel et al. 2005) |
| Hydraulic Fracturing Tests | In the granitic section of GPK-1 between 1,376 m and 2,000 m depth, eight hydrofrac or injection tests were conducted. These tests were characterized by several technical problems caused by using conventional packer technology in the hostile downhole environment: temperatures of up to 140°C and high gas and salt contents of the borehole fluid. (Rummel & Baumgartner 1991).<br><br>Aluminum packer technology developed for hydrofracturing in a hot (175 °C), gassy and geochemical aggressive downhole environment was a full success. Setting of the aluminum packers occurred at differential pressures of 20 MPa to 25 MPa, exactly as expected from the design of the new tool. Packer sealing at differential pressures up to 33 MPa was excellent. (Klee & Rummel 1993) |
| Resistivity Log | Induction measurements, which provide induced shallow-resistivity and induced-far-resistivity, were made in EPS1 over a depth range of 1,420 to 2,000 m. Large fractures and altered zones were clearly identified downhole because of lower resistivity measurements (<300 ohm-m). (Genter et al. 1997) |
| Open Borehole Dynamic Fluid Logging | During the second half of 1992 GPK-1 was deepened from 2 to 3.6 km. The interval from 2.2 to 3.6 km was geochemically logged and activities included: (1) continuous monitoring of physio-chemical parameter of drilling fluids at the well inflow and outflow (2) continuous analysis of drilling fluid gas content and (3) discontinuous drilling fluid sampling at the well inflow and outflow. (Aquilina & Brach 1995) |
| Drilling Parameters | A record of rock types and lithology changes encountered during drilling is documented for wells EPS1, GPK1 and GPK2. ROP data was collected from 1,410 to 3,883 m in GPK2. Changes in ROP correlated with low ROP in unaltered granite while high ROP were observed in altered and/or fractured granite zones. (Genter et al. 1997) |
| Spectral Gamma-Ray Log | Natural gamma ray spectroscopy logs including logs for total gamma, uranium, thorium and potassium were obtained over a depth of 1,420 to 2,000 m in EPS1 and over a depth of 2 to 3.6 km in GPK1. Uranium and thorium logs show a decrease with depth in both wells. (Genter et al. 1997) |
| Production Profile Survey | The production profile was not measured directly by but rather inferred primarily from geophysical logs, gamma ray spectral log, borehole image logs, temperature logs and other well logging data. Two scales of fracture networks are present in the granite: a highly connected network consisting of fractures with small apertures that maybe represents the far field reservoir, and another network that contains these isolated and wide fracture zones which develops an anisotropic permeability in the rock and allows for the hydraulic connection of the wells. (Sausse et al. 2008) |

| Method | Soultz Comment and References |
|---|---|
| Packer Tracer Tests | Inter-well tracer tests were conducted at Soultz at less than 3.9 km depth before the year 2000, and at about 5 km depth in the period 2000–2005. The paper discusses the results and conclusions drawn from tracer tests during hydraulic stimulation operations and a short-term circulation test in wells GPK-2, GPK-3 and GPK-4. The tracers behaved conservatively and when combined with the monitoring of conservative species such as dissolved chloride, the tracer tests consistently indicated that only low amounts of the injected fresh water were recovered and that the proportion of native brine was relatively high. (Sanjuan et al. 2006)<br><br>A new interpretation of tracer tests performed in 2005 at Soultz. The objective of this paper is an attempt to match and model the 2005 tracer test interpretation results proposed by Sanjuan et al. (2006) and to discuss the plausibility of the proposed model in light of the knowledge we have of the 3D network of connected, permeable fractures within the target rock volume between the wells (Radilla et al. 2012). |
| Drill Cuttings and Rock Flour Lithology Log | Different types of granite at the Soultz site were characterized and divided into several homogeneous petrographic units. This was achieved by studying approximately 100 thin sections of drill cuttings selected on the basis of well site cutting descriptions and conventional well logs. (Hooijkaas et al. 2006)<br><br>Drilling cuttings from borehole GPK2 were collected and characterized from 1,410 to 2,110 m. Below 2,110 m total mud loss occurred, and no cutting samples were collected until the final depth was reached at 3,883 m. (Genter & Tenzer 1995) |
| Fluid Samples Extracted from Cores and Whole-Rock Chemical Analyses | Fluids found as inclusions in healed microfissures from the deepest samples at Soultz display the same features as those observed in recent quartz veins from the shallow levels of the granite. They attest to discrete fluid sampling resulting from mixing of two main fluids: i) a basinal brine, probably issued from the Trias formations, and characterized by a high salinity of 20 wt-% eq. NaCl) a low salinity fluid which could correspond to a recharge water (deep meteoric fluid penetration from the Vosges mountains). (Cathelineau & Boiron 2010) |
| Drilling Fluids Log at the Surface | The analysis of drilling mud logging data and geophysical well logging data from the deep Soultz geothermal wells (GPK-2, GPK-3, GPK-4) reveals the occurrence of nine fracture zones situated at depths greater than 900 m in the limestones of the Muschelkalk (Middle Trias) and the sandstones of the Buntsandstein (Lower Trias). Based on indications of total or partial mud losses, these fracture zones have been classified as permeable or impermeable. (Vidal et al. 2015) |
| Onsite Water Quality Analyses | The drilling fluid was geochemically monitored in well GPK-1 between 1,426 and 1,998 m during drilling in the granite. The most informative parameters used to trace the formation fluids appeared to be pH, $HCO_3$, Cl, Na, Ca, and He, which is compared with the pH (expression of $CO_2$ release) and the dissolved ions. (Vuataz et al. 1990) |
| Offsite Water Quality Analyses | Deepening of the GPK-1 borehole to 3.6 km in the granitic basement has revealed that fluid circulation occurs to a depth of at least 3.5 km. Fluids sampled at this depth still lie within the same composition range as the fluids previously sampled in the upper part of the granite and the sedimentary cover, indicating that all these fluids have a similar origin. However, they have clearly undergone different evolutions. (Aquilina et al. 1997)<br><br>Analytical data of fluids discharged from the wells GPK-1, GPK-2, GPK-3 and GPK-4 are compiled from numerous research documents to determine the most representative chemical and isotopic composition of the deep Soultz geothermal brine (3.5 to 5 km). Data includes numerous element, isotope and gas concentrations sampled from the four wells. (Sanjuan et al. 2010)<br><br>The salinity of these deep fluids, sampled from both the granite and the sedimentary rock, can be explained by a three-step model: (1) evaporation of seawater which produces a primary brine; (2) mixing between a dilute fluid and the primary brine; and (3) dissolution of halite by the later fluid. The thermal waters sampled at shallower depths are the result of mixing of the deep saline fluid and surface water. (Pauwels et al. 1993) |

**Table 23. Crosswalk of Proposed DBFT Characterization Activities to Cajon Pass Project**

| Method | Cajon Pass Comment and References |
|---|---|
| Laboratory Core Testing | Measured permeabilities on core samples collected at depths from 2.1 to 3.5 km ranged from $10^{-19}$ to $10^{-22}$ m$^2$ for effective pressures between 36 and 56 MPa. In general, permeability values decreased with depth in a manner consistent with earlier studies between 500 and 2,100 m in the drill hole. (Morrow & Byerlee 1992) |
| | Petrologic and chemical analyses of cores from the Cajon Pass borehole confirm the vertical lithologic diversity of the basement rocks and suggest a large-scale tectonic juxtaposition of rocks which originally formed in quite different settings. (Silver et al. 1988) |
| | A lithologic column was generated, through the detailed study of drill cuttings and cores, and provides a record of the rock types and lithology changes encountered during drilling. The lithologic diversity encountered was much more significant than anticipated based upon observations of nearby surface exposures. (Silver & James 1988) |
| | The electrical resistivity of core samples determined at pressures of 200 MPa and frequencies 10 to 30 kHz ranged from 5 to 46 kΩ-m. The resistivities of cores recovered from depths of less than 1.6 km are about one order of magnitude greater than the measured *in situ* resistivity. However, at depths greater than 1.6 km laboratory and *in situ* resistivity measurements are in fairly good agreement suggesting the fractures, whether fluid filled or mineralized, are no longer well connected. (Hirsch & Wang 1988) |
| | Intact crystalline rock at depths greater than 1.5 to 2 km is devoid of the hypothesized pervasive distribution of fluid-filled micro-cracks. There is a remarkably close coincidence of the ultrasonic velocities determined at high confining pressure in the laboratory with *in situ* sonic velocities measured at selected intervals of the drill hole. Further, these intervals are characterized by homogeneous lithology and are devoid of macroscopic fractures detectable in borehole televiewer images. (Vernik & Nur 1992) |
| Borehole Imaging and Caliper Logs | The orientation, distribution and apparent aperture of natural fractures intersecting the Cajon Pass research well was determined through the analysis of borehole televiewer data from 1,829 to 2,115 m. Large open fractures have shallow inclination and tend to be aligned striking roughly N15OE. There is no apparent relationship between these fractures and the current stress state, as measured by the analysis of well bore breakouts and hydraulic fracturing experiments in the Cajon Pass well and as observed in other studies in the region. (Barton & Moos 1988) |
| | Initially designed by Schlumberger to image sedimentary sequences, the FMS was used to record a set of borehole electrical images in the crystalline basement of the Cajon Pass scientific drillhole. In all, over 800 fractures were mapped from 850 to 1,820 m. Whereas the foliations have generally low dips, the fractures are often steep. Most of the fractures strike NE-SW to E-W, in a direction orthogonal to the trace of the San Andreas Fault. (Pezard & Luthi 1988) |
| High and Low-k Packer Tests | Two *in situ* bulk permeability tests were conducted in the Cajon Pass pilot hole. In the first interval, from 1,829 to 1,905 m, an effective permeability of $0.5 \times 10^{-19}$ m$^2$ was measured. Over the second interval, from 1,829 to 2,115 m, an average permeability of $1.67 \times 10^{-19}$ m$^2$ was measured. (Coyle & Zoback 1988) |
| Vertical Seismic Profile (VSP) | A 3-component VSP data set was acquired in the Cajon Pass Drillhole, with a multiply-polarized shear-wave source and a conventional P-wave source, producing a 9-component data set. The data give evidence for three different sources of anisotropy. The upper 300 m look like normal deposition-related anisotropic sediments. Above and below the sediment-granite contrast, from ~300 to 1,000 m, the anisotropy is consistent with a fabric parallel to, and controlled by the San Andreas fault. Deeper in the well, the anisotropy changes suggesting a maximum horizontal compressive stress direction more or less between (varying ±20°) that inferred from earthquake strike-slip fault plane solutions (45° from the fault strike) and a direction normal to the fault. (Daley et al. 1988) |
| Gamma Density Log | The gamma density log reveals an abrupt contact at 1,432 m, from 2.73 to 2.63 g/cm$^3$, and is mirrored in all of the other log responses. The presence of a mylonitic zone is inferred from this and the other log responses. (Moos 1988) |

