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Feature Detection, Characterization and Confirmation Methodology: Final Report

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Feature Detection, Characterization and Confirmation Methodology

Final Report

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Earth Sciences Division

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NUMO-LBNL Collaborative Research Project Report

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Executive Summary

This is the final report of the NUMO-LBNL collaborative project: Feature Detection, Characterization and Confirmation Methodology under NUMO-DOE/LBNL collaboration agreement, the task description of which can be found in the Appendix.

We examine site characterization projects from several sites in the world. The list includes Yucca Mountain in the USA, Tono and Horonobe in Japan, AECL in Canada, sites in Sweden, and Olkiluoto in Finland. We identify important geologic features and parameters common to most (or all) sites to provide useful information for future repository siting activity. At first glance, one could question whether there was any commonality among the sites, which are in different rock types at different locations. For example, the planned Yucca Mountain site is a dry repository in unsaturated tuff, whereas the Swedish sites are situated in saturated granite. However, the study concludes that indeed there are a number of important common features and parameters among all the sites—namely, (1) fault properties, (2) fracture-matrix interaction (3) groundwater flux, (4) boundary conditions, and (5) the permeability and porosity of the materials.

We list the lessons learned from the Yucca Mountain Project and other site characterization programs. Most programs have by and large been quite successful. Nonetheless, there are definitely “should-haves” and “could-haves,” or lessons to be learned, in all these programs. Although each site characterization program has some unique aspects, we believe that these crosscutting lessons can be very useful for future site investigations to be conducted in Japan. One of the most common lessons learned is that a repository program should allow for flexibility, in both schedule and approach.

We examine field investigation technologies used to collect site characterization data in the field. An extensive list of existing field technologies is presented, with some discussion on usage and limitations. Many of the technologies on the list were in fact used during the characterization of Yucca Mountain and elsewhere by LBNL personnel. The study also includes emerging technologies and identifies the need to develop better estimation of important parameters for repository siting. Notable emerging technologies include 3-D seismic and satellite-based remote sensing and wireless micro electro mechanical systems (MEMS) sensors. They enable cost-effective and ubiquitous monitoring to be applied for site characterization.

We list and classify the types of uncertainties involved in site characterization. Uncertainties can exist in all aspects of site characterization: data, interpretation, conceptualization, and modeling. We use the Swedish program to exemplify such uncertainties. We also devote a chapter on geochemical issues regarding the interaction between groundwater and natural and engineered barrier materials. A recommendation has been made to take advantage of the recent advancement in geochemical modeling capabilities in natural systems. Although it is not of immediate relevance at the preliminary investigation stage, it serves as a good reminder that geochemical investigation efforts should not be overlooked at any stage in the repository program.

We construct a synthetic preliminary-investigation site based on an extensive data set available from a geoscientific project in Japan, which we use as a "real" site to evaluate uncertainties resulting from hydrogeological modeling and examine strategies for characterizing a new site. We plan various preliminary-investigation configurations and conduct preliminary numerical investigations at the synthetic site. We construct a model of the "real" site for each PI configuration, make predictions of particle travel times, and compare against the "real" data obtained from the "real" model. We conclude that drilling as many as nine boreholes does not necessarily improve the understanding of the site compared to drilling as few as three boreholes, unless there is an underlying structure that is larger than the spacing of the boreholes. The parameters that affect the outcome of the predictions most are: (1) effective porosity, (2) boundary conditions, and (3) fault properties, all of which are very difficult to estimate in the field and are full of uncertainties. Of the three, we recommend NUMO expend efforts to assess the latter two at preliminary investigation sites. To obtain large-scale averaged permeabilities, we recommend conducting long-time and long-interval pumping tests in boreholes. We also find that the temperature data can reduce some uncertainties regarding the boundary conditions.

Finally, we summarize recommendations that NUMO might consider during preliminary site investigations. The recommendations are written in Japanese to ensure quick and easy consumption by the NUMO personnel. Instead of presenting a listing of characterization activities, we make recommendations on some important and costly (expensive and time-consuming) activities. We lay out the relevant approaches and the mindset that NUMO can consider employing to prioritize and optimize the characterization activities at preliminary investigation sites. For example, we recommend conducting 3D seismic profiling, even if it may necessitate drilling fewer boreholes. For the same amount of drilling expenditure, we favor drilling more partially cored boreholes and fewer fully cored boreholes. We recommend against conducting tracer tests and GPR (ground penetrating radar) surveys. Although these recommendations may contradict those of others, we believe these measures yield a higher return on investment.

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1 Introduct ion

The Nuclear Waste Management Organization of Japan (NUMO) and the Department of Energy of the United States of America (DOE) established a cooperative agreement in the field of radioactive waste management on July 10, 2002. In May 2005, NUMO and the Regents of the University of California as the DOE Management and Operating Contractor for the Ernest Orlando Lawrence Berkeley National Laboratory (LBNL) entered into an agreement to collaborate and for LBNL to conduct work on the “Feature Detection, Characterization and Confirmation Methodology” project. This project is designed to further develop radioactive waste management technologies related to an investigation strategy and technology for detection, characterization, and confirmation of key geologic features at possible nuclear waste repository sites. It is envisaged that the technology developed as part of this project will help enhance existing confidence in overall repository science.

The “Feature Detection, Characterization and Confirmation Methodology” project is designed to combine the best technology available in the United States for detection, characterization, and confirmation of key geologic features with parameter sets available in the Japanese High Level Nuclear Waste (HLW) program—and extend these techniques and levels of understanding for improved repository science. While DOE’s Yucca Mountain Program is at the license application and performance confirmation stage, while NUMO’s program is at the site selection stage, both programs can benefit from refined strategies and improved technologies for characterization/confirmation. Results from the Project shall be used in both the United States and Japan, and will help build confidence and reduce uncertainties in the respective programs, allowing the techniques to be refined and extended for various locations. It is expected that the results of this Project will provide a technical basis for performance confirmation at Yucca Mountain and provide techniques for characterization, siting, engineering design, and long-term safety for NUMO.

There are three major tasks in the overall project, whose overview and the implementation plan for Tasks A, B, and C can be found in the Appendix 1. This is the final report, the compilation of the activities conducted at LBNL, lasting from December 2005 through March 2007.

In addition to this introduction, the report is comprised of seven main chapters: In Chapter 2, we examine the repository programs from the USA, Canada, Japan, Sweden, and Finland to study and identify key parameters at these sites. Tabulated lists of key parameters at each respective site are given at the end of the chapter, as well as the common parameters among the programs. Chapter 3 summarizes the lessons learned from these repository programs. It is intentionally written in Japanese to help NUMO personnel understand the contents readily and clearly. Chapter 4 lists and discusses existing and emerging field investigation technologies. It is not meant to be a complete list of available technologies. However, it covers the most commonly used ones, as well as those that are promising for future use. Chapter 5 discusses the uncertainties involved in site characterization, drawing lessons mainly from the Swedish program. Chapter 6 deals with geochemical issues that are more directly relevant at later stages in the repository program—but we feel that it is a good idea to include a "heads-up" article, because groundwater chemistry is an important factor in repository safety and should be integrated into the design. In Chapter 7, we use an extensive data set from a domestic study site and construct a "real" rock mass, in which we conduct numerical site characterizations using various drilling scenarios. Based on the data obtained from the boreholes, we construct site models and make predictions for particle travel times and compare them to the 'real' data—and also develop some insights regarding the numbers and locations of boreholes to be drilled at preliminary investigation sites. Chapter 8 summarizes the report by laying out the recommendations for how to approach and optimize preliminary investigation efforts.

2 Identification of Key Parameters for Site Characterization

In this section, we evaluate and list the geologic features and parameters being evaluated by various international investigations at a number of different sites (including the U.S. and Japan). The ultimate goal of this study is to identify the key parameters that need to be evaluated at various stages of repository siting that are common to the majority of the sites. The emphasis of the present study is on those parameters that are especially important at the site selection stage.

Site characterization is one of the key activities for establishing the geological conditions and parameters of a candidate site for safe nuclear waste disposal. During site characterization, intensive surface-based investigations are performed to improve scientific understanding of the geological, hydrological, geochemical, geophysical, and mechanical processes of a deep geological site.

2.1 U.S.A. (Yucca Mountain)

Yucca Mountain, Nevada, within the Nevada Test Site (NTS), is a potential site for a nuclear waste repository in the United States. The Yucca Mountain site was selected not only because of its geological characteristics, but also because investigators have found a number of attributes there that would be conducive to geologic disposal, including multiple natural barriers, remoteness, and an arid climate (McKelvey, 1976). Instead of isolating waste in salt or deep sites below the water table, as in many other nuclear waste programs (e.g., Finland, Sweden, Switzerland and Japan), at Yucca Mountain the waste could be disposed of at relatively shallow depths, well above the water table.

One of the main characteristics of Yucca Mountain that differs from other nuclear waste sites is the lithology—volcanic tuffaceous rock—and the location of the potential repository—in the unsaturated zone (UZ). The repository would be located ~300 m below the surface and ~300 m above the water table, primarily in a layer of welded tuff. The deep water table and thick UZ of Yucca Mountain is the result of the low surface-water infiltration rate, resulting from a low annual rainfall and high rate of evaporation and transpiration. Therefore, the conceptual model for Yucca Mountain is considered to have favorable hydrogeological characteristics such as (1) a desert setting with arid climate and; (2) a deep water table with a thick UZ (CRWMS M&O, 2002).

Although the potential disposal site for nuclear waste at Yucca Mountain is planned to be located in the UZ, the saturated zone (SZ) is equally important for site characterization, because hydrological processes below the repository may provide transport of radioactive materials to the accessible environment. Thus, in our review, we include key parameters and features for both the UZ and SZ at Yucca Mountain.

The Yucca Mountain Project is a unique program because of the size of the project, the involvement of numerous organizations, and the interaction of scientists from different fields and backgrounds. The Yucca Mountain site characterization program has progressed in response to advancements in scientific understanding and proposed changes in regulatory requirements. Data from site characterization have been used to develop conceptual and numerical models of the hydrologic, geochemical, thermal and mechanical processes that will determine how a repository at Yucca Mountain may behave over the next 10,000 years after repository closure (CRWMS M&O, 2002 Section 1.4.), which may be extended even longer.

At Yucca Mountain, the site characterization includes extensive surface and subsurface (i.e., potential emplacement tunnel) characterizations, laboratory studies, and modeling activities designed to provide technical information by which to determine long-term repository performance. In this study, evaluation is focused on surface and borehole data. Consequently, in this task, we have not focused on identifying parameters from borehole studies conducted at underground alcoves, drifts, or niches such as heater tests, seepage tests and studies conducted for engineered barrier purposes.

Yucca Mountain site characterization activities might be grouped into four distinct periods (Wang and Bodvarsson, 2003): (1) the early 1980s, (2) from 1986 to 1991, (3) the early 1990s and (4) the current period (middle 1990 to present). The main accomplishments from these periods are:

1. Surface and subsurface characterization, extensive drilling
2. Surface monitoring and extensive laboratory measurement and initial modeling
3. Excavation of the ESF and Cross Drift
4. Integration of UZ models and performance

According to the Yucca Mountain Science and Engineering Report (CRWMS M&O, 2002), the location of the underground facility was determined using several factors, including the thickness of overlying rock and soil, the characteristics of the rock, the location of faults, and the depth to groundwater. More than 200 boreholes were used to characterize the tuffaceous layers and structures at mountain-and site-specific scales.

At Yucca Mountain, specific studies for site characterization include:

- Climate and infiltration
- Geology and structure
- Geophysical investigation
- Hydrologic and hydrogeologic properties
- Geochemistry and isotope data
- Mechanical, physical and thermal properties

The main processes and related parameters and features identified in the Yucca Mountain Program are described below and summarized in Sections 2.1.1.7 and 2.1.2.5. A rather comprehensive list of parameters is shown in Appendix 2.A.

2.1.1 UNSATURATED ZONE PARAMETERS

Site data characterizing the ambient unsaturated system at Yucca Mountain have been collected since the early 1980s (BSC, 2004b, Section 2.1). There are several types of data (e.g., lithological, structural, rock hydrological properties, mineralogical, temperature, geochemical, and climate/infiltration) collected from surface-based activities (e.g., geologic mapping, installation of vertical boreholes).

During near-surface monitoring, intensive laboratory measurements of flow and transport parameters were conducted. Deep-borehole test sampling was conducted in the boreholes designated specifically for geological (G), hydrological (H), water table (WT) and the unsaturated zone (UZ) investigations. These boreholes were used to define the stratigraphy, locate the water table, collect cores, and test *in situ* borehole monitoring techniques (Wang and Bodvarsson, 2003).

Because of the complex interaction between geological, structural, hydrological, geochemical, and mechanical processes, some parameters are important for more than one process. Therefore, repetition of parameters may occur through this report, depending on how the processes are related.

2.1.1.1 CLIMATE AND INFILTRATION

Climate and infiltration are two processes that affect the UZ. Climate controls precipitation and temperature conditions at land surface, and climate patterns are responsible for surface conditions such as runoff, runon, and evapotranspiration. They also influence the redistribution of moisture in the shallow subsurface, infiltration ratio, percolation, and groundwater recharge (BSC, 2004a).

Various studies have been conducted to understand variations in past climatic patterns, such as of geological records (topography, stratigraphy, rock fracture characteristics, and fossils/microfossils), surface hydrology, type of soils, sea level change, isotopic data, variations of the earth's orbital clock and eccentricity—as well to predict future patterns. However, the chief concerns regarding climate change are processes impacted by humans, such as greenhouse-house effects, acid rain, global warming, and ozone layer depletion. Such processes produce great uncertainty with respect to predicting future climate (CRWMS M&O, 2002, Section 6.1)

Infiltration studies were conducted at Yucca Mountain between 1984 and 1995, using nearly 100 shallow boreholes across washes and on the crest to measure changes in water content profiles in response to precipitation and snowmelt events (Flint and Flint, 1995). The following corroborative geochemical studies were used to assess the infiltration flux: chloride mass balance, calcite data, ^{36}Cl and tritium isotopes, pore water chemistry, fluid inclusions, and oxygen isotopes. Meteorological parameters responsible for small-scale physical processes included the effect of topographic features (mountains and valleys). Key meteorological parameters measured at Yucca Mountain are temperature, average annual precipitation, average annual snow fall, average annual evapotranspiration, average annual infiltrated surface water runon, average annual mean outflow, and average annual net infiltration, humidity, wind velocity, and wind direction. These parameters are summarized in Table 2.1-1. Detailed descriptions of climate and infiltration can be found in BSC (2004a) and Simmons et al. (2004, Section 6).

Table 2.1-1. Climate and infiltration parameters

Regional Scale	Parameters
Climate	Temperature Precipitation Geology (topography, stratigraphy, fractures, fossils/microfossils) Surface hydrology Type of soils Sea level change Isotopic data Variation on earth orbital clock Eccentricity

Site-Specific Scale	
Meteorological	Topography Temperature Pressure Humidity Precipitation rate Snow fall rate Evapotranspiration rate Surface run –on Run-off Humidity Wind direction, velocity Net infiltration

Data from climate and infiltration processes have been collected since 1988. At Yucca Mountain, the climate is arid, with average precipitation (from rain and snow) about 190 mm per year and nearly 95% of all precipitation lost to evaporation (CRWMS M&O, 2002, Section 4.2.1.2.1). Evapotranspiration is high (less than 0.1 to more than 1.5 mm/day). Estimated values of infiltration range from 0.02 to 5.9 mm/yr with an average of 4.6 mm/y (CRWMS M&O 2002 Table 4.11).

Three potential climates states (interglacial, monsoon, and glacial transition) have been forecasted for the next 10,000 years, based on the results of field, laboratory, and modeling studies. Detailed information on climate and infiltration is described in BSC (2004a) and CRWMS M&O (2002, Sections 6 and 7).

2.1.1.2 GEOLOGY AND STRUCTURE

The geology of Yucca Mountain is composed of Miocene-age silicic volcanic rock represented by heterogeneous layers of anisotropic, fractured volcanic tuffs, with alternating welded and nonwelded ash-flow deposits. About 15 lithostratigraphic units (Simmons et al., 2004, Fig. 7.26), and five hydrogeologic units (Flint, 1998) have been identified. The Topopah Spring Tuff of the Paintbrush Group is the host rock for the repository and therefore one of the most intensely studied Yucca Mountain formations. Detailed geological mapping of Yucca Mountain was performed at scales of 1:24,000, 1:6,000 and 1:2,400 along fault zones (Simmons et al., 2004 Section 3.3)

As part of regional studies, extensive literature surveys and field mapping were conducted, and geological boreholes were drilled, to understand the stratigraphy and structure of the site. Findings showed that Yucca Mountain is dominated by a series of north-striking normal faults, with bedrock displaced several hundred meters (maximum ~600 m) along many of the faults, which occur within or along the flanks of Yucca Mountain (Fenster, 1999). Most seismicity is related to fault movement, which in turn is related to tectonic events. Studies of the tectonic evolution of the area (Day et al., 1998, pp. 17–19; Simmons et al., 2004, Section 4.6.3.3) demonstrate that most of the faulting occurred shortly before, during, and soon after the eruption of the tuffs that comprise Yucca Mountain. Evidence of seismicity exists for recurrent middle to late Quaternary fault displacement; however, there are no records of large-magnitude earthquakes near the Yucca Mountain site area for the past 2 million years (CRWMS M&O, 2002, Section 1.3).

Besides seismicity, volcanic activity is also a possible issue with respect to the safety of the proposed nuclear repository at Yucca Mountain. Recent aeromagnetic survey revealed 20 volcanic anomalies buried in a 20–30 km area around the proposed repository location. According to Smith and Keenan (2005), the probability of volcanic disruption in the Yucca Mountain volcanic field could be 1–2 orders of magnitude higher than the Environmental Protection Agency (EPA) standard.

The distribution and characteristics of fractures at Yucca Mountain are important, because in many of the hydrogeological units at the site, particularly the welded tuffs, fractures are the dominant pathways for water, air/gas, and heat flow. Fractures at Yucca Mountain are generally of three types: early cooling joints formed during the original cooling of the volcanic rock; later tectonic joints caused by faulting and rock stress; and joints caused by erosional unloading (CRWMS M&O, 2002 Sec. 1.3).

Although geologic heterogeneity (fracture and cavity abundance) is part of the complex natural geological system of Yucca Mountain, a statistical representation of fracture geometry, orientation, length, crosscut relationships, and infillings helps us to understand the tectonic history, stress field, and water-rock interaction, providing greater confidence in modeling and some constraints on uncertainty.

Site-specific, detailed mineralogical and textural studies provide information on physical and mechanical properties. Specifically at Yucca Mountain, parameters such as fracture frequency, hardness, weathering, rock-quality designation (RQD), and lithophysal data were collected from surface-based boreholes (Simmons et al., 2004, Section 3.7.2). Other geological-property parameters include mineralogy, variations in grain size and sorting, relative abundance of volcanic glasses, degree of welding, types and degree of crystallization, relative abundance of lithophysae, and amount and types of glass alteration (Simmons et al., 2004, Section 3.3).

A summary of the main geological, mineralogical, structural and physical parameters is listed in Table 2.1-2.

Table 2.1-2. Geological, structural and physical parameters

	Parameter
Geological	Lithostratigraphic units
	Alteration/weathering
	Mineralogy
	Percentage of volcanic glass
	Degree of welding
	Degree of crystallization
	Percentage of lithophysae
	Grain size
Textural	Sorting
	Abundance of volcanic glass
	Degree of welding
	Types & degree of crystallization
	Abundance of lithophysae
	Abundance and type of glass alteration
Structural	Lineaments trace
	Fault orientation
	Fracture geometry
	Fracture orientation, length
	Fracture frequency

Understanding the structural framework of Yucca Mountain is essential for assessing natural hazards. The main tectonic hazards at Yucca Mountain are basaltic volcanism and seismic activity. Active volcanoes no older than 70–80 ka are located about 50 km west of the proposed repository (Wells et al., 1992). A recent aeromagnetic survey covering an area of 865 km^2 around Yucca Mountain suggests that the volcanic threat could be higher than the 40% previously estimated, with an increase in recurrence rate and probability of disruption 1–2 orders of magnitude greater than the EPA standard (Smith and Keenan, 2005).
Since 1910, three seismic activity events have been reported within a 100 km radius of the site (Figure 4-19, Simmons et al., 2004, Figure 4-19), and about 105 faults with known or suspected Quaternary activity have been identified within the same area (Simmons et al., 2004, Section 4).

2.1.1.3 GEOPHYSICAL INVESTIGATIONS

Geophysical investigations used for surface reconnaissance provide information on existence of faults, distribution of stratigraphic units, and the shape of buried volcanoes (Ponce, 1996; Sikora et al., 1995). Because the primary question to be addressed in the site area is the amount, style, depth, and continuity of faulting in the repository block itself, various geophysical methods have been compared to evaluate their effectiveness in imaging faults. The surveys suggested that a combination of geophysical techniques were needed to provide accurate information on subsurface structures (Simmons et al., 2004, Section 3.5.7).

Regional geophysical data, such as gravity (model geometry) and magnetic anomaly data were used to constrain the shape of volcanic rocks, locate the contact between different lithologies, and define fault offsets (Langenheim, 2000c). Seismic refraction (S and P-wave velocities) was used to model the velocity structure of the upper crust in and around Yucca Mountain (Smith et al., 2000d). Recent aeromagnetic surveys have been used to define the size and shape of many buried volcanoes, providing detailed information on volcanic hazards in the region (Smith and Keenan, 2005).

Geophysical surveys have been useful in detecting faults producing at least tens of meters of offset. A combination of geophysical surveys was applied to confirm the presence of faults. Attempts were made to detect and characterize buried faults and geologic heterogeneities using the magnetotelluric method, but this method was found to be limited unless supplemented by other geophysical techniques. The general conclusion was that standard geophysical techniques were best suited for detection of faults with at least tens of meters of offset (Simmons et al., 2004 Section 4.6.5.3).

At a site-specific characterization, tomographic seismic imaging was used to identify fracture density and ground-penetrating radar tomography provided information on moisture and tracer movement through the fractures (Mejer et al., 1998; Simmons et al., 2004, Section 7.8.1.6). Use of magnetotelluric methods and seismic reflection data was limited. Other parameters obtained from the borehole geophysical log including caliper, gamma ray, density, induction, resistivity, and neutron porosity (Simmons et al., 2004, Section 3.3.3.4), provided a valuable set of data that allowed investigators to correlate lithostratigraphic features across Yucca Mountain. A summary of geophysical surveys and parameters are listed in Table 2.1-3.

Table 2.1-3. Geophysical parameters

Method (Regional)	Parameters
Aeromagnetic and gravity Seismic Refraction	Fault offset, stratigraphy, lithological contact, Size and shape of buried volcanoes Lithological contacts and fractures
Site Specific	
Tomographic seismic imaging Magentotelluric and Seismic reflection	Fracture density Lithological contacts and fractures
Borehole log	
Electrical resistance tomography Ground penetrating radar Neutron logging Cross hole radar tomography	Density Moisture content Porosity Saturation

2.1.1.4 HYDROLOGICAL AND HYDROGEOLOGICAL INVESTIGATIONS

Yucca Mountain is part of the Amargosa River drainage system. Surface hydrological processes within this system include precipitation, evaporation and transpiration, run-on and runoff, infiltration, moisture redistribution, and groundwater recharge. As described previously, climatic factors have a great influence on the surface and groundwater hydrology, generating variations in temperature, humidity, precipitation, and solar flux.

The major hydrogeologic units are divided into Tiva Canyon welded (TCw), Paintbrush nonwelded (PTn), (consisting primarily of the Yucca Mountain and Pah Canyon members and the interbedded tuffs), Topopah Spring welded (TSw), Calico Hills nonwelded (CHn), and Crater Flat undifferentiated (CFu) units (BSC, 2004b; Flint, 1998). Hydrogeologic properties of the units were measured directly using two distinctly different methods: matrix-properties analysis of rock cores and field-scale air-injection testing.

Most Yucca Mountain hydrogeological parameters, such as porosity, permeability, and hydraulic conductivity, are controlled by the interaction between rock types, the characteristics of faults and fractures, textural variations such as degree of welding, presence of cavities, mineral alteration, and groundwater flow chemistry.

Nearly 4,900 core samples were analyzed in the laboratory to measure important hydraulic properties. These properties include matrix porosity, bulk density, particle density, water content, water potential, saturated and unsaturated hydraulic conductivity, and moisture retention characteristics (Flint, 1998). Air-injection tests were performed to determine field-scale bulk permeability, porosity, and anisotropy of the major rock units above, below, and within the repository horizon (Simmons et al., 2004, Section 7.2; BSC, 2004b, Section 2.2.2; LeCain et al., 2000; BSC, 2003b, Section 6.1; BSC, 2003a, Sections 6.1 and 6.11). Matrix hydrologic properties such as matrix porosity and permeability were determined from laboratory measurements made on core samples (CRWMS M&O, 2000bt, Section 6.2). Permeability values for each lithostratigraphic unit and their relationship to fracture density and lithophysal cavities is described in Simmons et al. (2004, Section 7.2.2).

Hydraulic properties of fractures are dependent on fracture aperture and whether the fractures are open or filled with calcium carbonate or siliceous materials. At Yucca Mountain, fracture apertures have not been well characterized, but estimates have been made from borehole core logs (Flint et al., 1996). Data regarding fracture geometry (density, trace, length, dips and strike) were obtained from drift studies (LeCain et al., 2000; BSC, 2004b, Section 2.2.2). Fracture porosity and permeability were estimated from air injection and gas tracer tests, based on the geometry of fracture networks and calculated from borehole data (CRWMS M&O, 2000bt, Section 6.1.3).

Hydrologic data for fault zones are also limited. Air injection test and trace testing were conducted along the faults (e.g., Ghost Dance Fault, Bow Ridge Fault) to determine air permeability, porosity, and tracer transport (BSC, 2004b, Section 2.2.3). Faults can be major conduits for flow or may be locally impermeable to lateral flow, resulting in perched water (Flint et al., 2001). A summary of hydrological and hydrogeological parameters is listed in Table 2.1-4.

Perched water was characterized through borehole data. These perched water bodies were found primarily in the northern part of the repository area, where lower permeability and sparsely fractured zeolitic rock units predominate, and are located below the potential repository horizon. The occurrence of perched water suggests that certain layers of the lower vitric and upper zeolitic layers serve as barriers to vertical flow. Characterizing perched water is important because it has important implications for transport time and flow through the UZ (Rousseau et al., 1999, p. 170; 1997 pp. 21 and 22; CRWMS M&O 1997c).

Table 2.1-4. Hydrological and hydrogeological parameters

	Parameters
Surface Hydrological Properties	Precipitation Evaporation Transpiration Run-on Run-off Infiltration Moisture redistribution Groundwater recharge
Hydrogeological Properties of Matrix	Matrix porosity Bulk density Particle density Water content Matrix permeability Moisture retention relations Water potential Hydraulic conductivity
Hydrogeological properties	Fracture density

of Fractures	Fracture aperture Fracture porosity Fracture permeability Hydraulic conductivity
Hydrogeological properties of Faults	Fault permeability Fault porosity Tracer transport

2.1.1.5 GEOCHEMICAL PROPERTIES

Geochemical analysis includes samples from surface water, boreholes, and core samples. The objective of the geochemical (and isotope) analysis is to determine the major chemical and isotopic parameters of surface water, pore waters, perched water, gases, and fracture minerals collected from the Yucca Mountain UZ. Chemical and isotopic data are used to establish bounds on key hydraulic parameters and to provide corroborative evidence for model assumptions and predictions (BSC, 2004b, Section 2.3). Aqueous-phase hydrochemical data have been interpreted to determine possible flow mechanisms and residence times for pore water in the UZ.

The initial composition of Yucca Mountain groundwater is largely established by local precipitation and dry fallout (i.e., from aerosols and particles). The main geochemical and isotopic parameters for site characterization of the Yucca Mountain UZ are listed below (CRWMS M&O 2000bv Section 2.3; Simmons et al., 2004, Section 5.2.2.4.2 and 7.5; BSC 2004b, Section 2.31.1), and summarized in Table 2.1-5.

- Major cations and anions of pore water provide evidence of rock-water interaction.
- Stable isotopes (hydrogen and oxygen) were used to determine the origin of water. Hydrogen, oxygen, and carbon stable isotopes were used to infer paleoclimatic conditions (Winograd, et al., 1992, Coplen et al., 1994)
- Cosmogenic and atmospheric radionuclides (tritium, carbon-14, chlorine-36) are good indicators of water residence time. Carbon-14 and ^{36}Cl are used to constrain water age estimates, and ^{36}Cl from bomb-pulse are used to infer infiltration rates (Fabryka-Martin et al., 1993 and 1993)

- Radiogenic isotopes (isotopes of strontium, uranium, and uranium decay products) are used to evaluate the prevalence and frequency of fracture flow through the UZ and the issue of local recharge to the water table.
- Precipitated minerals in fractures are used to constrain the infiltration flux and provide spatial and temporal information on past water migration through the UZ (Dobson et al., 2003)
- Variations in temperature can influence the composition of water by increasing or decreasing the rates of important reactions and by changing the composition of the equilibrium assemblage in the system.
- Pressure variations will have a minor effect on water chemistry but could affect the gas flow patterns, including water vapor transport.

Other parameters—such as data on oxidation/reduction potentials, pH, major constituents, major species, gas concentrations, redox-sensitive elements, dissolved organic carbon and microbial populations—are pertinent to repository performance. They are used to predict corrosion behavior of the waste packages, solubility of the waste forms, and sorption behavior of the radionuclides released from the waste forms. (CRWMS M&O 2000bv, Section 6.2).

Table 2.1-5. Groundwater geochemical parameters

Category	Species/Element
Atmospheric radionuclides and Cosmogenic radionuclides	Tritium, ^{14}C and ^{36}Cl
Major ions	Al, Ca, Mg, K, Na, SiO_2, HCO_3, CO_3, Cl, NO_3, SO_4, total dissolved solids (TDS) and trace elements
Stable Isotopes	δD, $\delta^{18}O$, $\delta^{13}C$
Radiogenic Isotopes	$^{87}Sr/^{86}Sr$, $^{234}U/^{238}U$
	Temperature and pressure Trace elements

Some environmental tracers, including radioactive species from nuclear weapons testing, are found in the groundwater. ^{3}H, ^{14}C, and ^{36}Cl, produced in the atmosphere about 50 years ago by nuclear testing, have been measured in pore water. This indicates that some percentage of the water infiltrated to depth in less than 50 years (LeCain, 1997 Table 8).

Geochemistry of rocks and minerals are mainly affected by rock-water interactions along different lithostratigraphic units and secondary minerals precipitated along fracture and fault zones. This interaction includes rock/mineral-dissolution reactions, ion exchange reactions, hydrolysis reactions, precipitation reactions, oxidation reactions, and possibly other alteration reactions. Fault mineralogy can be critical in evaluating flow and transport. Faults can be highly transmissive if the fault contains no mineralization or if mineralization along the fault is limited. Detailed rock geochemistry of Yucca Mountain is described in Simmons et al. (2004, Section 3.3.5). Table 2.1-6 illustrates the important parameters related to rock geochemistry.

Table 2.1-6. Geochemical parameters

Category	Parameters
Rock geochemistry	Mineralogy (Calcite ($CaCO_3$) Opal (SiO_2)) Alteration minerals Major element compositions Secondary minerals Sorption properties Age $^{40}Ar/^{39}Ar$
Gas geochemistry	CO_2, $^{13,14}C$, ^{18}O, CH_4, Ar, N_2

2.1.1.6 MECHANICAL, PHYSICAL AND THERMAL PROPERTIES

Bulk properties such as mineralogy, grain density, bulk density and porosity, temperature, pressure, and stress determine the mechanical behavior of rocks (CRWMS M&O, 1997c; Simmons et al., 2004, Section 5.4.3.3). Mechanical properties were measured in large and small rock specimens to determine rock elasticity, tensile strengths and deformation properties and *in situ* stress conditions of intact and fracture samples from Yucca Mountain (BSC, 2003, Section 8.2.2).

Young's modulus and Poisson's ratio are the primary mechanical deformation indices of rock; they also indicate the elastic response of rock to stress. Intact-rock elastic properties were collected in core samples from surface and subsurface drilling efforts. In general, Young's modulus of the tuff depends on the degree of welding. Nonwelded tuff is weak and exhibits low Young's moduli; welded tuffs are stronger and exhibit significantly greater Young's moduli (Fenster, 1999, Section 8.4)

The compressive strength of a rock is its ability to withstand compressive stress without failure. Results of unconfined compression tests at Yucca Mountain indicate that the unconfined compressive rock strengths vary, depending on welding, porosity, and the fabric of the rock. Welded tuffs exhibited higher strengths than nonwelded tuffs. In addition, measurements in small-diameter core samples were also conducted, although they did not provide accurate strength or elastic properties for the lithophysal rock (Simmons et al., 2004, Section 5.4.3.3). *In situ* stress analyses were obtained primarily from hydraulic fracturing tests performed in the drifts. The results were in accordance with the orientation of the normal faults (Simmons et al., 2004, Section 3.7.5, p. 251).

Rock physical properties such as bulk porosity, saturation, permeability, and particle density were measured from 5,320 core samples (Flint, 1998). Flint's findings showed that permeability measured from air injection is variable and strongly dependent on mineralogy. Permeability also increases in the welded tuffs where fractures are abundant, providing flow pathways.

As part of the regional heat flow study, temperature measurements were obtained from boreholes. Thermal properties (including rock grain density, dry and wet rock thermal conductivities, and rock grain specific heat capacity) were also measured for rock samples collected from surface-based boreholes (BSC, 2003b, Section 6.3; Simmons et al., 2004, Sections 2.2.1 and 7.4.3). Thermal-mechanical tests were conducted on drill core samples and as part of drift-scale experiments to understand the effect of coupled processes in the fractured rock mass and to support the long-term performance assessment (Simmons et al., 2004, Section 5.4).

Additional information on mechanical properties is available in BSC (2003d CRWMS M&O (1997c), pp. 5–111; and Simmons et al. (2004) Sections 5.4.3.2 and 5.4.3.3); on physical properties in BSC (2003d Section 8.2); and on thermal properties in BSC (2003d Section 8.3). The main parameters for rock mechanics, physical and thermal properties are listed in Table 2.1-7.

Table 2.1-7. Mechanical, physical and thermal parameters

	Parameters
Mechanical Properties	Young's modulus Poisson's ratio Compressive strength Rock quality designation (RQD) Tensile strength In situ stress conditions Normal stiffness Shear stiffness Cohesion Friction
Physical Properties From core samples	Hardness Saturation Particle density Bulk porosity Permeability
Thermal properties	Thermal conductivity Heat capacity Thermal expansion coefficients Thermal diffusivity Heat dissipation

2.1.1.7 SUMMARY LIST OF IMPORTANT YUCCA MOUNTAIN UZ PARAMETERS

In this section, key parameters and/or processes are listed loosely in the order of importance. In particular, the first five in the list—(1) infiltration and percolation, (2) fault and fracture properties, (3) fracture-matrix interaction, (4) water-rock interaction, (5) seepage, and are probably the most important parameters and processes. **Error! Reference source not found.**is an illustration from the OSTI 2005 annual report that illustrates these parameters.

