Hydrogeologic Lessons Learned from Deep Drilling Projects Applied to Deep Borehole Disposal of Radioactive Wastes – 16133

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ABSTRACT

Hydrogeological results from the Kola SG-3, Gravberg-1, Cajon Pass, and KTB-VB and KTB-HB boreholes are applied to the US deep borehole disposal concept to assess whether old, saline, and reducing deep groundwater, in low bulk permeability crystalline basement rocks, could be found in a DOE proposed deep borehole field test. Each of the drilling projects faced characterization challenges, including obtaining sufficient information to characterize key parameters and their uncertainty, equipment limitations and failures, and obtaining samples that are representative of *in situ* conditions while maintaining sample integrity. Despite these characterization challenges, each project obtained sufficient data to directly measure or infer, for redox state, conditions at the 3 to 5 km (1.9 – 3.1 miles) target disposal depth of the US deep borehole disposal concept. The hydrogeologic data suggest that old, saline, and reducing deep groundwater could be found at a test site located in geologically stable crystalline basement. Although the DOE deep borehole testing program has not defined the magnitude of an acceptably low bulk permeability, bulk permeability results indicate that values used in current US deep borehole modeling efforts may be too low by an order of magnitude or more, as compared with *in situ* conditions.

INTRODUCTION

Disposal of radioactive wastes in deep boreholes is a proposed method for isolating radioactive material from the surface and near-surface environment. Several countries have reviewed the deep borehole disposal concept including Sweden [1], the United Kingdom (UK) [2], and the United States (US) [3]. In September 2014, Sandia National Laboratories (SNL) released a 5-year plan to complete a deep borehole field test to evaluate the feasibility of the deep borehole disposal concept [4]. The DOE field test program will attempt to characterize the environment at depth, test emplacement engineering, and examine borehole sealing materials and designs through above-ground testing [4]. SKB (Sweden) and Nirex (UK) used data from over 20 deep drilling projects, including those reviewed here, to evaluate deep borehole disposal of radioactive wastes. This paper reviews the hydrogeological results of the Kola SG-3, Gravberg-1, Cajon Pass, and KTB deep drilling projects that SNL is using to guide expectations for drilling, sampling, and testing conditions in the DOE deep borehole field test. The paper identifies results and experiences gained from the four deep drilling projects relative to the science objectives laid out for the field test.

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[a] The views expressed in this paper are those of the authors and do not necessarily represent the views of the U.S. Nuclear Waste Technical Review Board. The first author, while a staff intern for the Board during the summer of 2015, completed this study under the guidance of the second author who is a member of the Board's Senior Professional Staff.

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DISCUSSION

US Deep Borehole Disposal Concept and Field Test

The US deep borehole disposal concept envisions a 5 km (3.1 miles) deep borehole, with the bottom 3 km (1.9 miles) drilled in the crystalline basement (Figure 1).[c] Radioactive waste would be emplaced into the lower 2 km (1.2 miles) of the borehole and overlain by sealing and plugging zones [5]. As depicted in Figure 1, the borehole disposal depths are several times deeper than typical mined repositories [e.g., the proposed Onkalo, Finland repository and the Waste Isolation Pilot Plant (WIPP)].

Plans for the DOE deep borehole disposal field test include two 5 km deep holes, a characterization borehole and a field test borehole. The first borehole drilled, the characterization borehole, will have a bottom-hole diameter of 21.6 cm (8.5 inches) and will be used to characterize conditions in the crystalline basement. The second borehole, the field-test borehole, will have a bottom-hole diameter of 43.2 cm (17 inches) and will be used for testing the emplacement and retrieval of simulated waste packages that do not contain radioactive material [5].