| Method | Cajon Pass Comment and References |
|---|---|
| Full-Waveform Sonic Log | Sonic compressional and shear wave velocities were calculated from full waveforms recorded in the Cajon Pass drillhole from 250 to 1,829 m depth. Crystalline basement at Cajon Pass is characterized by numerous narrow low velocity zones. Some of these are due to mylonitic faults as illustrated by the low velocity zone at 1,440 m. Others are due to the presence of discrete fractures as illustrated by the zone at 840 m. (Moos 1988) |
| Spontaneous Potential (SP) Log | No references discussing spontaneous potential logging in the Cajon Pass borehole have been located. |
| Hi-Res Temperature Log | Temperature logging using both a thermistor and a high resistance platinum resistance transducer (RTD) was performed in the Cajon Pass borehole. Four reliable sets of temperature data were obtained and in all four cases temperatures obtained from thermistor and resistive temperature device agreed to better than 0.1°C at all depths. (Sass et al. 1992) |
| Neutron Porosity Log | No references discussing neutron porosity logging in the Cajon Pass borehole have been located. |
| Borehole Gravity Log | No references discussing borehole gravity logging in the Cajon Pass borehole have been located. |
| Induced Polarization Log | No references discussing induced polarization logging in the Cajon Pass borehole have been located. |
| Photoelectric Effect Log | The Geochemical Logging Tool (Trademark of Schlumberger) is a tool that illustrates application of the photoelectric effect. It was used to provide an estimate of elemental concentrations of Si, Al, Fe, Ca, K, Th, Ti, S and Gd. The resulting geochemical profiles were used to define the lithostratigraphy in the crystalline basement from 501 m to 1828 m. Measured variations in Gd, Th, Ti and S demonstrates that each of the major litholostratigraphic units is chemically distinct. (Anderson et al. 1988) |
| NMR Log | No references discussing NMR logging in the Cajon Pass borehole have been located. |
| Fluid Density or Downhole Pressure Log | No references discussing fluid density or downhole pressure logging in the Cajon Pass borehole have been located. |
| Hydraulic Fracturing Tests | Mechanical pressure gauges mounted below the packer system were used to measure pressure in the isolated interval in the inflatable packer elements and in the hole below the packers. Between 1 and 2 km the stress difference $S_v - S_{hmin}$ is relatively constant and then $S_{hmin}$ increases rapidly until it is nearly equal to $S_v$ at 2.09 km. This sudden change in the character of the stress field at ~two km requires a local dislocation such as an active fault that intersects the borehole. (Healy & Zoback 1988) |
| Resistivity Log | The resistivity logs show a stepwise increase from about 20 ohm-m in the sandstones to 200 ohm-m before increasing to background values above 1,000 ohm-m at greater depth in the basement rocks. (Moos 1988)<br><br>*In situ* measurements of electrical resistivity recorded with the duel laterolog are compared with laboratory measurements of resistivity and porosity in fracture-free core samples. This forms a basis for a simple electrical model of rock pore space from which both the matrix porosity and fractures have been derived. In addition, the borehole electrical images provide a means to identify the fractures and evaluate their frequency and orientation. (Pezard et al. 1988) |
| Open Borehole Dynamic Fluid Logging | The mud logging unit provided a continuous record of a variety of parameters including mud weight, drill fluid electrical resistivity, continuous $H_2S$, $CO_2$, $H_2$, and He gas detection, fluid volume gain/ loss, etc. Data was transmitted by a telecommunications system to the offices of the drilling contractor DOSECC. (Wicklund et al. 1988) |
| Drilling Parameters | An overview of the drilling plan and drilling summary is provided with some details on drilling parameters and the data collected during drilling operations. (Wicklund et al. 1988) |

| Method | Cajon Pass Comment and References |
|---|---|
| Spectral Gamma-Ray Log | Natural gamma spectroscopy log measurements of K, U, and Th abundances indicate an apparent secondary depletion of U in the upper 1.4 km. The depletion could be the result of extensive fluid flow but since the pattern of depletion is discontinuous the flow probably pre-dated the faulting along the San Andreas. (Williams et al. 1988) |
| Production Profile Survey | No references describing a production profile survey have been located. |
| Packer Tracer Tests | No references discussing packer tracer tests in the Cajon Pass borehole have been located. |
| Drill Cuttings and Rock Flour Lithology Log | During rotary drilling cuttings were collected at 3 m intervals of drilling penetration and examined to determine mineralogy and assess changes that warranted special core runs. (Wicklund et al. 1988) |
| Fluid Samples Extracted from Cores and Whole-Rock Chemical Analyses | Chemical analyses of cores from the Cajon Pass borehole confirm the vertical lithologic diversity of the basement rocks. Initial lead isotopic signatures of the plutonic rocks change dramatically with depth within the borehole. (Silver et al. 1988) |
| Drilling Fluids Log at the Surface | Some aspects of drilling fluids logging are summarized in (Wicklund et al. 1988). |
| Onsite Water Quality Analyses | No references discussing on site water quality analyses in the Cajon Pass borehole have been located. |
| Offsite Water Quality Analyses | The bulk of the formation water in the granitic rocks is an alkaline Na-SO$_4$ water with low salinity. The small amount of water produced at two test intervals would indicate that water movement near the San Andreas fault plays no significant role in in heat transport. Analyses of dissolved gases indicate there is no mantle component of CO$_2$ and in fact there are no significant mantle components of CH$_4$, He, or other dissolved and gaseous species. (Kharaka et al. 1988) |
| | Fluids sampled near 2 km depth contained He, H$_2$ CH$_4$, C$_2$H$_6$, and C$_2$H$_4$ in concentrations much greater than in air saturated water. The He was almost entirely radiogenic. The $\delta^{13}$C-CH$_4$ value (–36 per mill) and the (C$_2$H$_6$ + C$_2$H$_4$)/CH$_4$ ratio indicate that the dissolved methane was produced by the breakdown of organic matter likely sourced from the Miocene sediments which overlie the igneous basement. No evidence of mantle volatiles was found despite the proximity of the well to the San Andreas fault. (Evans et al. 1988) |
| | Measurements of Rn-222, Ra-226, and U-238 in were made in formation waters extracted from the Cajon Pass borehole. The radon distribution indicates that inflow of water occurs in several localized discrete fracture zones. (Kharaka et al. 1988) |

# Appendix B

# Planning to Mitigate Wellbore Damage in the DBFT

## B-1.  Background and Objective

Borehole breakout is conventionally defined as chevron-shaped elongation of the circular borehole cross-section, caused by localized failure of host rock near the borehole wall. Breakout results from fracturing and can therefore be classified as brittle, but it has been observed in a range of rock types including softer sediments as well as more indurated metamorphic and igneous rocks. The elongation occurs in the transverse directions perpendicular to the maximum compressive stress in the plane perpendicular to the borehole. It may occur in one of these directions, or commonly in both directions, on opposite sides of the borehole. For vertical boreholes, this means they occur in the direction perpendicular to the maximum horizontal principal stress, $S_H$ (and parallel to the minimum horizontal principal stress, $S_h$). They are generally caused by concentrated, compressive, *in situ* stress around the borehole opening that exceeds the rock shear strength. The local shear strength may vary with conditions of confinement, pore pressure, and temperature. *In situ* stress conditions sufficient to cause breakout typically occur at depth where the field stress approaches or exceeds the rock compressive strength, and where the stress state is deviatoric ($S_H/S_h$ >1). The state of stress must also have a third dimension, and the influence of the stress component oriented parallel to the borehole is discussed below.

Another type of wellbore damage consists of induced tensile cracks that form parallel to the borehole axis but are oriented parallel to $S_H$ (instead of perpendicular to $S_H$ as with breakouts). Induced tensile cracks may form at only one position on the borehole circumference, or in echelon geometry (Brudy & Zoback 1999), and not in opposite positions across the borehole as is common for breakouts. Induced tensile cracks may form, or pre-existing fractures may open, in the same orientation as hydraulic fractures and with similar effects on DBFT testing. However, tensile cracks are caused by the action of $S_H$ in strongly deviatoric stress conditions ($S_H/S_h \gg 1$) and in principle could form without fluid in the borehole. Tensile cracks tend to be observed in stronger rock (e.g., metamorphic or igneous) probably because strongly deviatoric stress conditions (e.g., $S_H/S_h > 2$) are uncommon in sediments. Tensile cracks are generally not observed together with breakouts, although coexistence is at least theoretically possible and has been reported (Guenot 1989; Zoback 2007 – see his Figure 6.4).