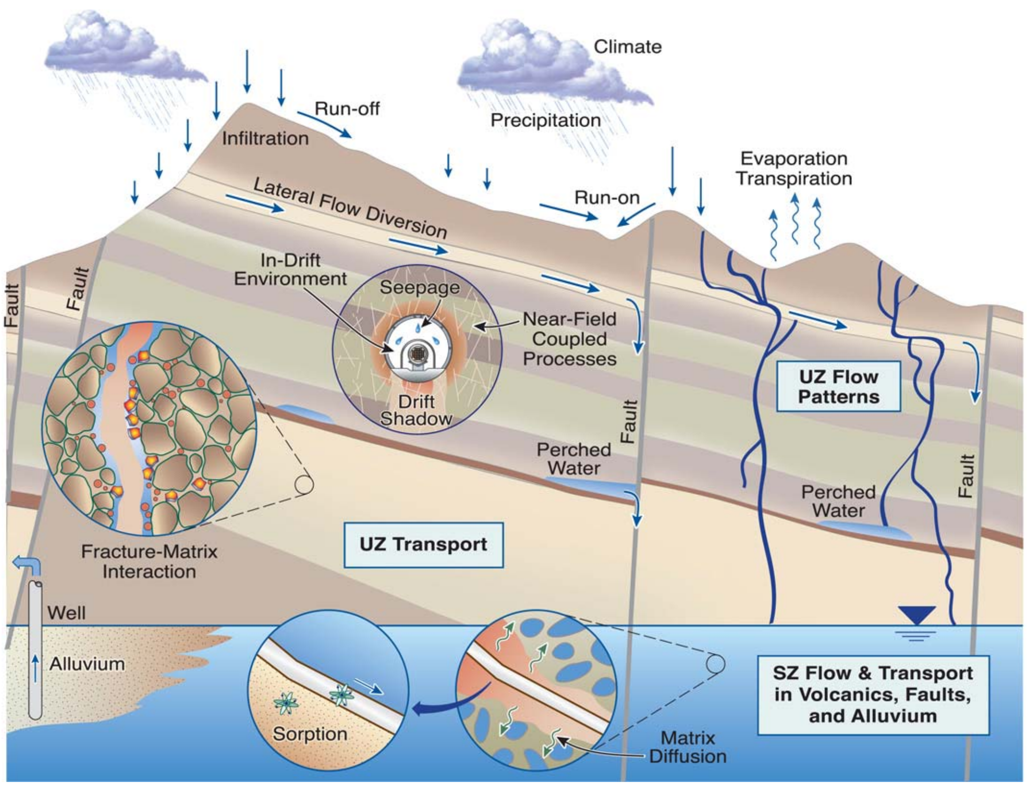

Figure 2-0-1. Important Yucca Mountain UZ parameters (Source: OSTI 2005 annual report)

2.1.1.7.1 *Infiltration and Percolation*

The conceptual model for the Yucca Mountain UZ is strongly affected by processes that include water flow. In a desert environment, water is limited, and the amount of water that enters the natural system is redistributed through the matrix and fractures/faults. When percolating water encounters an opening, much of the water is diverted by capillary forces, although the water could eventually result in seepage. Infiltration and percolation are governed by the climate, rock structure, and rock hydrological properties, which are essential for understanding the regional-scale process. The factors controlling net infiltration are:

- Topographic features
- Precipitation (rain and snow)
- Pressure
- Humidity
- Temperature
- Soil thickness
- Distribution of rock types (thickness, variations in texture and appearance, size and abundance of pumice and rock fragments, lithosphysal content) and lithologic contact
- Drainage characteristics (runon, runoff, evaporation rate, transpiration rate)
- Faults and fractures
- Matrix permeability
- Pore-water chemistry
- Moisture redistribution by flow in the shallow subsurface

To obtain accurate infiltration data, studies performed at the global scale provide input for understanding the climatic system. These studies are:

- Studies of glaciers
- Studies of storm activity
    - Storm amplitude
    - Storm frequency
    - Pressure systems
- Paleoclimate studies:
    - Geochemical analyses of sediments deposited in lakes

- Minerals deposited in springs
- Fossils of microorganisms that live in both lakes and springs
- Plant and animal remains preserved in caves
- Mapping minor spring and marsh deposits

To correctly estimate the percolation flux, the following processes and parameters need to be estimated:

- Drift seepage
- Lateral flow
- Fracture-matrix flow partitioning
- Flow into faults
- Water potential profiles
- Presence of perched water

2.1.1.7.2 Fault and Fracture Properties

Structurally, faults and fractures represent locations of weakness in the rock mass as a result of regional and/or local tectonics. Hydraulically, faults and fractures are considered the main pathways for fluid, gas, and heat. Although major faults can act as fast flow conduits or as barriers for fluid flow, they are the main concern for the transport of radionuclides through the geosphere. The factors controlling fault and fracture properties are:

- Tectonic history (seismicity and volcanic activities)
- Type of faults and width of damage zone
- Type and distribution of rock deformation
- Type and distribution of volcanoes and volcanic rocks
- Petrology and mineralogy
- Chemical composition of rocks and mineral alteration

- Age and distribution of mineral filling (calcite, opal)
- Rock physical and mechanical properties (density, porosity, permeability, strength, *in situ* stress, storage capacity, transmissivity)

Tools used for fault and fracture characterization include:

- Satellite imagery
- Geophysical surveys at different scales
- Regional and surface geological mapping
- Lineament mapping
- Sampling
- Geochemical and isotopic signatures in pore and perched water (chloride, tritium concentration) and infilling minerals.
- Tracer injection tests

2.1.1.7.3 Fracture-Matrix Interaction

Fracture-matrix interaction determines whether there is fracture flow when the matrix is not saturated. Thus it is critically important to correctly estimate the fracture-matrix interaction. Data/observations used to characterize fracture-matrix interaction include:

- Field observations
- Matrix saturation data
- Chloride concentration data
- Gravity-driven fingering flow

2.1.1.7.4 Rock-Water Interaction

Secondary minerals precipitated along faults and fractures provide information on the time of deposition and isotopic signatures of waters from which they precipitated. They are also important on promoting rock/mineral-dissolution reactions, ion-exchange reactions, hydrolysis reaction and possible other alteration reactions. In addition, this process has potential significance with respect to radionuclide retardation reactions (for example, sorption).

The main factors controlling water-rock interaction are:

- Moisture distribution
- Matrix flow
- Concentration of dissolved ions
- Viscosity of water at elevated temperature
- Surface tension of water at elevated temperature

The results of water-rock interaction include:

- Mineralogy of fracture coating (calcite, opal)
- Mineral alteration (zeolites)
- Calcite deposition analysis
- Near-surface carbonate deposits
- Ages and distribution of deposits
- Isotopic data
- Relative abundance of chlorine-36 in pore water (or extracted salts)
- Tritium signatures in perched waters
- Fingering flow
- Chloride concentration data

2.1.1.7.5 Seepage Rate

Seepage rate into the drift is probably the single most important parameter that needs to be estimated for the safety of the repository. Tests conducted to characterize and estimate seepage rate include:

- Surface and drift based seepage tests
    - Pulse releases to represent episodic percolation events

  - Use of dye tracers to characterize seepage flow paths

- Air-injection tests

2.1.2 SATURATED ZONE PARAMETERS

The saturated zone (SZ) system is expected to act as barrier to the migration of dissolved and colloidal radionuclides that may be released from the repository (BSC, 2003). With this in mind, the groundwater flow system beneath the Yucca Mountain has been characterized in order to predict radionuclide migration through the SZ. As part of the Yucca Mountain site characterization program, more than 150 hydraulic tests were conducted at 37 boreholes in and around Yucca Mountain, nearly all of them single-well tests over specific depth intervals. Tests included constant-discharge, fluid-injection, borehole flow meter, and radioactive tracer tests (BSC 2003)

Compared to the UZ, the SZ has not been nearly as fully characterized, and some of the studies related to it are still ongoing. Nevertheless, various data sets, including geologic, hydrogeologic and geochemical data, have been used to constrain the conceptual model of groundwater flow and transport properties for the SZ. The models were constructed using parameters from in situ field observations, field tests, laboratory tests, and literature surveys.

2.1.2.1 GEOLOGY AND STRUCTURE

The SZ below Yucca Mountain is within the Death Valley regional groundwater system. Groundwater flow in the SZ is controlled largely by the distribution of rock types and their respective permeabilities and porosities (Eddebbarh et al., 2003). The hydrogeologic units of the SZ vary from fractured, porous volcanic tuffs relatively close to the water table, to fractured carbonate rocks of Paleozoic age (limestones and dolomites) at much greater depths (BSC, 2003).

There are two main hydrogeologic units below the repository. Both of these units have vitric and zeolitic components that differ in their degree of hydrothermal alteration and thus hydrologic properties. Detailed characterization on hydrogeological units is described in Simmons et al., 2004 Section 8.2.2.1.

Regional tectonics, including folds and faults, can control the groundwater flow system by forming topographic features, by displacing and juxtaposing layers with different hydrologic characteristics, and by creating fractures network along fault zones. Fractures and faults within the hydrogeologic units constitute the dominant pathways for regional groundwater flow. The presence, orientation, and types of faults provide major controls on groundwater flow, producing topographic features that define the groundwater recharge and discharge areas; inducing highly permeable fractures, and in some cases, creating barriers to groundwater flow.

In the rock matrix, fluid stored in the matrix pore space can be important for radionuclide transport. Matrix diffusion can be caused by an exchange between fracture and matrix or sorption in the matrix, resulting in retardation of radionuclides. Details on transport properties are described in Section 1.1.1.2.4. Table 2.1-8 summarizes the main parameters related to geology and structure.

Table 2.1-8. Summary of geological and structural parameters

	Parameters
Geological	Stratigraphy Lithology Lithological contacts Mineral alteration
Structural	Fault orientation, types Fracture density Fracture network Folds

2.1.2.2 REGIONAL AND SITE-SPECIFIC GROUNDWATER SYSTEM

To characterize the SZ, we must have a general understanding of the regional groundwater flow system, including lateral boundaries, recharge and discharge, and hydraulic gradient. Variables affecting recharge and discharge include timing of precipitation, elevation, slope, soil and rock type, and vegetation. Potentiometric maps and information on recharge and discharge have been used in previous studies to illustrate the direction of groundwater flow, to calculate the gradient or slope, and to estimate the groundwater flow velocity (Simmons et al., 2004, Section 8.2.6)

As mentioned previously, the groundwater system in the SZ is part of the Death Valley flow system. Groundwater flow at both the regional and site scale is generally southward, from regions of high hydraulic head to regions of low hydraulic head (Eddebbarh et al., 2003).

Estimates on hydrologic characteristics of major lithologic units are derived by evaluating the water transmitting capabilities. Hydraulic conductivity and effective fracture porosity are the most important physical properties of aquifers; these parameters are needed for calculating the transport of groundwater and contaminants. Hydraulic tests include constant-discharge pumping tests, slug injection (falling head) tests, pressure injection tests, and fluid logging techniques (e.g., temperature measurement, fluid conductivity measurement, and tracer injection surveys).

The hydrogeologic characterization is based on direct outcrop observations, geologic observation from boreholes, and geophysical logs (especially resistivity and seismic surveys). Belcher and Elliot (2001) compiled estimates of transmissivity, hydraulic conductivity, storage coefficients, and anisotropy ratios for major hydrogeologic units within the Death Valley region. Rock permeability has been determined by single and crosshole hydraulic testing (BSC, 2003; Eddebbarh et al., 2003). Table 2.1-9 summarizes the main hydrological parameters.

Table 2.1-9. Summary of hydrological parameters

	Parameters
Regional Groundwater System (Recharge – Discharge)	Lateral boundaries Precipitation (rainfall, snowmelt) Evapotranspiration Altitude Soil type Rock type Slope Vegetation Hydraulic gradient Water level Direction of groundwater flow Flow velocity Transmissivity Hydraulic conductivity Porosity
Site Scale	Infiltration Fault orientation Fault type Fracture density Fracture porosity Matrix pore storage Transmissivity Flow velocity Dispersion Concentration of radionuclide
Borehole	Matrix porosity Fracture density Hydraulic head

2.1.2.3 REGIONAL AND SITE SCALE GEOCHEMISTRY

Chemical and isotopic analyses were conducted to determine the source area, flow directions, mixing relations, ages, and travel time. The application of hydrogeochemical and isotopic methods make it possible to reduce some uncertainties concerning regional groundwater flow patterns and flow rates. They also provide some bounds on the magnitude and timing of recharge of SZ groundwater (BSC, 2003, Section 2.2.4)

The main processes that control groundwater chemistry are:

- Precipitation (atmospheric) quantities and compositions
- Soil-zone processes in recharge areas

- Rock-water interactions in the UZ between the zone of infiltration and the water table
- Rock-water interactions in the SZ along the flow path, from the recharge location to the point where the water is sampled
- Mixing of groundwater from different flow systems.

The chemical signature of groundwater depends on factors such as host rock composition, mineral precipitation and dissolution processes, pH, oxidation potential, partial pressure of carbon dioxide, flow path length, and groundwater flux. Major-ion chemistry, isotopic composition, and trace-element abundances can be used to characterize chemical reactions between the water and host rocks, identify source areas for recharge, delineate flow paths, evaluate lateral and vertical mixing of groundwaters, and locate areas of evapotranspiration and groundwater discharge (Simmons et al., 2004, Section 8.2.7). In addition, the decay rates for radioactive isotopes such as ^{3}H, ^{36}Cl, and ^{14}C are known, and they can be used to indicate modern nuclear-age recharge as well as to date the time of pre-nuclear-age recharge. Major-ionic and isotopic chemistry of groundwater represent complementary approaches as indicators of regional flow and paleohydrologic conditions.

In Yucca Mountain area groundwater, sodium is the primary cation, and carbonate (as carbonic acid, bicarbonate, and carbonate) is the primary anion (Benson et al., 1983, p. 11; Ogard and Kerrisk, 1984, p. 16; Benson and McKinley, 1985). Other major cations are calcium, potassium, and magnesium; other major anions are sulfate and chloride, with lesser quantities of fluoride and nitrate (Simmons et al., 2004 Section 8.3.6.1.3). Isotopic data includes $^{234}U/^{238}U$ ratios, strontium, oxygen, deuterium, and carbon isotope ratios. Tracer and rare earth elements were used to evaluate regional groundwater hydrochemistry and flow paths (Simmons et al., 2004, Section 8.2.7.4). A summary of hydrochemical parameters is shown in Table 2.1-10.

Table 2.1-10. Summary of hydrochemical parameters

Regional Geochemistry	Parameters
	pH Eh
Isotopes	$^{234}U/^{238}U$ ^{14}C ^{36} Cl δ-deuterium $\delta^{18}O$ strontium
Major ions	Na, Ca, K, Mg Sulfate, chloride Nitrate, fluoride
Others	Tracer elements Rare earth elements

Isotopic analyses indicate that the water in the SZ and perched water have a similar origin, predominantly from vertical recharge through the UZ (BSC, 2003c, Section 6.7.6.6).

2.1.2.4 TRANSPORT PROPERTIES

The rate of radionuclide transport is a function of key radionuclide transport processes and parameters such as effective porosity, advection, matrix diffusion, hydrodynamic dispersion, and radionuclide sorption (i.e., retardation). To investigate the processes of radionuclide transport—such as matrix diffusion, dispersion, sorption and colloidal transport—hydraulic and tracer tests were conducted in the SZ (BSC, 2003, Section 1.2; Reimus et al., 2003). At Yucca Mountain, the effects of advection, matrix diffusion, dispersion, and sorption processes were investigated in fractured and porous media (i.e., alluvium). The parameters of transport properties are summarized in Table Table 2.1-11.

In fractured tuffs, advective transport occurs within fractures; the rate of advection is determined by the groundwater velocity, and thus, the effective fracture spacing and porosity are important for describing the advective velocity of dissolved constituents. Radionuclides that are transported through the fractures may diffuse into the surrounding matrix or sorb onto the fracture surfaces. If the radionuclides diffuse into the matrix, they may also be sorbed within the matrix of the rock.

A series of crosshole radial converging tracer tests were conducted to confirm the conceptualization of flow and transport in fractured tuffs (BSC, 2003, Section 3.2.1). The effect of fracture spacing and fracture effective porosity on advection is described in BSC (2003, Sections 3.2.1.1 and 3.2.1.2) and *Saturated Zone In-Situ Testing* (BSC 2003e). Matrix diffusion and dispersion tests were conducted in rock samples and in the field, using tracers (i.e., TcO_4, HCO_3, ^3H, bromide, lithium, and pentafluorobenzoic acid – PFBA) as diffusing species. Sorption data were estimated in the field tracer tests by using lithium. In these tests, lithium sorption was always approximately equal to or greater than the sorption measured in the laboratory (CRWMS M&O, 2000a, Table 3-4). Details of the methods used to obtain the field lithium sorption parameters, and discussions of possible alternative interpretations for the lithium responses, are provided by Reimus et al. (1999) and in *Saturated Zone In-Situ Testing* (BSC, 2003e).

In the alluvium, advective transport occurs through the porous matrix. Effective porosity and dispersivity were estimated from single-well tracer tests, and literature survey data (BSC, 2003, Section 3.2.2). Sorption tests using ^{129}I, ^{99}Tc, ^{237}NP and ^{233}U as tracers were conducted using alluvial materials. Sorption was strongly dependent on the presence of clay mineralogy as well as iron and magnesium oxides that have larger surface areas. In addition, ^{14}C and ^{13}C isotopic compositions were measured to infer recharge, water-rock interaction, groundwater velocity, and residence time. Detailed description of the transport processes is in BSC (2003, Section 3.2).

Table 2.1-11. Transport properties parameters

	Parameters
Porous media (alluvium)	Advection Sorption Dispersion Porosity Sorption ^{14}C, $\delta\,^{13}C$ isotopes
Fracture	Advection Diffusion Dispersion Fracture spacing Porosity Aperture Fillings Sorption

2.1.2.5 PARAMETERS AND FEATURES FOR FLOW AND TRANSPORT IN THE SATURATED ZONE

Compared to UZ investigations, very little effort has been spent on characterization of the SZ. Recently, there has been a renewed interest in the SZ to reduce uncertainties. The parameters that most affect the predicted performance of the SZ barrier are:

- Hydraulic gradient
- Hydraulic conductivity
- Recharge and discharge
- Specific discharge
- Flowing interval spacing
- Flow path length in fractured tuff and alluvium
- Effective porosity of fractured tuff and porous alluvium
- Dispersivity
- Effective mass transfer
- Sorption coefficient
- Matrix diffusion

- Advection

2.1.3 SUMMARY

Site characterization activities in the YM have been conducted for over 20 years. The conceptual model has evolved and improved essentially as a result of intensive field-testing activities, sampling, analyses, and modeling (Flint et al., 2001).

At Yucca Mountain, groundwater is considered one of the most critical parameter for nuclear waste disposal, with the amount of water contacting the waste package ultimately affecting all aspects of repository performance.

The main investigation conducted in the UZ encompasses: (1) climate (past, present and future), including meteorological, surface drainage, and topographic studies; (2) geology and tectonic evolution, including investigation of seismic- and volcanic-activity probabilities; (3) unsaturated hydrology, with the main focus on understanding infiltration, percolation, fracture-matrix interaction, and seepage; (4) geochemistry and isotope analyses to evaluate the chemistry and age of water and secondary minerals along faults and fractures; and (5) physical and mechanical properties, including porosity, permeability, in situ stress, and rock strength.

During the course of site characterization activities, several conceptual models were developed, numerical modeling was improved, and many uncertainties were addressed, including (1) estimation of infiltration and percolation, (2) effect of faults and fractures in the flow path, (3) fracture-matrix interaction, and (4) seepage.

In the SZ, the main investigation can be summarized as involving: (1) geology, including characterization of the hydrogeological properties of rock types and the influence of fault and fractures on the flow; (2) groundwater flow system, to evaluate recharge and discharge, and estimate the hydraulic characteristics of major hydrogeologic units; (3) geochemistry, to evaluate the flow path, water mixing, residence time and water-rock interactions; and (4) transport properties with emphasis on advection, diffusion, dispersion, and sorption. The main parameters affecting the performance of the SZ—by delaying the arrival of radionuclides to the geosphere and by attenuating the concentration of radionuclides—are: hydraulic gradient, recharge and discharge, hydraulic conductivity, porosity, flow interval and path, dispersivity, sorption coefficient, matrix diffusion, and advection.

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2.1.4.2 SATURATED ZONE FLOW

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2.2 Canadia n Approach

The governments of Canada and Ontario formally established the Canadian Nuclear Fuel Waste Management program in 1978. It was directed and carried out by Atomic Energy of Canada Limited (AECL). The concept investigated involves the burial of nuclear waste at an undecided depth from 500 m to 1,000 m within a plutonic rock mass of the Canadian Shield. Other options suggested for disposal included salt and shale deposits in sedimentary basins, but these options were not considered in depth because of the economic value of the salt and the presence of oil, coal, and gas deposits in shale formations (Davison et al., 1994).

In the official review of the Canadian Nuclear Program, the Seaborn Panel in 1998 indicated that although technically feasible, there was no broad public support for the AECL deep-geological-storage concept and the social safety was not demonstrated in the program. However, the panel also recommended that an implementing organization be established. As a result, in 2002, the Nuclear Waste Management Organization (NWMO) was established to consult and make recommendations to the federal government about an appropriate long-term management approach for used nuclear fuel (NWMO, 2005).

Several technical options, such as (1) deep geological disposal in the Canadian Shield; (2) storage at nuclear reactor sites and; (3) centralized storage above or below ground, were proposed for the future of nuclear waste disposal until the means of disposal are agreed upon. During these processes, which are predicted to take ~120 years, public involvement would be essential in deciding safety issues regarding the waste repository. For details on the technical options, see NWMO (2005).

As a result of the Seaborn Panel review, all activities related to development of site characterization technology by AECL gradually ended. In this report, we summarize the parameters for site characterization developed and recommended by AECL for future use in site screening and evaluation.

Plutonic rocks in the Canadian Shield have a number of characteristics that make it a suitable choice as a disposal medium for Canada (Davison et al., 1994):

1. Wide distribution–large exposure in regions of low topographic relief, indicating a low driving force for groundwater flow.
2. A geologically stable region. The Canadian Shield has been free of any major orogenic activity for at least the past 600 million years.
3. Low seismic activity in large areas of the Shield—although periodic earthquakes occur, they are clustered along structural weaknesses of ancient rift systems.

In addition to these characteristics, there are yet other advantages to using the plutonic rock of the Canadian Shield as host rock for a nuclear waste repository. Much of the plutonic rock: (a) is unlikely to be exploited as a resource, because of the limited mineral deposits associated with it; (b) has potentially beneficial thermal, hydrogeological, geochemical and geomechanical properties; (c) in general has good thermal conductivity, and radionuclide transport at depth is most likely to be via diffusion or advection, because fractures become sparse and fracture connectivity and permeability decrease with depth; (d) has minerals coating pores and fractures that react with many radionuclides, retarding their movement through the rock, and (e) have stable geomechanical properties for underground openings.

The major objective for the AECL's research and development program (R&D) was to develop and demonstrate methodology and technology for siting, construction, operation, decommissioning and closure of a disposal facility as well to evaluate the long-term safety and performance assessment of a disposal system. As for the geosphere, the main objective was to understand the behavior of plutonic rock and its associated groundwater flow system, to develop site and numerical models, and to access the performance of plutonic rock as a host medium (Davison et al., 1994 Section 2.4).

The proposed siting process developed and recommended by the AECL included *site screening* and *site evaluation*. They were aimed at developing and testing the equipment and methods for site characterization in plutonic rocks. The characterization approach during the siting stages would be to investigate progressively smaller areas in progressive greater detail (AECL, 1994b Section 5.1.2)

Site screening is the initial phase in site selection. During site screening large geographic areas of the Canadian Shield would be examined to find favorable (1) siting territories, (2) siting regions and (3) a potential candidate area. During siting territory suitable technical areas would be select based on decisions from the implementing organization such as the government and the owner of nuclear waste. Siting regions would involve reconnaissance investigations and an examination of existing information for prospective regions, during which a relatively large number of potential areas would be identified. The exclusion criteria for this stage would include seismic areas, areas with ancient rifts, areas that had a history of clustered earthquake activity, presence of mineral resources, geological and hydrological settings, degree of rock fracturing and environmental sensitivity. Identification of potential candidate areas would consider certain characteristics such as low topographic relief, few major lineaments, few open fractures between lineaments, absence of post-glacial faults, far from operating and abandoned mines, large areal extent of the plutonic rock, plutonic rock with uniform properties, extensive outcrop, an absence of valued environmental components (i.e. protected lands) and, an optimal location for construction and operation of the disposal facility (i.e. minimize transportation costs).

Next, through surface and subsurface characterization, the objective of site evaluation process would be to: identify one or more potential vault locations within each candidate area, identify a preferred vault location within each candidate area, identify the candidate site incorporating each preferred vault location, select a preferred route for transportation of nuclear waste to a disposal facility, confirm the suitability of the preferred site and, obtain approval for construction. Site evaluation would involve the use of field and laboratory investigations to obtain the knowledge and understanding of the important geotechnical and environmental conditions of the site. Site evaluation would be conducted by assessing relatively (1) large candidate areas of about 400 km^2 which would be subjected to detailed surface and subsurface investigations that would shrank the area for the (2) potential site to about 25 km^2, and finally to a (3) preferred candidate site of about 5 km^2 for construction and operation. In addition, during the reconnaissance studies of a candidate area, smaller study areas called grid areas of about 1-4 km^2 would be selected for detailed surface and subsurface (borehole) investigations. The study from the grid areas would provide detailed information of the geological, geomechanical and hydrogeological conditions of a candidate area.

From 1978 to about 1988 the Canadian Program carried out detailed surface characterization at three grid areas in the Canadian Shield: the granitic rocks at the Whiteshell and Atikokan Research Areas and gabbro at the East Bull Lake Research Area (AECLa, 1994, Section 5.8.1). These sites were selected because they offered opportunities to test and develop site evaluation methods in a variety of different lithologic and structural environments in the Canadian Shield (Davison et al., 1994, Section 2.4)

According to AECL (1994a, 1994b), the multidisciplinary investigations conducted at the surface-siting stage would include regional and detailed geological and geophysical mapping, borehole investigation (including geological core logging), geophysical testing, determination of geomechanical and hydrological properties, and determination of *in situ* stress. These investigations defined the tectonic style, groundwater flow regime, hydrogeochemistry, and location of major fracture zones in the rock mass at the prospective site. These studies also determined the general pattern and extent of smaller-scale fracturing, the distribution of permeability within the fracture zones and the regions of lower permeability (i.e., moderately and sparsely fractured rock), the mineralogy of fracture infilling and alteration, and the rock types and their petrography.

Through successive stages of site selection, characterization activities would be directed to confirm, define, or revise the following components of the site:

1. The general geology of the site and its potential for economic mineralization, as well as the search for guides to the dimensions, history, and fracture patterns of the rock

2. Location and characteristics of the groundwater flow network, including the major fault zones and fractures and the intact rock mass:
    - the fracture network
    - the hydrology of the fracture network
    - the groundwater chemistry and microbiology
    - the chemistry of the rock and fracture filling minerals

Information required in designing a potential facility so as to reduce thermal effects and excavation damage. This includes:

- thermal and mechanical properties of rock
- *in situ* stress field, thermal response of the rock mass
- coupled *in situ* response of the rock mass to induced effects of excavation and thermal loading.

Information from site evaluation would be combined to develop and calibrate regional scale model of the groundwater flow and solute transport of the candidate area. Sensitivity analysis with the model would assist in identifying where additional grid areas or borehole might be required to improve the understanding of the candidate area.

> One of the main concerns for the Canadian Nuclear Waste Program is the glaciation-deglaciation cycle. According to paleoclimate studies, glaciation and deglaciation has occurred nine times in the past 900,000 years. In each 100,000-year period, the ice cover builds up slowly for the first 90,000 years, whereas the melting and retreat phase last approximately 10,000 years. As melting and retreat occurs, it has a profound impact on the regional stress regime, hydrology, and climate (Peltier, 2003). The ice-sheet growth in the Canadian Shield during these periods effects mechanical loading of the ground rock due to mass of overlying ice, changes in the thermal regime of the rock matrix (including pore-water freezing, promoting fracturing), and increases in pore and rock pressure at depth.

According to Sykes (2003), the granitic rock of the Canadian Shield would provide a stable environment for a deep geologic repository, because of its wide spatial distribution, low topographic relief (in which driving forces are likely to be low) and low seismic activity.

2.2.1 SITE INVESTIGATION PARAMETERS

2.2.1.1 GEOLOGY AND STRUCTURE

As part of the development of site characterization technology and to find areas for detailed research (see three sites mentioned previously), geological reconnaissance in granite and gabro plutons were performed to obtain information on access, bedrock exposures and distribution of rock types, fracture density, analysis of large faults from lineament, and regional geophysics. The geological information obtained during site screening would be combined with a preliminary analysis of a large scale faulting obtained from airphoto lineament analysis, satellite radar and spectral image analyses, reconnaissance geophysical surveys, and maps of hydrological drainage catchments. More detailed ground mapping would be performed at the candidate areas. The main geological parameters for the recommended site screening stage are listed in Table 2.2-1.

Table 2.2-1. Geological and structural parameters recommended for site screening

Characteristics	Parameters
Lineament Analysis	Major fault and fracture orientation
Lithology	Major rocks types, petrology, mineralogy Mineral fabric Age of plutonic intrusion, rate of cooling, erosion rate Size and shape of pluton
Structure	Distribution, orientation, age relation of faults and fracture zones Fracture density

As part of the site evaluation, a detailed knowledge of the pluton such as size, shape, major lithologies (rock types), their geometry and the physical and chemical properties of the lithologies (mineral alteration, magma evolution, crystallization, hydrothermal fluid, thermal conductivity, strength, elasticity and fractures) would be evaluated to access the hydrogeologic properties of rocks that control contaminant transport. The main surface investigation would include systematic geological mapping and sampling of lithology and structural fabric elements in outcrop, careful examination of topographic maps to access faults and fracture zones and, mapping fractures in outcrops. Borehole investigation would be important to examine the subsurface character of major lithologic contacts or surface lineaments. Core samples would be selected for laboratory examination and determination of petrological, hydrological, chemical, structural, mechanical and thermal properties.

Structural style is important for evaluating the long-term stability of the rocks and the tectonic history of the region. Faults and fractures are the major structural features in the Canadian Shield, controlling groundwater movement in the granitic rocks. During site evaluation, detailed information on locations, dimensions, orientations and relative ages of the fractures at the site would be required to reliably predict the fracture patterns within the blocks of rocks which are bounded by the larger fault zones and to confirm the suitability of any candidate area for waste disposal.

During the development of the research program, AECL constructed an Underground Research Laboratory (URL) in the Lac du Bonnet batholith. This batholith, intruded over 2.6 billions year ago, is part of the crystalline rock of the Canadian Shield. The URL in granite has been used for large-scale testing and *in situ* engineering and performance-assessment-related experiments investigating key aspects of deep geological disposal. At the URL, three low-angle reverse faults and three main fracture domains were identified, on the basis of fracture frequency. These are intense, moderate, and sparsely fractured domains. Surface-based characterization of the URL site is described in detail in Davison et al. (1994, Section 7.2). The main parameters considered to be necessary for site evaluation are listed in Table 2.2-2.

Table 2.2-2. Geological parameters recommended for site evaluation

Method	Parameters
Field Investigation	Rock types Shape and size of plutons Percentage of dikes Geometry and distribution of dikes and veins Degree of metassomatic granitization Mineral alteration Distribution of U, Th and rare earth elements (REE)

Structures	Fractures (locations, dimensions, relative age, density, aperture, infillings) Faults (locations, orientations, extents, interconnections)
Rock Sampling	Mineralogy Fabric/deformation history Fracture filling minerals
Drill Core Analyses	Fracture density, spacing Fracture orientation Fracture aperture Fracture connectivity Fracture filling minerals Mineral alteration Rock type
Borehole surveys	Fracture location, orientation Lithologic variations Fracture infillings

2.2.1.2 GEOPHYSICAL SURVEY

A broad spectrum of geophysical measurements, using satellite, airborne magnetic, electromagnetic imagery, and radiometric survey, combined with aerial photography, were performed to identify major structural lineaments, topographic features (such as dikes and faults) and to identify radiometric anomalies (radiometric survey) (Davison et al., 1994, Section 4.4, Table 4-1). During site screening stage, the main parameters identified by the proposed geophysical survey (combined with LANSAT 5) included major lineaments and their spatial frequency and distribution, boundaries of granitic rocks, overburden thickness, fracture zones, and depth of batholiths. Table 2.2-3. lists recommended geophysical survey parameters to obtain at the site screening stage.

Table 2.2-3. Geophysical parameters recommended for site screening

Method	Parameters
Airborne EM and VLF-EM	Lithologic variations Faults, fractures zones Thickens of overburden deposits
Aeromagnetic	Shape, depth and boundary of pluton Subsurface lithologic variations Lineaments
Airborne Radiometric	Boundary of pluton
Gravity	Shape, depth, boundary of pluton, and rock units
Surface electrical	Large structural features, lithologic contacts, major fracture zones
Reflection seismic	Large fracture zones, lithologic variations in subsurface

During the site evaluation stage, regional reconnaissance airborne and land-based surface-based geophysical surveys (surface VLS/EM, radar, seismic reflection, and sonar reflection) would be conducted to complement the information from the preceding site screening phase and to understand the main lithologic and structural features of the candidate area.

The borehole geophysical surveying would be used to identify variations in rock properties and lithology as well as to identify fracturing in the rocks surrounding the borehole. Detailed descriptions of the recommended characterization methods used for the deep boreholes are found in Davison et al. (1994, Section 6.2.2, Table 6.5). The main recommended parameters obtained from borehole geophysical surveys are listed in Table 2.2-4.

Table 2.2-4. Geophysical parameters recommended for site evaluation

Surface	Parameters
Airborne magnetic Gravity Side-scanning radar survey	Depth, shape and lithological boundaries, faults and fractures Shape, depth and boundaries of pluton, distribution of lithologies Linear anomaly caused by lithology, fracture, fault
Ground based gravity Reflection seismic profile Ground penetrating Radar	Shape, depth, and boundaries of pluton Subsurface lithological variations, location of major fracture zones or faults Location of low dipping fractures up to 100m depth
Borehole	
Geophysical logs	Fracture depth, lithologic boundaries
Acoustic televiewer	Location of fracture
Single hole radar survey	Location, orientation of fracture away from borehole
Crosshole radar or seismic survey	Continuity and geometry of features between boreholes

2.2.1.3 HYDROLOGY AND HYDROGEOLOGY SETTINGS

Hydrology and hydrogeology include study of weather and climate, the topography of the land, and the occurrence, movement, and chemistry of surface water and groundwater. Hydrogeological setting includes the rate and directions of groundwater flow, recharge/discharge areas, water-rock and fracture-rock interactions. During site screening, hydrogeological knowledge will generally be limited by a lack of subsurface information (Davison et al., 1994, Section 3.5, 4.4.3). Most of hydrologic information would come from aerial inspection surveys, satellite images and topographic maps. Surficial geological deposits and rock outcrops would be examined for hydrogeological features to obtain information on groundwater movement within the candidate region.

The surface and groundwater flow system of plutonic rock is greatly affected by structures such as faults and fractures, as well as by the permeability, porosity, and groundwater pressure within the rock. In the Canadian Shield, a flat topography provides less variation in groundwater pressure, a lower hydraulic gradient, and therefore a slower groundwater flow (Davison et al., 1994, Section 3.5). During site screening, the recommended parameters that would be obtained are listed in Table 2.2-5.

Table 2.2-5. Hydrology and hydrogeological parameters recommended for site screening

Methods	Parameters
Satellite images, Air Photography, Topographic maps	Drainage (recharge/discharge areas) Runoff patterns Water level fluctuation
Mapping location of seepage and spring locations	Groundwater recharge and discharge rates

During the site evaluation stage the main surface investigation would include surveys of physical and chemical characteristics of groundwater springs and seepages or other evidences of discharge; surveys to determine surface water catchment areas, lake areas and lake depth; surveys to establish sediment accumulation rates in water bodies and the thickness of mixed sediments and; developing monitoring network for meteorological, hydrological observations.

Knowledge of the amount and temporal and spatial of precipitation, runoff, infiltration and recharge in the region surrounding the disposal site would be needed to construct a reliable model of the groundwater flow conditions. Thus, a variety of physical properties of the groundwater at the site must be determined to establish the groundwater flow rate and flow system. Knowledge of the properties of the groundwater transport pathways from vault depth to surface would be also used to develop and calibrate mathematical models which simulate long term movement of contaminants from the disposal vault to the geosphere. Matrix hydraulic conductivity or permeability, matrix porosity, spatial and temporal distribution of groundwater pressure and the compressibility of the groundwater and the rock matrix/fracture network needed to be determined in order to establish the rate and flow paths of groundwater.

Hydrogeological investigation conducted in borehole would include a broad range of permeability, porosity, natural groundwater pressure measurement performed in single as well in multiple boreholes.

Results from investigations and research indicate that the major structural features controlling groundwater movement in plutonic rock are the fracture zones. Fractures (including faults) are found at all depths, and the permeability of fracture zone varies, depending on aperture, fracture spacing, density, and connectivity.

Table 2.2-6 lists the main recommended hydrological parameters to obtain during site evaluation:

Table 2.2-6. Hydrology and hydrogeological parameters recommended for site evaluation

	Parameters
Meteorology	Temperature Wind speed and direction Evaporation rate Precipitation Run off rates Level of surface water Spring locations (recharge/discharge)
Rock/sediments	Porosity fracture network
Borehole	Hydraulic conductivity or permeability Porosity Groundwater pressure Compressibility Hydraulic head Hydraulic fracturing (stress)

2.2.1.4 GEOCHEMISTRY AND HYDROGEOCHEMISTRY

Regional reconnaissance studies of spatial and temporal variations in ionic content such as presence of salts, and measurement of Cl^- of the surface waters in a potential candidate area can provide information about groundwater discharge areas. Mapping variations of electrical conductance and using airborne or satellite thermal infrared imagery would be useful to detect anomalous patterns in the temperature of surface waters. Soil gas measurements have been used to detect locations where deep groundwater might be discharging from subsurface bedrock fractures. Table 2.2-7 lists the main parameters that would be obtained during the recommended site screening process.