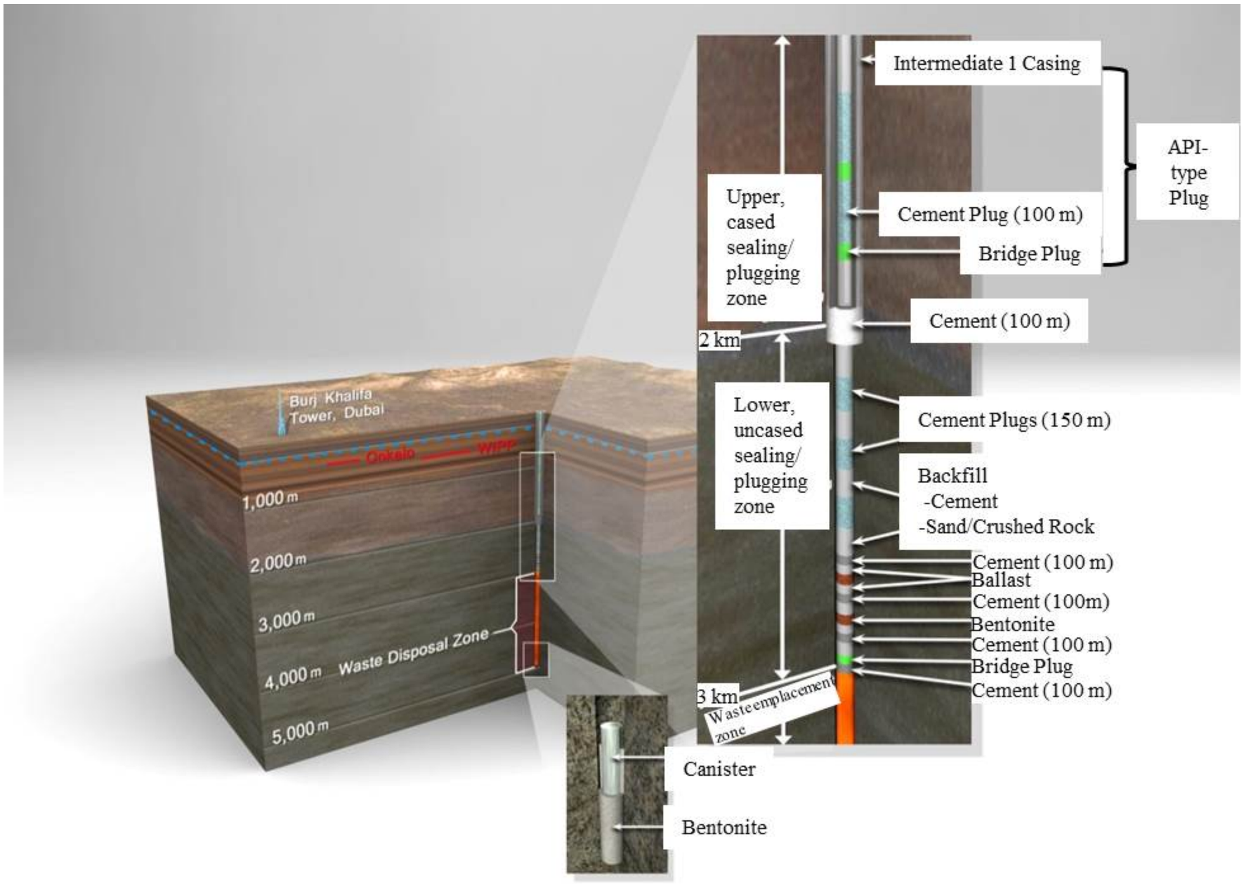

Fig. 1. The US deep borehole disposal concept (adapted from [5]).

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[c] The basement is the crust of the Earth underlying sedimentary deposits.

SNL described six science objectives for the characterization borehole and potential testing activities [6]. Three science objectives examined here involve confirming the following properties of the potential disposal zone: (1) deep groundwater is old and isolated from surface waters; (2) deep groundwater is saline and chemically reducing; and (3) crystalline basement has low bulk permeability.[d] Groundwater age is a measure of how long the sampled water has been isolated from surface environments. Deep saline groundwater would provide a stable fluid density gradient that would oppose upward flow of groundwater. A geochemically reducing environment would reduce the solubility and mobility of some radionuclides [7]. Bulk permeability, a measure of the ease with which a fluid flows through a medium, includes both the permeability of the rock formation and the permeability of through-going fractures. Low bulk permeability would imply stagnant, slow moving fluids. Permeability also plays a role in heat transfer, with low permeability (below 10^{-16} m^2) restricting heat flow to conduction [8].

Deep Crystalline Drilling Project Hydrogeological Results

SNL is using many deep crystalline drilling projects to guide expectations for the field test [6]. Borehole characteristics from four projects are presented here (TABLE I). The boreholes used in this report are the Kola SG-3 borehole in Russia, the Gravberg-1 borehole in Sweden, the Cajon Pass borehole in California, US, and the two KTB project boreholes, KTB-VB and KTB-HB, in Germany. All of these boreholes were

TABLE I. Summary Characteristics of Deep Boreholes

Deep Borehole	Location	Geologic Environment	Total Depth	Bottom Hole Diameter	Crystalline Portion
Kola SG-3	NW Russia	Baltic shield, Pechenga rift structure	12.2 km (7.6 miles)	21.6 cm (8.5 inches)	Surface to total depth
Gravberg-1	Central Sweden	Baltic shield, Siljan Impact Crater	6.6 km (4.1 miles)	16.5 cm (6.5 inches)	Surface to total depth
Cajon Pass	Southern California	4 km (2.5 miles) from surface trace of San Andreas Fault	3.5 km (2.2 miles)	15.9 cm (6.25 inches)	500 m (1500 feet) to total depth
KTB-VB	SE Germany	Zone Erbendorf-Vohenstrauss, sequence of folded and faulted rocks	4.0 km (2.5 miles)	15.2 cm (6 inches)	Surface to total depth
KTB-HB			9.1 km (5.7 miles)	16.5 cm (6.5 inches)	

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[d] The objective is defined as “confirm bulk permeabilities of the host rock and the borehole disturbed rock zone are acceptably low (i.e., permeability at the borehole scale, rather than the core scale)” [6].

drilled through substantial sections of crystalline rock. For each of these projects, salinity, redox, groundwater age, and permeability results are discussed and summarized in Figure 2.

The deep borehole field test is seeking stable continental crust, while previous deep boreholes were drilled in active tectonic environments, or environments that were active in the past. Thus, the hydrogeological results may not be directly comparable to the US deep borehole disposal concept and DOE deep borehole field test. Nonetheless, hydrogeological results from these projects allow some comparisons to be made and point to testing method limitations and the challenges of characterizing the rock and hydrologic conditions at depth.