Breakouts and tensile cracks have the potential to significantly affect borehole characterization and sampling planned for the Deep Borehole Field Test (DBFT). The greatest potential impact is ineffective sealing by packers against the borehole wall in affected intervals, which would then impact the ability to collect samples or conduct flow and tracer testing. Another effect could be the generation of artifacts in wireline logs and other surveys and imagery that are sensitive to borehole geometry. Note that a major purpose for the DBFT Characterization Borehole (CB) is to evaluate characterization methods (SNL 2016b) and that the occurrence of breakouts can be addressed by alternative methods (although these may be developmental or costlier). Despite these potential characterization issues arising from breakouts, it is believed that at a future deep borehole disposal (DBD) site waste could be effectively isolate radioactive waste even if breakouts occur during drilling.

## B-1.1  Wellbore Damage Control Strategy

Breakouts and induced fractures are managed for all deep boreholes. The primary means available to control damage during drilling and follow-on activities is the borehole fluid. Fluid characteristics such as pressure, density, viscosity, filtration and composition are selected for compatibility with the formation, and to provide sufficient hydraulic pressure and force on the borehole wall to control highly pressurized

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formation fluids and provide mechanical stability. The fluid serves these functions while pressure is limited to prevent hydraulic fracture, providing viscosity to remove cuttings during drilling, and carrying particulate matter that limits fluid invasion of permeable zones.

This appendix differs from much literature on breakouts and tensile cracks cited below, in that it evaluates how effectively wellbore damage can be prevented altogether using fluid density or pressure, and whether the fluid characteristics and pressure overbalance needed represent an acceptable degree of interference with DBFT science objectives.

For deep drilling in the crystalline basement, breakouts and tensile cracks are the most significant anticipated problems for which possible mitigation measures include: 1) adjusting borehole fluid density, 2) managed pressure drilling, 3) use of clay or lost circulation materials, and 4) cooling of the drilling fluid.

## B-1.2 Borehole Fluid Density

The connected porosity in crystalline rock is supported by the solid mineral framework and not fluid pressure, thus, formation fluid pressure is generally limited to that caused by the weight of the fluid column. Formation fluid may be saline and more dense than fresh water, but borehole pressure can be balanced using fluid with similar density and composition. While borehole fluid generally has uniform composition, formation fluid generally is more saline with depth. Thus, if the temperature profile is the same in the formation and borehole, then pressure balance at total depth implies overbalance at intermediate depths. Care must be taken to account for temperature (thermal expansion) when calculating fluid density (compressibility is a much smaller effect).

Fluid weight can be increased for overbalance, and to apply more pressure to the borehole wall for stabilization. If the overbalance causes fluid losses due to formation invasion, then a particulate component such as clay can be added to decrease permeability by 10 to 100 times through plugging of fracture pororosity that impedes flow. In sedimentary formations, this is called a "filter cake", but in crystalline rocks this would be expected to be different. Plugging of fractures may be accomplished with viscocifiers, clays, or lost circulation materials, but these would all likely have impacts on the formation fluid chemistry.

Another technique used to increase fluid pressure at depth is managed pressure drilling, whereby in addition to controlling fluid density, a dynamic positive pressure bias is maintained throughout the fluid circuit in the pipe and borehole annulus. During drilling the wellhead discharge is variably choked using a rotating control device installed on the return casing, around the pipe, above the blow-out preventers. Backpressure is controlled dynamically with this device, along with the fluid injection rate, typically in response to real-time measurements of downhole pressure (e.g., measurement while drilling). Pressure transients occur when tripping in/out or when adding pipe, if the internal pressure in the pipe at the surface drops to atmospheric. During such operations, the fluid density may be increased to control formation pressure.

If borehole fluid pressure can be applied on the borehole wall without infiltrating the formation, then the borehole fluid directly applies confining pressure to the wall rock, imparting additional strength. However, pore pressure in the formation can reduce the confining effect due to the effective stress principle. Following the discussion in Brudy & Zoback (1999) the effective stress principle is limited in low-porosity, low-permeability rock, so the strengthening response is expected. Borehole fluid pressure can then be used to control breakout damage. Greater borehole fluid pressure can produce greater confinement, however, if the pressure is too high then excessive invasion or hydraulic fracture can occur. The conditions that allow using borehole pressure to control breakout (i.e., low poroelastic efficiency) also allow hydraulic fracture. This appendix evaluates the potential for such damage with typical *in situ* stress and borehole fluid pressure conditions, and also simulates what happens when borehole fluid invades damaged rock around the borehole, reducing confinement.

## B-2.    Reference Conditions for Generic Analysis

The DBFT CB will be vertical and up to 5 km deep. Wellbore damage will be important over the full depth of the CB, but this analysis considers the depth range 3 to 5 km, corresponding to the emplacement zone in the deep borehole disposal concept (no waste will be emplaced for the DBFT; SNL 2016b). At shallower depths, the *in-situ* stresses will be smaller. This report presents generic analysis of breakouts and tensile cracks at depths of 3 and 5 km in the CB.

Locations in the conterminous US with potentially favorable geology to host deep borehole disposal, and where the crystalline basement is accessible (i.e., within 2 km of the surface) generally have basement stress conditions that correspond to strike-slip or thrust faulting regimes (Heidbach et al. 2008). Extensional tectonics with normal faulting and associated stress conditions are generally not observed in large regions with basement geology favorable to deep borehole disposal.

For this analysis, the focus is on strike-slip conditions which generally have greater $S_H/S_h$, in the range 2 to 3, and for which breakouts of the "A-mode" type of Guenot (1989), and tensile cracks (Brudy & Zoback 1999) are common in vertical boreholes. Even more deviatoric stress conditions ($S_H/S_h > 3$) are possible but uncommon (Zoback et al. 1985) and may be limited by rock deformation. For this analysis one principal stress axis is assumed to be aligned with the vertical borehole ($S_V$). This assumption is usually valid near the surface but may require reevaluation at depths of a few km, based on site-specific information. Similarly, the assumption that crystalline baesment rock is mechanically and thermally isotropic may be reevaluated. Focus on strike-slip conditions restricts the breakout geometry, depending on the type of constitutive model or strength criterion used to represent intact and partially failed rock (Zhou 1994).

Two values of $S_H/S_V$ and two values of $S_H/S_h$ are selected for analysis (Table 24). The maximum horizontal stress ($S_H$) is assumed to range from 150% to twice the vertical stress ($S_V$). These values approximate a range of conditions from the KTB pilot borehole to a highly stressed, highly deviatoric strike-slip condition ($S_H/S_V = 2$, $S_H/S_h = 3$). The KTB pilot borehole (Brudy & Zoback 1999) produced $S_H/S_h$ of 110/48 at 3 km and 209/90 at 5 km (these are minimum $S_H$ values), where $S_V$ was 90 and 140 MPa, respectively, at 3 and 5 km.

The numerical analyses presented in this report are 2-dimensional (2D) plane strain calculations, so the intermediate stress ($S_V$) is not used as input. The effect of $S_V$ on stability of vertical boreholes in three dimensions, is to provide additional confinement and so reduce wellbore instability (Al-Ajmi & Zimmerman 2006).

Combining depth and $S_H/S_h$ values gives a total of 4 cases (Table 24), where $S_V$ is 67 MPa at 3 km, and 111 MPa at 5 km. Note that in the shallow basement *in situ* stresses could be much smaller than these values. *In situ* temperatures were calculated using a mean annual surface temperature of 20 °C and a geotemperature gradient of 25 °C/km.

Comparing these cases (Table 24) to the stress field classification scheme of Guenot (1989, Figure 8) suggests that I.A and I.B would produce breakouts, and II.A and II.B are likely to produce tensile cracks or a combination with breakouts (for the borehole conditions used to construct the scheme). Both of these results depend on whether the stress magnitudes exceed tensile and shear strength criteria, and on the magnitude of borehole fluid pressure which can provide increased confinement (less breakout) but can also increase tensile stress (tensile cracking).

**Table 24. Stress conditions selected for generic analysis of breakouts and tensile cracks.**

| Case | Depth (km) | In Situ Temperature (°C) | $P_{water}$ (MPa) | $S_H/S_h$ | $S_H/S_v$ | $S_V$ (MPa) | $S_h$ (MPa) | $S_H$ (MPa) | $P_{Frac}$ @ Depth (MPa) [A] |
|------|-----------|--------------------------|-------------------|-----------|-----------|-------------|-------------|-------------|------------------------------|
| I.A  | 3 | 90  | 30 | 2 | 1.5 | 67  | 50 | 101 | 50 |
| I.B  | 5 | 150 | 50 | 2 | 1.5 | 111 | 83 | 167 | 83 |
| II.A | 3 | 90  | 30 | 3 | 2   | 67  | 44 | 133 | 67 |
| II.B | 5 | 150 | 50 | 3 | 2   | 111 | 74 | 222 | 74 |
| [A] Minimum borehole fluid pressure at depth, to produce hydraulic fracture (assuming negligible rock strength) or open pre-existing fractures. | | | | | | | | | |

This appendix is focused on generic analysis of wellbore damage in the deep crystalline basement, hence only crystalline rock with relatively high strength and low matrix permeability is considered. For example, analyses two constitutive models are selected: 1) a generic, high-quality granite with a Mohr-Coulomb strength criterion, similar to Westerly granite but with lower strength; and 2) the Lac du Bonnet granite with a bilinear constitutive law calibrated to laboratory triaxial testing and the Mine-By Experiment at the Atomic Energy of Canada Ltd. (AECL) underground research laboratory (Read & Martin 1996; Hajiabdolmajid et al. 2003). The generic Mohr-Coulomb granite is used to enable comparison to previously published Mohr-Coulomb analyses (e.g., Zoback et al. 1985; Brudy & Zoback 1999). Its reduced cohesion relative to reported laboratory values gives an approximation of the scale dependence of strength. The parameters of these constitutive models are listed in Table 25. The elastic moduli are parameters of the constitutive models, but their magnitudes are less important than strength criteria to the calculation of failure and plastic strain. At *in situ* temperature (e.g., 150°C) strength properties are slightly reduced, but not significantly compared to strength reduction at temperatures greater than 200°C (Tian et al. 2012).