Table 2.2-7. Geochemical and hydrogeochemical parameters recommended for site screening

	Parameters
Surface water analysis	Ionic content (Cl^-, presence of salt)
Electrical conductance and/or	Temperature
Airborne or satellite thermal infrared Imagery	Location of discharge
Soil gas analysis	Radon and Helium

Development of geochemical characterization techniques of host rock, fracture-infilling mineral, groundwater, and pore water have provided data for flow modeling and safety assessment, as well as information on groundwater ages, sources of salinity, and rock-water interactions. With this in mind, reconnaissance studies were carried out to locate groundwater discharge areas, determine the chemical composition of the water (through existing water quality information or water analysis), and locate gas discharge areas in soils and along fractures.

During site evaluation stage, more detailed investigations would need to be conducted, including laboratory analysis of rock specimens and core samples. The knowledge of chemistry of the groundwater would help to define the groundwater flow patterns at the site and surrounding area as well to determine the ratio of radionuclide migration to the geosphere. The main surface investigation would include surveys of levels of helium and radon gases in soils and surface waters to help to delineate groundwater recharge and discharge conditions, surveys of chemical characteristics of spring and seepages, chemical analysis of major and minor elements of whole rock and infilling minerals and, radiometric dating of primary and secondary minerals. The parameters that would need to be obtained during site evaluation are listed in Table 2.2-8.

Table 2.2-8. Geochemical and hydrogeochemical parameters recommended for site evaluation

	Parameter
Rock analysis	Major and minor elements in rock and fracture fillings Radiometric dating
Surface investigation	Radon, Helium in soils and surface water Chemistry of springs and seepages Recharge/discharge conditions

More specifically, the main recommended hydrogeochemical parameters to be obtained from boreholes include: total dissolved solids (TDS) contents, Eh, pH, elemental concentration (anions, cations, trace elements, dissolved organic carbon, colloids), and isotopic data (environmental isotopes, carbon isotopes, sulphate isotopes, halogen isotopes, strontium isotopes, uranium and radium isotopes, radon, dissolved gases, dissolved inert gas isotopes). Detailed descriptions of groundwater sampling can be found in Davison et al. (1994, Section 6.2.5, Table 6.4). The parameters are summarized in Table 2.2-9.

Table 2.2-9. Geochemical and hydrogeochemical parameters from boreholes

Category	Species/Element
Anions	HCO_3, SO_4, Cl, Br, F, NO_3, I
Cations	Na, Ca, Mg, K, Sr, Si, B
Trace Elements	Li, Fe, Mn, V, Al +Others
Dissolved Organic Carbon	Organic C
Colloids	Colloidal fractions
Environmental Isotopes	^{2}H, ^{3}H, ^{18}O
Carbon Isotopes	^{13}C, ^{14}C
Sulphate Isotopes	$S^{18}O_4$, $^{34}SO_4$
Halogen Isotopes	^{36}Cl, ^{129}I
Strontium Isotopes	$^{87}Sr/^{86}Sr$
Uranium and Radium Isotopes	U, $^{234}U/^{238}U$, ^{226}Ra
Radon	^{222}Rn
Dissolved Gases	H^2, He, O^2, N^2, CO^2, CH^4, Ar, H_2S
Dissolved Inert Gas Isotopes	He, $^{3}He/^{4}He$, $^{22}Ne/^{21}Ne$

The pH, Eh, and elemental concentrations data were used in study of rock-water interaction. The isotopic data were used to delineate rock-water interaction and to determine the relative age of the groundwater.

The hydrogeochemical data indicate that below 500 m at the URL and elsewhere in the Canadian Shield, groundwaters are very saline, reducing, and old (Gascoyne, 2000). Isotopic studies have shown that the groundwater changes with depth and with increasing residence times in fractures to over 1 million years below 400 m (Gascoyne, 2000).

2.2.1.5 STRESS FIELD

Knowledge of the stress field in plutonic rock can be used to understand the permeability distribution of faults and fractures (possibly affecting the groundwater system during site characterization) and to assess the long-term stability of an underground repository.

During the recommended site screening process, the large-scale rock stress was of interest for evaluating Shield stability. The *in situ* stress state comprises the effective lithostatic load, active tectonic stress, and remnant stress. The orientation of paleostress field could be used to constrain the stress heterogeneity and relationship with larger structural features (Davison et al., 1995, Section 5.5). The parameters are summarized in Table 2.2-10.

Table 2.2-10. Recommended stress field parameters for site screening

Stress field	Parameters
	Effective lithostatic load Active tectonic stress Remnant stress Paleostress orientation

The stress field in the plutonic rock can be also determined by hydraulic fracturing performed in boreholes. It would provide information on magnitude (and in some cases orientation) of state of stress in rock. Detailed descriptions of hydraulic fracturing for *in situ* stress measurement are found in Davison et al. (1994, Section 6.2.6).

2.2.1.6 ROCK MASS PROPERTIES

Rock properties would be determined in the laboratory using core samples from drillcore. The main developed and recommended methods included analysis of pore structure in fracture and rock matrix, as well as determining the thermal, mechanical, and magnetic properties. Table 2.2-11 illustrates the main laboratory rock properties.

Table 2.2-11. Rock-mass properties recommended

Laboratory Rock Properties	Parameters
Pore structure of fracture and matrix	Tortuosity Porosity (surface area, pore aperture) Micromorphology of pore Diffusion Permeability
Thermal properties	Thermal expansion Thermal conductivity Thermal diffusivity
Mechanical properties	Strength Elasticity Deformation
Magnetic properties	Magnetic susceptibility, magnetic anisotropy

2.2.2 SUMMARY

In Canada, the stable tectonics, as well as the wide exposure and distribution of plutonic rock in the Canadian Shield, make plutonic rock a suitable choice for storage of nuclear waste.

The Canadian Shield was used to develop site characterization technology and recommend approaches for site screening and site evaluation. The method implemented by the AECL included a multidisciplinary and staged approach (i.e. from regional scale to candidate area to candidate site). The recommended methods for site characterization were often the same at each stage (i.e. site screening and site evaluation) but as each site was narrowed down from a larger area to a smaller more specific site, characterization was carried out with increasing detail. The information obtained from site characterization was then used to construct conceptual site and numerical models. The results were used to reduce uncertainties in various parameters and models, to refine the understanding of the rock mass, geochemical and hydrogeological conditions of plutonic rocks, and to integrate these in the performance assessment models.

For the Canadian program site characterization, fracture characterization was very important, because it enabled investigators to identify different hydrogeological, geochemical, and geomechanical characteristics of plutonic rock. The plutonic rock of the Canadian Shield provides many advantages for safety storage, such as the large size and extent of plutonic bodies, extensive outcrops, a stable geological setting, with known seismic zones or no volcanic activity, and low topographic relief.

2.2.3 REFERENCES

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2.3 The Japanese Program

The Japanese Island arc is one of the best-studied active arc-trench systems in the western pacific (Taira, 1999). While the geological environment in most of Europe and North America is relatively stable, the Japanese Island is geologically and tectonically unstable. The island is located along active plate boundaries, resulting in frequent volcanic activities and crustal movements such as faulting, folding, uplifts and subsidence. Thus, the distribution of geological formation, topography features, major structural discontinuities, depth of water table and groundwater chemistry are controlled by the active geological system.

Site characterization for the Japanese nuclear waste program is focused on developing scientific expertise and improving the methodology and technology by which to understand geological, structural, hydrological, geochemical, and rock mechanics properties. Currently, Japan has two underground laboratory projects under construction, one in crystalline rock, a fractured medium (Mizunami Underground Laboratory—the MIU site) and the other in sedimentary rock, a porous medium (Horonobe Underground Research Laboratory). Both these projects follow the same approach, composed of three phases as follows:

- Phase 1. Surface-based investigation
- Phase 2. Construction of the underground laboratory
- Phase 3. Operation phase

Although the schedule for the MIU and Horobone sites is slightly different, both are currently in Phase 2 (shaft construction). The underground laboratory at MIU site is planned to have two levels, at depths of 500 m and 1,000 m, whereas the Horonobe Underground Research will have one level at a depth of 500 m.

2.3.1 CRYSTALLINE ROCK—OVERVIEW OF THE MIZUNAMI UNDERGROUND LABORATORY (MIU) IN TONO AREA

An extensive geological, geophysical, hydrogeological, hydrogeochemical and rock-mechanics investigation has been conducted in the Tono Area. Site characterization in the Tono Area includes data from boreholes drilled for the uranium exploration at

Tono Mine, boreholes for regional hydrogeological studies (RHS), deep boreholes at the Shobasama site, and ongoing characterization of the MIU site (JNC, 2000b, 2001, 2002, 2003; Kumazaki et al., 2003).

Surface geological characterization in the Tono Area started in the 1960s as part of the uranium exploration program. The Tono Mine is located a few kilometers west of the MIU site. A substantial amount of geological information has been accumulated since the beginning of the uranium exploration program. The shaft and gallery leading to the Tono Mine allow access to sedimentary rocks, including uranium deposits, at depth over one hundred meters. Surveys conducted in this region include studies of groundwater hydrology and geochemistry, mass transport via groundwater, and the effect of excavating galleries on the geological environment (Yusa et al., 1993). Knowledge of geological conditions in the mine subsurface has been used to develop models for the MIU project.

During the period of 1996 to 1999, preliminary site investigation and drill core was conducted at the Shobasama Site, the location of the underground facility. However, in 2002, the project in the Shobasama was relocated to a new site about 2 km southwest—the MIU Site. The MIU Site is currently the host for the underground laboratory, and the shaft is under construction (JNC, 2002, 2003; Kumazaki et al., 2003).

A geoscientific research program in the Tono area includes investigation of the groundwater flow system (over a 100 km^2 area) and regional geological mapping. Data from these programs have provided important knowledge for the development of the MIU-project conceptual models (Shigeta et al., 2003).

Specific studies conducted for site characterization in the Tono Area include:

- Geological and structural investigations
- Surface hydrological investigations
- Geophysical investigations
- Borehole investigations (geology, hydrogeology, hydrogeochemistry, and rock mechanics)

2.3.1.1 GEOLOGICAL AND STRUCTURAL INVESTIGATIONS

Geological and structural investigations were conducted to identify the surface distribution of lithofacies, depth of sedimentary rocks, lithological contacts, and characterization of fracture and faults (type, orientation, width of damage zone, mineral composition) (JNC 2000b, 2001, 2002, 2003a).

The Toki granite (of Cretaceous age) is the basement of the Tono Area. The granite intruded the Paleozoic-Mesozoic sedimentary rock of the Mino Tamba Belt and granite is overlayed by sedimentary rocks (mostly tuffaceous sandstone, mudstone, and conglomerate intercalated with lignite layers) of the Miocene and Pliocene age. Detailed geological description is found in JNC (2000a Section 3) and Kumazaki et al. (2003 Section 2).

Remote sensing techniques were employed at an early stage of site characterization to obtain information on topography, vegetation distribution, sedimentary layers, possible lithological distribution, lineaments/faults distribution, and landslide distribution (JNC, 2000b). Regional faults and fracture zones were investigated using lineament analysis. Satellite images (Landsat TM Imagery and French SPOT satellite) and aerial photography was useful in identifying trends and lengths of major discontinuities and in confirming locations of active faults. In addition, such analyses provided useful information on the tectonic stress distribution at the regional scale.

The main faults identified near Shobasama site are the Yamada Fault, the Shizuki Fault, and the Tsukiyoshi Fault. At the Shobasama site and at the Tono Mine, the EW-oriented Tsukiyoshi Fault—a reverse fault—is considered the major fault structure in the area. Although it has no surface expression, it is observed at depth at the Tono Mine and at drill core retrieved from 1,000 m depths. Estimated fault displacement is about 30 m. The fault damage zone is inferred to be >100 m on each side of the fault. Structural, mineralogical and geochemical evidence suggest that the fault has been subjected to more than one phase of deformation (JNC, 2001; Hama et al., 2003).

At the new MIU site, located in the hanging wall of the Tsukiyoshi Fault, several NNW trending structures are mapped. A NNW normal fault is inferred from lineament analysis, reconnaissance survey, seismic survey, and drill core studies (Kumazaki et al., 2003).

Because of the lack of bedrock exposure, (i.e., granite), a large part of the geological information at the MIU site has been obtained from borehole data and geophysical investigation (Shigeta et al., 2003). For these borehole investigations, geological studies included core logging, borehole geophysics, and borehole TV (BTV) surveys for both shallow deep and boreholes. Information about Toki granite is mainly from deep boreholes (1,000 m) drilled at the Shobasama site. At the new MIU site, boreholes drilled up to 200 m have reached the upper weathered zone of the Toki granite.

The main geological and structural parameters obtained from borehole and core data are:

1. Rock type, contact depth, grain size, texture, weathering, alteration, RQD, fracture distribution, density, shape, aperture, type, and mineral filling are obtained from drill-core samples. Borehole TV investigation recorded images of textural variations in the granite and fractures along the borehole wall such as depth, fracture shape, orientation, width, aperture and presence of fracture filling and zones of mineral alteration. Based on modal composition analysis, the granite is classified mainly as biotite-granite. Toki granite Granite is divided by textural variations into coarse- medium- and fine-grained biotite granite.
2. According to structural information of fractures orientation, distribution, and frequency, the granite was divided into three main domains: an upper fractured zone, a moderately fractured zone, and a fracture zone along fault zone (JNC, 2001).

A summary of the main geological and structural parameters is shown in Table 2.3-1.

Table 2.3-1. Geological and structural parameters

	Parameters
Geology	Depth, lithological contacts, stratigraphy Rock types, thickness of sedimentary layers Type of dikes, orientation, width Petrology, mineralogy of weathered/fresh granite Clay types and filling minerals in fault zone
Structural	Lineaments orientation Fault geometry, length, orientation Fracture geometry, orientation (strike/dip), shape Depth of unconformities Dikes orientation, width
Drill core/Borehole Investigation/ BTV	Rock type (petrology, mineralogy, mafic content) Contact depth Grain size Textural variations Degree of weathering/alteration RQD Fault and fracture distribution Fracture density Fracture shape Fracture aperture Type and mineral filling

2.3.1.2 GEOPHYSICAL INVESTIGATION

Using updated technologies such as high-resolution satellite imagery, a combined electromagnetic and detailed refraction/reflection survey was able to acquire subsurface information, such as depth of unconformity, location of major faults, lithological contacts, and thickness of sedimentary layers.

At the regional scale, geophysical surveys such as regional airborne geophysical surveys (including airborne magnetic, airborne electromagnetic, and airborne radiometric surveys were conducted with the purpose of identifying and estimating the main lithological contacts, formation thickness and depth, and locations of structural discontinuities such as faults and fractures. Site-scale ground electromagnetic (MT and CSMT methods) and seismic surveys were used to estimate depth and lithological contacts. According to JNC (2001), accurate results were not obtained by EM (electromagnetic telluric) and electric surveys.

In addition, apparent resistivity, density, neutron porosity, and P-wave velocities were obtained from borehole geophysical surveys for the three 1,000 m deep boreholes at Shobasama site. Table 2.3-2.summarizes the main parameters obtained from geophysical surveys.

Table 2.3-2. Geophysical parameters

Method (Regional)	Parameters
Airborne magnetic	Boundaries of granite, thickness of sediments, lineaments Density, lithology
Airborne electromagnetic	Thickness of sediments, contact sediment/granite
Airborne radiometric	Concentration of uranium, thorium and potassium
Ground geophysical	
Ground electromagnetic (MT and CSMT methods)	Depth of unconformity sediment/granite
Seismic Reflection/Refraction	Fault length, fracture zones, unconformities
Borehole log	
Electrical resisitivity	Fracture density
Density logging	Density
Neutron and gamma-ray logging	Porosity
Temperature logging	Temperature (geothermal gradient)
Caliper logging	Fracture, porosity, lithology
Acoustic logging	Velocity of intact granite, faults and fracture zone
Crosshole seismic radar survey	fractures, continuity and geometry of features between boreholes

2.3.1.3 HYDROLOGICAL AND HYDROGEOLOGICAL INVESTIGATIONS

Information on parameters used for surface hydrological investigation includes meteorological and river-flow measurements. Several meteorological monitoring stations were used to develop baseline meteorological data (e.g., precipitation, evapotranspiration, wind velocity, wind direction) and information on surface hydrology (e.g., water level, water budget, soil moisture, and drainage basins), providing input for hydrological boundary conditions. Boreholes for long-term monitoring of piezometric conditions have been drilled. These data are used to develop water-balance calculations for input to the hydrogeological flow simulations. In addition, surface water monitoring and groundwater simulation was conducted to estimate groundwater recharge (JNC, 2000b).

The main parameters obtained from hydrogeological investigations from borehole (i.e., geophysical logging, borehole TV, and, packer testing) and core data are: hydraulic head, hydraulic conductivity, hydraulic gradient, permeability, specific storage coefficient, porosity, pore pressure, flow rate, and transmissivity (JNC, 2000b; 2001; 2003). These data were used for hydrogeological-model and groundwater-flow simulation. Hydraulic properties such as location of major drilling, fluid loss, high transmissivity, and hydraulic conductivity are greatly enhanced by major fractures and fault zones. JNC (2000b; 2001; 2003) summarizes the hydrogeological investigations in the Tono Area.

The conceptual geological and hydrogeological model was constructed for the Tono Mine and MIU site based on surface mapping, geophysical surveys, and distribution of hydraulic conductivities and hydraulic heads (JNC, 2000; JNC 2001). The main hydrogeological parameters in the Tono Area are listed in Table 2.3-3.

Table 2.3-3. Summary of hydrological and hydrogeological parameters

Hydrology	Parameter
Metereology/ Surface hydrology	Precipitation Infiltration Evapotranspiration Water level Water budget Soil moisture Recharge Discharge
Borehole Hydrologeology	Hydraulic head Hydraulic conductivity Hydraulic gradient Permeability Specific storage coefficient Porosity Pore pressure Flow rate Transmissivity

Hydrogeological investigation from deep boreholes suggests that flow is controlled by topographical gradient (Koide et al., 1996). Results from hydrological conductivity studies in sedimentary rock and granite indicate that in the MIU site shows higher hydraulic conductivity than both the Shobasama site and Tono Mine. In addition, the hydraulic conductivity of the Tsukiyoshi fault and the NNW fault suggests that both act as barriers to flow across it (JNC, 2000, Section 3.2; Kumazaki et al., Section 4; Hama et al., 2003).

2.3.1.4 GEOCHEMICAL AND HYDROGEOCHEMICAL INVESTIGATION

Surface water chemistry from river and groundwater samples was used to estimate the origin and residence time of the surface water, groundwater chemistry, and presence of microbes in the groundwater.

The main hydrogeochemical investigations are aimed to identify:

- Chemistry of groundwater parameters such as pH, Eh, total dissolved solids (TDS), elemental composition (e.g., Si, Ca^{+2}, Na^{+}, HCO_3^{-}+CO_3^{-2}, Fe^{2+}), Fe^{3+}/Fe^{2+} for oxidation-reduction

- Rock isotope parameters such as concentration of gas Radon, radioactive minerals such as thorium, uranium, potassium
- Groundwater isotope such as hydrogen-oxygen isotope ratio, ^{14}C for age dating
- Microbe studies in groundwater to determine bacteria population and type
- Temperature
- Electrical conductivity

Fracture and fracture zones play a dominant role in the chemical evolution of groundwater, controlled mainly by water-rock interactions and chemical reactions that in turn depend on the rock mineral composition. Results from hydrogeochemical investigations indicate that the groundwater in the Toki granite is of meteoric origin and that the residence time is ~1,000 years (JNC, 2001, Section 4.3; JNC 2000b, Section 3.4). Based on chemical reactions, a conceptual model of the evolution of water-rock interaction in the Tono Area is documented in JNC (2000, Section 3.4, Figure 3.4.8).

In addition, analysis of groundwater, fracture filling minerals, and fault zone mineralogy were useful for identifying water-rock interaction processes along the fault zone. Recent studies of the NNW fault also suggest that the fault is a potential hydraulic barrier to flow (Kumazaki, 2003 Section 5).

Rock geochemistry such as major and minor elements, isotopes for radiometric dating and REE analysis were conducted in drill core samples. Results are reported in Chengdong, 2000.

The main geochemical parameters are listed in Table 2.3-4.

Table 2.3-4. Summary of geochemical parameters

	Species/Element
Groundwater Geochemistry	pH Eh Total Dissolved Solid Content (TDS) Temperature Electrical conductivity Chloride content Colloids Microbes
Major elements	Si, Ca^{+2}, Na^{+}, HCO_3^{-}+CO_3^{-2}, Fe^{2+}
Isotopes	^{2}H, ^{3}H, $\delta^{18}O$, δ13C, ^{14}C, $^{36}Cl/Cl$
Radiogenic Isotopes	Th, U, K, Rd
Rock chemistry	Major and minor elements in rock and fracture fillings Major elements (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, H_2O) Minor elements (F, Cl, Sr, Rb, Li, Zn, Cu, Pb, Sn, Be) Radiometric dating ($^{87}Sr/^{86}Sr$, U-Th-Pb) REE (rare earth elements)

2.3.1.5 ROCK MECHANICS

Rock mechanical data were obtained by a variety of methods, including borehole geophysics, in situ hydraulic fracturing, to determine *in situ* stress state, and a variety of laboratory tests were performed on core to determine rock-mass properties. Mechanical properties derived from borehole investigations consist of *in situ* stress measurements from hydraulic fracturing to obtain stress distribution, magnitude, and orientation; as well as from core samples, to obtain uniaxial compressive strength, Young's modulus, Poisson's ratio, tensile strength (by Brazilian test), cohesion, and internal friction angle (JNC, 2001). Determined physical properties of rock include apparent density, water content, effective porosity, and seismic wave velocity. The main rock mechanics and rock physical parameters are summarized in Table 2.3-5. The change of stress occurs at similar depths within high-density fracture zones. *In situ* stress also varies with depth, as described in JNC (2001, Section 4.4.2).

Table 2.3-5. Rock mechanics and rock physical parameters

	Parameter
Mechanical properties	Coefficient of elasticity Unconfined compressive strength Poisson's ratio Tensile strength Cohesion Internal friction angle
Physical properties	apparent density RQD effective porosity water content seismic wave velocity
In Situ stress determination	Hydraulic fracturing AE/DRA

2.3.1.6 TRANSPORT PROPERTIES

Investigation of transport properties in the Toki granite was carried out in the Tono Mine. The Tono Mine is a natural analogue for radionuclide transport because uranium deposits there are considered to have formed by leaching of natural uranium from granite to the sedimentary rocks (JNC, 2000, Section 3.6). Rock samples from the Tono Mine were investigated to characterize the transport of uranium through pore space. Sorption experiments using ^{233}U as tracer were conducted in the granite and sedimentary rocks (Yoshida, 1994; Ota et al., 1994). A description and results related to transport properties are described in JNC (2000, Section 3.6).

2.3.2 SEDIMENTARY ROCK—OVERVIEW OF THE HORONOBE UNDERGROUND RESEARCH LABORATORY PROJECT (HORONOBE URL)

The host rock for the Horonobe URL is sedimentary rock (diatomaceous mudstone and hard shale) of the Neogene age. The URL shaft and drifts are likely to be placed in this medium. Phase 1 of the geoscientific research for the Horonobe URL started in 2000, and will take place over approximately six years (Goto and Hama, 2003a, b).

During Phase 1, data from surface-based investigations (airborne surveys, geological mapping, ground geophysical survey, and borehole investigation) were conducted to obtain data on the geological environment and plan the construction of the

URL. Two vertical boreholes of about 700 m depth, and several boreholes up to 500 m depth, have been drilled in and around the URL area to provide data for geological modeling and URL construction (Goto and Hama, 2003b; Yamasaki, 2004).

2.3.2.1 GEOLOGICAL INVESTIGATIONS

Geological characteristics and distribution of geological formations were obtained from previous work (literature survey), while the lineament analysis was derived from satellite images, aerial photography, surface mapping, and petrological, mineralogical, and microfossil analysis (Goto and Hama, 2003a). The Horonobe URL is located in a tectonically active region characterized by earthquake swarms. Evidence of Holocene wetland subsidence and terrace uplift can be found along the coastal area (Yamasaki, 2004). In addition, the area is located in a potential oil/gas field. The main geological parameters are listed in Table 2.3-6.

Table 2.3-6. Main geological parameters

Geological	Parameters
Mapping	Lineaments Fault/ fracture zones
Core samples	Stratigraphy Degree of diagenesis Lithology Fracture distribution Mineralogical composition microfossils

The main geological formations in the URL area are diatomaceous mudstone (Koetoi Formation) overlain by hard shale (Wakanai Formation). They are considered soft rock because of their mechanical and physical properties. The presence of Opal CT and Opal provide information on silica diagenesis (Matsui, 2004). A transition zone between those two formations is inferred from rock-mechanics and hydrogeological analyses (Matsui, 2004; Hama 2004).

The main fault in the URL area is the Omagari Fault, a reverse fault with a left-lateral strike slip component. Maximum folding displacement is estimated to be over 1,000 m. The fault core is about 10 cm, and the damage zone of the fault is inferred to be >300 m (Hatanaka, 2004, Yamasaki, 2004). Several high-density fracture zones are observed in the drill core, related to faulting and folding. Presence of methane is observed in the shallow borehole (Matsui, 2004).

As part of the long-term stability study, seismographs were installed to conduct seismic monitoring in northern Hokkaido. In addition, measurements on crustal deformation related to fault, folding, uplift/subsidence, and the history of sea-level change were also part of the Phase 1 investigation task (Goto and Hama, 2003a,b). Seismological and diastrophic studies have been carried out to monitor micro-earthquakes and movements of the crust produced by tectonic process in the Horonobe area (JNC, 2004).

2.3.2.2 GEOPHYSICAL INVESTIGATION

Airborne surveys including magnetic, electromagnetic, and natural gamma-ray surveys were conducted for general surface characterization and for selecting boreholes locations. The main aim was to obtain information on structure (faults and folds) and the regional distribution of geological formations. Regarding potential URL locations, electromagnetic, seismic and gravity surveys were conducted to obtain information on subsurface geological and structural data (fault and fracture zones), as well as the geometry of geological formations and structures (Goto and Hama, 2003a, b). Geophysical parameters are summarized in Table 2.3-7.

Table 2.3-7. Summary of geophysical parameters

Regional Geophysical Survey	Parameters
Airborne magnetic Airborne electromagnetic Airborne gamma-ray	Geological formations, structures (faults, fractures and folds) at about 150 m depth Geological formations, structures (faults, fractures and folds) up to 2,000 m depth Natural radioactivity (U, Th, K)
Site-specific	
High density reflection seismic survey Gravity survey (05) Electrical survey Audio frequency magnetotelluric survey	Lithological contacts, structures (fault), geometry of formations Geological formation and structure by density contrast Structure (fault) Structure (fault)
Borehole/drill core sample	
Multi-offset VSP (vertical seismic profiling) Sonic logging	Lithological contacts, boundaries Porosity Density

The main structure in the region, Omagari Fault, was inferred by different geophysical tools such as seismic reflection survey, audio-frequency magnetolelluric survey, and borehole investigation (Matsui, 2004).

2.3.2.3 HYDROLOGICAL INVESTIGATIONS

Data acquisition activity for hydrological investigations include surface hydrological parameters such as precipitation, temperature, humidity, wind direction and velocity, evapotranspiration rate, river flow rate and water table—to estimate recharge and discharge (Goto and Hama, 2003b). Hydrogeological parameters such as head, transmissivity, and hydraulic conductivity are gathered from boreholes drilled in the URL area (Hama, 2004). Methane gas was observed during borehole investigations. The main hydrological parameters are summarized in Table 2.3-8.

Tracer experiments using core samples provide information on transport properties of fractures such as effective diffusion, transmissivity, dispersivity, hydraulic aperture and transport aperture (Shimo et al, 2003).

Table 2.3-8. Hydrological parameters

Hydrology	Parameters
Metereologica/surface Hydrologic	Precipitation Temperature Infiltration Humidity Wind velocity Wind direction Evapotranspiration Rive flux
Hydrological	Head Transmissivity Hydraulic conductivity

2.3.2.4 HYDROCHEMICAL INVESTIGATIONS

This investigation is still ongoing. Groundwater samples are being collected from packed-off sections of the boreholes and by squeezing of drill cores (Goto and Hama, 2003a; Hama, 2004). The main characteristics of the groundwater in the Horonobe area are its salinity and the presence of dissolved methane. The main geochemical parameters are listed in Table 2.3-9.

Table 2.3-9. Hydrochemical parameters

Geochemical Investigations	Parameters
	pH
	Eh
Dissolved gases	H_2, He, N_2, O_2, CO, CO_2, hydrocarbon
Isotope	D/H, $^{18}O/^{16}O$, ^{14}C, $^{13}C/^{12}C$, ^{36}Cl
Major elements	Na, K, Mg, Ca, Si. F, Cl, Br, I, alkalinity
Minor elements	Al, Fe, Li, Sr, Mn, S. T.P, PO_4 T.N, NO_{2-}, NH_4,
	Microbe types
	Methane gas

2.3.2.5 ROCK MECHANICS

Measurement for rock mechanics were conducted in drill core samples. The main studies conducted in the laboratory were rock physical-properties testing, seismic velocity measurements, uniaxial compressive tests, a triaxial compressive test, and slacking tests in core. *In situ* stress measurements were carried out in boreholes (Matsui, 2004; Morioka, 2004, Section 2 and 5.1). Table 2.3-10 lists the main rock mechanical and physical parameters:

Table 2.3-10. Rock mechanics parameters

	Parameters
Rock mechanical properties	Uniaxial compressive strength Elastic modulus Stress P-wave velocity Coehesion Friction Poisson's ratio Tensile strength Unit weight *In situ* stress
Rock physical properties	Porosity Density RQD Swelling factor Durability factor

	Dissolved gas

2.3.2.6 TRANSPORT PROPERTIES

As part of site characterization, diffusion coefficient, dispersivity, hydraulic aperture, and transport aperture have been measured in laboratory tracer experiments, and sorption experiments using cesium in sedimentary rocks were conducted for different types of groundwater (Hatanaka, 2004).

2.3.3 SUMMARY

A multidisciplinary approach has been applied to the MIU and Horonobe sites for surface-based and drilling investigations. Although the MIU site is located in crystalline rock and the Horonobe in sedimentary rock, both are developing and improving methodologies to (1) characterize geological and structural features, (2) understand the hydrological and hydrogeological properties, (3) characterize the chemical evolution of the groundwater, and (4) identify mechanical properties of the rock mass. Laboratory experiments using tracers have been conducted to address the transport properties of granite and sedimentary rocks. In addition, high quality data is being acquired by development and application of new technologies during site characterization. Based on the data set that was compiled, conceptual and numerical model of geological, hydrogeological and geochemical have been developed. Thus, the results from investigations and applied technology have been constantly evaluated, changes in the geological environment predicted, and uncertainties in the models reduced.

2.3.4 REFERENCES

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2.4 Example of the Swedish Approach

In this section we examine the site characterization approach undertaken by Sweden. A nuclear waste geological disposal program may include the following stages:

- General geological studies:
  - Country-wide:
- Site identification survey:
  - From hundreds of sites to about 2-5 sites
- Initial site investigation
  - Investigate the 2-5 sites in parallel from the surface.
- Complete site investigation:
  - Investigate the 2-5 sites in parallel from the surface
  - Selection of one site for construction of underground investigation facility.

These four stages represent the procedure taken by the Swedish Nuclear Fuel and Waste Management Company (SKB) to arrive at one particular site, for which license application will be presented to the Swedish regulatory authority for construction of an underground laboratory to confirm the suitability of the site as a nuclear waste repository. At this time, SKB is at the end of the third stage, i.e., at the end of the Initial Site Investigation.

Below we shall present the key parameters or data required at each stage, based on the multiple years of studies and consideration by the SKB. Thus the information below is extracted from SKB technical reports, where detailed discussions, methodology, and strategies may be found. Following the lists of key parameters, a series of key SKB reports from the first three stages are provided, which leads to the initiation of site investigation of two particular sites. This is to illustrate the type of efforts needed for these stages.

2.4.1 GENERAL GEOLOGICAL STUDIES AND SITE IDENTIFICATION SURVEY

At this first stage of 'General Geological Studies", no key parameters are defined, but all available and related geological information of bedrock over the country are collected and reviewed. The goal of this review is to provide data and information that can be used to identify regional areas potentially suitable to site a nuclear waste repository.

The stage of Site Identification Survey is carried out in three steps: identification of regional blocks at 100-200 km^2; identification of investigation areas at 5-10 km^2, and selection of sites for detailed characterization.

At the first step, suitable bedrock blocks of area 100-200 km^2 are identified through satellite photo interpretation and geological and geophysical maps. Regional blocks identified can number a few hundred.

At the second step, these regional blocks are studied for selection of about 100 investigation areas, with an area about 5% the size of the regional block. The following are data or information collected and evaluated during this step:

- Environmental factors:
    - Population density and transport connection
    - Preservation areas and groundwater basins
    - Land use plans
- Geological studies;
    - Satellite photo interpretation
    - Field checking
    - Stereo interpretation of aerial photos
    - Interpretation of topographic maps
    - Classification of fracture zones

Based on the above surveys and studies, the identified sites are evaluated further in the third step, concerning

- their geological variation;
- environmental factors, and
- discussions with communities next to the potential sites.

Out of such evaluations, two to five sites will be identified for detailed site characterization.

2.4.2 INITIAL AND COMPLETE SITE INVESTIGATION

The two stages of initial site investigation (ISI) and complete site investigation (CSI) are similar in that both are surface-based investigations to obtain parameters and information required to build up a site description model (SDM), for each of the two to five sites identified. Out of the work, one site will be selected for underground construction and subsurface investigation concerning its suitability as a nuclear waste repository.

The difference between ISI and CSI is in the amount of data collected during the two stages. ISI will include about 2-4 deep boreholes, 700-1000 m in depth, and reflection seismic surveys for identification of major structures at depth, together with field studies of geology, surface geophysics, and shallow boreholes. Data from the deep boreholes include geological stratigraphy, rock stresses, geochemistry and hydraulic conductivities. During the CSI stage, the number of deep boreholes will be increased to about 10 or more, with more intense data gathering, including data on major fracture zones and frequency and properties of fracture zones of less importance.

The focus of both ISI and CSI will be the construction of the Site Description Model (SDM). SDM will be built up in successive model versions corresponding to increasing data and information. Explicit dates for "data freeze" are selected and SDM versions constructed for these dates. Hence successive SDM versions will show how SDM develops and confidence in SDM will be enhanced as more data are obtained.

Data required for the key parameters of SDM are grouped according to the sub models within the SDM. These sub models are:

- Geological Model
- Rock Mechanics Model
- Thermal Properties Model
- Hydrogeological Model
- Geochemistry Model

- Transport Properties Model

Below we shall list the key parameters for each of these models that build up the SDM.

2.4.2.1 KEY PARAMETERS FOR THE GEOLOGICAL MODEL

- Topography: overview of structures
- Soil layers: thickness, soil type distribution, bottom sediments
- Lithology
    - Lithological structure: rock type distribution, dikes, contacts, age, ore potential and industrial minerals, etc.
    - Rock type description: mineralogical composition, microfractures; density, porosity, mineralogical alteration and weathering, etc.
- Structural geology
    - Plastic structures: folding, foliation, lineation, shear zones, veining, etc.
    - Brittle structures: faults, fractures or fracture zones
- Properties of discontinuities (brittle and plastic structures of mechanical importance)
    - Regional and local discontinuities: position, orientation, length, width, genetic type, internal structures such as fracture roughness and infill, etc.
    - Fractures: statistical properties of fracture sets, etc.

2.4.2.2 KEY PARAMETERS FOR THE ROCK MECHANICS MODEL

- Discontinuities: Geometries and geological parameters
- Mechanical properties, fractures in different rock masses: deformation properties in normal direction, deformation properties in shear direction, shear strength, fracture roughness in terms of JRC, and compressive strength of fracture walls, JCS

- Mechanical properties for different rock masses: Young's modulus, Poisson number, rock classification (RMR, Q) systems, dynamic propagation compressive and shear wave velocities, strength
- Mechanical properties of intact rock in the different rock masses: Young's modulus, Poisson's number, compressive and tensile strengths, indentation index and wear index; blastability
- Density and thermal properties
- Boundary conditions and related data: in situ stresses (magnitude and directions), external loads, observed deformation and seismic activities.