Kola SG-3

The Kola Superdeep Well (Kola SG-3) is located on the Kola Peninsula in northwest Russia, on the exposed crystalline basement of the Baltic Shield [9]. The Kola Peninsula portion of the shield has a complex developmental history including a synclinal stage of folding followed by a platform stage of major fractures and faulting [10]. Goals of Kola SG-3 included gaining data on the thermal regime and deep aqueous fluids, and developing deep-drilling and geophysical logging tools [11]. Drilling of Kola SG-3 began in 1970, and the superdeep well reached a final depth of 12.2 km (7.6 miles) with a bottom-hole diameter of 21.6 cm (8.5 inches) [6]. Testing methods were limited by the deep borehole environment; for example, formation testers attached to drilling equipment could not be used at the high pressures due to the possibility of serious failures [10].

The Kola SG-3 well was divided into four hydro-physical zones: (1) 0 – 800 m zone of regional groundwater flow; (2) 800 – 4,500 m upper zone of fracture waters; (3) 4,500 – 9,200 m zone of regional tectonic foliation and hydraulic disaggregation of rocks; and (4) 9,200 m and below, lower zone of fracture waters. Water in the third zone (from 4,500 – 9,200 m) is hydraulically isolated from the zones above. Water from this zone was dated at over one billion years old and attributed to extremely low permeability and isolated void space [10].

In situ bulk permeability is 1-2 orders of magnitude higher than results of core permeability testing in the laboratory [10, 12]. The bulk permeability (Figure 2) decreases with depth by several orders of magnitude, from about 10^{-12} m^2 at the surface to 10^{-17} m^2 at depth intervals 1,000 – 3,000 m and 4,500 – 5,000 m [12]. At a depth of 6,170 – 6,470 m, *in situ* permeability is 10^{-18} m^2.

The uppermost zone contained freshwater with salinity rarely exceeding 0.5 g/L. However, rocks containing sulfides showed higher mineralization with salinity values of 2 g/L and greater, associated with oxidation of the sulfide minerals. Below 800 m salinity increased. Two zones in a nearby exploratory well (250 m north of Kola SG-3) were tested and salinity was 24 g/L at 900 m and 51 g/L at depth interval 1,200 – 3,500 m [10]. Water composition from 800 – 5,000 m transforms from Na-Ca-Cl type, to a Ca-Cl type in the lower part. Water mineralization increases with depth and below