**Table 25. Strength and deformability properties for granites selected for analysis.**

| Rock Type | Cohesion (MPa) Initial →Final | Cohesion (MPa) Criterion [A] | Friction Angle (°) Initial →Final | Friction Angle (°) Criterion [A] | Dilation Angle (°) | Tensile Strength Cutoff (MPa) | Elastic Moduli (GPa) Bulk | Elastic Moduli (GPa) Shear |
|-----------|------|-----------|------|-----------|----|----|----|----|
| Generic Granite [B] | 150 | Constant | 48 | Constant | 0 | 10 | 40 | 24 |
| Lac du Bonnet Granite [C] | 50→15 | Linear from 0 to 0.2% $\varepsilon_{ps}$ | 0→48 | Linear from 0 to 0.5% $\varepsilon_{ps}$ | 30 | 10 | 40 | 24 |
| Notes: [A] $\varepsilon_{ps}$ = accumulated plastic strain  [B] Coulomb data fit (Al-Ajmi & Zimmerman 2005); intact tension (You 2015); moduli (Johnson 1984)  [C] Calibrated to AECL Mine-By Test (Hajiabdolmajid et al. 2003). | | | | | | | | |

Effects from temperature changes on wellbore damage are analyzed below. Cooling the wellbore can inhibit breakout formation but increases tangential tensile stress that can cause cracking. Representative thermophysical properties (applicable to both types of rock simulated) are shown in Table 26. Hydraulic conductivity values for intact rock are used to evaluate the extent of a DRZ around the borehole, and the poroelastic response from pore pressure increase within that zone.

**Table 26. Representative values for thermophysical properties for granite**

| Property | Value | Notes |
|---|---|---|
| Coefficient of thermal expansion ($\alpha$) | $0.6 \times 10^{-5}$ /°C | Brudy & Zoback (1999) |
| Thermal conductivity ($K_{th}$) | 2.8 W/m-K | Hardin et al. (2012) |
| Bulk density ($\rho$) | 2700 kg/m$^3$ | |
| Heat capacity ($C_p$) | 837 J/kg-K | |
| Hydraulic conductivity | $3 \times 10^{-13}$ m/sec (approximate) | Intact Westerly granite; Brace et al. (1968) |
| | $10^{-13}$ m/sec (approximate) | Sparsely fracture Lac du Bonnet granite; Read & Martin (1996) |

# B-3.    Models of Breakout and Tensile Crack Behavior

## B-3.1  Elastic Analysis with Mohr-Coulomb Failure Criterion

Zoback et al. (1985) published a seminal paper that interpreted borehole breakout orientation, size, and shape for evaluating *in situ* stress directions and magnitudes. The approach recognized the Mohr-Coulomb (M-C) failure criterion and used isotropic elasticity to map contours in the rock on which the shear and normal stresses indicate incipient M-C failure. Plots of these contours reproduced the general characteristics of breakouts although examination of actual breakouts showed them to be variable, and sometimes deeper.

The authors investigated the effects from borehole fluid pressure by superposing radial compressive stress at the borehole wall, and breakout development was found to be sensitive to the increased confinement. The stabilizing effect was judged not to be reduced by the effective stress principle, if the effects of pore pressure in low-porosity rock are insignificant (Nur and Byerlee 1971). The experimentally observed decrease in pore pressure with dilatancy as low-porosity, low-permeability rock is deformed was identified as a contributing factor. Other work has concluded that pore pressure effects are significant for crystalline rock (Zangerl 2003). The importance of pore pressure changes induced by formatoin invasion is addressed by numerical examples described later in this report.

The theory of Zoback et al. (1985) was essentially elastic and did not account explicitly for inelastic behavior (Zhou 1994). Inelastic deformation degrades cohesion and mobilizes frictional strength that can arrest breakout growth even as the geometry becomes less stable. Strength mobilization is demonstrated here with explicit simulation of Mohr-Coulomb elastic-perfectly plastic behavior for the four cases identified above, with and without applied pressure at the borehole wall (Figure 9 and Figure 10). The generic Mohr-Coulomb granite description is used (Table 25). These are 2D plane-strain calculations performed with FLAC V.7.0 (Itasca Consulting Group 2011a) and representing a 20-cm diameter borehole in a 1.4-m square domain. The fluid pressure applied at the borehole wall is assumed to be either zero, or the weight of a column of pure water at the depths indicated (approaching the maximum confinement that could be achieved). Figure 9 and Figure 10 compare the extent of yielding from creating the borehole, and the maximum shear stress, for these cases. Regions of plastic shear strain correspond in width and depth to predicted breakout contours, choosing a contour for accumulated shear strain of a few tenths of a percent (e.g., 0.25% shear strain).
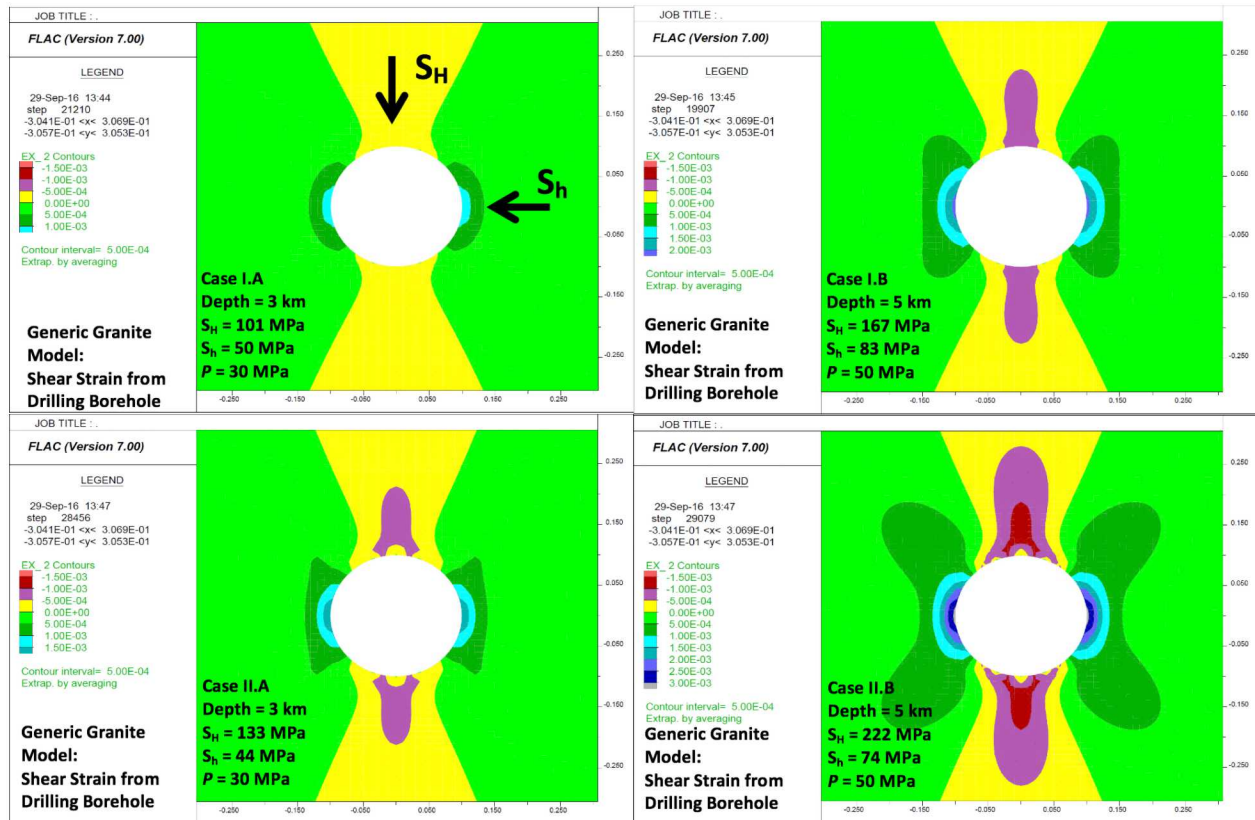
**Figure 9. 2D plane strain calculation of x-y shear strain change from introducing a borehole (Mohr-Coulomb) for stress conditions and borehole pressure values indicated (very low permeability and/or Biot effective pressure coefficient *M*=0).**
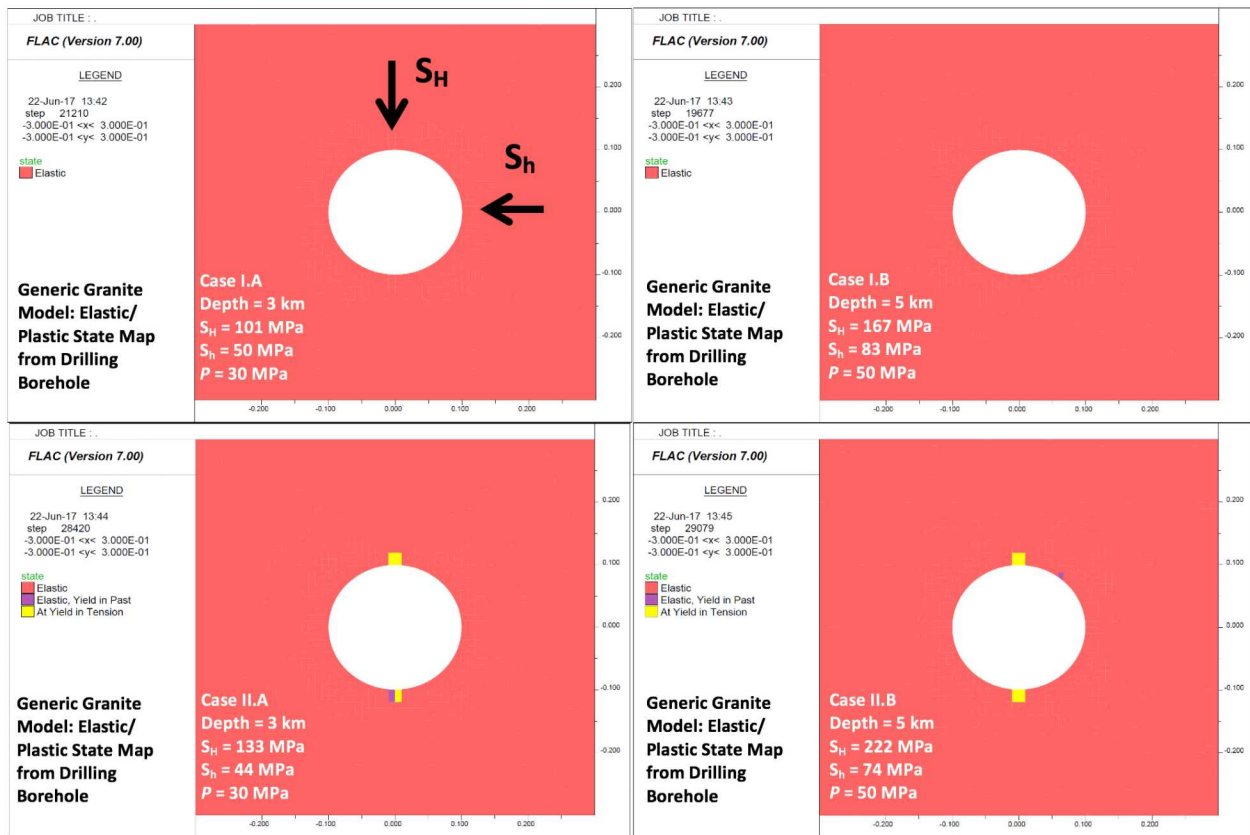
**Figure 10. 2D plane strain calculation of introducing a borehole, with Mohr-Coulomb, showing the deformation state of the rock after equilibration (possible states: elastic, elastic with shear yielding during deformation, and tensile yielding) for the stress and borehole pressure conditions indicated (very low permeability and/or Biot effective pressure coefficient *M*=0).**