2.4.2.3 KEY PARAMETERS FOR THE THERMAL PROPERTIES MODEL

- Thermal Properties of Rock: thermal conductivity and heat capacity of the rock, thermal expansion
- Temperatures: in rock and ground water; thermal boundary conditions and gradients

2.4.2.4 KEY PARAMETERS FOR THE HYDROGEOLOGY MODEL

- Deterministically modeled discontinuities: geometry from the geology model, permeability distribution, porosity
- Stochastically modeled discontinuities and fractures as well as rock mass: stochastic description of fractures, permeability distribution, porosity and storage coefficient, rock compressibility
- Hydraulic properties of ground water: salinity and temperature distributions
- Soil layers: conductivity, thickness, storage coefficient, etc., meteorological and hydrological data, etc.
- Boundary conditions and related data: boundary conditions, recharge and discharge areas, pressure head distributions, historical evolution data (paleohydrology)

2.4.2.5 KEY PARAMETERS FOR THE GEOCHEMISTRY MODEL

- Groundwater chemistry in the repository area
- Groundwater chemistry along potential release flow paths
- Groundwater chemistry on the site scale
- Mineralogy

The chemical components of importance along potential radionuclide release flow paths are pH, Eh, Fe^{2+}, HS^-, HCO_3^-, Cl^-, Na^+, Ca^{2+}, HA/FA, dissolved gases N_2, H_2, CO_2, CH_4 He, Ar, and also colloids and bacteria. Additionally, information on SO_4^{2-}, HPO_4^{2-}, F^-, HS^-, Fe^{2+} and Mn^{2+} may be useful.

2.4.2.6 KEY PARAMETERS FOR THE TRANSPORT PROPERTIES MODEL

- Properties on the near field: groundwater flow and chemistry, fracture aperture and geometry
- Properties of flow paths: dispersion, flow porosity, flow-wetted surfaces
- Properties of rock along flow paths: sorption data (Kd), matrix diffusivity, matrix porosity, maximum diffusion penetration depth, density of rock matrix, groundwater chemistry
- Transport properties of soil layers and receptors: water flux, flow porosity, sorption properties, biological activity
- Other data: tracer breakthrough curves, fracture filling; colloids and gases in groundwater

2.4.3 KEY PARAMETERS FOR SITE CHARACTERIZATION: THE ASPO CASE

SKB is conducting site characterization for two potential areas Forsmark and Oskarshamn (Laxemar and Simpevarp), in Sweden for nuclear waste storage. There are many reports on the efforts. The work is ongoing with evolving strategy and measurement techniques and analysis methodologies. Some key reports are listed below, with additional reports available from the SKB website: www.skb.se.

Andersson J., Berglund J. Follin S., Hakami E., Halvarson J., Hermansson J., Laaksoharju M., Rhen I., Wahlgren C-H., 2002b. Testing the methodology for site descriptive modeling. Application for Laxemar area, SKB TR-02-19, Svensk Karnbranslehantering AB.

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SKB 2005a. Preliminary site description, Forsmark area – version 1.2 SKB R-05-18. Svensk Karnbranslehantering AB.

SKB 2005b. Preliminary site description, Simpevarp area – version 1.2 SKB R-05-08. Svensk Karnbranslehantering AB.

SKB 2005c. Preliminary safety evaluation for the Simpevarp subarea based on data and site descriptions after the initial site investigation sage. SKB TR-05-12. Svensk Karnbranslehantering AB.

SKB's ongoing work for Forsamrk and Oskarshamn is substantial and is generating a large number of important reports, the above list being a small fraction of them. However these reports are under much review and discussions with SKI (Swedish Nuclear Power Inspectorate) and other oversight groups, and the methodologies and information in these reports are under a state of flux. Thus it is not appropriate to draw conclusions and lessons learned from the current SKB effort at this time. For the present report, it is useful to summarize the data SKB obtained for their Aspo project, which is serving as a prototype for their current work on Forsmark and Oskarshamn. The Aspo data and their measurement methods have been evaluated by SKI. They are best presented in two tables below adapted from the SKI Report (SKI 1996: SITE-94, Volume I, SKI-Report 96-36).

The first table presents the characterization methods used at Aspo, with the measurement scales implied for each measurement method. The methods are grouped into several categories:

- Survey/ remote sensing data
- Airborne geophysical surveys
- Surface geophysical surveys
- Drilling program
- Borehole geophysical logging
- Geochemical investigations
- Geomechanical measurements
- Hydrogeological measurements

Each of the methods is associated with a scale of measurement, which means that the data and derived parameter values cover a certain scale, which could be regional (30 km or larger), semi-regional (about 10 km), local (about 2-5 km), site scale, or scales of core-drilled boreholes and percussion-drilled boreholes. Specification of the relevant scales associated with measurements is important information, which is often overlooked in a site characterization program. Details of the methods under the categories, with their scales are listed in Table 2.4-1.

Table 2.4-1. Characterization methods used in the Aspo HRL preliminary investigations and for other sources of site data. Based on information from Stanfors et al. (1991), Alme and Zellman (1991), and Wikberg et al. (1991). Key to abbreviations: R= regional scale (30 km square or larger), S = semi-regional scale (ca. 10 km square), L = local scale (2-5 km square), A = site scale (southern Aspo onlu); K = core-drilled hole(s), H = percussion-drilled hole(s). (from Table 6.3.1 of SKI, 1996)

Method	Type of Information sought or obtained	Coverage
Survey/ remote sensing data		
Landsat thematic map ™	Land relief & features	R
Aerial photographs	Land relief & features	L
Topogrophical maps	Topography (land relief)	L
Digital elevation models (DEMs)	Topography (land relief)	R
Nautical charts and fair sheets	Bathymetry	R, S
Airborne geophysical surveys		
Magnetic	Bedrock variation; oxidation zones	R
VLF & horizontal-loop EM	Water-bearing fracture zones	R
Radiometric (U, Th, K)	Bedrock variation	R
Surface geophysical surveys		
Gravity	Bedrock variation	R
Magnetic profiles	Bedrock variation; oxidation zones; displacements	S, L
Electrical resistivity profiles	Water-bearing or clay-filled fracture zones	L
VLF & horizontal-loop EM profiles	Water-bearing fracture zons	S, L
Seismic refraction profiles	Fracture zones, fracture intensity changes with depth	S, L
Seismic refection profiles	Subhorizontal fracture zones	L
Ground radar profile	Fractures, lithological contacts	A
Geological surveys		
Geological field studies	Lithologic distribution & Structural character	R, L
Outcrop and trench mapping	Detailed lithology, structural character, fracture statistics	L
Drilling program		
Core logging	Lithology, fracturing, fracture mineralogy	L: 14K
Drill cutting analyses	Lithology	L: 19K
Thin-section analyses	Petrology	L: 13K
Chemical rock analyses	Petrology constraints on groundwater geochemistry	L: 5K
Fracture mineral analyses	Infilling mineralogy; indicators of groundwater geochem	L: 8K
Borehole deviation logging	Borehole positional information	L: All K, H
Borehole caliper logging	Borehole diameter, possible fracture zone	L: All K, some

Method	Type of Information sought or obtained	Coverage
	location	H
Borehole TV-logging / televiewer	Absolute fracture orientations (for selected sections)	L: 5K
Borehole geophysical logging		
Gamma-gamma (density	Lithology (bulk density)	L: 9K, 6H
Neutron	Lithology (mafic mineral content), or porosity (Fracturing)	L: 9K. 6H
Natural gamma	Lithology (potassium, uranium, and thorium content)	L: 13K, 17H
Magnetic susceptibility	Litohology (magnetite content)	L: 13K, 17H
Sonic (acoustic)	Fractured zones	L: 13K, 6H
Resistivity (normal & lateral)	Fractured zones	L: 13K, 17H
Borehole radar, dipole (semi-directional) antenna	Radar reflectors (large single fractures or fracture zones) and angle between reflectors and the borehole axis	L: 10K, 2H
Borehole radar, directional antenna	Radar reflectors and their absolute orientations	L: 4K
Fluid resistivity	Groundwater salinity and flowing fractures	L: 13K, 17H
Vertical seismic profiling	Fractures/ fracture zones	A: 1K
Geochemical investigations		
Sampling during drilling (SDD)	"First strike" indication of groundwater geochemistry (major elements, drilling water content)	L: 11K
Sampling in percussion-drilled holes	Groundwater geochemistry (major elements, 2H, 3H, 18O)	L: 5H
Sampling during hydraulic pumping tests (SPT)	Groundwater geochemistry (major, minor elements, drilling water content, stable isotopes, 3H & 14C)	L: 3K; HAS 13
Complete chemical characterization (CCC)	Groundwater geochemistry (major, minor elements, drilling water content, stable isotopes, 3H, & 14C), with downhole Eh, pH, and gas measurements	L: 4K
Sampling during monitoring (SDM)	Groundwater geochemistry major elements, Li, & Sr) of selected sections, 12-18 mos. After pumping	L:3K
Fracture mineral chemistry	Chemical characterization(trace elements * C, O isotopes of calcite); groundwater history, in-situ Kd	L:3K
Geomechanical measurements		
Hydraulic fracturing	In-situ stresses (Horizontal components)	L:2K
Overcoring stress measurements	In-situ stresses (Horizontal components)	L: 1K
Laboratory tests	Uniaxial comp. Strength, elastic parameters, brittleess, joint roughness coefficient, friction angle	L: 2K
Hydrogeological measurements		
Airlift tests (100 m intervals)	Preliminary transmissivity and pressure estimates	L: 14K, 20H

Method	Type of Information sought or obtained	Coverage
Packer tests (injection / recovery, 3m)	Detailed hydraulic conductivity distribution	L:8K
Packer tests (inj. Recovery, 30M)	Hydraulic conductivity / transmissivity distribution	L:3K
Flowmeter (spinner) logging	Inflow distribution; major hydraulic conductors	L: 11K
Pumping tests	Total well capacity / transmissivity	L: 10K, 20H
Interference tests	Characterization of major transmissive features	L:10K, 2H
Dilution tests	Natural flow through selected borehole sections	L:13K
Groundwater pressure monitoring	Monitor groundwater head in distinct borehole sections	L: 15K, 29H
Groundwater level monitoring	Monitor groundwater head in open boreholes	L: 4K, 6H
Radially convergent tracer tests	Connectivity and transport characteristics (porosity,water residence time) of major fracture zones	A: 1K

From the measurement methods listed above, data are obtained to characterize the Aspo site. SKI, in their review identified the key characterization data needed from both the SKB work as well as from SKI's own analyses. These are listed in Table 2.4-2 for Aspo. References for each data set are given in the right-hand column, with details given in the reference list following the table. This table can be considered as giving the type of key data that need to be collected in general for any site undergoing site characterization and evaluation.

Table 2.4-2. Summary of site-specific data for Aspo (modified from Table 6.4.1 of SKI, 1996)

Type of Data	Source
Survey/Remote sensing	
Borehole coordinate data from KAS01-14,16, KAV01-03, KBH01-02, KLX01, HAS01-21, HAV01- X B X X X 08, HLX01-09, HBH01-05, HMJ01	MRM,1993e,h
Caliper logs (borehole diameter) from KAS03	MRM, 1993c D
Detailed topographic map of Aspo	Tlren & Beckholmen, 1987
Digital elevation models (50 x 50 m grid)	LMV, 1987a
Topographic maps (1:250 000)	LMV,1987b
Nautical charts (1:50 000)	SFV, 1988a

Type of Data	Source
Fair sheets (1 :20 000)	SFV, 1988b
Prior lineament Interpretations	Tlren et al., 1987 Tlren & Beckholmen, 1988
Aerial photos (1:30 000)	LMV,1984
LandsatTM (one quarter scene)	Wltschard & Larsson 1987
Clarifications of Aspo coordinate systems	Dverstorp, 1993
Geological/Core logging data	
LIthology In core KAS02-09,11-14, KBH02, KLX01	MRM, 1993e
VelndatafromKAS02-09,11-14,KBH02,KLX01	MRM, 1993f
'Natural' Joints/fractures In core from KAS03-09,11-14, KLX01, KBH02	MRM, 1993f
Fracture frequency In core KAS02-09, 11-14, KLX01, KBH02	MRM, 1993h
Crushed zones in core from KAS03-09,11-14, KBH02, KLX01	MRM,1993f
Fracture alpha angles from core	MRM, 1993f
Oriented core from portions of KAS02-06	MRM, 1993h
Fracture infilling mineralogy from KAS03-09,11-14, KBH02 & KLX01	MRM, 1993f
Detailed fracture mineralogical analyses	Tullborg et al. 1991
Geological/Surface data	
Geological map of Asp/)	Kornfalt & Wlkman, 1988
Data from outcrop mapping of fractures on Asp/)	MRM, 1993h
Supplementary field studies	Tiren et al., 1996
Geological / Interpretation	
Regional geology	see Tlren et al., 1996
Regional sedimentary geologic maps and cross sections	Kornfalt & Larsson 1987; Ahlbom et al., 1990
Local geology	Kornfalt & Wlkman 1988; Munier 1989; Talbot & Rlad 1987; Wikstrom 1989; Talbot, 1990
Regional structural map (2D)	Tiren et al. 1996
Semi-regional structural map (2D)	Tlren et al. 1996
SKI 3D structural model of Aspo	Tlren et al. 1996
SKB structural model (dlgltlsed)	Geoslgma, 1994

Type of Data	Source
SKN structural model (digltlsed)	Geoslgma, 1994
Fracture statistics for DFN model	Geier & Thomas 1996
2D near-field fracture model simulations	Geier & Thomas 1996
Geophysical/Borehole logging	
Natural gamma radiation logs from KAS02-09,11-14, HAS02-20, HAV01-08, HLX01-07,KAV01-03, KLX01	MRM 1993c,h
Gamma-gamma (density) logs from KAS05-09,11-14	MRM 1993c
Magnetic susceptibility logs from KAS02-09,11-14	MRM 1993c
Lateral resistivity (1.6 -0.1 m) logs from KAS02-03	MRM 1993c
Normal resistivity (1.6 m) logs from KAS03	MRM 1993c
Sonic (acoustic) logs from KAS02-09,11-14	MRM1993c
Self-potential (SP) logs from KAS02-04	MRM 1993c
Single-point resistivity from KAS02-09,11-14, HAS02-20, HAV01-08, HLX01-07,KAV01-03, KLX01	MRM 1993c,h
Neutron near detector logs from KAS06-09	MRM 1993c
Neutron far detector 10 s from KAS06-09	MRM 1993c
Fluid conductivity & salinity logs KAS02-09,11-14, HAS02-20, HAV01-08, HLX01-07,KAV01-03, KLX01	MRM 1993c,d,h
Temperature logs KAS02-09,11-14,HAS02-14,18-20, HAV01-08, HLX01-03,OS-07, KAV01-03, KLX01	MRM1993h
Conventional borehole radar (dipole antenna) travel time data, KAS02-09,11, KLX01	Niva & Gabriel 1988; Carlsten 1989, 1990
Directional borehole radar travel time data KAS12-14	Carlsten 1990
Radar amplitudes from KAS02-14	Geoslgma, 1993
Geophysical/Above-ground surveys	
Airborne electromagnetic survey results	Nlsca 1987a,b
Airborne magnetic survey results	Nisca 1987a,b
Geophysical profiles: (VLF, magnetic, seismic, radar)	Stenberg, 1987; Barmen & Stanfors, 1988; Ploug & Klillen, 1989; Sundin S 8 X 1987; Sandberg et al., 1989
Detailed magnetic measurements	Nlsca & Trlumf, 1989
Detailed geoelectrical measurements	Nisca & Trlumf, 1989
Hydrologic	

Type of Data	Source
Groundwater pressures In boreholes	SKB, 1992b
Groundwater levels In boreholes	Strom,1992
Water table map	Lledholm, 1991
Injection test data (3 m) from KAS02-08,KLX01	MRM, 1992; 1993a
Interpreted K values from 3 m In]. tests	MRM, 1993b
GRF analyses (3 m section lengths) for KAS02-08	Geier et al., 1996a
GRF analyses (3 m section lengths) for KAS02-08	Geier et al., 1996a
Injection test data (30 m) from KAS02-08,KLX01	MRM 1992, 1993a
Interpreted K values from 30 m Inj. Tests	MRM 1993b
GRF analyses (30 m section lengths) for KAS02-08	Geier et al., 1996a
Flowmeter logs from KAS02-14,KLX01	MRM 1993d
KLX02 Hydrologic and salinity data	SKB, 1993a
Hydrological/lnterference tests	
Interference test data from short-term pumping tests In HAS13 & 20, KAS02,03,06,09,12,13 & 14	Strom, 1992
Interference test data from LPT1 (pumping In KAS07)	Strom, 1992
Interference test data from LPT2 (pumping In KAS06)	Strom, 1992
Tracer test data from LPT2	Strom,1992
Rock mechanics/Petrophysical	
Hydraulic fracturing stress measurements	Bjarnason et al., 1989
Overcorlng stress measurements	Bjarnason et al., 1989
Uniaxial compressive strength and elastic parameter measurements	Wlkberg et al., 1991
Porosity measurements from KAS02 and KLX01 [1]	MRM,1993e
Repository layouts	Geoslgma 1994
Geochemical	
Sampled during drilling (SOD): Major element concentrations and drilling water content	Wlkberg et al., 1991; Smelile & Laaksoharju 1992
Sampling from percussion holes: Major element concentrations, 2H, 3H,	SKB 1992a,c
Sampling during hydraulic pumping tests (SPT): Major & minor element concentrations, drilling water content, stable Isotopes, 3H, 14C	SKB 1992a,c

Type of Data	Source
Sampling for complete chemical characterization (CCC): Major & minor element concentrations, drilling water content, stable Isotopes, 3H, 14C, Eh pH, dissolved gases.	SKB 1992a,c,d
Sampling during monitoring (SPM): Major components, Isotopes (2H, 3H, 180)	KTH 1993a,b
Baltic seawater analyses: Major elements & Isotopes for Baltic sea water	SKB 1992d; KTH 1993b
Rainwater Isotope analyses (2H, 3H, 18O)	SKB *1992d;* KTH 1993b
Detection limits for chemistry data	SKB *1992d*
Origin of drilling water	SKB 1992d. KTH 1993a
Geochemical	
SKB analysis of groundwater composition [2]	Smeille & Laaksoharju 1992
SITE-94 classification of groundwater types at Aspo	Glynn & Voss, 1996

The above tables serve as a good summary of key data needed and the associated measurement methods for site characterization. Note that data needs for site characterization may be different from data needed for safety or performance assessment of a potential nuclear waste repository. The latter may be a subset of the former data set, dependent on the conceptual models and computer simulators used in the safety assessment. A good example of a discussion of safety assessment data needs may be found in the SKB report (SKB 1999: SR97 – Data and Data Uncertainties, Compilation of data and data uncertainties for radionuclide transport calculations, by J. Andersson, TR-99-09). In general, site characterization data are broader, providing an understanding of the site features and processes as the foundation for subsequent safety assessment.

2.4.4 REFERENCES

The following list of references serves to illustrate the depth of SKB's work in the first stages of site selection that lead to the selection of two sites for detailed site characterization. As mentioned above, SKB is currently at the stage of characterizing these two sites (at end of ISI and beginning of CSI) and the selection of one site, out of these two, is expected in 2008.

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2.5 Features and Parameters at Olkiluoto, Finland

In this section we will enlist the paratеters collected and the field activities used to obtain such paremeters at Olkiluoto, Findalnd. The following list is compiled from the publicatios listed at the end of the section including the POSIVA report entiteled 'Baseline Conditions at Olkiluoto', that pertain to the data collected up until the end of year 2002. This timeline is more relevant to Preliminary Investigations, which is before the construction of Onkalo.

In May 2001, Finland became the first country to approve plans for a geologic repository. The Finnish waste-disposal company, Posiva Oy, will research possible sites and plants at which to start building the repository in 2010. For more than 20 years, Finland has studied nuclear waste disposal in crystalline rock. Out of this study, conducted by Posiva Oy, came the recommendation for construction of a single, deep geologic repository for spent nuclear fuel disposal.

The goal of the preliminary site investigation was to characterize the candidate sites to the extent needed to judge their suitability for hosting a repository. The approach used for preliminary site investigation was based on characterization of the crushed-tectonic-block structure or shear zones of the Finnish bedrock. Those shear zones, which have lengths of dozens of kilometers, were further divided into smaller sections according to smaller fracture zones. A total of 327 large regional blocks were initially identified and reduced to five areas for preliminary site investigation, based primarily on geologic, geographic, and environmental factors (Posiva 2003a). The investigations at each of the five sites included drillings and samplings, various geophysical, geohydraulic, rock mechanical, chemical, and mineralogical studies, and modeling of the bedrock structure and groundwater flow in the area. At least five deep (500 to 1000 m) cored boreholes were drilled, in addition to a number of shallow boreholes (Posiva 2003a).

Detailed site investigation related to the disposal of spent fuel at Olkiluoto Island started in 1987. This work concentrated on an area of about 6 km2 (Paulamäki 1989, Posiva 2003a). A total of 23 deep (300–1000 m) boreholes and 35 shallow (20–30 m) boreholes were used for site characterization. Special attention was been paid to the fractured and hydraulically conductive zones, their location, orientation, and properties.

Results of the site investigations have been compiled in the bedrock model describing the rock type distribution and fractured zones. In the next sections, we describe field activities used to obtain the parameters for site characterization at Olkiluoto. The information is compiled from publications listed at the end of this section and includes the POSIVA report “Baseline Conditions at Olkiluoto,” which preceded the construction of Onkalo, the underground rock characterization facility.

2.5.1 GEOLOGIC DATA

The crystalline rock of Finland is part of the Precambrain Fennoscandian shield, with ages ranging from 3,100 Ma to 1,250 Ma. The rocks are composed of a complex mix of meta-sediments and meta-igneous units that have undergone several episodes of metamorphism and tectonic deformation. The major part of the Olkiluoto study site consists of various biotite-rich migmatitic mica gneisses.

According to lineament studies, the Olkiluoto site is located inside of an elongated regional bedrock block, 11 × 3.5 km in size bordered by regional fracture zones. According to seismotectonic studies, the area within 100 km of Olkiluoto is characterized by low seismicity (i.e., relatively few and minor earthquakes).

Geological studies included mapping outcrops, trenches investigation, and borehole interpretation (Anttila et al. (1999), Lindberg & Paulamäki 2003, Paulamäki 2004a, 2004b, Paulamäki & Aaltonen 2004). In addition to surface mapping, petrographic and lithogeochemical studies were conducted on samples from outcrops, trenches, and drill core, based upon the following (Kärki & Paulamäki 2004):

- Lithological classification
- Metamorphic grade, texture, and structure
- Major mineral composition
- Petrophysical measurements (Paananen 2004)

A summary of major geological parameters are listed on

Table 2.5-1.

Table 2.5-1. Geological parameters

	Parameters
Regional mapping	Rock types Lineaments Fracture zones
Geological (investigation trenches, outcrops, and borehole samples)	Lithology Fracture mineralogy Fracture (dip, dip direction, fracture frequency, length, aperture) Ductile and brittle deformation (foliation, fold axis, axial plane, fault plane, lineation) Hydrothermal alteration minerals
Petrographic and lithogeochemical (protolith and genesis)	Metamorphism (mineral paragenesis and metamorphic grade) Mineral composition Migmatitic texture and structures

Additional data were collected to support geological data of the Olkiluoto site and summarized in Table 2.5-2. This included the distribution and thickness of overburden and characteristics of the main soils, shoreline displacement, mapping of sea bottom sediments, and radioactivity surveillance in sea water, groundwater, and shoreline sediments (Posiva 2003a).

Table 2.5-2. Overburden, sea bottom sediments, shoreline displacement parameters

	Parameters
Overburden	Uplift rate Thickness Density of soil particles Grain size distribution (Hellä et al. 2004) Permeability (Lahdenperä et al. 2005) Soil water chemistry from lysimeter studies
Sea bottom sediments	Sediment thickness, depths Topography Sediment density, quality, texture, structure Radionuclides
Shoreline displacement	Glacio-isostatic depression/uplift rate Global eustatic sea level lowering/rise rate Mass transfers Erosion rate

2.5.2 GEOPHYSICAL DATA

Several geophysical surveys have been carried out in the Olkiluoto area from the air, on the ground, and in boreholes. Airborne geophysical surveys included magnetic, paleomagnetic, and radiometric measurements (Suomen Malmi 1988). Ground and subsurface geophysical parameters were obtained using the following methods:

- Acoustic-seismic studies
- Microseismic monitoring network
- Ground penetrating radar (GPR)
- Produced images from side-scan sonar
- Single-channel reflection seismic
- Surface-based refraction seismic measurements
- 3-D reflection vertical seismic profiling (VSP) method
- Horizontal seismic profiling (HSP)
- Integrated global position system (GPS) monitoring system for local crustal deformation studies
- Charged potential surveys
- Standard logging (magnetic susceptibility, single point resistivity, resistivity, density, natural gamma-gamma radiation, seismic P-wave velocity, caliper, and fluid logging
- Seismic VSP
- Cross hole and walk away surveys
- Borehole radar

Table

Table 2.5-3 summarizes the main geophysical parameters:

Table 2.5-3. Geophysical parameters

	Parameters
Regional Airborne	Total field and gradient of the magnetic field Total field and vertical quadrature Total potassium, uranium, and thorium
Ground geophysical data	Total field and gradient of the magnetic field Lithological variations, thickness Fracture distribution Water salinity Fracture zones Crustal movement
Borehole	Rock types, depth and distribution of fractures, radionuclides, temperature of water Fracture and fracture zones distribution

2.5.3 HYDROGEOLOGICAL DATA

Hydrogeological measurements have been carried out at various depths, including surface, near-surface, and subsurface (deep) bedrock. These hydrogeological studies had as their goal a greater understanding of the site-scale flow conditions and determination of the spatial and temporal variations in the groundwater table, groundwater recharge and residence times, and groundwater pressure distribution at depth (Posiva, 2003a).

The surface hydrology studies included catchments areas and surface runoff. Olkiluoto is located on the island of Olkiluoto, which forms a hydrological unit of its own. Surface waters there flow directly into the sea (Posiva, 2003-02). The low topography and high evaporation (over 60% of precipitation evaporates) mean that only a few percent of precipitation infiltrates into the bedrock (Ahokas & Herva, 1992, Posiva, 2002–03, Ikonen et al. 2003, Mattila 2004)

Hydraulic conductivity and hydraulic head were mainly obtained from double-packer tests, long-term pumping tests in fracture zones, flow logging, long-term monitoring of the groundwater table and its fluctuations, and direct measurement of natural groundwater flow by cross borehole flow in shallow and deep boreholes. Transmissivity was estimated by cross-borehole flow measurement for the upper 150 m of the rock mass. The investigations carried out in this phase are presented in detail in reports by Tuominen (1994), Snellman et al. (1995), Ruotsalainen & Snellman (1996), Bath et al. (2000), Pöllänen & Rouhiainen (1996a,b, 2000, 2001a,b, 2002a,b), Rouhiainen (2000), Kukhonen & Lindberg (1995); and Kukhonen (2000). Table 2.5-4 illustrates the important hydrogeological parameters.

Table 2.5-4. Hydrogeological parameters

	Parameters
Surface	Runoff Flow rates Infiltration rate Evaporation Transpiration
Boreholes	Hydraulic conductivity (1, 2) Hydraulic head Transmissivity Porosoity Permeability

At site scale, groundwater flow is affected by several factors, including the structure of the bedrock, transmissvity of bedrock structures, porosity of rock, effective hydraulic conductivity between the host rock and fracture zones, surface infiltration, chemical composition and temperature of groundwater, and surface topography and land uplift (Posiva, 2003a).

2.5.4 HYDROGEOCHEMICAL PROPERTIES

Water samples from Olkiluoto site were collected from precipitation, surface water (reservoir, wells, and springs), Baltic seawater, and groundwater (shallow and deep boreholes). The aim of this study was to understand the hydrogeochemical characteristics of the site, identifying recharge and discharge areas, special coverage of samples at various depths, and distribution and concentration of saline groundwater and dissolved gases in saline groundwater (Posiva, 2003a). For more detail on these hydrogeochemical studies, see Olkiluoto Site Description 2004. Table 2.5-5 summarizes the main hydrogeochemical parameters.

Table 2.5-5. Hydrogeochemical parameters

	Parameters
Phyisogeochemical Variables	pH Electrical conductivity Temperature Density Dissolved organic carbon (humic and fulvic acids) Salinity
Anions	HCO_3, CO_3, Cl, Br, F,Br, SO_4, PO_4, NO_3, NO_2, N, P
Cations	Na, Ca, Mg, K, Al, Fe, SiO_2, NH_4
Trace elements	Sr, Li, Ba, Cs, Zr
Organics	Total Organic carbon Dissolved organic carbon
Isotopes	δ^2H, ^3H, $\delta\ ^{18}O$, ^{222}Rn, $\delta^{13}H$, ^{14}C $^{234}U/^{238}U$, ^{34}S, ^{18}o, $^{87}Sr/^{86}Sr$ Total inorganic carbon
Dissolved gases (deep borehole samples)	N_2, O_2, CO_2, CO, CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H8, H_2, He
Others	Microbes (sulfur reducing bacteria (SRB), iron reducing bacteria (IRB) Colloids Methane (CH_4)

The hydrogeochemical data above are a compilation of the following:

- Hydrochemical data (Posiva 2003a) and baseline properties (Pitkänen et al. (2004))
- Geochemical studies of groundwater (e.g. Pitkänen et al. 1994, 1996, 1999a, b, 2004)
- Hydrothermal alteration

- Fracture mineral studies
- Mineral compositions
- Petrological studies

2.5.5 ROCK MECHANICS DATA

The mechanical properties of migmatitic gneisses, granite/pegmatite and grey (tonalite) gneiss, were carried out in intact rock samples and fractured rock from outcrops and drill cores (Front et al. 2002, Lahti & Heikkinen 2004, Klasson & Leijon 1990, Ljunggren & Klasson 1996, Malmlund & Johansson 2002, and Sjöberg 2003). The primarily role of rock mechanics studies included the evaluation of the long-term stability of the bedrock, *in situ* stress, and seismic monitoring (Posiva 2003a). The geophysical methods employed at different scales included:

- Seismic P- and S-wave velocities (Front et al. 2002, Lahti & Heikkinen 2004),
- Surface-based refraction seismic measurements (Geotek 1975, 1978, Ihalainen & Lahti 2002, Ihalainen 2003),
- Reflection seismic methods, crosshole reflection (Enescu et al. 2003, Enescu et al. 2004),
- Tomographic investigations (Enescu et al. 2003, Enescu et al. 2004),
- Microseismic monitoring system (MS) (Saari 2003) and
- GPS and surface leveling measurements

The main laboratory tests conducted on intact rock samples consisted of uniaxial and triaxial loading tests, damage-control tests, tensile tests, and acoustic emission measurements (Matikainen & Simonen 1992, Kuula 1994, Johansson & Autio 1995, Tolppanen et al. 1995, Hakala & Heikkilä 1997a, b, Eloranta 2004). Some anisotropic testing has also been undertaken by Hakala & Kuula (2004) and Eloranta (2004).

The mechanical properties of fractures were based on estimates of geological descriptions, such as their roughness, undulation, mineral filling, openness, and type (e.g. slickensided) (Posiva 2005-3 vol. 1 pp 36-, Rautakorpi et al., 2003). Studies performed to obtain fracture properties included the following follows:

- A description of the geological and structural style of fracturing

- Identification of the mineralogical species of the fillings, including an approximation of the percentage of filling phases and their geochemical characteristics
- Determination of the physical properties of the fractures and fracture fillings, including an estimate of the thickness of the fillings and their degree of cohesiveness
- Determining the relationship between individual fractures, fracture zones, and the fracture system
- Obtaining evidence for ancient fluid flow and for existing groundwater circulation
- Special characteristics of the fractures and fracture fillings, including corroded cavities and those filling phases
- Mechanical strength and deformation properties
- Hydraulic fracturing and overcoring (Klasson & Leijon 1990, Ljunggren & Klasson 1996, Malmlund & Johansson 2002, and Sjöberg 2003)

The presence of several brittle and ductile deformation zones at Olkiluoto represent major discontinuities in the mechanical continuum. The foliation in the ductile deformation zones has an effect on their mechanical properties. Using empirical correlations based on rock engineering classifications and additional analytical methods, it was possible to generally determine the mechanical properties of deformation zones.

Horizontal *in situ* stress state was obtained from hydraulic fracturing at deep boreholes. Detailed description of the measuring methods and the field work was presented in Klasson & Leijon (1990) and Ljunggren & Klasson (1996). *In situ* stresses have been measured in deep boreholes by hydraulic fracturing and overcoring methods (Klasson & Lejon 1990; Ljunggren & Klasson, 1996) and bedrock stability has been monitored.

Thermal properties of intact rock were determined in the laboratory, mainly by mineralogical composition such as feldspar, micas, and quartz, and on samples taken from boreholes. Thermal anisotropy and heterogeneity resulted from variations in texture, mineral composition, and orientation of migmatitic banding and foliation (Kuhhonen 2000, Posiva 2003a). Table 2.5-6 summarizes the mechanical and thermal parameters.

Table 2.5-6. Rock mechanical and thermal parameters

	Parameters
Rock mass	Uniaxial compressive strength Crack initiation strength Long term strength Peak strength Tensile strength Young's modulus Poisson's ratio Shear modulus Deformation module Stress orientation Creep Fatigue Complete stress tensor Horizontal stresses Seismic velocity (P and S-wave)
Fracture	Poisson's ratio Cohesion Friction angle Normal stiffness Shear stiffness RQD Roughness Undulation Filling Openness Type
Deformation zones	Deformation module Displacement rate
Thermal properties	Conductivity Heat capacity Diffusivity Expansion Scale effect Mineralogical composition

2.5.6 OTHER DATA

2.5.6.1 CLIMATE AND METEOROLOGY PROPERTIES

Climate and weather conditions define the time-dependent boundary conditions for the system at Olkiluoto. Finland has experienced several periods of glaciations, with the last one ending about 13,000 years ago. This event diluted the seawater and resulted in sea level rise, affecting geological, geochemical, and hydrological properties. As part of the present surface conditions, long-term climate and meteorology monitoring are considered to obtain average values for each of the parameters listed in Table 2.2-28.

Table 2.2-28. Climate and metereological parameters

	Parameters
Climate and meteorology	Temperature (1, 2) Precipitation Snow cover and ground frost thickness (1, 2) Water content (1, 2) Wind speed Wind direction Chemical deposition of precipitation (pH. DOG, N, NH_4-N, NO_3-N, Ca, Mg, K, Na, SO_4-S, Cl)

2.5.6.2 BIOSPHERE

The Environmental Impact Assessment (EIA) of the Finnish program indicates that mapping and identification of key biotypes for the land and sea environments have been periodically undertaken since 1997. Sea surveillance includes analysis of physical, chemical, and biological parameters related to water quality, fish, and sea bottom vegetation (Ikonen at al 2003a, Posiva 2003a). Concentration of radionuclides and stable isotopes such as Cs-137, Sr-90, H_3 have been under extensive regulatory surveillance within marine and land environments, owing to the presence of a nuclear power plant near Olkiluoto.

2.5.7 SUMMARY

Site characterization at Olkiluoto has been ongoing for 20 years. During detailed investigation, special attention was been paid to the fractured and hydraulically conductive zones, their location, orientation, and properties. The main investigations in the crystalline rock have been: (1) bedrock studies, including characterization based both on geological and geophysical (airborne, ground surveys, and borehole logging); (2)

hydrogeology studies, to understand the site-scale flow conditions and to determine the spatial and temporal variations of the groundwater table, groundwater recharge, and residence times, as well as groundwater pressure distribution at depth; (3) hydrogeochemistry studies, to identify recharge and discharge areas, special coverage of samples at various depths, and distribution and concentration of saline groundwater and dissolved gases in saline groundwater; and (4) rock mechanics, to evaluate the long-term stability of the bedrock, *in situ* stress, and seismic monitoring.

2.5.8 REFERENCE LIST

URLs

Posiva 2005-03-Olkiluoto Site Description 2004-Volume 1
http://www.posiva.fi/raportit/Posiva2005-03_vol1.pdf

Posiva 2005-03-Olkiluoto Site Description 2004-Volume 2
http://www.posiva.fi/raportit/Posiva2005-03_vol2.pdf

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2.6 GENERAL SUMMARY

As mentioned previously, characterization of a prospective high-level nuclear-waste repository site is one of the most important activities for establishing the geological conditions and parameters of the site. In countries like the USA, Canada, Sweden, and Finland, site characterization has been conducted for over 20 years. Although site characterization is being carried out in different types of lithology (volcanic, plutonic, crystalline, metamorphic, and sedimentary), at different conditions (unsaturated and saturated zones) and in different tectonic and hydrological settings, it is clear that groundwater is one of the main issues for the safety of nuclear waste programs. In the evaluated programs, the amount and the rate of water contacting the waste package will ultimately affect all aspects of performance, from waste package lifetime to radionuclide movement.