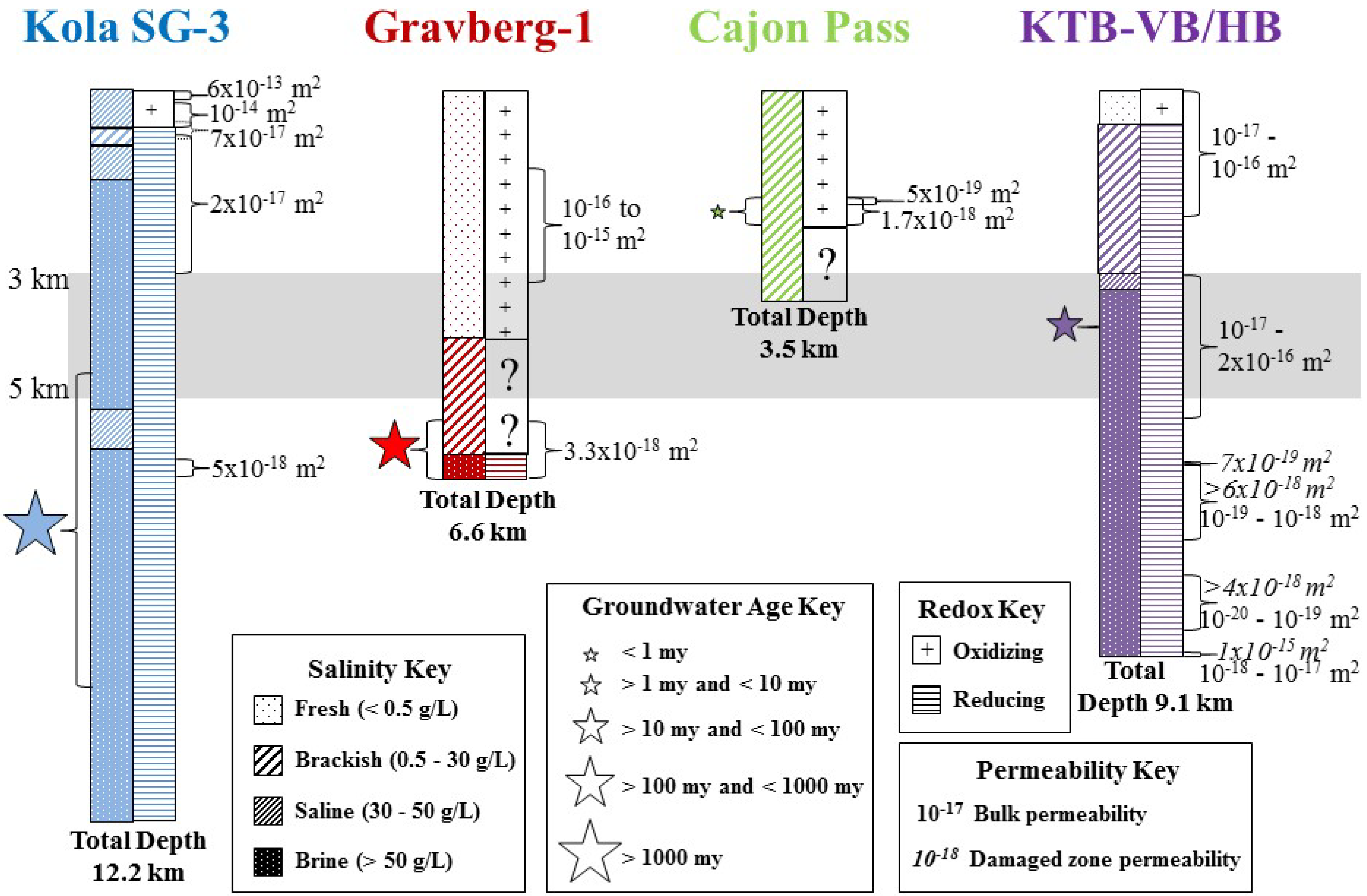

Fig. 2. Hydrogeologic results for Kola SG-3, Gravberg 1, Cajon Pass, and KTB-VB and KTB-HB boreholes, with the proposed disposal depth for the US deep borehole disposal concept shaded in grey.

7,000 m, the water becomes highly mineralized. There was a lack of complete fluid analyses below 8,000 [10, 11].

Dissolved gases were analyzed in the drilling mud and in rocks at the surface. Dissolved gas studies were difficult due to drilling fluid contamination and degassing as samples were brought to the surface. Atmospheric contamination of gas samples is another source of uncertainty. Below 800 m the gas composition varied, but predominant gas species are hydrogen, methane, helium, and carbon dioxide [10]. Reducing conditions at depth are indicated by the reduced mineral assemblages, including sulfides and graphite, and the predominance of hydrogen in the gas phase.

Gravberg-1

The Vattenfall Deep Gas Project was established to evaluate the hypothesis that commercial quantities of methane gas from the mantle of the Earth could have accumulated in the crystalline rocks in Sweden. The 360 million year-old Siljan Ring meteorite impact structure in central Sweden was selected as a site based on the potential for gas reservoirs and a mantle conduit [13]. The Gravberg-1 deep borehole site is just outside the meteorite crater [14]. Drilling of Gravberg-1 began in 1986 and reached a depth of approximately 6.6 km (4.1 miles) with a 16.5 cm (6.5 inches) bottom-hole diameter [6]. Due to drilling problems, the borehole consists of an original hole and three sidetracks of increasing depths. Contamination by the drilling fluid and the artificial creation of gases during drilling were concerns for interpreting permeability and gas data [13].

Leak off tests and drill stem tests (DSTs) were used to determine *in situ* permeability [13]. Permeability of core samples was measured in the laboratory. Average permeability values in the first leak off test interval 1,250 – 3,165 m, are 10^{-16} m^2 – 10^{-15} m^2, similar to the values obtained from core testing. Testing from the second leak off test interval 4,167 – 5,020 m suggests an increasing trend in permeability. However, due to the addition of bentonite clay in the drilling fluid, permeability data are qualitative only. Of the five DSTs, three were successful. DST-2 and DST-4 were unsuccessful because of inadequate packer seals due the misshaped borehole from wellbore breakouts. The permeability results from DST-1 interval 1,304 – 1,335 m, and from DST-3 interval 1,949 – 2,011 m, are on the same order as the leak off test results. Permeability in DST-5, from 5,453 – 6,957 m, was markedly lower on the order of 10^{-18} m^2. However, this low permeability value was questioned by scientists and could have been caused by solid additives in the drilling fluid, lost drill string, or deformation of the rock during water injections of hydrofracture testing [13].

Relatively uncontaminated pore fluid was recovered during DST-5 and during pumping operations from the open, uncased[e] portion of sidetrack 1 (below 5,453 m) [13]. Excess helium-4 dating[f] of the brine indicates a minimum time of 210 million years for the concentrations of helium to accumulate. Several assumptions go into the age calculation, including the percent of helium that enters the pore fluid [15].

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[e] Boreholes are cased with a liner to provide stability.

[f] Excess helium-4 is a dating method for estimating the time required for measured amounts of helium-4 to accumulate in a sample.

Concentrations of gas samples were generally too low for isotopic analysis and methods had to be derived to collect large enough volumes [13].

Chemical analyses of DST-3 fluid (from about 2,000 m depth) indicates sodium bicarbonate fresh water with total dissolved solids less than 0.5 g/L [13]. Hydrogen and oxygen isotopic analyses place this fluid on the modern meteoric water line. This freshwater lens is estimated to extend to depths of 4,000 m. Based on borehole logs, below the freshwater lens is a transition zone with salinities estimated at 2 – 4 g/L. The borehole log results indicate chloride concentrations of 0.16 g/L around 1,300 m, 0.58 g/L around 2,000 m, and 93 g/L at depth and are consistent with major ion composition of the fluid from DSTs and pumping. For example, highly saline calcium chloride fluids (about 150 g/L) were encountered in DST-5 and wireline logs indicate the fluid is from below 6,000 m. There was also a portion of freshwater flow during pumping from depth, suspected to originate from a hole in the borehole casing [13].

There are limited data on the redox condition below the freshwater lens. Wireline logging marked a zone of high thorium concentration around 4,650 m depth, in which thorium was moved by migrating fluids. Juhlin et al. [13] inferred that this movement required high temperature, reducing fluids. The oxygen gas concentrations in DST-5 are attributed to minor atmospheric contamination [13], therefore the corrected very low oxygen gas concentrations suggest reducing conditions at depth.