Brudy & Zoback (1999) accounted for pressure transients during drilling, and thermal expansion/ contraction, in the interpretation of breakouts and tensile cracks observed in the KTB pilot hole in Germany. Pressure transients and cooling of the borehole wall were shown to increase the potential for tensile cracking. Borehole fluid that is colder than the formation causes a decrease in compressive stress and less breakout (Gomar et al. 2014) but increased potential for tensile failure (Guenot 1989).

Breakout interpretation was extended to elastic analysis of deviated boreholes (Mastin 1988), later elaborated using numerical analysis. Breakout studies have increasingly used numerical analysis which allows for incorporating:
More complex constitutive laws (Gomar et al. 2014),
3-dimensional (3D) strength criteria with deviated boreholes (Rahimi & Nygaard 2015),
Formation anisotropy (Zou et al. 1996; Kanfar et al. 2016), and
Strain localization functions (Papanastasiou & Thiercelin 2011; Crook et al. 2003).
Whereas simulations in 3D are mostly limited to geometric stress analysis for deviated boreholes and anisotropic media, the process of breakout formation ahead of the drilling face ("bottom breakout") has also been analyzed in 3D (Ito et al. 1998).
Time-dependent wellbore instability was observed in gneissic rock encountered in the KTB research borehole (Schoenball et al. 2014) with latency of 20 to 100 days, and even longer delays have been reported elsewhere. The behavior is disruptive to drilling progress when rock debris falls on drilling tool assemblies. Time-dependent breakout was explained as brittle creep (Schoenball et al. 2014) which may be essentially the same as static fatigue, at *in situ* temperature. Other possible mechanisms for time-

dependence include poroelastic weakening as borehole fluid permeates rock near the borehole (Gelet et al. 2012). These mechanisms are discussed further below in the context of the effectiveness of possible measures for preventing wellbore instability.

## B-3.2 Breakout Analysis Using Constitutive Model from the AECL Mine-By Experiment

The AECL Mine-By Experiment produced unique observations of breakout at a larger scale (nominally 3.5 m diameter) in well-characterized, lithologically uniform, sparsely fractured rock where the state of *in situ* stress was accurately known. Breakout was uniform along the length of the tunnel. Acoustic emission detected tensile failure activity in the directions of $S_H$, as well as shear failure in the breakout regions (direction of $S_h$).

Large diameter boreholes have similar dimensions and can behave similarly to mined openings in high-quality rock. Hollow-cylinder studies (Meier et al. 2013; Dresen et al. 2010) showed that the critical value of tangential compressive stress at the borehole wall for onset of breakout behavior, decreases with increasing diameter but approaches a constant at diameters of a few cm value (2× unconfined compressive strength was reported). In any case, the nature of breakout in the AECL Mine-By tunnel suggests that which could occur around a large diameter borehole in high-quality crystalline rock with similar properties.

As part of the AECL program Martin (1997) and others performed extensive laboratory triaxial tests, and interpreted the onset of inelastic behavior, damage state from cumulative plastic strain, cohesion loss, and friction mobilization. These behaviors were incorporated by Hajiabdolmajid et al. (2003) in a 2D constitutive model implemented in FLAC. The approach was able to simulate the observed breakout geometry in response to excavation, whereas elastic-perfectly plastic (Mohr-Coulomb) and elastic-brittle (Hoek-Brown) models did not (Hajiabdolmajid et al. 2002). The parameters of their calibrated, bilinear, plastic-strain dependent constitutive model are given in Table 25.

The bilinear model of Hajiabdolmajid et al. (2002) was implemented in FLAC using the accumulated plastic shear strain as the state variable in a bilinear model to soften and harden the material (Figure 11). These calculations are similar to those published for the AECL Mine-By Experiment (Hajiabdolmajid et al. 2003) but with gravity acting along the borehole axis. The calculation is scale-independent and can be compared directly to similar plots from Hajiabdolmajid et al. (2002, 2003).
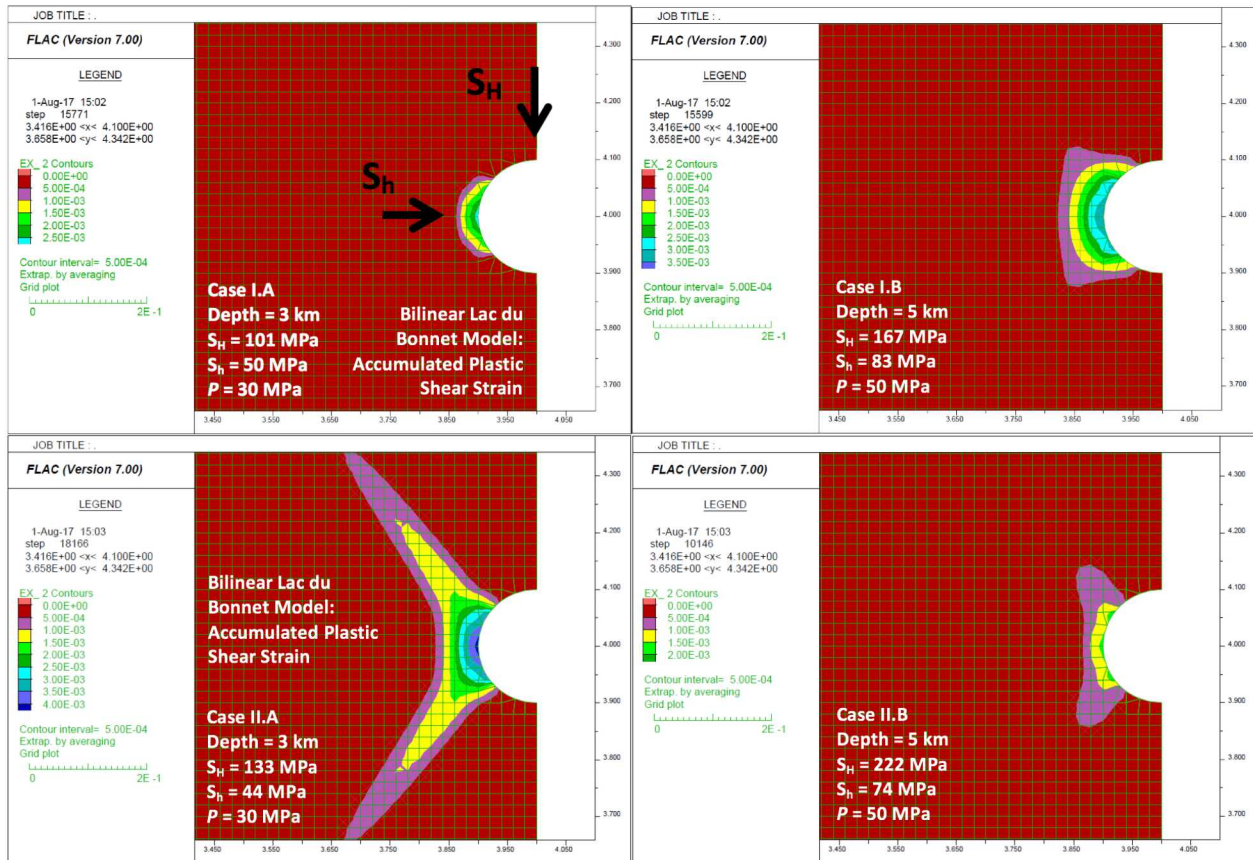
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**Figure 11. 2D mechanical plane strain calculation of accumulated plastic shear strain from introducing a borehole (calibrated bilinear granite model) for stress conditions and borehole pressure indicated. The pressure is applied to the borewall without pore pressure effects, which corresponds to very low permeability and/or effective pressure coefficient *M*=0.**

## B-3.3 Plastic Shear Strain (Breakout)

The calculations shown in Figure 11 include the pressure of a column of pure water in the borehole, acting on the borehole wall. Without such pressure considerable weakening and breakout conditions would be calculated. The calculations do not include pore pressure effects in the rock, although the borewall pressure boundary condition would be the same if pore pressure were included (coupled thermal-hydrologic-mechanical simulations are discussed below).