In the USA, the potential repository is located in unsaturated volcanic rock, with low infiltration, episodic records of earthquakes, and surrounded by Quaternary volcanoes. In the beginning of the program, given investigators' simple understanding of the geology, hydrology, and fracture properties and the lack of numerical or mathematical models, the conceptualization of Yucca Mountain was very simple. It included low flux, extensive lateral flow, and no fracture flow. With better understanding of the geology, fracture properties, and the main hydrological properties (especially related to infiltration, percolation, and seepage), the main issues for the long-term performance of the repository system could be assessed, and uncertainties could thereby be reduced.

In Canada, because of the stable tectonic region and large exposure and distribution of plutonic rock in the Canadian Shield, this rock is believed to be a suitable medium for storage of nuclear waste. The plutonic rock was used to develop a concept for disposal that involved the geosphere, vault (near-field) and biosphere and to develop related models for performance assessment. A major part of the geosphere research was to develop methodology and technology for site characterization. The method implemented by the AECL included a multidisciplinary and staged approach (i.e. from regional scale to candidate area to candidate site). For the Canadian program, fracture characterization was particularly important, because it allowed investigators to identify different hydrogeological, geochemical, and geomechanical characteristics of the plutonic rock.

Japan is located in an unstable geological setting, with active volcanoes as well as seismic and uplift/erosion processes. This makes the Japanese program one of the most challenging for nuclear waste disposal. Nevertheless, site characterization for an underground laboratory has been ongoing in two distinct rock types: plutonic and sedimentary rocks. Some similarities that Japan has with the Canadian, Swedish, and Finnish programs is that all these countries have been conducting main investigation in saturated rocks and using a multidisciplinary approach for the URL site selection. In these programs, one of the main concerns is fractures and fracture zones, considered to be major structural features controlling the groundwater movement in the saturated zone. However, at depth, as fractures become sparse and permeability and porosity decrease, the main radionuclide transport may be significantly affected by diffusion and sorption.

In Japan, extensive numerical modeling has been conducted to evaluate the effects of geological, hydrological, geochemical, and mechanical properties in the long-term performance of the system. Other important parameters affecting the performance of the saturated zone are hydraulic gradient, amount of recharge and discharge, hydraulic conductivity, flow interval and path, dispersivity, and advection.

In Finland, the Olkiluoto site is located in a relatively stable geological setting. The island is composed by crystalline rock, primarily migmitite and gneiss. During detailed site characterization, special attention was placed to the fractured and hydraulically conductive zones, their location, orientation, and properties. Emphasis has been on characterizing the bedrock, and hydrogeological, hydrogeochemical, rock mechanical, tectonic and seismic conditions of the site.

Table 2.6-1 summarizes the main parameters identified by the USA, Japan, Canada, Sweden, and Finland during site characterization. In this study, we have identified parameters commonly used during site characterization (Table 2.6-2). All sites have conducted similar studies, as follows:

1. Regional and site-specific geological mapping and drilling. During surface-based reconnaissance, traditional methods for field geology (i.e., surface-based

mapping, sampling, and testing of geological and hydrological properties) and features that represent the surface expression of major pathways for groundwater flow (i.e., major lineaments recognized from satellite images, aerial photos and geophysical survey) were used to establish the geological framework of a candidate site. The common parameters include: major lineaments, lithological contacts and depths, petrology, mineralogy, fractures, and faults (orientation, lengths, and fracture zones).

2. Metereological investigation to understand surface and underground flow system. The physical process that controls the movement of water seems to have an enormous impact on site characterization, conceptual model and numerical modeling. The common parameters are precipitation, temperature, evapotranspiration, infiltration, wind direction and velocity, and recharge and discharge.
3. Regional and site-specific geophysical investigations. A broad range of surveys were used to confirm major structures, depth of unconformities, faults, and thickness of lithologic units and contacts. Satellite images, airborne electromagnetic, radiometric, magnetic; seismic velocity, electric surveys, and geophysical logs in boreholes were the main types of surveys to confirm the existence of faults and fracture zones, rock boundaries, lithologic contacts and thickness, and depth of discontinuities.
4. Surface and groundwater hydrological investigations to understand surface and groundwater flow system, including fracture-matrix and water-rock interactions. The common parameters for surface hydrology include: water level, drainage recharge, and discharge, runon and runoff, precipitation, evaporation, and moisture redistribution. Hydrogeological parameters for matrix and fractures include: porosity, permeability, hydraulic conductivity, hydraulic head, transmissivity.
5. Geochemical and isotopic investigations to understand characteristics and variations on the physico-chemical properties of groundwater. Isotope analysis provides information on the origin and residency time of water. The main

hydrogeochemical parameters are: pH, Eh, major ions (cations and anions), total dissolved solids, trace elements, temperature, isotopes, dissolved gases. The main geochemical parameters for rock include: major and minor elements, secondary minerals, isotope to constrain the age of rock and infillings.

6. Rock physical properties and rock mechanics measurements to understand the variations in porosity, density, rock strength, stress conditions at different depths, and the influence of rock properties on groundwater hydrology and chemistry.
7. Investigation of transport-properties using tracer tests to understand the processes of advection, diffusion, dispersion, and sorption.
8. Development of conceptual and numerical modeling. All sites have developed and improved their conceptual models based on results from data and data analysis. Numerical modeling has been conducted to predict and estimate the effect of parameters in the natural system and to reduce data uncertainties.

Table 2.6-1. Summary of important parameters for site characterization from evaluated sites

Country	Rock Type	Geological & Structural Parameters	Geophysical parameters	Climate & Meteorological Parameters	Hydrogeological Parameters	Geochemical Parameters	Physical Parameters	Mechanical Parameters	Thermal Properties
USA Yucca Mountain Unsaturated zone	Volcanic Rock Age: 14 - 7.5MA	<u>Regional Geology</u> -Lithostratigraphic untis -Alteration & weathering -Mineralogy -Grain size and sorting -Percentage of volcanic glass -Degree of welding -Degree of crystallization -Percentage of lithophasae -Abundance and type of glass <u>Textures</u> - Grain size - Sorting -Abundance of volcanic glass -Degree of welding -Type and degree of crystallization -Abundance of lithophasae -Abundance and type of glass alteration <u>Structures</u> -Lineaments -Fault orientation -Fracture geometry -Fracture orientation, length -Fracture frequency	<u>Regional</u> -Fault offset -Stratigraphy -Lithological contact -Size and shape of buried volcanoes -Fracture density <u>Borehole</u> -Density -Moisture content -Porosity -Saturation	<u>Climate</u> -Temperature -Precipitation -Geology (topography, stratigraphy, fractures, fossils/microfossils) -Surface hydrology -Type of soils -Sea level change -Isotopic data -Variation on earth orbital clock -Eccentricity <u>Meteorological</u> -Topography -Temperature -Pressure-Precipitation rate -Snow fall rate Evapotranspiration rate -Surface run on & runoff -Humidity -Wind direction, velocity -Net infiltration	<u>Surface hydrology</u> -Precipitation -Evaporation -Transpiration -Run-on -Run-off -Infiltration -Moisture redistribution -Groundwater recharge <u>Matrix</u> -Matrix porosity -Bulk density -Particle density -Water content -Matrix permeability -Moisture retention relations -Water potential -Hydraulic conductivity <u>Fractures</u> -Fracture density -Fracture aperture -Fracture porosity -Fracture permeability -Hydraulic conductivity <u>Faults</u> -Fault permeability -Fault porosity -Hydraulic conductivity -Tracer transport	<u>Groundwater</u> -TDS -Major-ion chemistry (Al, Ca, Mg, K, Na, SiO_2,HCO_3,CO_3, ^{36}Cl, NO_3, SO_4) -Trace elements -Isotopes (H, ^{3}H, ^{18}O,$^{36}Cl/Cl$,^{14}C, ^{13}C,$^{87}Sr/^{86}Sr$, $^{234}U/^{238}U$) <u>Rock</u> -Mineralogy -Alteration minerals -Major elements compositions -Secondary minerals -Sorption properties -$^{40}Ar/^{39}Ar$ <u>Gas</u> CO_2, $^{13,14}C$, ^{18}O, CH_4, Ar, N_2,	-Hardness -Saturation -Particle density -Bulk porosity -Permeability	-Compressive strength -Tensile strength -Young's modulus -Poison's ratio -Hardeness -Cohesion -Angle of internal friction -Normal stiffness -Shear stiffness	-Thermal conductivity -Heat capacity -Thermal expansion coefficients -Thermal diffusivity -Heat dissipation

Country	Rock Type	Geological & Structural Parameters	Hydrogeological Parameters	Geochemical Parameters	Transport Properties
USA Yucca Mountain Saturated Zone	Volcanic and Sedimentary (carbonate) Rocks Age: since Paleozoic	<u>Geology</u> -Stratigraphy -Lithology -Lithological contacts -Mineral alteration <u>Structures</u> -Fault orientation, types -Fracture density -Fracture network -Folds	<u>Regional</u> <u>Recharge and Discharge</u> - Lateral boundaries - Precipitation (rainfall, snow melt) -Evapotranspiration -Altitude -Soil type -Rock type -Slope -Vegetation -Hydraulic gradient -Water level -Direction of groundwater flow -Flow velocity -Transmissivity -Hydraulic conductivity -Porosity <u>Site-Scale</u> -Infiltration -Fault orientation -Fault type -Fracture density, porosity -Matrix pore storage - Transmissivity - Flow velocity - Dispersion - Concentration of radionuclide <u>Borehole</u> -Matrix porosity -Fracture density -Hydraulic head	-pH -Eh -Isotopes ($^{234}U/^{238}U$, ^{14}C, ^{36}Cl, δ-deuterium, $\delta^{18}O$, strontium) -Major ions (Na, Ca, K, Mg, sulfate, chloride, nitrate, fluoride) -Trace elements -Rare Earth Elements	<u>Porous Media (alluvium)</u> -Advection -Sorption -Dispersion -Porosity -Sorption -Isotopes(^{14}C, $\delta^{13}C$) <u>Fracture</u> -Advection -Diffusion -Dispersion -Fracture spacing -Porosity -Aperture -Fillings -Sorption

Country	Rock Type	Geological & Structural Parameters	Geophysical Parameters	Meteorological Parameters	Hydrogeological Parameters	Geochemical Parameters	Stress Field Parameters	Rock Mass Properties Parameters
CANADA URL Whiteshell Research Area (WRA) Saturated Zone	Plutonic (Granite) Age: 2679 MA	Site Screening - Major lineaments (fracture and fault orientations) - Pluton geometry (shape and size) - Rock boundaries - Lithological contact - Fracture zone - Petrographic analysis Site Evaluation - Rock type, - Percentage of dikes -Degree of metassomatic granitization, - Fracture (orientation, density, length, aperture, infillings), - Mineralogy, - Fabric (texture, deformation) - Mineral alteration - distribution of U,Th,REE Drill core - Fracture (density, orientation, aperture, connectivity, fillings) - Mineral alterations - Rock types	Site Screening -Major lineaments (spatial frequency and distribution) -Length distribution -Boundaries of pluton -Overburden thickness - Fracture zones -Depth of batholiths Site Evaluation -Lithologic variations -Thickness -Fracture/fault zone -Stress orientation, -Rock boundaries and contacts -Shape Borehole -Location of fractures - Continuity and geometry of features between boreholes	-Temperature -Windspeed and direction -Rainfall -Precipitation -Evaporation rate -Runoff rates -Spring locations (recharge/discharge)	Site Screening -Drainage recharge/discharge -Runoff pattersn -Water level -Groundwater recharge/discharge Site Evaluation/borehole -Porosity -Fracture network -Permeability -Hydraulic conductivity -Groundwater pressure Compressibility hydraulic head -Hydraulic fracturing	Site Evaluation -Major and minor elements -Radiometric dating -Radon and helium in soil Water -Surface water runoff/ groundwater discharge ratio -Water temperature BoreholeWater -Eh -pH -Anions (HCO_3, SO_4, Cl, Br, F, Fe^{+2}, SiO_2, NO_3, I) -Cations (Na, Ca, Mg, K, Sr, Si, B, total Fe) -Total Dissolved solids (TDS) -Trace elements (Mn, Cu,Zn, Ni, V, Pb, Li, Ba, Al, Cr, Co, Cd , As and P, Li, Fe, Mn, V, Al +Others) -Dissolved organic carbon -Colloidal fractions -Density -Temperature -Isotopes (H, ^{2}H, ^{3}H, ^{18}O , $^{36}Cl/Cl$, ^{14}C, ^{13}C, $S^{18}O_4$, $^{34}SO_4$, $^{87}Sr/^{86}Sr$, U, $^{234}U/^{238}U$, ^{36}Cl, ^{129}I, ^{226}Ra, ^{222}Rn) - Dissolved Gases (H_2 ,He, O_2, N_2, CO_2, CH_4, Ar, H_2S) -Dissolved Inert Gases(He, $^{3}He/^{4}He$,Ne isotopes)	Site Screening -Effective lithostic load -Active tectonic stress -Remnant stress Site Evaluation -In situ stress (hydraulic fracturing) Drill core -Uniaxial compressive strength, -Triaxial test for deformation, -Stress history -In situ stress -elasticity	Drill core -Tortuosity - Porosity (surface area, pore aperture) - Micromorphology of pore - Diffusion - Permeability - Thermal expansion -Thermal conductivity -Thermal diffusivity -Magnetic susceptibility -magnetic anisotropy

Country	Rock Type	Geological & Structural Parameters	Geophysical Parameters	Meteorological Parameters	Hydrogeological Parameters	Geochemical Parameters	Rock Physical Parameters	Mechanical Parameters	Transport Properties
JAPAN URL Mizunami Underground Laboratory (Shobasama and Mizunami Sites) Saturated Zone	Granite Age: 70 MA Cover rock: Sedimentary	Regional Geology -Stratigraphy -Geological units (contact, depth) -Petrology & mineralogy of fresh and weathered granite -Thickness sediment layer -Type of dikes, orientation, width -Infilling minerals in fault zones Structures -Lineament orientations -Faults (geometry length, orientation) -Fracture (distribution, density) Core Samples -Rock type -Textural variations -Mafic mineral content -Contact depth -Degree of weathering/alteration -RQD -Fracture (density, location and dip, shape, aperture) -Nature of alteration products along fracture -Mineralogy of fracture filling minerals	Regional -Boundary of granite -Geological unit thickness -Lineaments -Depth of unconformities -Fault length -Fracture zones -U, Th, K Borehole -Fracture density -Density -Porosity -Lithology -Temperature -Velocity	-Precipitation -Infiltration -Evapo transpiration -Wind velocity -Wind direction -Water level -Water budget -Soil moisture -Recharge -Discharge	-Hydraulic head -Hydraulic conductivity -Hydraulic gradient -Permeability -Specific storage coefficient -Porosity -Pore pressure -Flow rate -Transmissivity	Groundwater -pH -Eh -Total Dissolved Solid Content (TDS) -Temperature -Electrical conductivity -Chloride content -Colloids -Microbes -Major elements (Si, Ca^{+2}, Na^{+}, $HCO_3^{-}+CO_3^{-2}$, Fe^{2+}) -Isotopes (^{2}H, ^{3}H, $\delta^{18}O$, $\delta^{13}C$, ^{14}C, $^{36}Cl/Cl$) -Radiogenic isotopes (Th, U, K, Rd) Rock -Major elements (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, P_2O_5, H_2O) -Minor elements (F, Cl, Sr, Rb, Li, Zn, Cu, Pb, Sn, Be) -Radiometric dating ($^{87}Sr/^{86}Sr$, U-Th-Pb) -REE	-Apparent density -Effective porosity -Moisture content -Seismic wave velocity (P-wave) -RQD	-Coefficient of elasticity -Unconfined compressive strength -Poisson's ratio -Tensile strength -Cohesion -Friction - In situ stress -Hydraulic fracturing -AE/DRA	-Uranium sorption -matrix diffusion

Country	Rock Type	Geological & Structural Parameters	Geophysical Parameters	Meteorological Parameters	Hydrogeological Parameters	Geochemical Parameters	Rock Physical Parameters	Mechanical Parameters	Transport Properties
JAPAN URL Horonobe Underground Laboratory Saturated Zone	Argilite Age: Neogene	Regional -Major lineaments -Stratigraphy -Major fault/fracture zones Core samples -Stratigraphy -Degree of diagenesis -Lithology -Fracture distribution -Mineralogical composition -Microfossils	Regional/Site-specific -Geological formations, structures (faults, fractures and folds)at depth - U, Th, K Borehole -Lithological contacts, boundaries -Porosity -Density	-Precipitation -Temperature -Infiltration -Humidity -Wind velocity -Wind direction Evapotrasnspiration rate -River flux	-Hydraulic head -Hydraulic conductivity -Transmissivity	Groundwater -pH -Eh -Dissolved gases (H_2, He, N_2, O_2, CO, CO_2, hydrocarbon) -Isotopes (D/H, $^{18}O/^{16}O$, ^{14}C, $^{13}C/^{12}C$, ^{36}Cl) -Major elements (Na, K, Mg, Ca, Si. F, Cl, Br, I, alkalinity) Minor elements (Al, Fe, Li, Sr, Mn, S. T.P, PO_4 T.N, NO_{2-}, $NH_{4,}$) -Microbe types -Methane gas	-Porosity -Density -Swelling factor -Durability factor -Dissolved gas	-Uniaxial compressive strength -Elastic modulus -Stress -P-wave velocity -Cohesion -Friction -Poisson's ratio -Tensile strength -Unit weight -*In situ* stress -RQD	-Diffusion coefficient -Dispersivity -Hydraulic aperture -Transport aperture

Country	Rock Type	Geological & Structural Parameters	Hydrogeological Parameters	Geochemical Parameters	Rock Mechanics	Thermal Properties	Transport Properties
Sweden *SKB* Saturated Zone	Crystalline rock	<u>Site Identification (100-200km2)</u> - lineaments <u>Investigation Area (5-10km2)</u> - lineaments - field descriptions - classification of fracture zones <u>Site Description Model (SDM)</u> - topography - soil layers - lithology <u>Structural for SDM</u> - ductile structures (folds, shear zones) - brittle structures (faults, fractures)	- permeability - porosity -storage coefficient -rock compressibility - salinity -pressure head distribution	- pH - Eh -Fe^{2+},HS^-, HCO_3^-, Cl^-, Na^+, Ca^{2+}, HA/FA -dissolved gases N_2, H_2, CO_2, CH_4 He, Ar - colloids - bacteria -SO_4^{2-}, HPO_4^{2-}, F^-,HS^-,$Fe^{2+}$and Mn^{2+}	- discontinuity - deformation properties - compressive / tensile strength - shear stress - fracture roughness - shear direction - young's modulus - Poison number - rock classification (RMR, Q) - shear wave velocities - indentation index - wear index - blastability	-thermal conductivity - heat capacity - thermal expansion - temperature in rock and groundwater - thermal boundary conditions - thermal gradient	- dispersion - flow porosity - flow-wetted surfaces - fracture aperture/geometry - sorption - matrix diffusion - matrix porosity - biological activities - tracer - colloids and gases in groundwater

Country	Rock Type	Geological & Structural Parameters	Geophysical Parameters	Climate & Metereology	Hydrogeological Parameters	Hydrogeochemical Parameters	Rock Mechanics	Thermal Properties
Finland *Olkiluoto* Saturated Zone	Crystalline (Metamorphic) Rocks Age: Pre-Cambrian	Regional scale - Rock types - Lineaments - Fracturing Trenches, outcrop and boreholes - Lithology/mineralogy - Fracture mineralogy - Fracture (dip, dip direction, fracture frequency, length, aperture) - Rock texture and structure - Ductile deformation (folds axis, axial plane, foliation) - Brittle deformation (fault plane, lineation) - Hydrothermal alteration minerals Petrographic &Lithogeochemical (protolith and genesis) - Mineral paragenesis - Metamorphic grade - Mineral composition - Migmatitic texture and structure Overburden - Uplift rate - Thickness - Density of soil particles - Grain size distribution Sea bottom sediments - Sediment thickness - Sediment depth - Topography - Sediment density, quality, texture, structure - Radionuclides Shoreline displacement - Glacio-isostatic depression/uplift rate - Global eustatic sea level lowering/rise rate	Regional -Magnetic field - Frequency - Total field and vertical quadrature -Total U, Th, K -Crustal movement Ground geophysical - Magnetic field - Lithological variations, thickness - Fracture distribution - Water salinity - Fracture zones Borehole - Rock types - Fracture (depth and distribution) - U, Th, K -Temperature of water	- Temperature - Precipitation - Snow cover and ground frost thickness - Water content - Wind speed - Wind direction - Chemical deposition of precipitation (pH. DOG, N, NH_4-N, NO_3-N, Ca, Mg, K, Na, SO_4-S, Cl) -Cs-137, Sr-90, H_3	Surface -Flow rates - Infiltration rate - Evaporation - Transpiration Boreholes - Hydraulic conductivity - Hydraulic head - Transmissivity - Electrical conductivity - Porosity - Permeability	- pH - Electrical conductivity - Temperature - Density - Dissolved organic carbon - Anions (HCO_3, CO_3, Cl, Br, F,Br, SO_4, PO_4, NO_3, NO_2, N, P) - Cations (Na, Ca, Mg, K, Al, Fe, SiO_2, NH_4) - Trace elements (Sr, Li, Ba, Cs) - Organics (Total Organic carbon, Dissolved organic carbon) - Isotopes (δ^2H, ^3H, $\delta\,^{18}O$, ^{222}Rn, $\delta^{13}H$ $^{234}U/^{238}U$, ^{34}S, ^{18}O, $^{87}Sr/^{86}Sr$ - Total inorganic carbon -Microbes (sulfur reducing bacteria (SRB), iron reducing bacteria (IRB) - Colloids - Methane (CH_4)	Rock mass -Uniaxial compressive strength - Crack initiation strength - Long term strength - Peak strength - Tensile strength - Young's modulus - Poisson's ratio - Shear modulus - Deforma tion module - Stress orientation -Creep - Fatigue - Complete stress tensor - Horizontal stresses - P and S-wave velocity Fracture zones -Poisson's ratio -Cohesion -Friction angle -Normal stiffness -Shear stiffness -RQD -Roughness -Undulation -Filling Deformation zones -Deformation module	-Thermal conductivity - Heat capacity - Thermal expansion - Mineralogical composition

		- Mass transfer - Erosion rate					-Displacement rate	

Table 2.6-2. List of common parameters

Geological Mapping and drilling	**Meteorological Investigations**	**Geophysical Investigations**	**Hydrological and hydrogeological Investigations**	**Geochemical and Isotope Investigations**	**Rock Properties**	**Transport Properties**	**Conceptual and Numerical Modeling**
-Major lineaments -Lithological contacts, boundaries and depths -Petrology -Mineralogy -Fracture and faults (orientation, length, locations)	-Precipitation -Temperature -Evapotransipiration -Infiltration -Wind direction and velocity -Recharge and discharge	-Location of faults and fracture zones, -Rock boundaries -Lithological contacts, thickness -Depth of discontinuities	Surface hydrology -Water level -Drainage recharge, discharge -Run on and runoff -Precipitation -Evaporation -Moisture redistribution Hydrogeology -Porosity -Permeability -Hydraulic conductivity -Hydraulic head -Transmissivity	Groundwater -pH -Eh -Major ions (cations and anions) -Total dissolved solids (TDS) -Trace elements -Dissolved gases -Isotopes (^{3}H, ^{18}O, ^{36}Cl, U) Rock -Major and minor elements -Secondary minerals -Isotopes (U, Th, K, Ar, Rd)	-Porosity -Density -Rock strength -In situ stress -Friction -Cohesion	-Advection -Diffusion -Dispersion -Sorption	-Geological, hydrological, geochemical and coupled processes

3 Lessons　Learned

本セクションではヤッカマウンテンやその他の内外のサイト特性調査プロジェクトで得られた教訓を列挙する。これから日本で行われるであろう概要調査段階でこれら全てがあてはまるとは必ずしも言えないが、今後、遅かれ早かれまた、多かれ少なかれNUMO が直面するであろう課題に深く関連すると思われるものを選んで以下に述べる。列挙した順序は必ずしも重要度とは関連していない。

3.1 複数の概念モデル（アルターナティブモデル）が重要

ヤッカマウンテンプロジェクトの初期から、涵養量が年間 1mm 以下であり、山に滲み込んだ水の大部分は未固結の降下火山灰層に沿って処分場を迂回して斜め水平に流れ、少量の水は垂直に処分場方向に流れるが、水はすべてマトリックスの中を通り、フラクチャーは不飽和のままであり、核種が漏れても処分場の直下に位置するゼオライトを多く含んだ地層が吸着するという概念モデルのみに基づいてモデリングやサイトの調査が15 年間続けられて来た。近年になって涵養量は 5mm から 80mm の間であり、山に滲み込んだ水の殆どは垂直に流れ、一部はフラクチャーを通り、処分場以深ではゼオライトの地層を迂回する流れが存在するという概念モデルがより実際に近いという事が分かって来た。マトリックスが不飽和でありながら、フラクチャーの中を流れる水が存在するというのは当初の概念モデルでは全く考えられていなかった。ところが最近のモデリングやサイト調査の結果、マトリックスとフラクチャーの相互作用が理想状態よりはるかに弱い可能性があることが判明した。

サイトの調査を進めるにおいて、概念モデルの構築は重要であるが、ただ 1 つの概念モデルに頼るのは避けるべきであり、代替モデルを平行して構築するのが肝要である。

3.2 平行した数値モデルが必要

上記の概念モデルに平行して数値モデルを構築することが必要である。数値モデルは概念モデルのシナリオの検証やサイト調査データを反映させたり、逆にサイト調査の方向付けに役立つ。ヤッカマウンテンでも当初から数値シミュレーターで検証が出来ていれば近年の概念モデルの大幅な修正は避けられたかも知れない。ただし、数値モデルは、概念モデルの具現化であり、あくまで限界がある事を常にわきまえておく必要がある。時として数値モデルがあたかも現実のような錯覚にとらわれる傾向があるので注意が必要である。

3.3 主要パラメータ

サイト特性調査で同定されるべき主要パラメーターは各国のサイトのほぼ共通していると言って良い。一見、不飽和領域に処分場を予定しているヤッカマウンテンと他国の飽和領域のサイトでは共通項は無いように思いがちであるが、実際は同定されるべき重要パラメーターやフィーチャーは共通している。それらを以下に列記する。

- 断層

- フラクチャー･マトリックスの相互作用
- 通過流量
- 境界条件

特に我が国においては、断層は遍在的に存在し、地下水の流れの方向や流量、速度を大きく左右していると考えられる。また、H17 取りまとめ（JNC, 2005）からも明らかなように、処分場の性能はマトリックス拡散に大きく依存するので重要なパラメーターである。通過流量は透水係数と動水勾配に依存し、我が国のような飽和領域でのプログラムでは比較的計測しやすいパラメーターである。一方、境界条件の同定は容易でない。

3.4 100m 毎に１、２本の透水性の高い亀裂

オルキルオト、東濃、レイモンド（米国カリフォルニア州）はそれぞれフラクチャー性の花崗岩のサイトであるがこれらにサイトに共通している点は、それぞれの孔井においておよそ 100m に 1 本か 2 本の透水性の高い亀裂が観測されている事である。また、カナダの URL、スウェーデンのストリパ、スイスのグリムゼルサイトでも同様な観測がなされている。無論、幾何学的な亀裂に関してはボアホールテレビやコア観測から 100m の区間では数十から 100 本程度記録されている。言い換えればおよそ 100 本の亀裂に 1 本の割合で透水性の高い亀裂が観測されている。また、透水性の高い亀裂と層でない亀裂が外見的には区別がつかない場合が多い。

3.5 フラクチャーマッピングはあまり有用でない

前記のように結晶岩においてはフラクチャーが主な水みちであるのは疑問の余地がなく、堆積岩環境においてもフラクチャーが透水係数に大きく寄与している例は多々ある。このようにフラクチャーは水の流れを解明するためにはきわめて重要であるが、フラクチャーの幾何学的な情報は今までのところあまり役立っていない。ヤッカマウンテンプロジェクトの初期の 1980 年代後半には各地層の路頭でスキャンラインやグリッドを用いて精細なフラクチャーのマッピングが行われた。さらに、1990 年代の ESF（Exploratory Studies Facility）トンネルの掘削中は TBM に連結された長い台車に数人の地質学者が乗り込んで 24 時間体制で TBM の前進に合わせてトンネル壁に現れるフラクチャーのマッピングが行われている。しかしながら、おそらく数十億円を掛けたであろう膨大な量のデータは未だに安全評価に使用されずじまいである。ストリパプロジェクトでもフラクチャーのマッピングが行われ、統計的なデータからフラクチャーネットワークを作成し、水の流れを予測する試みがされたが事実上、成功を収めたとは言えない。

原因はフラクチャーの幾何学的性状と実際の水の流れに相関性が無いからである。瑞浪やレイモンドにおいても孔井で観測されるフラクチャーの密度と岩体の透水係数の相関性が極めて低いという結果が出ている。従って、少なくとも概要調査の段階でフラクチャーのマッピングは不必要であると考えられる。

3.6 物理探査データはソフトデータ（間接的なデータ）

ヤッカマウンテンでは水みちや宙水層の位置を同定すべく種々の物理探査が行われた。弾性波、電磁、電気抵抗探査などがそれである。しかし、何れも十分な成功を収めたと

いえない。弾性波探査は亀裂の発達した岩盤ではあまり有効でない。また、物理探査手法は水理的特性を直接測るのではなく、岩の密度や電気抵抗からフラクチャーや水の存在を間接的に推測するのであくまでソフトなデータとして扱うのが望ましく、今後の改良が望まれる。

3.7 温度、ジオケミのデータは非常に有用

ヤッカマウンテンにおいて不飽和領域を通過する水の流量は最重要パラメーターの 1 つであるが、これを直接計測する事は困難である。そこで、温度分布や地層中の残存塩素の濃度を元に通過水量を逆解析的に推定すると、過去に推定されていた流量（1mm/y 以下）よりはるかに多い 5mm~80mm という値が推定された。この数字は不飽和領域にも拘らず、フラクチャーの中を水が流れていることを示しており、ESF トンネル内で核実験起源の Cl^{36} や C^{14} が観測されていることの説明がつく。

水理データ（圧力、飽和度）は水の流れを推定する為に第一義的に重要であるが、フラクチャー等が存在する不均質な場では点的なデータである事と測点数に限りがある事により、不確実性が大きく、信頼性のある解析が難しい。そこで、自然に平均化が行われている温度や地球化学的データを使用する事によって不確実性の幅を低減する事が可能になる場合がある。

3.8 バックグラウンドデータの取得を早期に開始

ヤッカマウンテンでは 1990 年代初頭から TBM を使用して直径 7.5m、長さ 8km に及ぶ ESF が掘削された。これは言わば大規模な孔井試験のようなものであり、調査段階でサイトに与えうる人工的なインパクトとしては最大級のものである。しかしながら、トンネルの掘削が与える影響についてのモニタリングは特に行われす、大きなスケールの試験データを取るチャンスを逃してしまった。近年、各種のセンサーの解像度や精度が上がってきているが、いわゆるタイムラプス(経時的な)データを取ることによって解像度はいっそう向上することも鑑みると残念なことであった。

サイト調査を始めるにあたって、まず場を乱す前にバックグラウンドのデータの取得を開始するべきである。

3.9 QA の必要性

ヤッカマウンテンではエンジニアリングと地球科学的調査との根本的な差異を無視して原子力発電所の建設に適用される QA（Quality Assurance）をそのままサイト調査の QA に当てはめた事に因る弊害が数多く出た。QA 第一主義を徹底させた結果、サイト調査に関わる研究者はゆうに 50%以上の時間を QA 関連の書類を書き込む事に費やし、肝心の研究調査そのものがおろそかになった。QA の書類が揃っていない為に有用なデータが採取できなかったり、データは存在しても規定の書式に沿ってない為に解析に使用できなかったりした。しかしながら、適切な QA は必要不可欠のものである。

データそのものの信用性や解析の正確さを保証したり、シミュレーターの正しさの検証は科学に携わる者にとっては常識的な事ではあるが、時に見過ごされることがある。

現行の日本のシステムではサイト調査は業者によって行われるが、再現性や追跡可能性を第三者に保障する為にも実施主体が講じる QA 制度が必要である。

原位置調査においては計測対象以外の要因が正しい計測を妨げる事が良くある。ヤッカマウンテンの飽和領域でスラグ試験（3.1.3.1.2.3 参照）が数多く行われたが、最も透水性の高い地層でのスラグ試験では装置の圧力損失が大きく、結果的に地層の透水係数を測らず装置の透水係数を測っていたが、後年まで誰も気がつかなかった。レイモンドのサイトで行ったトレーサー試験では臭素の濃度が LBL のラボで誤って同定されていたが、暫く分からなかった。化学分析においてはダブルブラインドのサンプルを入れて複数のラボで行うという常識が守られていなかった

入力データや解析条件に無限の組み合わせがあるので数値シミュレーターのバグは時として発見が困難である。2003 年の米国北東部大停電や数百億円掛かった火星探査機の衝突もソフトウェアのバグが原因であった。ソフトウェアの QA も見落してはならない。

3.10 サイエンスは重要

当初、ヤッカマウンテンプログラムでは処分場の特性評価は既存の技術で実証できると考えられていたが、処分場通過水量やフラクチャーの性状に関して不確実性が大きい事が判明した為、近年 OSTI（Office of Science Technology and International）という課を発足させ、研究開発に力を入れ始めた。実際、地球科学の分野では未だに解明されていない課題は多い。上記の主要パラメータのセクションで挙げた項目は何れもサイトの安全評価の為に重要であるが、現状では不確実性が大きく、研究開発によって出来る限り正確に同定されるべきものである。

3.11 想定外’を想定する

近年ヤッカマウンテンにおいて不飽和体でありながら、水がマトリックスに毛管圧で吸い込まれずにフラクチャーの中を流れる現象が認められたのは当初の想定外であった。また、2006 年 3 月にヤッカマウンテンの南の飽和領域で行われた fulid logging (4.1..3.1.1.3 参照)試験でこれまでの想定の 1000 倍の流速と推測されるデータが観測された。また、ESF の掘削中の埃やラドンによる被爆が人体に害がある事が最近になって問題視されてきた。これらも当初は想定外であった。しかし、ヤッカマウンテンが特別な訳ではなく、他のサイト調査でも類似した事は起こっている。フィンランドの Olkiluoto では、孔井から 80g/l という濃い塩分濃度が観測されている。現在のバルト海の塩分濃度は 10g/l である事を考えると、想定外である。また、異常定圧ゾーンやメタンガスも観測されているが、何れも想定外である。無論、データの QA が出来ていて初めて想定外のデータが信用されるべきであるが、地球科学の分野では想定外は良く起こるとあらかじめ想定しておくべきである。

3.12 スケジュール最優先は危険

スケジュール最優先の調査は避けるべきである。特に日本では単年度予算の為に 3 月末までに何が何でもスケジュールを消化しようとする傾向があるが、これは極力避けるべきである。孔井内圧力試験を例に取れば、仕様を満たす為に短期で終わらせた 5 回の

試験結果より、1 回の正確に行われた長期試験の方がはるかに価値がある。QA の観点から、また、安全面からもスケジュール最優先は避けられなければならない。また、距離が近い複数の孔井を同時に掘削することも避けたい。1 孔を掘削中に他孔でモニタリングするのは非常に有用である。

3.13 フレキシブリティが必要

上記 2 つのセクションで述べたように、地球科学関連の調査では想定外の事態は必ずといって良いほど起こる。従ってスケジュールや調査計画も臨機応変である必要がある。ヤッカマウンテンでは全ての調査に事前の QA 手続きが必要であった為、突然起こった集中豪雨の影響をモニターする為の手続きが間に合わず、結局貴重な涵養量に関するデータが取れなかった。時には即断も必要であるという教訓である。

当初良いアイデアだと思われていた事が後になって実はまったく逆であったケースは他の分野に於いて過去に例が多くある。ダムもその 1 例であろう。また、かつて米国で 2,30 年前に古タイヤを漁礁として使うプロジェクトがあり、古タイヤの再利用と魚の環境保護を謳い、フロリダの海底に 100 万本以上のタイヤが沈められたが、結局魚は住み着かず、タイヤは波の力で転がり回ってサンゴ礁まで破壊してしまい、現在は撤去作業が進められている。また、鉛に代わるガソリン添加物として大々的に導入された MTBE (Methyl Tert-Butyl Ether) は近年になって発癌性がある事が分かり使用が中止された。処分場建設のような何十年も掛かるプロジェクトでは、その期間中に種々の発明、技術革新がなされ、新しい理論が構築される可能性もある。それによって、それまでの方針や手法と違う方向の展開になるとしても、その時点ごとにベストと思われる選択をする勇気とフレキシビリティが必要である。

3.14 謙虚さ、透明性が重要

2005 年に米国地質調査所（USGS）のある研究者がデータの取得日に関して虚偽の記述を認めた Email が明らかになり問題となった。この事件に関する教訓は２つある。 1 つは DOE の QA システムが虚偽を発見し、公にした事である。透明性に関しては正しい処置であった。しかし、実際の実験や観測データが捏造されたわけではなく、処分場の安全性や解析の科学的な品質が損なわれた訳ではないが、ヤッカマウンテンプログラムの信頼性に大きな打撃を与えた。

前に者べたが、地球科学の分野ではまだまだ解明されていない課題が多い。分からない事は分からないと認める謙虚さが必要である。その上で研究開発を進めていく必要があると考える。

4 Evaluation of Field Investigation Technologies

Field investigations play a prominent role in the site characterization process. Numerous field investigation and exploration technologies are employed throughout the world to investigate contaminated sites, characterize waste disposal facilities, or search for oil, gas and mineral resources. Many of these are directly applicable to site characterization activities related to geologic storage of high-level radioactive waste. A review of existing and emerging geological, geophysical, hydrological, geochemical and geotechnical field testing, monitoring and analysis techniques follows. Their usable ranges, accuracies, and their applicability to site characterization will be evaluated.