Cajon Pass

The purpose of the Cajon Pass Scientific Drilling Project was to study the San Andreas Fault stress/heat flow paradox; heat flow observations predict a lower shear stress than the calculated shear stress using *in situ* and laboratory measurements. The Cajon Pass drilling site is located approximately 4.0 km (2.5 miles) from the trace of the fault. Drilling started in 1986, and phase-1 was completed in 1987 to a depth of 2.1 km (1.3 miles) [16]. During phase-2, the borehole reached a depth of 3.5 km (2.2 miles) with a bottom-hole diameter of 15.9 cm (6.3 inches) in 1988 [6].The crystalline bedrock portion of the Cajon Pass borehole extends from 500 m to total depth [14].

In situ permeability measurements were made during phase-1 of the Cajon Pass well. Clean water was used to clear drill cuttings from the hole and fluorescein was used to tag the clean water. Bulk permeability was measured at 0.5×10^{-18} m^2 over the interval 1,829 – 1,905 m and 1.67×10^{-18} m^2 over the interval 1,829 – 2,115 m. These values are 1 to 3 orders of magnitude greater than those of the core samples measured in the laboratory [17, 18]. The greater permeability is caused by fluid conducting fractures found in these intervals. An examination of log data confirms fluid flow, with the majority of flow coming from a fracture around 2,076 m depth [8].

Groundwater samples were taken in the same two intervals as the *in situ* permeability measurements. Samples were taken using downhole samplers and from pipe stands in drill stem testing [19]. Of the roughly 50 groundwater samples taken, results from the eight least mixed and contaminated samples (these samples still contained 2-8% drilling fluid) were published [20]. Water sampled in the first interval represents water from two different fracture systems. One of the fracture systems contains fluid with a total dissolved solids concentration of 2.15 g/L, with relatively high concentrations of Cl, Ca, and Fe, and low concentrations of HCO_3 and SO_4. Water from the second fracture system has a total dissolved solids concentration of 0.95 g/L and relatively high concentrations of Na, HCO_3, and SO_4. Groundwater in the second interval is more consistent with the composition of other groundwater in the area, which contains 1.15 g/L total dissolved solids, dominated by Na and SO_4, and lower concentrations of Ca, Cl, and HCO_3. These differences in composition are indicative of separate evolutionary paths that occur in relatively close yet isolated fracture systems [20].

Analyses of oxygen isotopes confirm contributions from two fracture systems in the first sampled interval, and a single fracture system in the second interval [19]. These data also indicate a meteoric origin of the water and little water-rock interaction [19]. Excess helium-4 groundwater age approximations, using different estimates for the percent of produced helium-4 that enters the fluid phase, indicated an age range from 0.033 – 5 million years, with the best estimate being 0.3 million years [15].

KTB-VB & KTB-HB Boreholes

The German Continental Deep Drilling Program (KTB) was designed to investigate the deep continental crust [21]. The research goals included geophysical characterization, identification of stress fields and thermal structures, determination of crustal fluid composition and transport processes, and interpretation of the structure and evolution of the geological basement. The boreholes are on the western part of the Bohemian Massif in Bavaria, on an outcrop of Zone Erbendorf-Vohenstrauss, a unit of the Variscan orogeny [22].

The KTB concept consisted of two stages: a pilot borehole (KTB-VB drilled from 1987 to 1989) and then the superdeep borehole (KTB-HB drilled from 1990 to 1994). The depths and diameters of both boreholes are listed in TABLE I. As little was known about the conditions at depth, the pilot borehole was used to gather geoscientific data to get maximal value out of the superdeep borehole. The one-year experimentation program in the completed pilot borehole influenced the drilling and testing program for the superdeep borehole [21]. KTB-HB was about 200 m from the pilot borehole [23]. After KTB-HB was drilled, the two boreholes were used as deep crustal laboratories in a five-year testing program [21].

The KTB project measured core permeability in the laboratory and by *in situ* testing, including build-up tests, injection tests, and long term pumping, to determine geohydraulic properties. The geometric mean of laboratory core permeability measurements is 7.4×10^{-20} m^2, with more than one order of magnitude standard deviation [24]. These core samples were taken from KTB-VB to a depth of 4,000 m and from KTB-HB to a depth of 7,400 m. In general, the bulk permeability decreases from 10^{-16} to 10^{-20} m^2 with increasing depth; however, high permeability zones were found in KTB-VB at 3,450 m and below 3,850 m. In addition, the highest *in situ* permeability in KTB-HB was measured between 9,030 – 9,101 m with values of 5×10^{-18} m^2 to 1.3×10^{-17} m^2 [24].

Additional hydraulic testing below 6,000 m in KTB-HB determined the thickness and permeability of skin zones (*i.e.*, damaged rock zones) surrounding the borehole [24].[g] Skin zones are formed during the drilling process and can either raise the permeability due to fracture formation, or lower the permeability due entry of drilling fluid additives. Shut-in hydraulic testing was affected by non-equilibrated borehole temperatures [24]. Tests between 6,000 m and 8,700 m depth only provided a lower bound of permeability due to the injection of drilling mud obstructing flow. First skin zone thickness varied from 0.7 m to 2.7 m thick with permeability estimates on the order of 10^{-18} m^2. Second skin zone thickness extended beyond the first skin zone with permeability estimates on the order of 10^{-19} m^2. The skin zone permeability calculated for the 9,030 – 9,101 m buildup-test was relatively high with the first skin zone on the order of 10^{-15} m^2 and the second skin zone on the order of 10^{-17} m^2 [24].