The borewall pressure condition used in Figure 11 produces a reasonable upper bound on borewall stability if the rock stresses are unmodified by pore pressure. The stability represented in Figure 11 could be achieved if the coefficient of effective stress is low (i.e., $M \to 0$) which may be common in low-porosity crystalline rock as discussed previously. Alternatively, stability could persist for some time if the rock permeability is small, even with $M > 0$.

More breakout might occur if $M \to 1$ and there is sufficient permeability for borehole fluid pressure ($\Delta P$ in excess of *in situ* pore pressure) to penetrate rock in the vicinity of the borehole. Thus, pore pressure could contribute to wellbore damage by degrading the confinement provided by boreohle pressure $P$ at the borewall. Pore pressure effectively reduces all normal effective stresses (even where concentrated by geometry) by the same amount, which does not change the magnitude of shear stress that causes damage, but can weaken the rock by locally reducing confinement, especially near the borehole. However, the effect of borehole pressure applied at the borewall should be the dominant stabilizing effect if $M < 1$,

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since nearly 100% of the borehole pressure is applied to the solid framework in low-porosity rock (with a possible correction for borewall porosity) compared to the relatively inefficient effect from pore pressure.

Similarly, underpressured conditions ($\Delta P < 0$, with $M \to 1$) could locally increase normal effective stresses but decrease confinement by the borehole pressure. The dominant effect should be destabilization caused by reduced borehole pressure applied to the borewall. These effects are explored in coupled simulations presented below.

Plastic shear strain can occur throughout a significant volume around the borehole, caused by concentration of $S_H$, especially for those cases with $\Delta P = 0$. Breakout (e.g., represented for the AECL Mine-By as accumulated plastic shear strain > 0.2%) penetrates into the rock especially with $S_H/S_h = 3$ (Cases IIA and IIB). Borehole pressure at the levels used in Figure 11 significantly reduces the accumulated plastic shear compared to zero borehole pressure. (Zero pressure is not calculated here, but would correspond most closely to drilling with gas as circulating fluid.)

Comparing Figure 9 and Figure 11 (Mohr-Coulomb shear strain vs. bilinear granite model accumulated plastic shear strain) suggests that hardening behavior makes strength more sensitive to confinement. Thus, strength increases as friction angle and dilation increase in the bilinear Lac du Bonnet granite model, and the effect of borehole pressure is more stabilizing. Such a strengthening effect was noted by Zhao et al. (2010) who allowed dilation angle to evolve with accumulated strain (in addition friction angle and cohesion) and observed that this reduces plastic strain.

## B-3.4 Plastic Tensile Strain (Tension Cracking)

Calculations of accumulated plastic tensile strain (Figure 11) without thermal effects or pore pressure, show that tensile yielding and possibly fracture may occur for all cases considered but especially for greater $S_H/S_h$ (i.e., Cases IIA and IIB defined in Table 24). According to elasticity, borehole pressure always induces a numerically equal tangential tension at the borehole. Any pore pressure increase within the rock also produces a tension (corrected by the effective stress coefficient). These relationships are summarized in Table 27, which shows that tension (negative stress) is closely associated with greater $S_H/S_h$ and may be further increased by pore pressure (effective stress) if $M > 0$.

Cooling the borehole fluid has been previously proposed to control breakout but may increase tensile cracking as discussed above. The effect from cooling on tangential stress (Table 27) can be approximated as

$$\Delta\sigma \approx E\alpha\Delta T$$

where $E$ is Young's modulus and $\alpha$ is the coefficient of linear thermal expansion. The temperature change $\Delta T$ is transient, so the stress field around the borehole continues to evolve with the temperature field (e.g., Figure 12 shows the results after 10 days of cooling). The estimate of $-33$ MPa (Table 27) is an upper bound, relevant immediately after drilling (within a few hours) with cooling of the borehole by $-50$ K. This temperature change is selected as a practical limit, for which the actual cooling of recirculating drilling fluid at the surface could be substantially greater than 50 K. The breakout-stabilizing effect of $\Delta T < 0$ could persist with time as a larger region cools, however, adjustment of the rock mass to thermal stress redistribution could later lead to greater compressive stresses after cooling ceases and the rock returns to initial temperature (Figure 13).
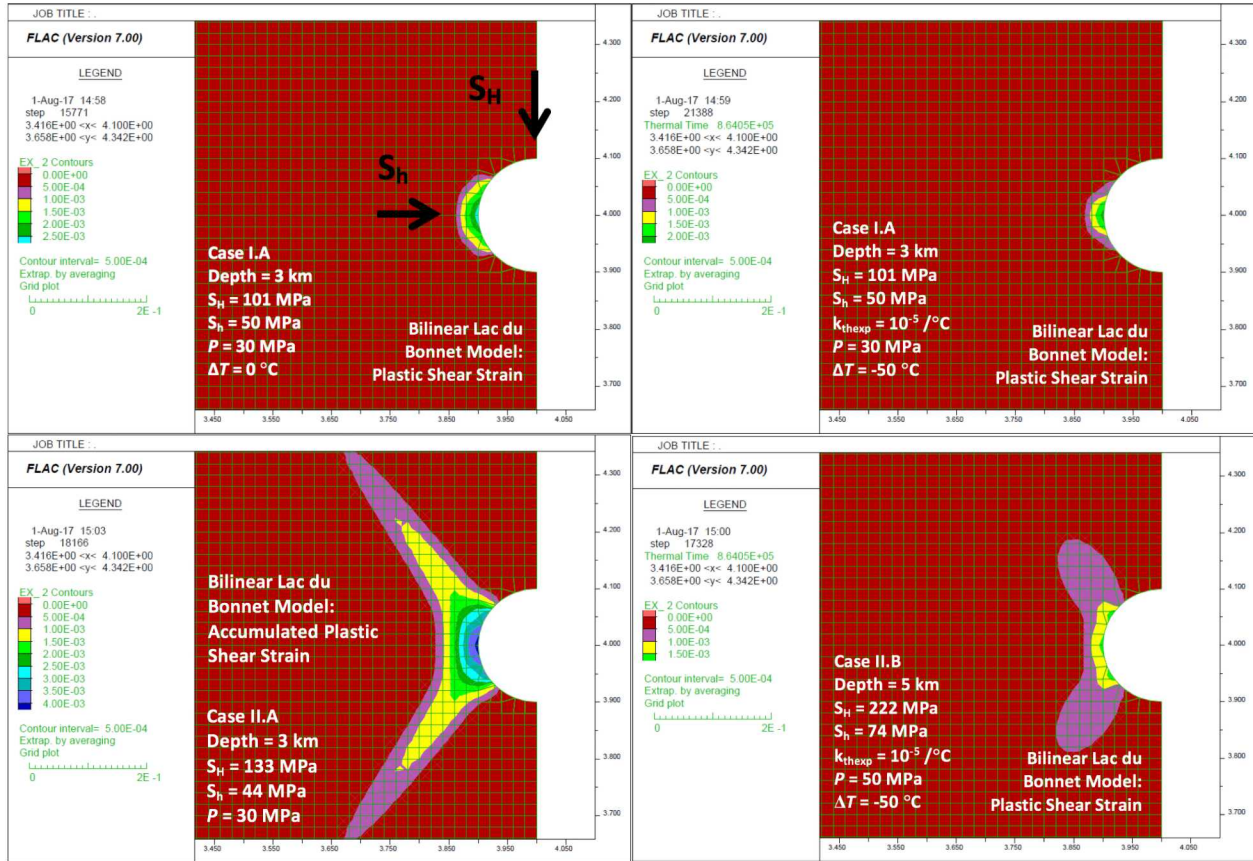
**Figure 12. 2D thermomechanical calculation of accumulated plastic shear strain, 10 days after introducing a 20-cm borehole (bilinear Lac du Bonnet granite model) for borewall applied pressure and temperature difference values indicated. Pressure applied to the borewall without pore pressure effects (i.e., very low permeability and/or effective pressure coefficient *M*=0).**

Fluid pressure $P$ applied at the borewall moderates shear strain to an extent comparable to −50 K of cooling (Figure 11 and Figure 14), depending on the *in-situ* stress state. In Figure 12, the −50 K temperature effect on decreasing plastic shear strain is stronger for Case IA ($\Delta P = 3$ MPa, 3 km depth), while in Figure 14, the ±10% pressure effect is stronger for Case IIB ($\Delta P = 5$ MPa, 5 km depth).

In summary, cooling effectively reduces plastic shear strain that causes breakout damage (Figure 12, bilinear granite model). However, the influence of $\Delta T = -50$ K on tension, and the potential for tensile cracking, is significant (comparable to the difference in stress conditions at 3 km vs. 5 km, comparing depths A and B from Table 24). Accordingly, cooling could be more useful to control wellbore damage where $S_H/S_h \leq 2$ and the rock is failing in shear, and less useful for larger values of $S_H/S_h$ where the rock is under tension in the $S_H$ direction.