4.1 Evaluation of Existing Field Investigation Technologies

4.1.1 GEOLOGICAL TECHNOLOGIES

Regional and site geologic and geomorphic features including faults, fracturing, sediment structure, erosional unconformities, volcanic features, and rock type form the framework for most site characterization models (SCMs). Therefore, it is important to characterize surface and subsurface geology using drilling, logging and surface mapping techniques to build the geologic framework needed for the model.

4.1.1.1 DRILLING TECHNIQUES

Numerous drilling techniques are used to install borings and wells with the most common methods being solid and hollow stem auguring, direct-push methods, air rotary, air percussion, cable tool, mud rotary and diamond coring. Numerous textbooks and articles have been written on the subject of drilling, with the oil, gas, water well, environmental, and mining industries being the major source of this material. Detailed descriptions of drilling methods, including the advantages and disadvantages of each drilling type, abound in the literature (Driscoll, 1986; Lehr et al., 1988; Bradley, 1992; Hartman). It is not the purpose of this section to describe each of the drilling techniques; rather it is our intent to point out subtle issues related to drilling that can have a significant impact on site characterization and data quality.

Drills and drilling techniques are used to install borings and wells, which are integral components of any site characterization program. Borings and wells are designed to provide access to the subsurface for sampling, testing, and evaluating conditions that cannot otherwise be observed using remote sensing techniques.

Drilling is an intrusive site characterization technique, and as such, it disturbs the rock, pore fluids and environmental conditions (e.g., temperature and pressure) in close proximity to the boring. Therefore, careful consideration must be given to the drilling method, speed, and downhole pressure exerted by the bit during the drilling process, type of drilling fluids used to flush the drill cuttings from the hole, and material used in the construction of wells, to insure minimal disturbance of samples and ambient formation conditions. For example, drilling fluids including compressed air, water, drilling muds, and additives must be carefully selected to minimize changes in pore-fluid quality if hydrochemical sampling and evaluation is the primary purpose of the boring or well. The type of material used for the casing and well screens, cementing agents and well development techniques must also be carefully selected for the same reason.

The high cost of drilling deep wells for site characterization purposes can lead to the installation of only a few wells, thus limiting access to the subsurface and creating competition between scientist programs (hydrology, geology, geophysics, etc.) for their use. Fewer wells typically translate into borings or wells used for multiple activities that may have conflicting data requirements and goals. Therefore, each field activity must be carefully examined to determine the impact that it will have on the accuracy and data quality of the remaining field activities. Program priorities should be assigned to each activity in advance of drilling with the goal of minimizing test interference. Boring and well specifications are then developed based on the requirements of the highest priority activities. Competing activities of equal importance, but requiring significantly different well/boring design, may require installation of two or more holes to satisfy all program requirements.

4.1.1.2 GEOLOGIC SAMPLING TECHNIQUES

Geologic sample collection is an important component of any site characterization program. Samples are collected for various reasons including soil and rock-type identification, petrographic examination, and field and laboratory testing of samples for geomechanical, hydrological and geochemical properties. Collection techniques range from simple grab samples to complex oriented rock or soil cores. Grab samples consist of physically grabbing samples that are generated during drilling (e.g., drill cuttings) and are readily available. By design, the sampler gives little attention to the exact depth, orientation, or precise location of grab samples. Grab samples are typically used to identify general lithology and the sample's structure is often disturbed or destroyed during collection. At the other end of the spectrum, cored-rock samples or unconsolidated sediment samples collected using direct-push methods are least disturbed, thus preserving sample structure and integrity. Orientation and spacing of fractures and faults, dip direction and dip amount of bedding planes, and depth to geologic features can be determined from cores if the orientation and depth of the core barrel is maintained during the drilling operation. Cores are typically collected in the direction of bit travel; however, coring devices are also available allowing collection of side-wall core samples. Side-wall coring devices produce short cores called plugs, whereas axial core samples can be of any desired length.

Sample specifications and procedures should be defined in advance of sampling to ensure that proper identification, preservation, and handling techniques are used to preserve the scientific and legal integrity of the sample. Samples must be labeled with unique identifiers. Preservation techniques may be required to stabilize the sample and keep it from degrading after collection. Hold times for samples or expiration dates must also be observed to ensure sample integrity. This is especially true for environmental samples that are analyzed for chemical composition. Special handling procedures may also be warranted to prevent the sample from crumbling, drying, or becoming jumbled or disoriented if its original orientation was maintained during drilling. Chain-of-custody procedures are used to document the transfer of samples from its original collector to subsequent custodians, eventually ending only when the sample is disposed of or destroyed. Finally, archiving of samples for subsequent logging, confirmation and use by other project participants is often desirable. This may require construction of a sample or core library designed to preserve and house samples.

4.1.1.3 MUD LOGGING

Mud logging refers to the process of collecting and examining rock fragments cut by the drill bit (drill cuttings) and washed out of the hole by the drilling fluids, i.e., grab samples. Drilling fluids typically consist of compressed air, water, drilling muds and various additives. Muds are made up of a base fluid (water, diesel or mineral oil, or a synthetic compound), weighting agents (most frequently barium sulfate [barite]), bentonite clay to help remove cuttings from the well and to form a filter cake on the walls of the hole, and lignosulfonates and lignites to keep the mud in a fluid state.

The mud logger collects samples of the drill cuttings during the drilling operation to identify the lithology and petrology of the rock strata. The logger estimates the sample depth by calculating and tracking the "lag" time, which is the time it takes for the cuttings to travel from the bit to the land surface. The greater the depth, the greater the "lag" time. The cuttings are labeled, washed, dried and examined with a binocular microscope to identify the predominant rock type. Rock types are often correlated with drilling rates to provide further information on the depth and subsurface distribution of the rock strata. Mud logging is an inexpensive screening tool with limited accuracy. Factors that affect accuracy include logger experience in a given geographic area, improper calculation of lag times, interbedded thin layers of multiple rock types, finely-ground rock fragments, sloughing of uphole rock material, and diligence of the logger.

4.1.1.4 CORE LOGGING

Drill cores are collected and inspected to identify formation lithology and fracture orientation, spacing, and coatings. Cores are collected using a diamond-impregnated bit attached to the end of a hollow tube (called a core barrel) and the drill pipe. When the drill rig turns the drill pipe, core barrel and bit, the donut-shaped bit cuts the rock adjacent to the outer bit face, but leaves the center rock intact. The uncut rock in the center of the bit travels up into the hollow core barrel as the bit advances deeper into the rock. After the core barrel fills with core, the drill pipe and core barrel are pulled back to the surface where it is emptied. Alternatively, some coring systems use an inner barrel that holds the core and fits inside the drill pipe and outer core barrel. A wireline device is sent down the interior of the drill pipe where it latches onto the inner barrel and pulls it back to the surface to retrieve the core.

Due to the relatively high cost of retrieving core, core logging may also include taking images of the core using digital or conventional photography, or scanning the cores using various geophysical techniques. For example, x-ray computed tomography has been used to create images of the core's interior and rock density without breaking or destroying the samples.

4.1.1.5 GEOLOGIC MAPPING

- Detailed surface geologic mapping
  - Faults & structure
  - Stratigraphy & unconformities
- Detailed geologic cross sections
  - Correlation of borehole logs
  - Underground maps from mines
- Fracture pavement studies
- Aerial photography/mapping
- Digital photography
- Surface Sampling/verification

4.1.2 GEOPHYSICAL TECHNOLOGIES

Geophysical surveys are commonly employed in the oil and gas, water well, environmental, and mining industries to explore for natural resources and to define the nature and extent of fluids or contaminants. Applied geophysics is the science of using physical measurements or experiments performed on the land surface, in the ocean, air, or from boreholes drilled from the surface to determine the physical properties and processes in the subsurface. Geophysics is ideally suited for remote sensing. That is, measurements made at a readily accessible location or surface (such as land surface or from a boring) are interpreted and used to infer larger-scale, volume-averaged properties of the porous media or fluid below the surface. In addition, geophysical methods do not necessarily measure the rock or fluid property directly, but instead measure a related parameter that must be interpreted to indirectly derive the desired property. For example, open-hole resistivity logs measure the electrical resistance of the fluid surrounding the tool, which is correlated to the total dissolved solids or salinity of the fluid, which may be further correlated to porosity or permeability.

Geophysical surveys can be divided into the following general categories or methods (Telford et al., 1976): 1) gravitational; 2) magnetic; 3) electrical; 4) electromagnetic; 5) seismic; 6) radioactivity; and 7) miscellaneous chemical, thermal and well/borehole logging methods. For the most part, most geophysical methods are not intrusive, meaning survey measurements can be made at the land surface or interface without cutting into, drilling, or otherwise disturbing the medium. However, deployment of geophysical sensors in boreholes and wells can provide detailed information regarding the vertical distribution of parameters, increase accuracy and provide added value to surface-based surveys.

4.1.2.1 SURFACE-BASED GEOPHYSICAL SURVEYS

4.1.2.1.1 Gravity Surveys

Gravity surveys involve measuring small differences in the Earth's gravitational field caused by local variations in rock density. Gravity anomalies are very small compared to the Earth's gravitational field requiring the use of delicate and precise gravity meters. Data interpretation is complex, detailed topographic information must be available to evaluate the data, and the surveys are relatively slow and expensive. Surveys may be performed on a ship, in the air or above or below ground. Gravity is used for oil exploration and as a secondary method used for mineral exploration. Alternative applications include:

- Mapping bedrock topography under landfills or alluvial-filled valleys;
- Locating subsurface cavities; and
- Locating geologic contacts.

4.1.2.1.2 Magnetic Surveys

The magnetic method measures variations in the Earth's magnetic field. An induced magnetic field is created around a buried ferrous object when the object is placed in the Earth's field. A magnetometer is used to measure the local variations or distortions in the magnetic field, which are referred to as magnetic anomalies. Magnetometer surveys measure the magnetic field strength at evenly-spaced points over the area of interest. The gradient method uses two magnetometers to simultaneously measure the total magnetic field at two elevations at the same location. The difference in magnetic intensity between the two magnetometers divided by their separation distance equals the vertical gradient. The gradient method reduces interference from solar magnetic storms and regional magnetic changes and is used for locating and determining the depth of small, shallow objects. The data acquired are processed and plotted as line profiles and/or contour maps. The size, shape, and amplitude (intensity) of the magnetic anomaly are used to identify the object. Magnetometer surveys have been used successfully to:

- Explore for mineral resources;
- Locate buried objects including underground storage tanks and buried drums;
- Delineate landfill perimeter;
- Identify geologic bedrock features such as mafic dikes or geologic contacts; and
- Delineate military ordnance;

Utilities, power lines, buildings, metallic debris, and solar storms can cause interference with magnetometer surveys. The size and depth of an object also influences its detectability using this technique.

Langenheim et al. (1993), Langenheim (1995), Langenheim and Ponce (1995), and Blakely et al. (2000) performed and interpreted aeromagnetic and ground-based magnetic surveys to investigate several buried magnetic anomalies in the Yucca Mountain, Nevada region. The assessments were undertaken to characterize the likelihood of volcanic activity disrupting the proposed repository (DOE, 2001). O’Leary et al. (2002) concluded that the due to the strong magnetization, the anomalies were probably of volcanic origin, consisting primarily of basalt dikes and cones from the Plio-Pleistocene, and less likely consisting of Miocene tuff.

4.1.2.1.3 Electrical Surveys

4.1.2.1.3.1 Self potential

Self potential (SP) refers to the natural or spontaneous potentials or voltages that occur in the subsurface caused by natural electrochemical or mechanical processes. These potentials are associated with weathering of sulphides, variations in mineral content of rocks at geologic contacts, bioelectric activity, corrosion, and thermal and pressure gradients in underground fluids. Groundwater is the controlling factor in each case (Telford et al., 1976).

The SP method uses special electrodes and a millivoltmeter to measure potentials at various locations. The end result is a series of profiles or contour map of equipotentials. Amplitudes range from a few millivolts (mV) to one volt, with values exceeding 200 mV representing good SP anomalies. SP surveys have shown that large anomalies are associated with mineral deposits; therefore, SP is used extensively in mineral exploration.

4.1.2.1.3.2 Surface Resistivity

The surface resistivity method involves driving two metal electrodes into the land surface and then applying a known current across the electrodes (point sources). A second set of electrodes is used to simultaneously measure the voltage drop, allowing calculation of the subsurface effective or apparent resistivity from the known electrode spacing and geometry, applied current, and measured voltage. Line sources consisting of electric lines in contact with land surface are also used in place of point electrodes to make the measurements. Surface resistivity is used to:

- Determine depth of overburden;
- Map the water table surface;
- Investigate the depth, structure and resistivity of flat-lying sediments; and
- Explore for mineral resources;

Surface resistivity is sensitive to minor variations in conductivity near land surface complicating data interpretation. The depth of investigation of this technique is dependent on the electrode spacing and applied current. Depth of penetration using commercially available, portable surface resistivity meters ranges from 50 to 100 m.

4.1.2.1.3.3 Induced Polarization (IP)

Induced polarization surveys use the standard four-electrode resistivity configuration to inject electric current into the earth. After a direct current is applied, the potential drops quickly eventually taking a few seconds for the voltage to decay to zero. The earth will retain charge, rather like a capacitor, with the decay rate depending upon clay content or type of minerals present. The decay voltage will be zero if there are no polarizable materials present. IP surveys can be performed in two modes of operation including time and frequency domain. In either case, the voltage response measured by the receiver is a function of conductive minerals disseminated throughout the survey area. This method can be used to probe to subsurface depths of thousands of meters. Uses include:

- Detection of disseminated metallic minerals; and
- Discrimination of clay from silt or sand where formation resistivities are similar.

4.1.2.1.4 Electromagnetic Surveys

Electromagnetic (EM) methods include some of the most commonly employed geophysical techniques used for near-surface environmental and geotechnical studies. Electromagnetic methods fall in two categories, frequency domain and time domain. Frequency domain measures the amplitude and phase of an induced electromagnetic field. Time domain measures the decay time of an electromagnetic pulse induced by a transmitter. EM surveys measure variability in subsurface conductivity, which can be naturally occurring (differing lithologic materials), or man-made (soil/groundwater contaminants or buried metal). EM surverys may be used to:

- Locate buried metallic objects (drums, tanks, etc);
- Map leachate plumes;

- Map soil salinity and salt water intrusion;
- Delineate landfill and trench boundaries;
- Map soil and groundwater contaminants;
- Detect location and orientation of faults;
- Identify small non-ferrous metallic objects such as ordnance;
- Map lateral and vertical distribution of soil type;
- Locate water resources;
- Identify karst bedrock features; and
- Predict areas prone to slope failure.

Ground penetrating radar (GPR) provides a high resolution, cross-sectional image of the shallow subsurface. A short pulse of electromagnetic energy is radiated downward. When this pulse strikes an interface between layers of material with different electrical properties, part of the wave reflects back, and the remaining energy continues to the next interface. Depth measurements to interfaces are determined from travel time of the reflected pulse and the velocity of the radar signal.

GPR surveys were successfully used to monitor changes in rock water saturation during several experiments performed underground at Yucca Mountain as part of the US Department of Energy's site characterization program (Tsang et al., 1999). Additional uses of GPR include:

- Map the location and burial depth of drums, underground storage tanks, and utilities;
- Image man-made subsurface structures;
- Delineate disposal pits, trenches, and landfill boundaries;
- Locate voids and washouts along pipelines, under roadways, parking lots, and building floors;
- Screen proposed borehole locations for subsurface interference;
- Map water table and bedrock topography;
- Delineate inorganic and organic free-phase contamination plumes;
- Map stratigraphic layers;

- Evaluate mine and quarry rock; and
- Investigate archaeological sites and cemeteries.

4.1.2.1.5 Seismic Surveys

Two types of seismic surveys are commonly performed including seismic refraction and seismic reflection. In seismic refraction surveys, the travel time is measured for a wave to pass through a layer to another, refract along the interface, and return to the geophones at the surface. For shallow investigations (less than 100 feet), refraction is commonly utilized for mapping bedrock topography. Seismic reflection surveys make use of travel time and amplitude of all the reflected acoustic energy returning to each geophone. Reflection surveying can produce detailed images of subsurface geologic structures. This method is often applied to map faults, and fracture zones, which may represent migration pathways for contaminants. Additional uses of seismic include:

- Determine bedrock depth and topography;
- Determine groundwater depth;
- Resolve strata and aquifer thickness;
- Map fault and fracture zones;
- Measure overburden thickness; and
- Engineering properties: bulk or shear moduli

Figure 4-1. Installation of an orbital vibrator borehole seismic source used for cross-well seismic surveys in east Texas, USA.

Seismic surveys take on several different configurations depending upon the location of the sources (e.g., vibrator, shots) and receivers (e.g., geophones) and scope of the survey. Two-dimensional, 3-dimensional, and 4-dimensional (i.e., time lapse) surveys have been reported in the literature. These surveys are used to image the subsurface by placing both the source and receivers at land surface. Time-lapse surveys (4-D) can be used to investigate changes in formation velocity resulting from changes in formation and fluid properties, such as changes in water saturation that occur during an immiscible CO_2 flood. Recently 3-D seismic survey is rapidly becoming a common exploration/characterization tool. Vertical seismic profiling (VSP) and cross-well seismic surveys take advantage of wells or borings. A string of receivers is placed in a borehole during a VSP survey to record the seismic response from a series of controlled shots from various source-offset locations. Cross-well seismic surveys utilize two wells or borings (one for the source and another for the receivers) to image the earth between the two wells (Figure 4-).

Gritto et al. (2004) performed a surface-to-tunnel seismic survey to estimate fracture intensity and distribution in the repository host rock at Yucca Mountain, Nevada. A 5-km-long source line and a 3-km-long receiver line were located on top of Yucca Mountain and inside the mountain along the main drift of the Exploratory Study Facility (ESF), respectively. Tomographic inversion of the travel time data revealed a low-velocity zone in the south central area of the proposed repository. Conversion of the velocity results to fracture-density tomograms showed good correlation with an area of intense fracturing mapped along the tunnel walls of the ESF.

4.1.2.1.6 Radioactivity Surveys

Uranium-238, thorium-232, and the progeny of their decay series and potassium-40 are the most common emitters of natural-gamma radiation. The two elements, uranium and thorium, are important sources of fuel for nuclear reactors. Radiation surveys should be performed prior to waste acceptance to establish background levels for the facility. Naturally occurring radon, a colorless odorless gas, which is an alpha emitter, was detected in the volcanic rocks at the U.S. Department of Energy (DOE) proposed nuclear waste site at Yucca Mountain. The DOE implemented administrative and engineering controls to limit worker exposure to radon and integrated these controls into the existing site health and safety program.

4.1.2.2 WELL AND BOREHOLE-BASED GEOPHYSICAL LOGS

Numerous cased (i.e., well) and open-hole geophysical surveys are performed in the oil and gas, water well, and environmental industries to evaluate physical properties of the formation and fluid therein. Logs are performed by lowering a sensor, tool or device on a wireline or slickline into the well while continuously recording the sensor output for the parameter of interest (Figure 4-). Post processing of the sensor output is often needed to interpret the results. Many of the logs rely on the same principles of physics described in surface-based methods described earlier. The radius of investigation of cased and open-hole logs is small, typically penetrating only a few centimeters, and rarely more than a meter, into the formation. The most common logs in use are described in this section.

4.1.2.2.1 Caliper Log

When actuated, spring-loaded arms extend from the caliper tool pressing them up against the boring wall. The tool is slowly removed from the boring dragging the arms along the wall. Deflections in arm positions are measured electronically, producing a continuous record of the inside average diameter of a boring or well. Deviations in boring diameter are related to fracturing, lithology, and drilling technique and deviations in well diameter are caused by well-casing integrity. Caliper logs are often correlated with fluid-resistivity and fluid-temperature logs to identify fluid-bearing fractures or zones. Caliper logs are also used to identify smooth sections of borehole for setting inflatable packers.

4.1.2.2.2 Well Deviation Survey

Borehole deviation logs, also called dipmeter logs, record the deviation of a borehole from its true orientation. Deviation of vertical boreholes is common because the drill bit glances off of subsurface objects or “walks” down dip in stratified formations causing the drill bit and string to deviate from its intended vertical direction. Horizontal or inclined holes have a tendency to “walk” down and in the general direction of bit rotation because of gravity and the cutting action of the bit. Deviation logs are used to calculate true orientation of the boring/well, depth of geologic features of interest and

Figure 4-2. Wireline logging operation in East Texas, USA.

to correct the strike and dip of fractures or bedding obtained from acoustic televiewer logs.

4.1.2.2.3 Video Log

Special video cameras equipped with external lights and designed to fit inside borings and wells are used to visually inspect open boreholes, well casings, well screens, and perforations. A permanent record of open borehole conditions, fracture spacing and orientation, lithology, well screen placement, and casing and well-screen integrity can be determined from the video log. Depth and orientation of the camera must be recorded to determine fracture spacing and orientation and the depth of a given feature.

Two types of cameras are typically used including axial view and side view cameras. Axial view cameras point down the axis of the boring allowing the user to identify and inspect hole obstructions, washouts or lost tools. Side view cameras look directly at the wall of the hole or well allowing close inspection of fractures, breakouts, and geology. Video images may be analog or digital, color or black and white, with various degrees of resolution depending upon the camera manufacturer's make and model.

4.1.2.2.4 Spontaneous potential (SP)

Records small differences in voltages caused by differences in physical and chemical properties of various rocks and differing fluids. The differences permit identification of bed thickness, lithology, and changes in formation water quality. See self-potential.

4.1.2.2.5 Natural gamma ray

Natural-gamma logs (or gamma-ray logs) record the natural-gamma radiation emitted from rocks penetrated by the borehole. Gamma radiation can be measured through casing, but the gamma response is dampened. Uranium-238, thorium-232, and the progeny of their decay series and potassium-40 are the most common emitters of natural-gamma radiation. Used to map lithology and provides relative porosity of soil and rock based on clay content.

4.1.2.2.6 Resistivity

Fluid-resistivity logs measure the electrical resistance of soil, rock, and pore fluid in the borehole. Resistivity is the reciprocal of fluid conductivity, and fluid-resistivity logs reflect changes in the dissolved-solids concentration of the borehole fluid. Fluid-resistivity logs are used to identify water-bearing zones and to determine intervals of vertical borehole flow. Water-bearing zones usually are identified by sharp changes in resistivity. Measures the electrical resistivity of soil, rock, and pore fluid. Maps lithology and provides for contaminant identification based on conductivity of pore fluids.

Ramirez and Daley (1997) used electrical resistivity tomography (ERT) surveys at Yucca Mountain to map the change in rock water content around an artificially heated underground opening. Approximately 200 ERT probes were installed in 12 borings surrounding a heated drift. The work was performed as part of the Drift-Scale Test designed to simulate the heating and cooling of the rock caused by thermal/radioactive decay of the nuclear waste after emplacement.

4.1.2.2.7 Electromagnetic induction (EM)

Measures the conductivity of soil, rock, and pore fluid. Provides similar information to resistivity with the advantage of logging capability through PVC casing.

4.1.2.2.8 Density Log

The density logger is a tool that contains a concentrated source of gamma rays (usually Cesium-137) and a detector (Geiger or scintillation counter). The device has a lead-shielded window that when pressed against the borehole wall allows gamma rays to penetrate 10-20 cm into the formation. The gamma rays that return are detected, allowing the measurement of the bulk density of the formation based on the reduction in gamma ray flux caused by Compton scattering.

4.1.2.2.9 Neutron Log

The Neutron Log is used to measure formation porosity and water content. Modern neutron logging tools use sealed radioactive sources (Americium-241/Beryllium, AmBe), which bombard the surrounding formation with fast neutrons. The neutrons collide with hydrogen atoms of similar mass and are eventually captured emitting a secondary gamma ray. Older tools detect the gamma ray (neutron-gamma log), whereas most modern tools detect or count slow (thermal) neutrons (neutron-neutron log).

The Neutron Log responds primarily to the amount of hydrogen in the formation including hydrogen contained in oil, natural gas, and water. When the hydrogen concentration is large, most of the neutrons are slowed down or captured close to the wellbore resulting in a low-count rate, indicative of high porosity. In constrast, a small amount of hydrogen near the wellbore allows the neutrons to penetrate deeper into the formation producing a high-count rate, indicative of low porosity. Hard, dense formations usually have higher count rates compared to porous zones (including low permeability shales), which usually have lower count rates. Neutron logs are commonly used in unsaturated zone studies to measure water content.

Neutron logs can be used in open and cased holes, separately or in conjunction with virtually any other log. The Neutron Log can be run in any type of borehole liquid (water, oil, or mud), or the hole can be air or gas filled (significant log shifts are seen when logging through a liquid / gas contact in the borehole).

4.1.2.2.10 Sonic logs

This is a technique used in the oil and gas industry to record the formation compressional slowness. It is a type of acoustic log that displays P-wave travel time versus depth. The tool emits a sound wave that travels from the transmitter (source) located in the well to the formation and back to the receiver, located above or below the transmitter. Acoustic-amplitude and microseismogram (variable-density logs) logs are two additional sonic logs (Telford et al., 1976) that measure the amplitude of the first arrivals and the entire sonic wave train (i.e, first arrival plus the wave form), respectively. These logs are often used to measure the quality of the cement bond between cement-to-casing and cement-to-formation.

4.1.2.2.11 Acoustic Borehole Televiewer Log

The acoustic borehole televiewer log is a magnetically oriented, 360 degree, photograph-like image of the acoustic reflectivity of the borehole wall. The acoustic televiewer is an ultrasonic imaging tool operating at a frequency of about 1 megahertz that scans the borehole wall with an acoustic beam generated by a rapidly pulsed piezoelectric source rotating at about three revolutions per second as the tool is moved up the borehole. Digital images from the televiewer are recorded by the computer, which collects and records the data. A smooth and hard borehole wall produces a uniform pattern of reflectivity. The intersection of a fracture with the borehole wall scatters the acoustic waves, producing a dark, linear feature on the image. Because the image is magnetically oriented, the dip and strike of the fracture can be determined. The advantage of a televiewer over a video log is that it can be used even when the borehole fluid is not clear.

4.1.2.2.12 Nuclear magnetic resonance

The Nuclear Magnetic Resonance (NMR) method measures the quantity of free water in soils and rocks. Free hydrogen nuclei are oriented using a strong applied field. When the field is shut off, the nuclei briefly gyrate about the earth's field before becoming randomly oriented again. This wobble sets up an alternating magnetic field that is detected by a receiver. Fluid-bearing zones can be identified using this technique, which is not sensitive to heavy hydrocarbons (like tar and asphalt) or water found in clay lattices.

4.1.3 HYDROLOGICAL TECHNIQUES

Transport of radionuclides in the groundwater from the waste package to the accessible environment (where receptors are present) is the most realistic and likely exposure scenario. Contaminated groundwater may discharge to surface water bodies including lakes, rivers or ocean or be pumped from wells and consumed, potentially leading to receptor overexposure to contaminants. Hydrologic field-testing and monitoring techniques are used to characterize the hydrologic system and to help quantify the risk of exposure. Key components of a hydrologic characterization program may include:

- Developing a general understanding of regional and site hydrology;
- Identifying important economic and water resources including potable water supplies, fisheries, etc. that require protection to prevent exposure;
- Identifying and characterizing key aquifers, aquitards and aquicludes;
- Identifying and evaluating important flow and transport mechanisms and properties;
- Identifying and evaluating preferential pathways (e.g., faults, fractures or high permeability sedimentary units) that can lead to fast flow and increased risk of exposure;
- Identifying and characterizing important hydrologic boundaries including recharge (e.g., infiltration), discharge (e.g., springs, seeps) and interfaces between groundwater and surface water systems; and
- Estimating liquid and contaminant fluxes.

Hydrologic information gained from a well-designed and executed characterization program provides the framework for the SCM. Existing field testing techniques used in hydrologic characterization programs are described in the following sections.

4.1.3.1 SATURATED ZONE TESTING

Hydrologic field characterization of the saturated zone is accomplished using borehole logging, active testing and passive monitoring techniques.

4.1.3.1.1 Hydrologic Borehole Logging Techniques

Many of the geophysical logs described in previous sections are used to measure important hydrologic parameters including porosity, permeability and water quality. The hydrologic borehole logging techniques described in this section supplement the geophysical logs.

4.1.3.1.1.1 Fluid Temperature and Pressure Logs

A temperature/pressure sensor is connected to a wireline and lowered into the boring to record downhole temperature and pressure of the fluid. Fluid-temperature logs are used to look for evidence of geothermal activity, identify fluid-bearing formations, and determine intervals of vertical borehole flow. The geothermal gradient is the natural increase in the Earth's temperature with depth caused by internal heat production from radioactive decay and long-term cooling of the earth. The average geothermal gradient reported by Freeze and Cherry (1979) is 25ºC/km; therefore, identification of geothermal gradients much steeper than the average using fluid temperature logs could indicate thermally active areas. Sharp changes in the natural temperature also occur where fluids are entering or leaving the boring. Little or no temperature change is recorded along sections of borehole where fluid is moving vertically within or parallel to the boring. Temperature and pressure measurements can be used to estimate gas and liquid densities if the composition of the fluid is known.

4.1.3.1.1.2 Heatpulse Flowmeter

The direction and rate of borehole-fluid movement are measured with a high-resolution heatpulse flowmeter. The heatpulse flowmeter operates by diverting nearly all flow to the center of the tool where a heating grid slightly heats a thin zone of water. If vertical borehole flow is occurring, the water moves up or down the borehole to one of two sensitive thermistors (heat sensors). When a peak temperature is recorded by one of the thermistors, a measurement of direction and rate is calculated by the computer logging the data. The range of flow measurement is about 0.01-1.5 gallons per minute in a 2- to 8-inch diameter borehole. Heatpulse-flowmeter measurements may be influenced by poor seal integrity between the borehole and the flowmeter or contributions of water from storage within the borehole during pumping. If the seal between the borehole and the heatpulse flowmeter is not complete, some water can bypass the flowmeter, resulting in flow measurements that are less than the actual rate. The quantity of water bypassing the tool is a function of borehole size and shape and degree of fracturing. Although the heatpulse flowmeter is a calibrated tool, the data primarily are used as a relative indicator of fluid-producing zones.

4.1.3.1.1.3 Flowing Fluid Electrical Conductivity Log

The flowing fluid electrical conductivity log can be performed in an open borehole or across the screened interval of a well to identify the depth of inflow and to evaluate the transmissivity of the formation and electric conductivity (salinity) of the fluid at each inflow point (Tsang and Doughty, 2003). The well bore water is replaced by deionized or constant-salinity water at the start of this logging technique (Figure 4-). The borehole is then slowly pumped at a constant rate, during which a series of electric conductivity logs are run along the well bore. Changes in electric conductivity indicate inflow locations, or water bearing zones.

4.1.3.1.2 Hydraulic Testing Techniques

Numerous testing techniques have been developed in the oil and gas, water supply, environmental and mining industries to evaluate reservoir (aquifer) performance and measure formation properties. A select number of hydraulic testing techniques follow.

Figure 4-3. Flowing fluid electrical conductivity log performed in 420 meter open borehole in the Amargosa Valley, Nevada.

4.1.3.1.2.1 Drillstem tests

Drillstem tests (DST) are used in the oil and gas industry to collect reservoir fluids, evaluate flow rates, measure static and flowing bottom-hole pressures and to perform a short-term transient test (Earlougher, 1977). DST tests are performed during the drilling process prior to well completion to measure reservoir conditions and properties, fluid composition, and formation damage caused by drilling; assess the economic potential of a new reservoir; and to provide information for optimum well design and completion.

A special DST tool is attached to the drillstem and lowered to the desired depth in the borehole. Inflatable or mechanical packers (part of the DST tool) isolate the formation from the mud column in the annulus. Formation fluid is allowed to flow into the drillpipe, while the pressure is monitored using bottom hole pressure transducers. The drillstem testing sequence typically consists of a short production period (initial flow period), a short shut in period (initial buildup), followed by a longer flow period and a final shut in period (final buildup). The pressure response obtained during the initial and final buildups are analyzed for formation permeability, skin factor, and damage ratio using the Theis (1935) or Horner (1951) method.

4.1.3.1.2.2 Modular Formation Dynamics Tester (MDT)

The MDT is a downhole tool developed for the oil and gas industry that consists of individual modules that can be configured to meet almost any testing and sampling need. The MDT tool can be used to collect and analyze discrete downhole liquid and gas samples for fluid identification, measure reservoir pressures, and evaluate small-scale *in situ* horizontal and vertical permeability. The tool is deployed in an open hole and has a modular design, allowing the tool to evolve as new measurement technologies and options are developed.

4.1.3.1.2.3 Single-Well Hydraulic Tests

Single-well tests, as the name implies, use a single well test configuration to measure formation properties and wellbore conditions. Fluid is pumped from (or injected into) the well while monitoring the flow rates and downhole pressure response. The resulting pressure transient data are analyzed using a variety of techniques (Matthews and Russell, 1967; Earlougher, 1977; Freeze and Cherry, 1979; Lee et al, 2003) to yield estimates of the saturated hydraulic conductivity and formation storativity. Wellbore storage (van Everdingen and Hurst, 1949) and skin (van Everdingen, 1953) may influence the observed bottom-hole pressure response observed during the test, producing erroneous estimates of the formation storativity. Therefore, single-well tests are normally used to measure saturated hydraulic conductivity and wellbore skin factor, the latter being a measure of wellbore damage or improvement effects.

Different types of single-well tests can be performed, with constant rate, constant head (pressure), slug (bail), and pressure buildup (recovery) tests being the most common. As the name implies, a constant pumping rate or constant water level are maintained in the well during a constant rate and constant head test, respectively. The pressure and flow rate responses are monitored in time and analyzed to estimate formation properties (Theis, 1935; Cooper and Jacob, 1948; Ehlig-Economides, 1979; and Chen and Chang, 2003). Slug tests are common in the environmental industry because they are inexpensive and quick to perform. A slug (or bail) test involves quickly adding (or removing) a known volume of water from the well, then monitoring the sudden change in water level with time (Ferris and Knowles, 1954; Cooper et al., 1967; Bouwer and Rice, 1976; Bouwer and Rice, 1989; Karasaki, 1986). The flow-period data from a DST can be analyzed using the slug test method, as long a flow does not reach the surface (Ramey et al., 1975). Finally, a pressure buildup test (Earlougher, 1977) involves shutting in a well after pumping it at a constant rate for a known period of time. The pressure increases (builds up or recovers) when pumping ends, approaching its pre-pumping static pressure conditions.

4.1.3.1.2.4 Multi-well Interference Tests

Multi-well interference tests are also used to measure formation properties and wellbore conditions. This method utilizes a production or injection well and one or more observation wells where bottomhole pressures are measured. Unlike single-well tests, interference tests provide reliable estimates of formation storativity, as long as the pressure response from the observation well is used in the analysis, rather than the pumping well response. In addition, interference tests can be used to investigate the nature and location of aquifer boundaries and to evaluate formation anisotropy (Hsieh, 1983; Hsieh et al., 1985a, 1985b), if three or more wells are available.

Numerous examples of analytical and numerical solutions can be found in the literature for analyzing single- and multi-well hydraulic tests performed on porous media and fractured rocks (Matthews and Russell, 1967; Earlougher, 1977; Freeze and Cherry, 1979; Lee et al, 2003).