Water chemistry and isotopic results from KTB-VB were affected by the drilling fluid additives [25]. Inflows were detected by monitoring changes in the drilling mud, mainly temperature and salinity. In KTB-VB, groundwater of meteoric origin extended to a depth of at least 650 m. Saline inflows were detected beginning below 2,000 m, with high-salinity fluids from inflows detected below 3,400 m. Two pumping tests were run at the bottom of KTB-VB from 3,850 – 4,000 m, in the only fracture system in the pilot hole that was not a closed, isolated system. The fluid obtained from the pumping test is referred to as the 4,000 m fluid. A fluid composition with 61.2 g/L total dissolved solids was measured from the first pumping test, though the fluid was contaminated with mud additives, including organic polymers. The second pumping test was run for several months to decrease contamination, but the fluid still contained organic additives. The composition of the fluid had a higher salinity of 68.3 g/L total dissolved solids. This 4,000 m fluid is of the Ca-Na-K-Cl type, similar in composition to measurements of fluid inclusion composition [25].

The 4,000 m fluid was dated using excess noble gas concentrations [25]. Excess helium-4 dating estimated a groundwater age of 15 – 80 million years old and an argon-40 accumulation time was estimated as 30 – 300 million years. Excess neon-21 dating generally agreed with these results. The wide range of potential ages is due to calculations that cover a range of potential uncertainties [25].

In KTB-HB, several drawdown tests were performed at 3,003 m, 5,523 m, 6,018 m, and 9,101 m [23]. Fluid inflow zones determined from the drawdown tests and changes in drilling fluid composition are at 1,325 m, below 3,160 m, 3,550 – 4,120 m, and between 4,850 m to 5,300 m. Fluids from inflows below 3,160 m are Ca-Na-Cl type, similar to the 4,000 m fluid from KTB-VB, but with a lower salinity of 41 g/L total dissolved solids. Chloride contents of *in situ* fluid samples are approximately 32 g/L at 3,600 m, 60 g/L at 4,900 m, and 62 g/L at 5,300 m. No fluid composition analysis was done below 6,000 m due to the high content of drilling mud in samples. The drilling mud originated from the backside of the casing, and was sucked in through the leaking cementation because of the high draw down pressure in tests [22]. Hydraulic communication was observed between KTB-VB and KTB-HB boreholes. Pressure variations in KTB-HB interval 3,000 – 6,000 m and an injection test at 9,101 m

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[g] SNL [4] describes the same damaged rock zones as disturbed rock zones.

resulted in significant fluid level change in KTB-VB from the open section at 3,850 – 4,000 m [24]. In addition, simultaneous monitoring of KTB-HB during a four month long pumping test in KTB-VB confirms communication through fracture networks [21]. Measurements of redox potential indicate a gradual change from oxidizing conditions to reducing conditions below 500 m depth [23].

Comparison of Hydrogeologic Results to U.S. Deep Borehole Field Test Science Objectives

Three science objectives for the field test [6] are compared here to results from the four deep drilling projects to examine whether the conditions anticipated by the science objectives for the DOE deep borehole field test characterization borehole have been found elsewhere at depth. Both the hydrogeologic results and the proposed disposal zone at 3-5 km (1.9 -3.1 miles) in the US deep borehole disposal concept are depicted in Figure 2.

Old and Isolated Groundwater

SNL [6] states that old groundwater would be “as much as millions of years old” and isolated “for a long time.” Groundwater dated from Kola SG-3 was collected from a zone that was hydraulically isolated from the zones above it and was more than a billion years old. Formation fluid pumped from below 6000 m depth in Gravberg-1 was estimated as 210 million years old. This water was highly mineralized compared to samples taken in shallower portions of the borehole, and was only obtained after hydrofracturing. Groundwater from the Cajon Pass borehole is less than a million years old, with a best estimates age of 0.3 million years. However, the fluid dated was taken from the shallowest interval around 2,000 m. Fracture systems within the Cajon Pass borehole were isolated, with fluids showing separate evolutionary paths. Three different dating techniques yielded ages between 15 and 3,000 million years for the 4000 m fluid from KTB-VB. However, there was hydraulic communication between KTB-VB (from 3,850 – 4,000 m) and KTB-HB (from 3,000 – 6,000 m and at 9,101 m).

The objective of confirming groundwater at depth can be millions of years old or more is supported by the hydrogeological results in this report. Groundwater at depth can be isolated from the surface, but the depth of isolation is not uniform. Communication upwards and fluid flow through the crystalline basement at measurable rates is possible as seen in the KTB results. There are differences between the geologically active sites of the four drilling projects (Table I) and the stable continental crust sought for the field test site exist, which may contribute to greater isolation at the field test site. For example, the stable crust is unlikely to have crustal scale linear features, such as regional faults, that could allow connectivity with surface groundwater.