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**Table 27. Tensile stress near the borehole wall caused by borehole pressure, pore pressure (effective stress), and cooling of the borehole, for cases considered.**

| Case | Borehole Pressure, $P$ (MPa) | Major Principal Horizontal Stress, $S_H$ (MPa) | Minor Principal Horizontal Stress, $S_h$ (MPa) | Horizontal Stress Ratio ($S_H/S_h$) |
|---|---|---|---|---|
| Stress Conditions (from Table 24) | | | | |
| I.A | 30 | 101 | 50 | 2 |
| I.B | 50 | 167 | 83 | 2 |
| II.A | 30 | 133 | 44 | 3 |
| II.B | 50 | 222 | 74 | 3 |
| Contributions to Tensile Cracking in the $S_H$ Direction[A] | | | | |
| | Solid Continuum Tangential Stress ($\approx 3S_h - S_H - P$) | Effective Stress where Tension < 0 (subtract $M \cdot P_p$) | With Borehole Fluid Cooling Effect (subtract $E\alpha\Delta T$) | |
| Borewall Tangential Stress for Effective Stress Coeff. $M=0$ and $P=P_p$ (all values in MPa) | | | | |
| I.A | 19 | 19 | −14 | |
| I.B | 32 | 32 | −1 | |
| II.A | −31 | −31 | −64 | |
| II.B | −50 | −50 | −83 | |
| Borewall Tangential Stress for Effective Stress Coeff. $M=1$ and $P=P_p$ (all values in MPa) | | | | |
| I.A | 19 | −11 | −44 | |
| I.B | 32 | −18 | −51 | |
| II.A | −31 | −61 | −94 | |
| II.B | −50 | −100 | −133 | |
| [A] Tensile stresses are negative. | | | | |

# B-4.    Coupled THM Behavior

## B-4.1   Pore Pressure (HM Coupling)

Simulations with pore pressure (Figure 14 through Figure 16) show that hydro-mechanical (H-M) coupling can significantly increase the extent of shear damage, due to effective stress and loss of confinement (which does not require flow). Hydro-mechanical simulations were done to explore effects from borehole underpressure and overpressure, and effective stress behavior, in the near-field.

The default condition in FLAC applies the full magnitude of the pore pressure to compute effective stress (high-$M$ simulations, $M = 1$). The option for Biot poroelasticity is not used. Also, consistent with code documentation the borehole fluid pressure is applied as a mechanical load on the borewall (Itasca Consulting Group 2011b, p. 1-29).

In the simulations, the pore pressure effect on deformation stabilizes after a steady flow regime is established (as quickly as a few hours in simulations with $k = 10^{-18}$ m²; see Figure 14 and Figure 15). The calculations with increased or decreased borehole fluid pressure relative to the formation show that reasonable changes (e.g., ±10% change in static borehole fluid pressure at depth) have little effect on plastic shear strain, which depends more critically on the *in-situ* stress conditions (Figure 14). From the examples calculated, underpressure and overpressure can change stability conditions in the near-field only slightly. The calculations were done for $M = 1$, but if modified for $M < 1$ the same result would be hold because: 1) borewall stability is greater for M < 1 as discussed below because effective stress behavior is

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reduced; and 2) the magnitude of the effective underpressure or overpressure in the formation would also be reduced by *M*. An explanation for this result is that changes in pore pressure do not affect shear stresses (regardless of *M*), and the effect from increments of borehole pressure on confinement in the near-field is inefficient (modified by frictional properties in the constitutive law).
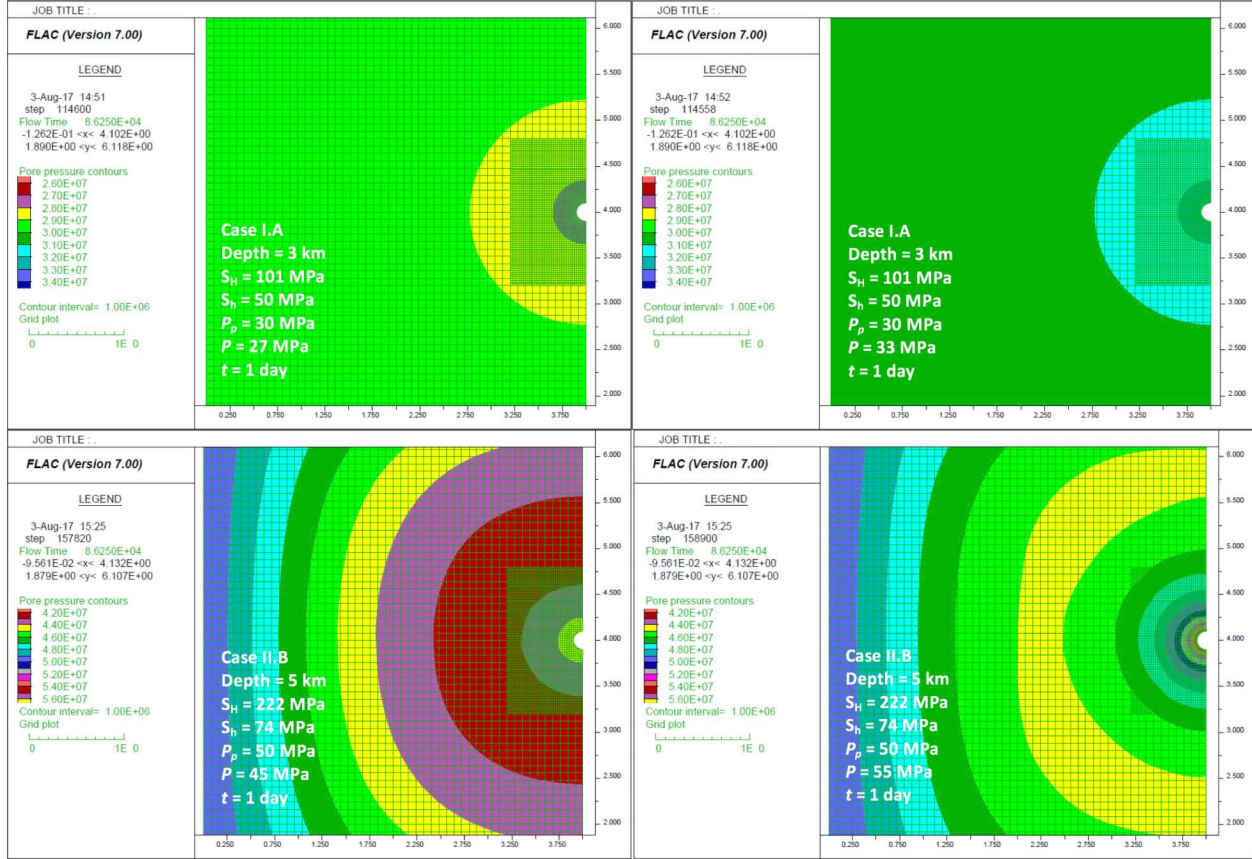


**Figure 13. 2D HM calculation showing pore pressure 1 day after introducing a 20-cm borehole (bilinear Lac du Bonnet granite model) with and without 10% borewall under-pressure and over-pressure as indicated (effective pressure coefficient *M*=1).**

For Figure 15 (low-*M* simulations, $0 < M < 1$) the effective stress behavior was limited by reducing the fluid pressure in the borehole and the formation (e.g., by a factor of 10) while increasing permeability (10-fold) and setting the mechanical pressure of fluid on the borewall equal to the full fluid pressure. The result represents a medium with $M = 0.1$, and pressure on the borewall corresponding approximately to a column of pure water extending to the ground surface (borehole fluid density $10^3$ kg/m$^3$).

For both low-*M* and high-*M* simulations, dilation associated with post-peak plastic shear damage causes a steep local drop in pore pressure in the $S_h$ direction associated with breakout. Local softening of the rock occurs from effective stress behavior, depending on the value of *M*.

For both low-*M* and high-*M* simulations, elastic dilation associated with stress redistribution extends outward for many borehole radii, well beyond the plastic region, and lowers the pore pressure by as much as 10% for the cases simulated (Figure 15). This far-field pore pressure transient does not appear to have a significant impact on near-field rock deformation and wellbore stability, but it dominates the fluid pressure response beyond approximately one radius into the rock. Equilibration of this pressure response to the boundary conditions is the only change that occurs in these models after a few hours of simulation time.
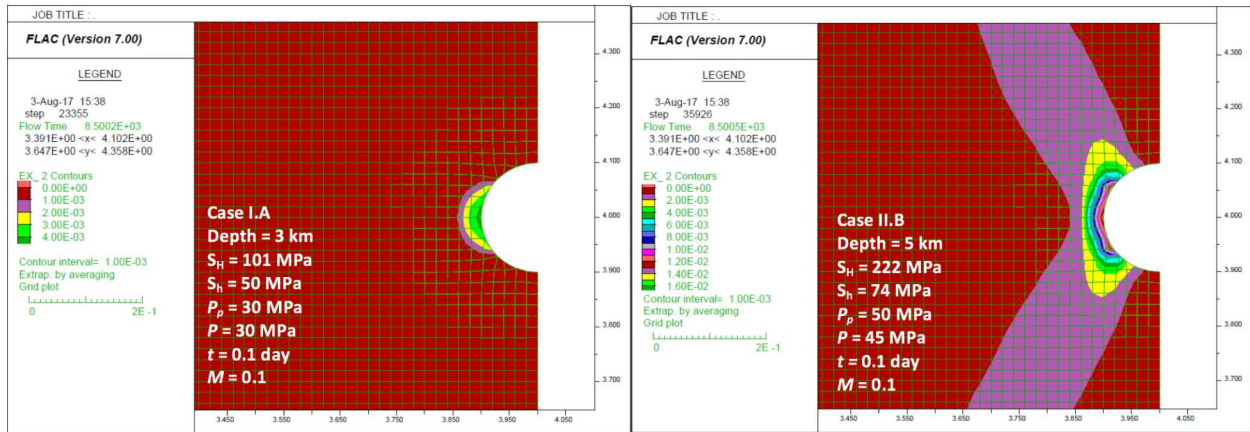
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**Figure 14. 2D HM simulation of accumulated plastic shear strain, 0.1 day after introducing a 20-cm borehole, with formation effective stress 10% of pore pressure (*M*=0.1).**

If the effective stress coefficient is large ($M \rightarrow 1$) the HM effect on rock strength in the near-field is substantial (compare Figure 14 and Figure 15, for Cases IA and IIB, noting scale changes). If the effective stress coefficient is small ($M \rightarrow 0$) the effect on potential damage from plastic shear is much smaller, on the order of half the severity and extent of damage, or better (compare Figure 14 and Figure 16). This may be the most important rock characteristic for wellbore stability (i.e., $M \rightarrow 0$) and suggests these measures to mitigate breakout:

- If the natural state of the rock mass limits effective stress behavior ($M \rightarrow 0$) then drilling fluid weight (and downhole pressure) should be increased to prevent creation of a damaged zone where $M \rightarrow 1$.
- If the natural state of the rock mass supports significant effective stress behavior ($M \rightarrow 1$) or if a damaged zone is produced, then fluid invasion control (e.g., underpressured drilling, and fluid viscosity and caking additives) should be used to avoid weakening the near-field.
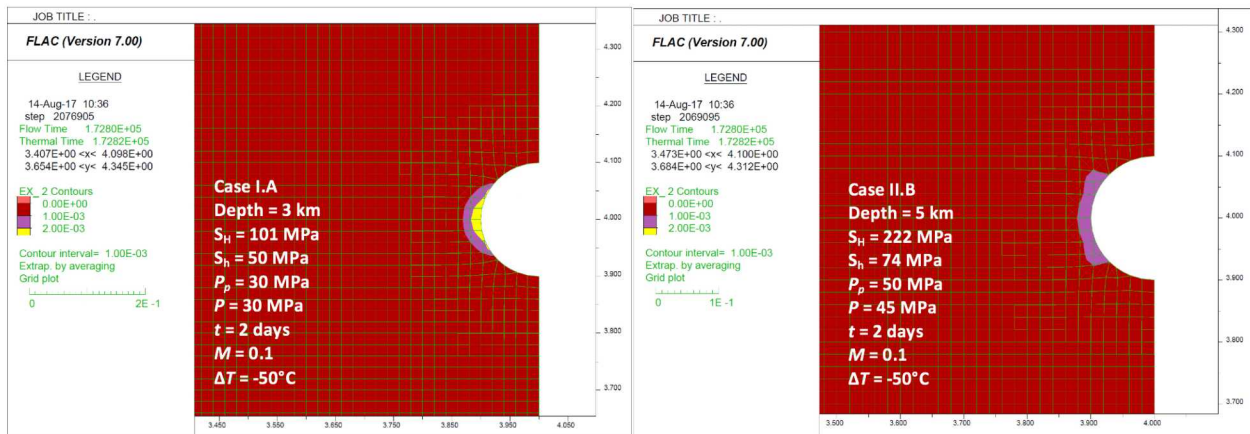


**Figure 15. 2D THM coupled simulation of accumulated plastic shear strain, 2 days after introducing a 20-cm borehole, with formation effective stress 10% of pore pressure (*M*=0.1), and cooling of the borehole (*ΔT* = –50 K).**

In summary for HM couplings, adding pore pressure in the simulations shows that dilation (positive volume strain) immediately reduces pore pressure in a region around the borehole. Where plastic shear occurs (bilinear granite model) there is a steep reduction in pore pressure, but pore pressure is also reduced to a lesser extent in a much larger region from elastic dilation. In the larger region, plastic shear is not initiated so the effect on near-field wellbore stability is insignificant. For the permeability values used, the dilation effect persists for days until the pore pressure equalizes.

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Invasion of fluid into the formation occurs in response to the pore pressure gradients, enhanced if the borehole is overpressured ($\Delta P > 0$). Invasion increases pore pressure in the near-field and is potentially destabilizing if $M > 0$.

## B-4.2   Thermal-Hydrologic-Mechanical Coupling

T-H-M simulations explored whether cooling of the borehole by drilling fluid could counteract damage from plastic shear, increased by pore pressure effects.

The HM and thermal models in FLAC were coupled externally by alternating the fully explicit submodels, with a preset cycle time between updates (e.g., 10 sec). The thermal module explicitly calculates energy transport by fluid flow, and the fluid pressure effect from thermal expansion/contraction of the solid framework and the fluid. For average permeability typical of granite, fluid flow is slow enough that thermal convection is insignificant. The same scheme described above for low-$M$ simulations ($0 < M < 1$) was used, to represent host rock with $M = 0.1$.

As discussed above, cooling stabilizes the near-field by reducing the tangential normal stress and associated shear stresses. Stress trajectories are redistributed farther away from the borehole where the rock is more confined in the radial direction and therefore stronger. Over a period of days or weeks, stress conditions may revert after cooling of a large region around the borehole. The simulations presented here (Figure 12 and Figure 17) are truncated at times from 2 to 10 days. At 2 days, the temperature field is developing, while at 10 days the constant-temperature boundary conditions are starting to be expressed around the borehole. These simulation times were chosen to reflect the near-term and longer-term benefits that might be obtained from $\Delta T < 0$.

Thermal-mechanical test cases (Figure 12, Cases IA and IIB, for 10 days) show that $\Delta T < 0$ (without pore pressure) has limited influence on formation damage, depending on the initial state of *in situ* stress. Test cases with thermal-hydrologic-mechanical (THM) coupling show cooling may have more influence if effective stress effects are limited (compare Figure 16 and Figure 17, Cases IA and IIB). This comparison suggests a hierarchy of strategies: if pore pressure coupling to total stress is minor in the formation ($M \ll 1$) then cooling could be effective, and a first priority during drilling is to limit breakout using greater fluid pressure, while limiting pore pressure changes by controlling fluid invasion, so that cooling remains an effective option.

**Table 28. Concentrated tangential stress near the borehole wall caused by borehole pressure, pore pressure (effective stress), and cooling of the borehole, for cases considered.**

| Case | Borehole Pressure, $P$ (MPa) | Major Principal Horizontal Stress, $S_H$ (MPa) | Minor Principal Horizontal Stress, $S_h$ (MPa) | Horizontal Stress Ratio ($S_H/S_h$) |
|---|---|---|---|---|
| **Stress Conditions (from Table 24)** | | | | |
| I.A | 30 | 101 | 50 | 2 |
| I.B | 50 | 167 | 83 | 2 |
| II.A | 30 | 133 | 44 | 3 |
| II.B | 50 | 222 | 74 | 3 |
| **Concentrated Tangential Normal Stress in the $S_h$ Direction[A]** | | | | |
| | Solid Continuum Tangential Stress ($\approx 3S_H$ -$S_h$ -$P$) | Effective Stress where Tension < 0 (subtract $M\cdot P_p$) | With Borehole Fluid Cooling Effect (subtract $E\alpha\Delta T$) | |
| **Borewall Tangential Stress for Effective Stress Coeff. $M=0$ and $P=P_p$ (all values in MPa)** | | | | |
| I.A | 223 | 193 | 160 | |
| I.B | 368 | 318 | 285 | |
| II.A | 325 | 295 | 262 | |
| II.B | 542 | 492 | 459 | |
| **Borewall Tangential Stress for Effective Stress Coeff. $M=1$ and $P=P_p$ (all values in MPa)** | | | | |
| I.A | 223 | 223 | 190 | |
| I.B | 368 | 368 | 335 | |
| II.A | 325 | 325 | 292 | |
| II.B | 542 | 542 | 509 | |
| [A] Tensile stresses are negative. | | | | |

# B-5.   Summary and Recommendations

The *in-situ* state of stress and rock constitutive behavior pose the principal controls on wellbore stability and near-field damage. The tendency for effective stress behavior ($M > 0$) in the rock, or in a damaged zone around the borehole, is apparently the most effective THM parameter. Simple calculations show that effective stress behavior increases both tensile cracking and shear failure in the near-field (Table 27 and Table 28). Whereas the effective stress coefficient ($M$) is an intrinsic property of the rock (or damaged zone), mitigation may be possible using fluid pressure, composition, and temperature:

- Potential drilling controls are overpressure and control of formation invasion by underpressure and/or use of viscosifying or caking additives (increasingly important with larger $M > 0$). Note that control of formation invasion would be ineffective to prevent breakout if $M \approx 0$, and that extreme underpressure could be destabilizing by decreasing confinement at the borewall and introducing radial flow stresses.
- Cooling of the borehole fluid would be difficult but could achieve further reductions in stress and improve wellbore stability, if effective stress behavior is limited ($M \rightarrow 0$).

Breakout prediction is significantly complicated by constitutive behavior (dilation, hardening, effective stress, response to temperature changes, and possible coupling between deformation and permeability). Simulations with the Lac du Bonnet bilinear granite model, for a range of *in situ* stress conditions that might be encountered, suggest that threshold effects occur (dilation, hardening) that directly affect wellbore stability and are associated with constitutive behavior. For successful control of breakout in a

research borehole, understanding of constitutive behavior and the potential for threshold effects, and measurement of *in situ* stress, are needed *early* during the drilling phase to inform breakout mitigation.

Infiltration of drilling fluid into the formation (i.e., lost circulation) must be controlled. Drilling fluid pressure is raised using increased density fluid to control breakout and simultaneously we must control infiltration of this higher-pressure fluid in the formation (i.e., lost circulation).

Constitutive models should be calibrated to laboratory tests. The types of laboratory tests should evaluate strength development response, friction and dilation, and permeability changes vs. accumulated shear or volume strain (or other indicators).

Additional modeling sensitivity studies are needed using site-specific information on stress conditions and rock characteristics. More advanced simulations should incorporate longer simulation periods, parameter sensitivity studies, other constitutive mechanical models, grid refinement, and alternative codes.

The oil-and-gas literature has examples of constitutive relationships, and 3D simulation methods for non-vertical boreholes and/or non-vertically aligned principal stress directions. Such extensions would be appropriate for deep borehole disposal investigations, depending on borehole orientation, formation anisotropy, and *in situ* stress conditions.

Another potentially important extension is 3D analysis of core discing, which has not been addressed by this study. Control of discing may be closely related to breakout: the average stress from a drill bit is small compared to the *in-situ* stress magnitude and fluid pressures (Ito et al. 1998) so the means to mitigate discing are limited to drilling rate (rheological) and drilling fluid controls such as those described above.

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