4.1.3.1.2.5 Tracer Tests

Tracer tests are frequently used to provide estimates of flow and transport properties, characterize flow paths, and directly assess contaminant migration. These may be difficult to obtain using conventional hydraulic or geophysical techniques. Tracer tests can be used to estimate the formation thickness-porosity product, hydraulic dispersivity coefficient, and the linear groundwater velocity.

There are numerous articles appearing in the groundwater and surface water literature, and to a lesser extent in the oil and gas literature, describing studies that have used microbes, radionuclides, gases, or soluble organic (e.g., dyes) and inorganic compounds as tracers. A conservative tracer does not react with the porous medium or fluids in the formation. Rather, it moves with the groundwater, and its concentration is only affected by hydrodynamic dispersion. Ideal tracers have the following positive attributes: 1) The tracer is not present in the natural formation fluids (e.g., groundwater, surface water, oil); 2) the tracer does not absorb to aquifer material, nor is it retarded by other natural abiotic and biotic processes occurring in the porous medium (e.g., precipitation, oxidation/reduction, biological uptake or destruction by plants or bacteria); 3) the tracer concentration is easy to quantify using analytical techniques; 4) it is safe to handle or use in potable water supplies; and 5) it is inexpensive to use. Reactive tracers that are relatively safe to use, are sometimes used as analogs to study the migration of hazard chemicals or radionuclides, which are known to react with the porous materials or fluids.

There are three general categories of tracer tests including natural-gradient tracer tests, forced-gradient tracer tests, and recirculation tracer tests. Each test involves injecting one or more tracers into the groundwater, geothermal or oil and gas reservoir at a known concentration. Tracer injection may consist of an instantaneous pulse, slug (i.e., pulse of finite length), or continuous release at constant concentration. Arrival of the tracer and its concentration in time are monitored at a nearby observation well located downgradient from the tracer injection point (multi-well test), or the decrease in concentration of the tracer is monitored in time at the injection point (single-well test). The time dependent concentration measured at the observation point(s) results in a diagnostic plot referred to as a tracer breakthrough curve.

During natural-gradient tracer tests, the tracer migrates through the formation under conditions reflective of the natural hydraulic gradient, allowing measurement of the natural linear groundwater velocity. If multiple wells are used, then the average direction of groundwater flow can also be determined. Test methods utilizing a single well configuration include the point dilution method (Drost et al., 1968) and single-well drift-and-pumpback method (Leap and Kaplan, 1988). A major disadvantage of the natural-gradient technique is that it may take a long time for the tracer to migrate under natural conditions to the observation point. In addition, the point dilution and drift-and-pumpback methods require prior knowledge of the effective porosity (and a flow distortion factor in the case of the point dilution method) to be able to calculate the linear velocity.

Forced-gradient and recirculation tracer tests combine the benefits of a hydraulic test with that of a tracer test. These tests take advantage of the artificially steep hydraulic gradient created during a hydraulic test to force the tracer to the observation point much faster than would otherwise occur during a natural-gradient test. Forced-gradient tests typically consist of wells arranged in a radial test configuration. During a converging radial test, the tracer is introduced as a pulse or step in an observation well and the concentration is measured at a distant pumping well, whereas, in a diverging radial test, the tracer is injected into a recharge well and the tracer distribution is observed in surrounding observation wells. A recirculation tracer test is a special type of forced-gradient test requiring a minimum of two wells. Tracer is introduced into a recharge well and its breakthrough is measured at a distant discharge well. Water and tracer from the discharge well is pumped (i.e., recirculated) back into the recharge well creating a dipole-shaped groundwater flow pattern (Grove and Beetem, 1971). Forced-gradient and recirculation tracer tests can be used to estimate formation dispersivity and the formation thickness-porosity product.

4.1.3.1.2.6 Monitoring

It is standard practice to measure the hydraulic head in three or more monitoring wells to determine the hydraulic head gradient and groundwater flow direction (assuming the reservoir is isotropic and homogenous) for a given site. Routine measurement of hydraulic head should be made and piezometric surface maps should be created throughout the year to evaluate seasonal changes in the piezometeric surface. (Care should be taken to plot only piezometric data believed to be from the same aquifer). Examination and comparison of piezometric surface maps can lead to discovery of aquifer recharge and discharge areas, groundwater divides, perched water bodies, zones of vertical groundwater movement between aquifers, or other hydrologic features. Further investigation of these features should be undertaken if it is believed that they could have a significant impact on the site's ability to isolate waste.

Static water level measurements are made in wells by hand using a wetted tape, electric water level tape, sonic water level meter, or airline method, or measured automatically using a pressure transducer and data logger (Lehr, 1988). Measurements should be referenced to a known location on the casing that's been surveyed, so that static water levels measurement from all the wells can be converted to hydraulic heads having a common datum.

Seasonal water level fluctuations in monitoring wells are usually caused by seasonal variations in precipitation and evapotranspiration, which influence aquifer recharge. Daily, weekly and monthly water level fluctuations can be caused by on-off cycling of nearby irrigation or production wells, or in some cases by fluctuations caused by ocean tides, earth tides and barometric pressure changes (Todd, 1980). Water levels in wells penetrating confined aquifer systems have been shown to fluctuate because of barometric pressure changes. The so-called barometric efficiency of a confined aquifer can be measured and expressed in terms of aquifer and water properties, including the storage coefficient (Jacob, 1940).

4.1.3.2 UNSATURATED ZONE AND SURFACE TESTING

The primary source of unsaturated zone field experience is derived from studies associated with soil science, soil physics, agricultural engineering, radioactive waste disposal, and oil and gas exploration (i.e., multiphase flow). Soil-related unsaturated zone studies abound in the literature, and typically address near-surface flow and transport processes including infiltration, precipitation, evapotranspiration, runoff, soil moisture redistribution in the subsurface, and pesticide transport. Deep unsaturated zone field studies are rare; however, the USDOE radioactive waste disposal program at Yucca Mountain is one exception. Site characterization work performed at Yucca Mountain over the past 20 years has produced a plethora of knowledge on deep, unsaturated flow and transport through fractured volcanic tuffs. In addition, the oil and gas literature is an important source of information for field-testing techniques, equipment and case studies describing multiphase, multicomponent (brine, water, gas and oil) flow through deep reservoirs.

4.1.3.2.1 Pneumatic-Testing Techniques

Pneumatic testing is equivalent to hydraulic testing with the exception that gases are used as the test fluid to measure formation permeability. Single-well and multi-well interference test configurations are still applicable, as are pulse (i.e., slug), buildup, constant rate and constant pressure test methods. Equipment used for pneumatic testing is similar to hydraulic testing.

The compressibility of the gas must be taken into account when analyzing pneumatic test results. The partial differential equation and boundary conditions used to describe compressible gas flow through porous media are nonlinear, making rigorous analytical solutions to transient well-test problems impractical (Muskat, 1937). Techniques have been developed to linearize the equations producing approximate transient solutions that are formulated in terms of the gas pressure (p), pressured-squared (p^2) or pseudo-pressure function (ERCB, 1975; Aziz et al., 1976). Steady-state gas flow equations, which do not include the nonlinear transient storage term, are linear and have been solved for various flow geometries. Steady-state pressure distributions were found to develop relatively quickly during low-pressure gas injection tests performed at Yucca Mountain, allowing the data to be analyzed using steady-state solutions (LeCain, 1997; Cook, 2000). History matching of gas flow data using a numerical model is another option when boundary conditions become too complicated to evaluate the data using analytical techniques.

4.1.3.2.2 Gas-Tracer Tests

Gas tracer experiments are equivalent to hydraulic tracer tests, with the exception that gases are used in place of liquids to trace the ambient gas present in the formation. Gas tracers can be used to measure formation dispersivity and porosity (Freifeld, 2001) in a single-phase system, measure gas and liquid saturations in two-phase systems (Pruess, 2005; Trautz et al., 2005) and identify flow paths. Test configurations and methodologies used for hydraulic tracer tests can be applied to gas tracer tests; however, specialized equipment is typically needed to analyze the gas samples to determine the tracer concentrations.

4.1.3.2.3 Infiltration and Recharge Evaluation

Infiltration refers to the process of water entry into soil, which generally occurs through the soil (or rock) surface and progresses vertically downward through the soil profile. The infiltration boundary at the land surface forms the upper boundary of the SCM; therefore, characterization of this boundary is important because it controls the amount of water entering the subsurface as recharge. Recharging water may eventually come in contact with buried waste causing corrosion of the waste canister, hastening subsequent migration of the waste from the repository.

Numerous articles describing infiltration theory, test methods, and field equipment appear in the soil science and agriculture engineering literature. The majority of these studies focus on the relation between infiltration and the resulting availability and uptake of moisture by plants. In contrast, infiltration studies performed as part of the USDOE nuclear waste program at Yucca Mountain focused primarily on development and calibration of a large-scale infiltration model used to predict regional groundwater recharge,

Figure 4-4. Water containing fluorescent dye seeps out of fractures intersecting the ceiling of an underground opening during an artificial infiltration experiment performed at Yucca Mountain.

under different climate scenarios. In addition, site-specific process models and small-scale infiltration experiments were performed at Yucca Mountain to investigate the movement of water and solutes through faults and fracture systems (Salve et. al., 2004; Liu et al., 2004) and seepage into underground openings (Figure 4-, Wang et al., 1999; Trautz and Wang, 2002; Cook et al., 2003; Finsterle et al., 2003; Ghezzehei et al., 2004).

Flint et al. (2000) provide a brief overview of the approaches used to estimate regional recharge in the Death Valley Region of the Mojave Desert, an arid area of the United States, encompassing Yucca Mountain. These approaches include water balance (Winograd and Thodarson, 1975), rainfall distribution (Hevesi and Flint, 1998), chloride-mass-balance (Lichty and McKinley, 1995), and applied soil-physics techniques (Winograd, 1981; and Nichols, 1987). Flint et al. (2000) developed a detailed numerical model to simulate infiltration at Yucca Mountain using components of the mass-balance equation for near surface infiltration. The mass-balance approach and applied soil physics techniques are the most common methods used to estimate infiltration and recharge.

4.1.3.2.3.1 Mass-balance approach

The mass-balance approach uses a control volume to represent the soil column. The upper surface of the control volume represents the land surface and the lower surface represents an imaginary plane, below which, recharge takes place. Water entering the control volume as net precipitation (i.e., precipitation minus surface water runoff) at land surface, either exits the lower surface as recharge or is stored within the control volume, causing an increase in soil moisture content. Evapotranspiration removes soil moisture from the control volume by transferring it back to the atmosphere via transpiring plants or by evaporation, thus slowing or halting recharge altogether. A brief description of field methods used to measure precipitation, evapotranspiration and soil moisture conditions leading to recharge estimates are provided below.

4.1.3.2.3.1.1 Precipitation measurements

Precipitation is commonly measured using various types of mechanical rain gages (e.g., non-recording gages including cylindrical containers or recording rain gages including weighing, float and tipping-bucket type, Linsley et al. 1982). Mechanical precipitation gages are quite accurate, but because of their limited size, measure precipitation at a given point in space. Therefore, a network of gages must be installed and averaging or interpolation between stations must be performed to produce precipitation distribution maps. Newer methods of measuring precipitation include ground-based radar. Most local weather radars transmit radio pulses that have a horizontal and/or vertical orientation. The electromagnetic radio pulses reflect off of clouds creating backscatter that is detected by the same station. The backscattered energy from the reflector and wave propagation effects (i.e., phase change and power attenuation) are interpreted to produce precipitation estimates. Interpretation can be quite challenging because reflectance properties are dependent upon complicated atmospheric conditions including rain and ice particle size, storm intensity, cloud shape and height, and presence and density of aerosols in the atmosphere to name a few (Chandrasekar et al., 2003).

4.1.3.2.3.1.2 Evapotranspiration measurements

Evapotranspiration is the combined process of evaporation from open water bodies (e.g., lakes, reservoirs, rivers or playas), bare-soil evaporation and transpiration by vegetation (Freeze and Cherry 1979). Bare-soil evaporation represents the amount of water evaporated from a bare soil surface, which for deep unsaturated soils is limited by the near-surface supply of soil moisture. Transpiration is the uptake and transfer of water to the atmosphere by vegetation. If the soil (or fractured bedrock) becomes drier than what is conceptually referred to as the wilting point, transpiration will not occur even though there may be residual water in the root zone. Transpiration is much more efficient than bare-soil evaporation in removing water from soils and fractured bedrock. This is because plant roots typically extend deeper than the near surface dry-out zone influenced by bare-surface evaporation, and plants can exchange large amounts of soil water with the atmosphere through the process of transpiration.

Actual evapotranspiration is a function of 1) the potential evapotranspiration; 2) the availability of water at the ground surface and within the root zone; 3) vegetation characteristics such as timing of plant growth and root density; 4) and the chemical and hydrologic properties of the root zone. These processes are not independent, but, in general, the primary factors controlling actual evapotranspiration are potential evapotranspiration, soil-water availability, vegetation density, and seasonal vegetation growth. The more saturated the soil (or fractured bedrock) and the denser the vegetation, the closer the actual evapotranspiration rate is to the potential evapotranspiration rate. (Potential evapotranspiration is an energy-limited rate and is a measure of the ability of the atmosphere to remove water from the surface through the evapotranspiration process assuming unlimited availability of water).

Numerous methods for estimating actual and potential evapotranspiration exist, none of which are globally applicable to all sites, conditions, and circumstances (Linsley et al. 1982). Long-term measurements of actual evapotranspiration are rarely made or readily available because of difficulty of measurement and cost and time required to obtain this information. Actual evapotranspiration measurements are typically reserved for calibrating and validating meteorological models.

Direct measurement of actual evapotranspiration is a difficult undertaking, because it requires accurate measurement of various energy balance, mass transfer, or soil water balance parameters. Methods employed to directly measure evapotranspiration include the Bowen ratio (Flint and Childs 1991), weighing lysimeter, and eddy correlation (Figure 4-, Levitt et al. 1996). These methods are often expensive, labor intensive, demanding in terms of accuracy of measurement and not readily amenable to sampling large study areas exhibiting numerous vegetative covers, microclimates and soil types.

Evaporation-pans are the most widely used instrument for measuring potential evaporation from surface water reservoirs or saturated soils (Linsley et al. 1982).

However, the application of pan data to determine actual or potential evapotranspiration from vegetated or bare soils is very limited, especially under arid conditions where soils dry or drain rapidly so that saturated conditions (representative of pan conditions) do not persist for prolonged periods of time.

Meteorological models were first introduced by Penman (1948) to overcome these limitations by indirectly predicting or estimating evaporation. Penman (1948) combined the energy balance equation with a physically based mass transfer function describing advection of water vapor and energy above a horizontal surface to derive an equation to compute the evaporation from a thin free-water surface. The utility of Penman's original approach is that it uses standard climatological records of sunshine, temperature, humidity, and wind speed (which are relatively easy to measure) to estimate evaporation, rather than relying on direct and difficult measurements of actual evapotranspiration. However, limiting assumptions and simplifications used by Penman (1948) to model the aerodynamic or mass transfer component of evaporation, make the Penman equation only useful for estimating potential evapotranspiration.

Penman's (1948) method was further refined by numerous researchers over the last five decades and has been extended to bare and cropped soil surfaces by introducing surface resistance factors and (or) parameters limiting evapotranspiration from water-supply limited soils. Monteith (1965) modified Penman's original equation using surface resistance factors allowing calculation of actual evapotranspiration from cropped soils. The Penman–Monteith equation, however, requires detailed knowledge of the resistances to heat and water flow at the land surface, making it difficult to apply without having extensive measurements for the resistance parameters (e.g., aerodynamic resistance, bulk stomatal resistance, and active leaf area index). The Penman–Monteith equation is typically applied to extensive cropped soils where water availability is not an issue. The Food and Agriculture Organization of the United Nations (FAO) has adopted the Penman-Monteith equation as the standard method for estimating reference evapotranspiration, and for evaluating other methods (Allen et al., 1998).

Priestley and Taylor (1972) suggested an alternative, simpler form of the Penman equation that requires a single effective surface resistance parameter (Flint and Childs

1991; Levitt et al. 1996) to estimate the potential evapotranspiration rate. The Priestley-Taylor equation includes an empirical scaling term, which is multiplied by the energy balance term in the original Penman equation. The Priestley-Taylor method does not utilize the aerodynamic resistance term found in the Penman and Penman-Monteith equation, but rather accounts for advection above the evaporating surface using the single empirical scaling term. Levitt et al. (1996) and Flint and Childs (1991) demonstrated the successful application of the modified Priestley-Taylor equation for modeling evapotranspiration for arid climate conditions near Yucca Mountain and xeric soil conditions in Southern Oregon, USA, respectively.

4.1.3.2.3.1.3 Soil moisture storage

Changes in soil moisture storage can be determined from time-dependent measurement of water content at different soil depths. Alternatively, changes in soil moisture storage can be inferred from time-dependent measurement of soil water potential with depth, provided the functional relation between water potential and water content is known or measured in the laboratory. Section **XX** describes in greater detail applied soil physics techniques used to measure soil water content and potential.

4.1.3.2.3.2 Applied soil physics techniques

Soil physics is a branch of soil science that deals with the physical properties of soils, with special emphasis on the state and transport of matter (water) and energy through soil systems (Hillel, 1971). Applied soil physics techniques (used in the context of this paper) refer to a broad class of field and laboratory testing techniques used to measure liquid fluxes in the unsaturated zone from which estimates of infiltration and recharge rates may be determined. These techniques have evolved over the past 80 years beginning with and attributed to the important experimental work of Richards (1928, see also Gardner (1972)). Numerous books and articles have been written on these techniques; therefore, it is not the intent of this paper to provide an exhaustive overview of this vast body of work. A relatively recent collection of papers on the characterization and measurement of hydraulic properties of unsaturated porous media is provided in van Genuchten et al. (1997) and Looney and Falta (2000).

It is important that the reader recognize that liquid fluxes derived from applied soil physics techniques are highly uncertain because of the highly heterogeneous nature and distribution of soils. Furthermore, analyses are typically limited to one-dimensional vertical flow at a given location, which essentially represents a single horizontally distributed point measurement. Given the complexity of soils and their inherent variability, a large number of tests must oftentimes be performed to adequately characterize even small study plots. With this said, liquid fluxes are typically determined using direct or indirect applied soil physics techniques.

4.1.3.2.3.2.1 Direct rate and flux measurements

Direct measurements include small-scale infiltration tests and fluxmeters. The most common methods of measuring small-scale infiltration rates include single and double ring infiltrometers (Amoozegar and Warrick, 1986), Guelph permeameters (Reynolds and Elrick, 1985; Reynolds and Elrick, 1991), and tension (or disk) infiltrometers (Ankeny et al., 1988; Perroux and White, 1988). Data obtained from infiltration tests are used to estimate saturated hydraulic conductivity, sorptivity and parameters associated with soil capillarity. These devices are typically deployed at land surface providing direct estimates of surface infiltration at or near saturated conditions.

Sensor systems designed to measure flux directly are based on two general principles (Gee et al., 2002). The first method involves introducing a pulse of heat and then monitoring the temperature decline as the pulse is convected away from the source by groundwater flowing through unsaturated (Byrne et al., 1967, 1968; Byrne, 1971; Kawanishi, 1983; Cheviron et al, 2005) or saturated (Ren et al., 2000) soils. Test interpretation is dependent upon prior knowledge of the heat load and thermal properties of the soil. The heat-pulse method can be used to measure relatively high fluxes ranging from 10^3 to 10^6 mm/yr, but is not practical for measuring fluxes less than 1000 mm/yr.

The second method involves intercepting soil water using a fluxmeter. Numerous approaches have been used ranging from buried ceramic cups connected to water-filled reservoirs and drip counters to buried containers or funnels, which collect water. The buried fluxmeter can cause a reduction in permeability or create a capillary barrier above the meter resulting in diversion of natural flow around the meter itself. This results in an underestimation of the true flux. Gee et al. (2002) describe a fluxmeter with a flow divergence control mechanism capable of measuring unsaturated fluxes ranging from less than 1 mm/yr to more than 1000 mm/yr.

4.1.3.2.3.2.2 Indirect flux measurements

Indirect flux measurements are determined by measuring the individual components of the Darcy flux (written for unsaturated porous media) including the unsaturated hydraulic conductivity and water potential (or water content)[1] gradient (Hillel, 1971; Freeze and Cherry, 1979). Measurement of unsaturated hydraulic conductivity and its relation to water potential (or water content), referred to as characteristic curves, are typically performed in the laboratory under controlled conditions (Dane and Topp, 2002). These are tedious measurements, which can be highly uncertain because of the difficulty in obtaining undisturbed soil samples from the field. Field collection can modify or destroy pore and soil structure, thus changing the measured soil properties. Samples can be repacked in the laboratory and tested, but this rarely produces results that are comparable to undisturbed samples. Therefore, special care must be used when developing and implementing soil collection and handling procedures that minimize soil disturbance in order to produce representative laboratory results.

Water potential (or water content) gradients can be measured and monitored directly in the field using invasive and noninvasive techniques. The overwhelming majority of techniques include installation of instruments in borings or wells, which by design provide intrusive access to subsurface soils. Surface-based geophysical techniques like ground penetrating radar or electromagnetic induction are noninvasive, but these instruments can also be used in downhole applications to determine the vertical distribution of soil properties. Gee and Ward (1997) and Scanlon et al. (1997) provide excellent summaries (including range and accuracies) of the instruments used for monitoring water potential and soil water content listed below:

<u>Water/matric Potential</u>

- Psychrometers (Richards and Ogata, 1958)

[1] If water content is measured in the field, then the characteristic curve relating soil water content to water potential must be measured in the laboratory to convert water content gradients into equivalent water potential gradients needed to calculate the Darcy flux.

- Heat dissipation probes (Phene et al., 1971)
- Tensiometers (Richards, 1950; Faybishenko and Finsterle, 2000)
- Osmotic tensiometers (Evans, 1983)
- Granular matrix resistance probes
- Water activity method
- Filter paper method

Soil Water content

- Time domain reflectometry (TDR; Topp et al., 1980)
- Neutron scattering (Gardner and Kirkham, 1952)
- Capacitance methods
- Ground penetrating radar (Hubbard et al., 1997; Alumbaugh et al., 2002)
- Electromagnetic induction
- Fiber optic sensors

4.1.4 GEOCHEMICAL TECHNIQUES

The geochemistry of subsurface fluids provides insight into important processes occurring in the subsurface related to: 1) dissolution and precipitation of minerals leading to changes in formation porosity and permeability; 2) tectonic deformation; 3) origin and age of groundwater; 4) heat transport in geothermal ground water systems; and 5) fate and transport of hazardous wastes injected into the subsurface (Kharaka and Hanor, 2004). A geochemical sampling program should be developed in advance of sampling, which addresses monitoring objectives, data quality objectives, collection of representative samples, and design and construction of sampling points (e.g., wells, borings). Sample specifications and standardized sampling procedures should be developed in advance of field work to ensure that proper identification, preservation, and handling techniques are used to preserve the scientific and legal integrity of the fluid samples.

Proper on-site preservation and handling of samples at the wellhead is essential to the scientific credibility and legal integrity of environmental samples. Many chemical constituents have limited hold times (e.g., ferrous iron, nitrate and nitrite) before they begin to naturally degrade or decay, or are sensitive to environmental conditions such as heat or sunlight (e.g., fluorescein tracer). A good sampling plan developed prior to sampling should identify: 1) the type of media (water, soil, gas), approximate number and frequency of samples to be collected; 2) chemical constituents and analytical methods to be used in their evaluation; 3) collection, preservation, and handling requirements; and 4) data quality requirements. Numerous analytical testing techniques are available in the literature for evaluating fluid chemistry (USEPA, 1983; USEPA, 1986; and Clescrel et al., 2005); the large number of analytes and techniques prevents us from describing them here. Instead, a brief description of the most common fluid sample collection techniques is provided below.

4.1.4.1 SAMPLE COLLECTION TECHNIQUES

Figure 4-6. Multi-stage electrical submersible pump used for testing and sampling a deep brine reservoir (Photo courtesy of Seah Nance, Texas Econ. Bur. of Geology).

This section briefly describes three conventional fluid sample collection methods using pumps, gas-lift, and wireline techniques. The U.S. Environmental Protection Agency (USEPSA, 1992, 1996) has published extensive information on groundwater sampling techniques and protocols related to environmental site characterization and remedial investigations.

Pumps, bailers, and to a lesser degree, gas-lift techniques are used to purge fluid from a boring or well prior to sampling to ensure that stagnant fluids are removed from the casing and fresh representative samples of the formation are obtained. Numerous types of pumps are available for sampling purposes (Figure 4-). Pump selection must be based on depth to water and power requirements needed to lift fluids to the land surface. Pumps having wetted parts that come in contact with the fluid must either be decontaminated between wells to prevent cross contamination of subsequent samples or dedicated to sampling only one well.

A bailer consists of a round tube with a one-way ball or check valve located at the bottom and a plastic or wire bail located at the top. A string or steel wireline is attached to the bail and the device is lowered into the well where it sinks in the fluid. The one-way valve at the bottom of the bailer allows fluid to enter the bailer, but prevents it from exiting the bailer when the bailer is pulled back to the surface. Bailers are typically constructed of stainless steel or plastic, which can be decontaminated between uses. Disposable bailers made of plastic and designed for one-time use are commercially available.

Gas-lift techniques consist of injecting compressed gas generated at land surface through a pipe, hose or tube to the bottom of a well (Nicklin et al., 1962). Compressed gas injected at the bottom of the well rises because of buoyancy effects, expanding and displacing water along the way. The lifting action of the piston-like gas bubble pushes groundwater out the top of the well. Gas-lift pumping techniques are commonly used for well development because there are no moving mechanical parts downhole that can be abraded or become clogged during operation. Therefore, the method is well suited for pumping both liquids and abrasive solids (e.g., sand). Gas-lift methods are not typically used to collect geochemical samples because the gas performing the lift comes in direct contact with the groundwater in the well. Direct contact may potentially contaminate and strip dissolved gases or highly volatile components from the liquid being sampled.

Standard practices involve purging and sampling groundwater from wells using bailers or high-speed pumps to remove 3 to 5 casing volumes before sample collection begins. Grab water samples are normally collected during the purge process and evaluated on-site for wellhead parameters (e.g., dissolved oxygen, pH, specific conductance, temperature and oxidation-reduction potential) using handheld portable water analyzers. Once the wellhead parameters stabilize, final sample collection for on-site and off-site analyses can begin.

Purging the well too aggressively can cause large changes in fluid pressure and turbidity, impacting fluid chemistry and sample quality. The USEPA (1996) recommends the use of low-flow rate sampling techniques in shallow wells to prevent samples from becoming too turbid. However, this practice may be impractical for sampling deep wells containing large volumes of water. In addition, collecting representative samples from wells penetrating deep reservoirs is complicated by the fact that dissolved gases in equilibrium with downhole temperatures and pressures, may suddenly exsolve as fluid pressures drop, when samples are pumped to the surface. Groundwater chemistry may also change when gases exsolve and fluid pressures change, requiring immediate analysis of the sample upon collection at the wellhead.

The Kuster sampler (Kuster Co., Long Beach, California, USA) is a simple wireline tool that allows the user to collect fluid samples at reservoir pressure, allowing it to deployed in deep-well sampling applications. The device consists of a sample chamber, spring-loaded valves, a locking device, and a mechanical clock. Operation consists of winding a manual timer or clock and lowering the tool into an open hole or well on a steel wireline. When the clock winds down to the appointed sampling time, it automatically releases the locking mechanism, the inlet valves open and the sample chamber fills. The valves close once the fluid pressure inside the chamber equilibrates with the *in situ* fluid pressure. Once the sample has been taken, the sampler must not be lowered deeper into the well, otherwise the increase in external pressure will re-open the valves and the sample will be contaminated. Contamination may also occur when warm samples are cooled as they are pulled back to the surface by the wireline. Cooling may cause a reduction in fluid volume and pressure inside the sample chamber, allowing the spring to reopen and leakage to occur. At the surface, the pressurized sample must be released using a special extractor body and transferred into a pressure-rated vessel.

4.1.5 GEOTECHNICAL TECHNIQUES

Earthquakes and active volcanism can cause serious disruption of waste operations and damage to surface facilities associated with nuclear waste disposal. Seismic monitoring networks can be used to predict volcanic eruptions and provide early warning of increased seismicity, potentially leading to a devastating earthquake. Tiltmeters have been successfully used to monitor volcanic activity (Dzurisin, 1992; Murray, et al., 1996). The repeated rise of magma into the dome at Mount St. Helens (Washington, USA) before the 1986 eruptions produced ground tilt on the crater floor that began 2 to 4 weeks before magma erupted onto the dome. Ground tilt was one of the

Figure 4-7. Micro-earthquake monitoring station (foreground) and geothermal power plant (background) at the Geysers, California, USA.

most reliable measurements of deformation used to accurately predict the Mount St. Helens eruption.

Additional methods used to measure surface deformation associated with volcanism include short-range (<10 km) and mid-range (< 50 km) electronic distance meters (EDMs), GPS, and satellite interferometry (see Section **XX**). When magma rises, it builds up pressure, melting and pushing solid rock both horizontally and vertically in advance of the intrusion, distorting the land surface by as little as a few millimeters (mm) to tens of meters. Benchmarks are established at land surface and changes in distance between benchmark pairs is frequently monitored using EDM (Lockwood et al., 1987). Short-range EDMs transmit and receive electromagnetic radiation in the near visible infrared wavelength with an accuracy of approximately 5 mm.

Monitoring earthquake activity associated with tectonic movement of plates is typically performed using seismometers. Vibrations generated by earthquakes, volcanic tremors and explosive eruptions are predominately < 6 Hz and typical seismometers used to monitor these events have frequency responses < 2 Hz. The United States Geological Survey (USGS) uses acoustic-flow monitor (AFM) seismometers to monitor for lahars (air-born debris flows associated with volcanic eruptions) that are sensitive to ground vibration with higher frequencies than a typical seismometer (Hadley and LaHusen, 1995). An AFM has a frequency response of 10-250 Hz. Ground vibration generated by lahars is predominantly in the frequency range of 30-80 Hz.

Induced seismicity resulting from changes in rock stress caused by mining (rock bursts), oil production, waste injection and geothermal energy production has also been reported in the literature and could be of concern to the integrity of a waste repository.

Majer and McEvilly (1979), Stark and Majer (1989) and Stark (2003) installed an extensive network of micro-earthquake stations at the Geysers region of California to study the effect of geothermal energy production on induced seismicity. An extensive array of micro seismic stations (Figure 4-) was installed to monitor the effect of fluid production (steam) and injection (water) into the geothermal field near Cobb Mountain, California. Water injection was found to be a common trigger causing induced seismicity, but other reservoir conditions and properties including temperature, fluid and gas content, fracturing, permeability, and whether the area was tectonically active prior to injection were also found to be important factors. All of these properties may either interact to increase the seismicity when the system is perturbed by injection or withdrawal, or may constructively interact to have a smaller effect on seismicity.

Land subsidence resulting from reservoir compaction during oil, gas, and groundwater production is common. Vasco et al. (2001) performed a coupled inversion of tiltmeter measurements made at land surface and pressure measurements made during hydraulic tests performed on a shallow fractured aquifer to determine subsurface permeability variations. Changes in fluid pressure resulting from pumping, caused small surface deformations measured using tiltmeters, allowing Vasco et al. (2001) to image a high permeability, north trending channel in a fractured zone at the Raymond field site in California.

4.2 Evaluation of Emerging Field Investigation Technologies

4.2.1 EMERGING DRILLING TECHNIQUES

Cryogenic drilling and microhole technology represent two innovative drilling techniques that have been evolving over the past 5 to 10 years. Cryogenic drilling techniques were developed at the University of California – Berkeley and field tested at Lawrence Berkeley National Laboratory (Simon and Cooper, 1994; Cooper and Simon, 1995). Low-temperature nitrogen gas or liquid is injected through the drill pipe to the bit, flushing the drill cuttings from the borehole and stabilizing the boring by freezing the surrounding ground. This technique is well suited for drilling in loose, unconsolidated soils that tend to collapse when disturbed. Freezing keeps the borehole walls from collapsing, provided sufficient moisture is present in the formation. It also facilitates installation of a monitoring well by keeping the borehole open.

Los Alamos National Laboratory (LANL), in collaboration with oil industry partners and the USDOE, is developing the microhole-drilling technology (Albright, et al., 1998; 1999; Dreesen et al., 1997; Thomson, 1999). The technology takes advantage of recent advances in instrument electronics, which will result in smaller downhole logging tools and sensors (see section 4.2.2). Expensive, large-diameter borings will no longer be required to accommodate these tools and sensors. Instead, smaller borings and wells, installed at significantly lower cost, will be used to obtain important site characterization information. The microhole drilling system uses components, which are also used at a larger scale on commercially available coiled tubing rigs. These components consist of a mechanical rotary bit, a hydraulically powered positive displacement downhole drill motor, and a coiled-tubing drill stem. LANL has successfully drilled and cased 2-3/8-in.-diameter microholes to depths of 850 ft in basin-and-range valley fill and volcanic tuff (Thomson et al. 1999). Dreesen and Albright (2000) determined that it should be possible to drill microholes to a depth of 10,000 ft using coiled tubing and miniaturized conventional drilling components.

4.2.2 EMERGING SENSOR TECHNOLOGIES – MEMS AND MOTES

Figure 4-8. A MEMS sensor

Promising new sensor technologies have started to emerge that could potentially lead to low cost, densely spaced, sensor networks used to characterize and monitor micrometeorological, hydrological and geological processes. Micro-Electro-Mechanical Systems (MEMS) are integrated mechanical elements, sensors, actuators, and electronics on a common silicon substrate (Warneke and Pister, 2002). The electronics are fabricated using integrated circuit technology employed in the computer industry coupled with micromechanical components fabricated using compatible "micromachining" processes. MEMS could potentially revolutionize nearly every product by bringing together silicon-based microelectronics with micromachining technology, creating intelligent systems-on-a-chip (Figure 4-).

MOTES (short for reMOTES) are small devices that incorporate communications, on-board processing, MEMS-based sensors, and a power source into a very small package. MOTES represent autonomous sensor nodes that can communicate with one another using radio telemetry, thus creating a non-obtrusive, unattended (or unmanaged), and dynamically reprogrammable sensor network. Conceivably, they can be mass-produced and distributed throughout the environment, potentially producing a relatively low cost sensor network. MOTES can monitor virtually all physically measurable quantities, such as acceleration, strain, displacement, atmospheric gas composition, quantitative microseismics, and magnetic fields. MEMS-based force balance accelerometers, magnetometers, light-sensitive detectors, and high-quality MEMS-based temperature and humidity sensors are currently available. Future work includes MEMS interferometers based on corner-cube retroreflectors, laser spectroscopy, and radiation sensors. Long-term research needs include alternative power sources including harvesting energy from vibration, thermal gradients, or water and airflow (Warneke and Pister, 2004).

4.2.3 INNOVATIVE FLUID SAMPLE COLLECTION TECHNIQUES – U-TUBE SAMPLER

Collection of fluids from deep wells at reservoir conditions is very challenging using standard sampling techniques described in Section **XX**. Pumping-induced changes in fluid pressure can force dissolved gases out of solution, potentially changing gas and liquid chemistry. Gas-lift techniques strip dissolved gases out of the liquid and dilute or contaminate gas-phase samples, thus compromising gas chemistry. Kuster samplers collect samples at reservoir pressure, but are not completely fail safe because of their mechanical locking and timing mechanism.

Freifeld et al., (2005) developed an innovative sampling device, called a U-tube sampler, to collect fluid samples at reservoir pressure from deep wells. The U-tube sampling device utilizes compressed gas to move the fluid to be sampled through a small diameter tube that goes from the surface to the zone of interest (in a boring or well) and returns to the surface forming a "U" (Figure 4-). A short stinger with a check valve (located at the bottom of the U-tube) passes through a pneumatic packer used to isolate the perforated section of the well bore and terminates at an inlet filter sitting in the fluid to be sampled. Compressed nitrogen gas is injected into the drive leg of the U-tube at land surface causing the downhole check valve to close and the fluid in the tube is forced to the land surface via the sampling leg of the U-tube. After the fluid is sampled, the gas in the U-tube is vented to the atmosphere allowing the downhole check valve to open and reservoir fluid to reenter the U-tube through the inlet filter for the next round of samples.

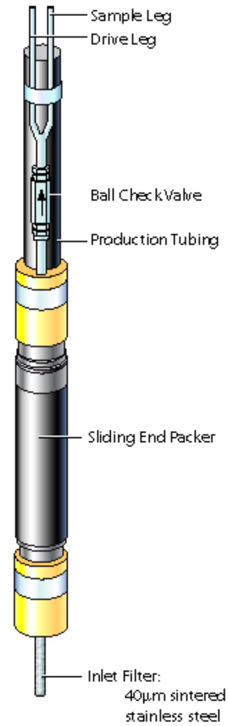

Figure 4-9. Downhole assembly for the U-tube sampler.