Saline and Reducing Groundwater

Increasing salinity with depth would provide a stable density stratification of the groundwater column that could limit upward movement of groundwater. SNL [6] gave no specific value of salinity that it considers acceptable. Freshwater extended down to 800 m in Kola SG-3, followed by a zone of increasing salinity with highly saline waters at depth. This pattern is similar to the results of the KTB boreholes; a zone of surface groundwater extended to a depth of about 650 m, followed by an intermediate zone of brackish water, underlain by saline fluids and brines. In contrast, the results of Gravberg-1 and Cajon Pass show low salinity waters extending to a greater depth. The Gravberg-1 freshwater lens extends to a depth of 4,000 m, followed by a transition zone of slightly brackish water. Highly saline waters were found at depth, pumped from below 6,000 m. Cajon Pass waters tested from 2,000 m have low salinity (about 2 g/L or less), and there was no trend in salinity.

SNL [6] also has demonstration of chemically reducing deep groundwater as part of its objectives. The hydrogeological results from the Kola SG-3 borehole show an oxidizing environment in the shallow groundwater, and a reducing environment at depth. The KTB results are similar with oxidizing conditions shifting to reducing conditions below a depth of 500 m. Limited Gravberg-1 results suggest reducing conditions in the water below 4,650 m, but Cajon Pass water samples from 2000 m are oxidizing. Compared to the other factors examined in this report, the data on oxidation state are limited. Results from Gravberg-1 and Cajon Pass indicate that low salinity and oxidizing fluids can be found at the proposed disposal depths. Those deep, low salinity fluids could reflect the active (San Andreas Fault), or previously geologically active (meteorite impact) processes that are unlikely to be found in stable continental crust. In all cases where density (salinity) stratification was observed, the stratification was stable with less saline and oxidizing fluids underlain by more saline and reducing fluids. Thus the objective of finding saline and reducing fluids at depth in the field test is supported by previous deep drilling projects, but variation does exist in salinity and oxidation state across the sites, as seen in Figure 2.

Low Crystalline Basement Bulk Permeability

The SNL report [6] did not define a value for acceptable low bulk permeability at depth. However, SNL thermal-hydrologic modeling of the deep borehole disposal concept used permeability values on the order of 10^{-16} m^2 to 10^{-18} m^2 for the crystalline rock at depth from 2,500 – 7,000 m, 10^{-17} m^2 for the waste disposal interval from 3,000 – 5,000 m depth [26]. SNL sensitivity analyses used a base case permeability of 10^{-19} m^2 for the surrounding rock and 10^{-16} m^2 for the skin zone, also called the damaged rock zone [27]. The sensitivity study used rock permeability varying from 10^{-19} m^2 to 10^{-16} m^2 and skin zone permeability ranging from 10^{-19} m^2 to 10^{-12} m^2 [27].

Kola SG-3 shows decreasing permeability values from laboratory core measurements, with depths of 3,000 – 5,000 m having an average permeability on the order of 10^{-17} m^2. There were no *in situ* measurements of permeability within the depth range of the proposed disposal zone; however, at other depths in the borehole *in situ* permeability is one to two orders of magnitude higher than core permeability values. *In situ* hydraulic testing from Gravberg-1 gives permeability of 10^{-16} – 10^{-15} m^2 right above the depths of a disposal zone, and shows increasing permeability from about 4,000 – 5,000 m (only qualitative data are available). Cajon Pass core permeability decreases from 10^{-16} m^2 at the surface to 10^{-22} m^2 at depths equivalent to the top of a disposal zone. *In situ* permeability at 2,000 m is on the order of 10^{-18} m^2 and core permeability at this depth is 100 times lower. The KTB boreholes have core, corrected with respect to *in situ* pressure [24], and *in situ* permeability for disposal zone depths in the range of $10^{-17} – 10^{-16}$ m^2. Calculated skin zone permeability values in KTB-HB are from depths greater than those of a disposal zone that vary from about 10^{-18} m^2 to 10^{-15} m^2.

An important factor for low bulk permeability in the deep borehole field test is the presence or lack of hydraulically conductive fractures. Measured core permeability in all of the deep drilling projects falls within the range of bulk permeability values used in previous sensitivity analyses and modeling of the U.S. deep borehole disposal concept, and generally decreases with depth in the deep drilling results. However, the bulk permeability values at the disposal depth, which could include fracture zones, varied in the boreholes, in some cases falling within modeled values, and in other cases slightly higher than the 10^{-17} m^2 used by Arnold and Hadgu [26] and several orders of magnitude higher than Hadgu et al.'s [27] base case for deep borehole thermal-hydrologic models used for the U.S. deep borehole disposal concept.

Potential Characterization Challenges in the US Deep Borehole Field Test

The deep drilling projects faced challenges in characterizing the hydrogeological environment at depth. These challenges include parameter challenges, testing challenges, and data collection challenges. Parameter challenges are inherent to the parameters being measured, *i.e.* these challenges exist regardless of the environment being characterized. Testing challenges are related to the testing procedures and data collection challenges are related to collecting samples. Technical advances in the years since completion of these projects may reduce some of these potential challenges for the deep borehole field test.

Parameter challenges include the variability of parameters, selecting representative volumes, and uncertainty. For the first parameter challenge, groundwater flow varies both spatially and temporally. Spatially, the values for permeability were not constant throughout the boreholes. Morrow and Byerlee's [18] examination of fracture zones at Cajon Pass concluded that three processes are active including recrystallization, crack healing, and crack sealing, processes that can close fractures, changing permeability with time. The composition of fracture fluids and formation fluids can differ, evidenced by high salinity inflows. At Cajon Pass, two fractures within relative close proximity had separate evolutionary histories [20]. For the second parameter challenge, selecting a test volume that is representative of the formation of interest is important in measuring bulk permeability. Core permeability results were a few orders of magnitude lower than *in situ* results due to the presence of fractures [8, 10, 12, 17, 18]. Locating hydraulically conductive fractures that should be subject to permeability measurements is difficult. In the deep drilling projects, changes in the drilling fluid composition were a sign of inflow; however, the depth of inflow was not always clear [13]. The third parameter challenge is uncertainty in the variables. Assumptions need to be made about the environment at depth in order to perform calculations, such as the density of water at depth. This particular challenge is one of the reasons the age estimates are imprecise [13, 15, 25]. When using excess helium-4 dating, one of the variables needed is the percentage of helium-4 produced that enters the fluid. Values used in individual boreholes and across the drilling projects varied [13, 15, 25].

Testing challenges include equipment failure and limitations, replicating at-depth conditions in the laboratory, and designing a test program. Equipment failure occurred during hydrogeological testing and sampling [10, 11, 13, 23]. Five DSTs were performed in Gravberg-1, but only three of the tests were successful. Packers were unable to seal properly in the boreholes, which had been misshaped due to breakouts, leading to packer leakage [13]. Fluid analyses in KTB-HB below a certain depth were unsuccessful due to technical problems [23]. The next testing challenge is replicating at-depth conditions in the laboratory. While *in situ* testing is performed at ambient conditions (though drilling may have altered the conditions), laboratory testing conditions must be chosen, introducing uncertainty. In all of the deep drilling projects, core samples were brought up and tested in laboratories [10, 13, 17, 18, 24, 28]. In some instances, the laboratory tests were performed at surface temperatures and pressures, then corrected to at-depth conditions (KTB) [24]. In other cases, laboratory testing was performed at surface temperatures, with pressure corresponding to estimates for at-depth conditions (Cajon Pass) [17, 18]. The last testing challenge is designing a test program. The order in which testing is performed is relevant to the results. For example, in Gravberg-1, the permeability results are uncertain due to the opening and closing of fractures from previous operations (drilling and hydrofracture testing) [13]. Another consideration is the time allotted for each test. Fluid flow is relatively slow in the low permeability formations encountered in the deep drilling projects. *In situ* testing requires more time to equilibrate compared to testing in higher permeability environments [8].

Collecting data is the final category of challenges presented in this report. The two data collection challenges include achieving representative samples and maintaining sample integrity. There were many sources of contamination introduced by the drilling process and drilling fluids [10, 13, 20, 23, 24, 25]. In some cases the composition of the drilling fluid was similar to formation fluids, so the contamination had less effect on the results [20]. Drilling additives included clays and organic compounds [19, 25]. At Cajon Pass, fluorescein was added to clean water and used to flush drill cutting and fluids out of the borehole before sampling. Yet, geochemical results from only a handful of the 50 some samples collected were presented due to contamination [20]. Fluid contamination is not present in fluid inclusion sampling and analysis; however, fluid inclusions are limited by their volume [19, 29]. In addition, artificial and secondary gases, which are not present in the undisturbed environment, can form during the drilling process due to exposure to drilling fluids and pressure release [10, 13]. These gases are a second form of contamination. The second, but related, data collection challenge is maintaining sample integrity. As core samples were brought from at depth conditions to surface conditions, the release of pressure led to stress relief cracking [8, 28]. The lower pressure and temperature at the surface can also lead to phase changes in materials recovered from depth. For example, volatiles can escape from fluid samples as they are brought to the surface [10].

CONCLUSIONS

Hydrogeological results from the Kola SG-3, Gravberg-1, Cajon Pass, and KTB-VB and KTB-HB boreholes are applied to the US deep borehole disposal concept to assess whether selected science objectives for the DOE deep borehole field test might be met.

The stable continental crust sought for the field test site and groundwater dating results from more geologically active sites indicate that the test's science objective of confirming that groundwater at depth is millions of years old or more and isolated from the surface is feasible. However, hydraulic data collected during a long-term pumping test in KTB-VB and KTB-HB boreholes indicates that hydrologic connection can occur at potential disposal depths, laterally over 100s of meters and vertically over a kilometer scale. At sites that are near an active fault or subjected to meteorite impact freshwater was found to extend into depths corresponding that those of the proposed disposal zone. However, all boreholes where sufficient salinity information was measured had a stable fluid density gradient. The deep borehole test's science objective of confirming deep groundwater is saline and chemically reducing seems likely to be successful given the salinity data and inferred redox state (redox potential was only directly measured in the KTB boreholes) of deep groundwater and the stable continental setting sought by the US test program. Whether the field test objective of documenting low crystalline basement bulk permeability is met depends on the value of permeability that is deemed acceptably low. That value is currently undefined. However, measured bulk permeability at projected disposal depths is comparable to or higher than values SNL used in thermal-hydrologic and seal permeability sensitivity studies. Despite the many characterization challenges that past drilling projects faced, and that the DOE field test will likely face, sufficient characterization data can be collected to assess whether the science objectives that old, saline and reducing groundwater in low bulk permeability crystalline basement rocks will be discovered at the DOE field test site.

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