The U-tube sampler was used to monitor changes in fluid chemistry and phase-changes during CO_2 injection into a brine reservoir at a depth of 1,500 m below land surface. Samples consisting of brine and dissolved gases were collected every 50 minutes from a nearby observation well using the U-tube sampler, producing high frequency sample results. Increasing levels of dissolved CO_2 were detected in brine samples collected just prior to arrival of free-phase CO_2. A quadropole mass spectrometer provided real-time gas analysis for gas tracers injected along with the CO_2 and strain gauges mounted beneath high-pressure sample cylinders located at land surface allowed accurate measurement of changing fluid density. The U-tube sampler successfully captured the first arrival of the CO_2 plume and tracers, and on-site analyses revealed rapid changes in fluid geochemistry.

4.2.4 SATELLITE-BASED REMOTE SENSING

Numerous satellite-based sensors have been launched into orbit since the early 1960s to image the Earth's surface and study atmospheric processes. Early satellite missions focused primarily on measuring meteorological conditions. In the early 1970s, earth resource satellites (Landsat) were designed and deployed to map and monitor land cover, enabling direct observation of changes in global land surface caused by natural events and human action. Currently, more than a dozen satellites carrying different types of sensors are providing important data that improve our understanding of the Earth's atmosphere, oceans, ice, snow and land (U.S. Congress, 1993).

Numerous instruments have been deployed on satellites ranging from radiometers (NOAA's AVHRR[2]), spectroradiometers (NASA's MODIS[3]), microwave sounders, visible and infrared scanners (TRMM[4]), radar magnetometers and ion scintillation monitors to name a few. The majority of instruments deployed detect reflected light or radiation from the Earth's surface, clouds, or moisture in the atmosphere allowing measurement of land, cloud and aerosol boundaries, heights and properties; ocean color and properties (phytoplankton distribution and biogeochemistry); surface temperatures; and atmospheric temperature and vapor content.

Recent advances in satellite-based instrumentation and image resolution has resulted in numerous geologic, hydrologic, and geotechnical applications. For example, interferometric synthetic aperture radar (InSAR) is a powerful tool used to construct digital elevation maps (DEMs) and image centimeter scale deformations of the Earth's surface. Smith (2002) summarizes the many geotechnical and hydrologic applications of InSAR including:

- Detection of slow slope movement;
- Ground subsidence;
- Erosion and deposition;
- Measurement of soil moisture content;
- Surface water extent and water level changes caused by flooding;
- Extent of snow cover; and
- Extent of river ice, leading to ice jams and flooding.

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[2] National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (USA).
[3] National Aeronautics and Space Administration's Moderate Resolution Imaging Spectroradiometer (USA).
[4] The Tropical Rainfall Measuring Mission Visible and Infrared Scanner (TRMM-VIS) is NASA's first mission dedicated to observing and understanding the tropical rainfall and how this rainfall affects the global climate. It is a joint mission with the National Space Development Agency of Japan.

Smith (2002) compares the accuracy of InSAR-based DEMs and deformation maps with conventional measurements including airborne laser altimetry, photogammetry, and ground-based surveys using GPS and laser total station technology. In general, airborne laser altimetry and GPS are more accurate, but measurements are labor intensive or expensive, making detailed coverage of broad areas impractical.

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5 Investigation of Uncertainties

5.1 Introduct ion

The state of various nuclear waste disposal programs over the world is still at an early stage, such that successes, failures, and lessons learned with respect to treatment of uncertainties cannot yet be ascertained. This is true even for the more advanced programs like Sweden's. Nevertheless, sufficient consideration and evaluation of methodologies for site characterization and repository development have been conducted, and from these evaluations we can extract information on key uncertainties, as well as possible approaches to address them.

Under this task, we have reviewed the planned or ongoing site characterization and safety assessment activities in the Swedish, UK, and Finnish programs, drawing extensively from the NIREX95 (1995), SITE94 (1996), TILA99 (1999), and SR97 (1999) reports published under these programs. In fact, these reports have "learned" much from each other, so that there is much agreement on their approaches and considerations. Additional information is gathered from recent reports from SKI in their current review of ongoing site investigation activities in the SKB nuclear waste disposal program. The objective of this task is to identify and discuss potential site characterization and safety assessment uncertainties.

We shall discuss uncertainties related to nuclear waste repository development in two steps. The first is more general and includes various uncertainties that need to be considered for the safety assessment of a potential nuclear waste geologic repository. The second is focused more specifically on uncertainties during the site investigation stage, a crucial first step to obtain information and data for determining the suitability of a site for locating a repository.

5.2 Uncertainties Involved in Safety Assessment

5.2.1 CONTEXT FOR DISCUSSING UNCERTAINTIES IN SAFETY ASSESSMENT

A number of reports published by the Nuclear Energy Agency (NEA 1991, 1997, 1999, 2005) have summarized the international practice of classifying and treating uncertainties in the safety assessment of a nuclear waste repository. Generally, safety assessment involves an analysis of how a geologic system (with its current flow and solute transport patterns) will evolve after emplacement of a waste repository and under various internal physical, chemical, mechanical, and biological processes—and after a series of external events and influences such as climatic change and future human activities. In particular, we are interested in estimating whether the repository can be isolated for hundreds of thousands of years and, if the repository degrades, how much leakage of radionuclides will occur and over how long a time would it take the radionuclides to reach the biosphere. The time frame of concern is typically from ten thousands to a million years.

Uncertainties to be evaluated in safety assessment may be grouped according to the main elements that compose such a safety assessment. One way to categorize these elements is presented as follows:

- System Characteristics. Under this category, the concerns are: what features (F) are present in the geological system, what processes (P) are active, and what events (E) may trigger these processes. Here, features include fracture zones and other geologic structures; processes are all physical, chemical, and biological processes that may have an impact on the isolation and safety of the waste repository; and events include seismic events and also construction activities and creation of a large underground opening for the repository. They are referred together as FEPs.

- Scenario Selection. This is to predict or anticipate possible conditions for the future environment at the geological site where the repository is located, such as climatic conditions and future human activities, e.g., mineral exploration. Sometimes these are discussed as external features, events, and processes: External FEP's. Obviously, these conditions will have an impact on fluid flow and solute transport around the repository system thousands of years into the future.

- Data and Specific Knowledge of Geologic Structures and Physico-Chemical Conditions. While "system characteristics" as defined above mainly identifies the types of features present in the geologic system, this particular element focuses on the quantitative determination of the geometric locations and hydraulic or chemical properties of these features, as well as those of the fluids in the pore space. Multiyear site characterization programs are conducted at the site for such information. The results of site characterization will be integrated as a Site Descriptive Model (SDM) of the site.

- Modeling. Based on our knowledge of system characteristics and specific quantitative data on geologic structures and properties, modeling can be conducted to study system responses to various possible future scenarios and to calculate the isolation potential of the repository and the flow and solute transport potential within the geologic medium. Modeling results will be the main input to risk and safety assessment.

5.2.2 DISCUSSING UNCERTAINTIES RELATED TO SYSTEM CHARACTERISTICS

Here, the main issue is the comprehensiveness with which all FEPs important for repository safety have been identified and evaluated in a qualitatively correct way. Fortunately, there exist international FEP databases, which include thousands of possible FEPs that may occur in geologic systems. In the context of a particular site, many of these FEPs can probably be discarded quickly. However, to reduce the uncertainty in evaluating FEP's (i.e., possibly discarding the wrong FEPs), care must be taken, and the experience and skill of the persons responsible for making such decisions must be at the proper level. Furthermore, some of the FEPs cannot be discarded without some evaluations. These FEPs need to be carefully reviewed for correctness. It is easy for a national waste program to conduct an FEP identification in a quick and superficial way, which can be a significant source of uncertainty.

One important area of uncertainty in identifying FEPs is in determining the initial or current condition of a geological system. Often the system is assumed to be at steady state, which may well be inappropriate, especially considering the very long time frame covered by safety assessment. Determination of the appropriate, possibly transient, state of the initial system condition is not an easy exercise and can be a source of uncertainty. This uncertainty can be addressed to some degree by paleo-hydro-geochemical modeling, which evaluates how the system under study has reached the current hydrochemical conditions. For such modeling, a good set of data on current hydraulic and geochemical conditions is needed.

In identifying processes that are active in the geologic system, we must recognize that processes often do not act independently of each other. Identification of influences among processes is not straightforward and can also be a source of uncertainty. Some approaches have been developed to try to identify and evaluate, in a systematic way, these couplings among processes.

5.2.3 DISCUSSING UNCERTAINTIES RELATED TO SCENARIO SELECTION

The international FEP databases include “external” FEPs, which can be used to build up alternative future scenarios. Uncertainty, in this context, concerns the selection of a sufficient set of potential scenarios, which for the most part is done subjectively. To reduce such uncertainty, a structured and logical approach for developing the scenarios needs to be applied. To keep the potential scenarios to a reasonable number, we would discard some possible cases as having insignificant impact on repository safety—often done by simplified evaluation or bounding calculations. This practice needs to be carefully reviewed as it is a potential source of uncertainty.

After identification of a scenario—for example, future glaciation events and climatic changes—a detailed definition of the scenario (along with its time dependence) often cannot be made with certainty. A range of possible time-dependence behaviors in these scenarios will need to be included in any safety assessment.

5.2.4 DISCUSSING UNCERTAINTIES RELATED TO DATA AND SPECIFIC KNOWLEDGE OF GEOLOGICAL STRUCTURES AND PHYSICO-CHEMICAL CONDITIONS

This is related to development of Site Descriptive Models (SDMs) and will be the subject of discussion in a later section (below).

5.2.5 DISCUSSING UNCERTAINTIES RELATED TO MODELING

Modeling uncertainties include all the uncertainties associated with system characteristics, scenarios, and geologic structures discussed above, since they are inputs to modeling. But in addition, modeling raises other uncertainties.

One modeling uncertainty can be termed “Abstraction Uncertainty.” In model calculations, model design is normally simpler than the structural details present at the site, and, also, processes are often described by equations corresponding to a simpler representation of these processes. Such simplifications introduce uncertainties that need to be evaluated and bounded. Also, the model thus constructed will include parameters describing hydraulic or chemical properties of the different components of the model, and parameter values will have to be abstracted from available site investigation data. This abstraction process involves potential uncertainties that need to be evaluated and understood.

One example of this kind of uncertainty, one which is relatively well known, is the so-called upscaling problem. Since measurements at the site are often over a scale very different from the scale of parameters being used in the model calculation, methods need to be developed to relate the data between the two scales. This is not just a mathematical problem but a physical problem, since new physical structures and processes may become involved in the transition from one scale to another. Thus, it is important not only to develop upscaling methods, but also to conduct laboratory and field tests to confirm their applicability for the particular site and for their specific use in modeling.

Another model uncertainty involves the treatment of spatial variability in the geologic medium. While major features, such as fracture zones and geologic stratigraphy, can be included deterministically in models, the smaller-scale heterogeneity has to be accounted for by averaging (smoothing) or stochastic methods. The impact of these methods on flow and solute transport modeling is often not obvious—and can be a source of uncertainty that needs to be evaluated.

5.2.6 INTEGRATION OF UNCERTAINTIES IN SAFETY ASSESSMENT

In the safety assessment of a nuclear waste repository, all the uncertainties discussed above tend to act together, and some of them are coupled with each other. For example, the identification of FEPs, their representations in model calculations, and the site data that provide estimates of the model parameters are closely related. Methods for uncertainty integration will need to be developed, especially for cases in which data uncertainties and the spatial variability of property parameters are represented by probability distributions, which are then used in models based on stochastic methods.

5.3 Uncertainties in Site Investigations TO OBTAIN Data and QUANTITATIVE INFORMATION of Geological Structures and Physico-Chemical Conditions

Site investigation is a crucial first step in a national waste repository development program. It provides needed data to determine whether a site is suitable for hosting a repository and to conduct a safety assessment. More directly, the goal of site investigation is to arrive at a "Site Descriptive Model (SDM)," which gives the locations and characteristics of site features (such as fracture zones, type of rocks, topography, stress conditions, and water chemistry distributions), as well as the physical, chemical, and biological processes occurring at the site. The SDM is constructed from site data and information, and should be constructed in stages, as more and more data become available. Thus, each SDM is given a version number. Each stage or version is then based on site data available at that time, and successive versions represent improvements over the previous versions. In this way, the bases for the various details in an SDM, in terms of site information and data, can be tracked, reviewed, and verified, with their confidence level assessed. Of critical importance for site characterization (and the subsequent assessment of repository safety) is the understanding of uncertainties in the SDMs.

5.3.1 TYPES OF SITE INVESTIGATION UNCERTAINTIES

From site measurements to a SDM, several types of uncertainties can be identified:

- Data uncertainties. These are measurement errors caused commonly by instrumental limitations. They are well recognized and can be handled through sensitivity analysis to arrive at parameter uncertainties.

- Interpretation uncertainties. Given measurement data, parameters characterizing the SDM need to be derived. These often require assumptions about the conceptual model that may not be valid. One very simple example is pressure transient data from a pressure-pumping test across a fracture zone. If we assume that the fracture zone is homogeneous, with constant permeability over its plane, the value of the permeability can be calculated. However, if the fracture zone is actually heterogeneous and anisotropic, with varying properties over its plane (as is commonly the case), a homogeneous, constant-permeability assumption will introduce significant uncertainty into the interpretation.

- Conceptual or structural uncertainties. These are uncertainties involving the structures in the SDMs, such as positions of fracture zones, rock type distributions, and boundary properties. Since data are often sparse in space, it is often hard to pin down the extent, continuity, and direction of these features.

- Simplification uncertainties. Geologic structures are detailed, with multiple levels of substructures. In SDMs, there is a need to simplify and average out details to a manageable resolution. Such simplification presents uncertainties. These uncertainties are a function not only of simplification approaches and methods, but also a function of the physical character of the underlying substructures or heterogeneity, and of the SDM's uses (and its sensitivity to the simplified structures).

Note that the above uncertainties are site characterization uncertainties, which are to be distinguished from the more general safety assessment uncertainties that have been discussed above. On the one hand, the latter is based on the former and includes further uncertainties in modeling codes, model construction, and accounting for heterogeneity (for example, the use of stochastic methods). On the other hand, safety assessment is narrowly focused on issues that impact safety and would for the most part be concerned with uncertainties in potential radionuclide transport and dose calculations for risk assessment. Generally, site characterization is aimed more broadly at identifying site features and structures, as well as understanding the hydrological, geochemical, geomechanical, and biological processes present at the site, whether or not they have an impact on repository safety. In this sense, it has a broader view and forms the foundation upon which safety assessment models can be built.

Below, we will not discuss commonly known uncertainties, such as instrument accuracies, but rather focus our discussions on site investigation uncertainties, which are often not recognized.

5.3.2 DISCUSSING UNCERTAINTIES RELATED TO STRUCTURAL MODEL

Three remarks may be made regarding these uncertainties:

- Site descriptive models (SDMs) may include structural uncertainties (geometries of deformational or fracture zones, rock type locations and extents, transmissivity distributions) that cannot be handled statistically or treated by conventional sensitivity calculations. To deal with such uncertainties, we must consider additional (perhaps two, three or more) alternative SDMs, sometimes referred to as Alternative Conceptual Models (ACMs). These are models that are consistent with all available data and information, and yet different from each other. These ACMs need to be defined and tracked. Some of them may be modified or proven invalid as more data come in; however, it is expected that some ACMs would remain valid, and these should be carried through to the stage of assessing repository performance. At this point, the results will need to be presented as a range encompassing the predictions of all SDMs and ACMs, thus contributing to uncertainty estimation in repository safety assessment.

- Special care needs to be placed in determining the boundary conditions of the SDMs. Often the boundaries are located according to the convenience of model construction, or according to measurement boundaries dictated by political or social factors. Wherever possible, the boundaries should be placed based on hydrogeological information. For example, a line along a ground water divide or a hydraulically non-conducting fault may be a good boundary to use. Also, in general, evaluation should take into account whether the conditions along the boundary are constant in space and in time. Often, constant conditions are assumed without justification. Uncertainties in terms of transient and varying boundary conditions need to be assessed, documented, and tracked in the SDM or as part of an ACM.

- In some waste disposal programs, because of the lack of site data, "expert judgment" is sometimes used. One example of this type of data is probability distributions of parameter values in a flow domain, developed by expert elicitation. In this elicitation, a group of experts with substantial experience in these parameters are requested to provide their best estimates of the distributions. Uncertainty in this process is hard to assess, but careful documentation of the basis and process of the elicitation is critically needed, so as to allow for future review and update.

5.3.3 DISCUSSING UNCERTAINTIES RELATED TO DATA BIAS

Three remarks may also be made about these uncertainties.

- We must ensure that the existence or absence of features in a SDM does not result from variation in data density. For example, an area may be assumed to contain no fracture zones just because no measurements for fracture zones have been made in that area. Another common example is to assume a low occurrence of vertical fractures only because observational boreholes are mostly vertical and they are more likely to detect horizontal fractures and not vertical ones. Thus, it is helpful and important to evaluate different parts of the SDM and assign uncertainty levels to areas where data density is low.

- Geologic formations are heterogeneous. In evaluating their parameters, we must identify the "support scale" of the parameters. In other words, measurements are related to a spatial scale over which the parameter values represent some kind of average. For example, a pumping test may involve a spatial dimension of tens to a hundred meters (the so-called cones of influence), whereas measurements on core samples involve the dimension of only a few to tens of centimeters. If these support scales are not documented, significant uncertainties could be introduced into these parameters. Further, site characterization should aim at not only measuring averaged values (over the "support" scale), but also their variations (for example, in terms of standard deviations) over a wider area.

- To manage data uncertainties, a proper Quality Assurance (QA) program needs to be established, to ensure that all data are traceable and transparent. Under a QA program, for example, the measurement tools used and interpretative methods applied will be documented. However, it is important to emphasize that a proper QA program should aim at ensuring only that data are traceable to their sources and transparently tied to how they are obtained. A proper QA program should not be a project management tool or a decision-approval procedure, which should be a separate unit in a nuclear waste management organization. Confusing these two functions can become a major cause of frustration and disruption to project progress.

5.3.4 DISCUSSING UNCERTAINTIES RELATED TO OTHER ISSUES IN SITE INVESTIGATION

An important and useful method to assess SDM uncertainties is to study the consistency between the geological (geophysical), hydrological, and hydrogeochemical aspects of the SDM. For example, it may be found that geological structures do not fully correlate with hydraulic flow zones. In one study of the Aspo site in Sweden, it was found that only 11% of the flow indicators in boreholes at the site corresponded to enhanced fracture densities in these boreholes, and that 23–34% of flow indicators did not correspond to obvious borehole structures. All these need to be understood. Similarly, whether water chemistry distributions are consistent with the identified geologic structures and calculated flow patterns can be used to assess uncertainties in the SDM. A substantial modeling effort is needed within a site characterization program to evaluate such uncertainties.

Other issues related to SDM uncertainties include

- The need to identify and characterize recharge and discharge areas of the hydrogeologic system. These areas provide very useful information on the flow field in the SDMs.

- The importance of anisotropy as a characteristic in geologic systems. Ignoring it generates significant uncertainties. Thus, attempts need to be made to measure anisotropy in thermal properties, stress fields, permeability fields, and fracture networks, as well as single-fracture transmissivities.

- In evaluating laboratory data, the need to consider stress releases on samples when they are extracted from a deep borehole. These stress releases could cause microfractures that in turn could introduce significant uncertainties into laboratory measurements of porosity, diffusivity and other properties

The above present some of the not-so-well-recognized uncertainties that can have a significant impact on development of site descriptive models through site investigation.

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6 Geochemical Issues

6.1 Introduct ion

In this section, we will look ahead a little and discuss some geochemical issues that are relevant to the Japanese waste isolation program. Although it is highly unlikely in Japan that a preliminary investigation site will be found unsuitable because of its groundwater chemistry, it is nonetheless important that the ground water chemistry is at least chemically compatible with the planned engineering barrier design.

The Japanese program to store processed high level radioactive waste (HLRW) underground takes advantage of two engineered barriers in addition to the geologic barrier in order to ensure long-term containment of radionuclides. The two engineered barriers are respectively (1) a thick (approximately 15 cm) thick sacrificial steel overpack container, and (2) a backfill consisting primarily of bentonite. The natural geologic barrier is tentatively identified as a sedimentary rock of argillaceous composition. Such a rock type could possess favorable characteristics where incipient faulting and fracture generation resulting from excavation of the repository may tend to self-seal after closure.

If spent fuel from a nuclear reactor is effectively processed, and all actinides are recovered, the residual HLRW will consist almost entirely of fission product radionuclides. Most of these radionuclides possess relatively short half-lives, with the exception of Cs-135 and I-129, with half lives of 2.3E+6 yr and 1.5E+7 yr respectively. Chemical separation of I-129 should be feasible, and the small quantities of this radionuclide could be handled separately, either through construction of a dedicated repository with a 5.0E+7 containment period, or more practically, by neutron capture, or some other nuclear transformation in a reactor. The separation of Cs-135 from Cs-137 is, however, impractical. If both I-129 and Cs-135 are co-disposed with the remaining short-term radionuclides, then it must be presumed that their release from the waste container will become a near certainty after 1E+6 yr.

After 1,000 yr, only Cs-135 will be the surviving Cs isotope, and if released, it will be subject to ion exchange with K^+ and native Cs-133 in clays. Therefore, it will be both retarded and diluted during transport. I-129 will also be diluted with native I-127.

Retardation might be effected through anion exclusion, especially in compacted clays of the backfill and host rocks. Because both I-129 and Cs-135 are β emitters with long half-lives, their toxicity is relatively low and they are unlikely to constitute a serious radiation hazard unless ingested in significant quantities; a very unlikely outcome.

The processed HLRW is likely to contain traces of actinides, their concentrations depending on separation efficiency. If the residual concentrations were sufficiently low, special requirements to ensure containment over prolonged time periods, i.e., 1E+5 to 1E+6 yr would not be necessary. Although some produced actinides possess very long half lives, e.g., U-233 (1.59E+5 yr), U-236 (2.34E+7), Np-237 (2.14E+6 yr), Pu-242 (3.75E+5 yr), Pu-244 (8.0E+7). Cm-247 (1.56E+7 yr), their concentrations in HLRW would be for the most part low, depending on the type of fuel cycle used, and the processing technology. The potentially most hazardous radionuclides could be U-233, U-236 and Np-237.

6.2 Radionuclide Containment

Geologic repositories for the storage of radioactive waste must be designed with several considerations in mind. These considerations involve a consensus as to what radiation doses would be considered tolerable for given radionuclides to prevent adverse environmental and human health effects, the minimum required containment period to meet these requirements, and the uncertainties associated with predictive calculations to estimate the containment period. The containment period relates to the duration of the confinement of all radionuclides in a circumscribed volume of the geologic medium. To minimize risk, containment is achieved through the imposition of a multiplicity of barriers to radionuclide migration. They are divided into two categories; natural, i.e., geologic barriers, and engineered barriers. The barrier system must provide assurance of adequate containment at reasonable cost. In other words, if the cost of ensuring the required degree of safety for a given site proves to be excessive, then alternative combinations of engineered and geologic barriers must be considered.

The design of an effective geologic repository is predicated on an ability to predict radioelement transport through multiple barriers with varying chemical and physical properties under the influence of transient thermal, chemical and radiation fluxes.

Much has been written on this topic over the past thirty years, and a large number of experimental, theoretical and modeling studies have been conducted in an attempt to clarify chemical processes and increase the confidence of repository performance predictions. These studies have been conducted in the United States, Canada, Japan, several European countries, and in Russia, but only in Russia have large quantities of high level radioactive waste actually been disposed of in underground repositories, and then primarily in the form of liquid processing waste. Although the Russian approach to subsurface waste disposal has not lead so far to any major reported environmental catastrophes, public and scientific opinion elsewhere is averse to the direct disposal of high-level liquid radioactive waste, regardless of the confidence placed in the long-term functionality of natural geologic barriers. Elsewhere, and more recently in Russia, the primary emphasis has been on repositories designed to accept solid waste, either as Spent Unreprocessed Fuel (SURF), or as reprocessed High Level Radioactive Waste (HLRAW). Repository designs vary form country to country depending on the nature of the waste form, availability of suitable geologic formations, and *a priori* concepts upon which subsequent research is tailored to provide the needed justification. Discussion of these various design concepts is beyond the scope of this communication. Instead, emphasis is placed on the conceptual issues that should be addressed in repository design, and how modeling would allow for the design to be optimized in relation to containment and cost constraints.

6.3 Engineered Barrier Design

Figure 6-1 illustrates a cross section of a conceptual design of an engineered barrier system to confine high-level reprocessed radioactive waste. The design incorporates five barriers to radionuclide migration. Their characteristics are described in the following paragraphs:

(1) The Waste Form. The most common method of treating fission product radionuclides from waste reprocessing is to dissolve the radionuclides in a sodium borosilicate melt. Most will dissolve, but some may remain as discrete oxides in suspension. Other waste forms have been proposed, including “Synrock”, a concept developed by A.E. Ringwood of Australian National

University, Canberra, Australia, involving the synthesis of high-temperature crystalline alumino-silicate rock, designed to incorporate radionuclides in various igneous-rock forming mineral hosts, and a low-temperature ceramic assemblage of hydrated alumino-silicate mineral hosts that would form stably at hydrothermal temperatures, i.e., 100-250 C, an idea originally proposed by R. Roy at Pennsylvania State University. Ideally, HLRAW stored in sedimentary formations should be designed to be thermodynamically compatible with the conditions of storage, a low ambient temperature being one of them. Chemical stability can be engineered, in part, by consideration of the chemical composition of additional barriers. It is thus evident that low-temperature hydrated ceramics would be the preferred choice. However, the technology for design and fabrication of such waste forms has not proceeded to the stage of commercialization. Another neglected consideration is the need to consider whether or not the waste form could to corrode the container. Ideally, the waste should be in thermodynamic equilibrium with the container within the temperature range expected following repository closure. However, it should be recognized that the HLRAW will emit a significant radiation flux, which will cause radiolysis, affecting the stability of both the waste and phases comprising the surrounding engineered barriers. In most geochemical modeling, these issues are not taken into account, and therefore, the conditions to minimize the potential likelihood of radionuclide release from the waste form are ignored.

(2) The Waste Canister. The terminology for the waste containers has varied over the years. In this context, the waste canister is defined as that container directly in contact with the waste. The waste canister is usually thin-walled, and when holding a borosilicate glass waste form, could be the container into which the molten borosilicate liquid was initially poured. Although the canister could be fabricated of any of a number of metal alloys, a particularly suitable material would be an invar alloy, particularly that with the composition NiFe. The reason for this selection is that this alloy would be more noble than steel, and if a steel overpack is used, and is in contact with the canister, it would be galvanically protected against corrosion for as long as the any apart of the steel overpack

remains uncorroded. Naturally occurring crystallized NiFe has been observed in association with kamacite (α-Fe) as a secondary mineral resulting from the hydrolysis of ultramafic rocks consisting dominantly of olivine and/or enstatite. A NiFe canister would be fabricated from rolled sheet taenite γ-(Ni,Fe) of the given composition rather than the structurally ordered form, which can only form at low, subsolidus temperatures below ≈ 400 °C. However, it has been reported that a high radiation flux will induce sub-solidus ordering. This flux can be conveniently supplied by the decay of fission product radionuclides in the waste form itself. The cost of the canister can be controlled, as its thickness needs only to be sufficient to maintain physical integrity, as it will not corrode so long as the enclosing steel overpack has not corroded away. After the overpack has been sacrificed, more oxidizing conditions could cause the formation of a layer of spinel, e.g. $(Ni,Fe)O.Fe_2O_3$, on the Ni-Fe canister, which could act as a passivating layer, thereby further inhibiting canister corrosion.

(3) Sacrificial Steel Overpack. The primary purpose of the steel overpack is twofold; to provide physical protection to the waste form and canister during transport, and to act as a radiation shield during handling. Normally, a thickness of approximately 15 cm is sufficient to ensure both physical and radiation protection. If, after burial, the waste overpack is to be utilized as a sacrificial anode to protect the canister, then it should be fabricated from a low carbon steel, in order to minimize hydrogen embrittlement, and premature failure.

(4) Composite Redox-Stabilized Protective Barrier. The engineered barrier surrounding the steel overpack should be constructed of materials that induce reducing conditions, and limit or even prevent corrosion of the overpack while retarding access of water. By analogy with the thermodynamic stabilization of kamacite in serpentinized dunites, this barrier should consist primarily of comminuted olivine in a plastic matrix. This matrix could be composed of antigorite and kerolite or talc together with an expandable clay with saponitic affinities. The olivine mesh size should be such that its reactivity will generate a sharp interfacial boundary between the redox state where kamacite is close to

thermodynamic equilibrium, and the anoxic reducing conditions typical of a sedimentary argillaceous formation. The weight fraction of olivine should be maximized consistent with matrix plasticity and convenience of physical emplacement. The water content should be kept to a minimum, and matrix permeability should be minimized. It is assumed that in olivine, the following reaction is operative:

$$3FeO^{(ol)} + H_2O = Fe_3O_4 + H_2$$

The hydrogen partial pressure rises to the point where Ni-Fe alloys are thermodynamically stabilized, and the stability field of a-Fe is closely approached. In effect, the barrier is also sacrificial, in that it protects the steel overpack from corrosion until all of the olivine has altered through hydrolysis. If, during the protective phase of this barrier, the waste package were to fail, and radionuclides were to be released, then the reducing conditions would immobilize any residual actinides to the insoluble (III) and (IV) states. Nuclides of Tc, Mo, Ni and Sb could also be immobilized in the insoluble (II) state or metallic state, respectively. Note, however, that radiolysis of water could lead to the formation of hydrogen peroxide and hydrogen, thus:

$$2H_2O + \gamma = 2OH\bullet + 2H\bullet; 2OH\bullet = HOOH; 2H\bullet = H_2$$

Although it is possible that NiFe might catalyze the recombination of the products of radiolysis, it is more likely that hydrogen will diffuse from the barrier in a quasi-inert state, leaving reactive HOOH. The extent of this adverse reaction would depend on the effectiveness of the steel overpack as a radiation shield, and the time after emplacement of the waste.

(5) <u>Clay Retardation and Sealing Barrier.</u> The essential purpose of the outer engineered barrier, assumed to be constructed primarily of bentonitic clay, is twofold; to provide an effective seal against the advective penetration of ground water, and to act as a barrier to radionuclide migration. Many studies have been conducted to assess the potential of a smectite barrier to retard radionuclide migration, and it has been found that retardation is modest. The mobility of

cations through the hydrated interlayers and between individual crystallites can be significant, and compaction is rarely sufficient to have a material effect in decreasing matrix permeability beyond a certain point.

Various amendments can be incorporated into the inner composite and outer clay sealing barriers to serve specific purposes. For example, a key requirement in maintaining the integrity of the steel overpack and NiFe canister is preventing the ingress of sulfate, which would be reduced to sulfide and precipitate various Ni and Fe sulfides. Because $SO4^{2-}$ is ubiquitous in groundwaters, some means of retarding barrier penetration by sulfate should be found. There are numerous potential solutions to this problem, some more practical than others. For example, $Ba(OH)_2$ could be incorporated in the outer clay layer, which would be reactive, and initially displace Ca^{2+} from the smectite. However, both $Ca(OH)_2$ and $Ba(OH)_2$ would react with sulfate to precipitate either gypsum (or anhydrite if the temperature is high enough) or barite, which is extremely insoluble. The precipitation of these phases will cause an net increase in the volume of solids, and could decrease barrier permeability temporarily inhibiting migration of $SO4^{2-}$. Dissolved $Ca(OH)_2$ and $Ba(OH)_2$ could also diffuse into the pore and factures of the adjacent country rock, precipitating sulfates *in situ* and encapsulating the waste /barrier system.

Another amendment might be the addition of Cu_2O as a "getter" for I-. Thus:

$$Cu_2O + 2NaI + H_2O = 2CuI + 2Na(OH)$$

CuI is extremely insoluble, and could be one means of containing I-129. However, NaI(aq) would also be in competition with NaCl(aq). Thermodynamic calculations would have to be performed to establish whether Cu_2O would be an effective amendment for this purpose.

There are undoubtedly other creative modifications that could be introduced. For example, illite is known to be an effective ion exchanger for Sc+. Therefore, Cs migration the clay barrier might be decreased through the admixing of illite. The introduction of mafic hyaloclastite to the clay barrier could expand the reducing environment beyond the inner redox composite layer. Hyaloclastite reaction with water will produce secondary nontronite and excess silica, which could precipitate in adjacent fractures in the country rock, thereby decreasing its permeability in a manner similar to that described above for alkali earth sulfates.

Control of actinide transport could be established adjacent to the steel overpack in the composite barrier through the addition of a reactive form, e.g. amorphous uraninite synthesized with U-238 (depleted uranium). During recrystallization, it would capture U-233, U-236 and Np-237 radionuclides. Because the concentration of U-238 would exceed the hazardous radionuclides by orders of magnitude, and the solubility of UO2 is low, isotopic dilution could lower the concentration of mobile U-233, U-236 and Np-237 correspondingly by orders of magnitude.

6.4 The Natural Geologic Barrier

It is almost axiomatic that geochemists are inclined to place greater faith in engineered barriers as a primary defense against radionuclide migration, whereas engineers, mindful of the limitations of engineering design, are inclined to place greater faith in the geologic barrier. Geologic formations tend to be heterogeneous by nature, and it is only in a restricted range of geologic environments where formations are sufficiently uniform that their lateral continuity can be predicted with confidence. Such environments are usually found offshore, where sedimentary deposits show widespread lateral uniformity, although variations in the vertical direction can be extreme. However it is the vertical dimension that can be characterized in detail during excavation of a geologic repository, and if the lateral extent can be confidently predicted, and all faults and their transmissivities determined, then the associated hydrologic regime can be similarly predicted with a fair degree of confidence. Furthermore, hydro-geochemical characterization of the formation waters can be used to quantify groundwater migration rates and go a long way towards calibration of the hydrologic model.

The chemistry of groundwater migrating past the emplacement drifts will be modified in chemical composition, and pick up any radionuclides released by the repository. Although some secondary precipitation and/or ion exchange and adsorption can occur adjacent to the repository due to minor chemical incompatibilities between the engineered barrier system and the host rocks, as noted in the preceding section, radionuclide transport is likely to be affected primarily by adsorption and ion exchange alone. A proper characterization of these properties in situ will therefore allow for the formulation of a model where radionuclide migration might be predicted with reasonable confidence.

6.5 Modeling the Geochemistry of the Barrier System

During the last 40 years, an enormous degree of progress has been made in developing the capabilities for modeling chemical processes in natural systems. However, many limitations still prevent quantitative predictions from being made with the confidence expected in the performance of many other civil and geologic engineering structures, primarily because repository performance must be predicted over time spans of unprecedented length, even exceeding the duration that modern man has existed on earth. Therefore uncertainties of the order of one to two orders of magnitude in model predictions are to be expected.

Current state of the art reactive geochemical transport models will permit the modeling of engineered barrier systems of the type illustrated schematically in Figure 6-1. One code used extensively for the modeling of both the near and far field environments at Yucca Mountain geologic repository in the United States is TOUGH-REACT (Xu et al., 2006). Other codes are also available that can perform similar functions. Almost all codes will require modification and adaptation to meet engineered barrier needs, especially if the code is to be used to model complex barrier systems involving major variations in pH and Eh. However, such modeling can be supported by the wealth of experimental data that has been conducted to assess the performance of bentonite backfills.

A key requirement in geochemical modeling of geologic repositories is the need to know the uncertainty of model predictions, and to understand the sensitivity of various design parameters in affecting the repository containment requirements. Such requirements are generally in response to licensing or regulatory needs, and are subject to critical review. Government agencies recognize current limitations of model analysis and the lack, or insufficient accuracy, of available data, and require that additional modeling be performed to identify and assess those aspects that contribute significantly to uncertainty. Regulations also tend to place greater weight on conservative assumptions rather than realistic estimates. Unfortunately, this emphasis on conservatism, and time constraints in meeting licensing deadlines, can result in sidestepping the challenges associated with rigorous modeling of geochemical processes in favor of simplistic and unrealistic models in conjunction with excessively conservative assumptions to compensate for their inherent uncertainties. The regulatory burden, by diverting resources into conservative demonstrations therefore has the unintended consequence of deterring model refinements, which could ultimately provide scientifically more convincing demonstrations of environmental integrity.

The continued use of overly simplistic geochemical models and associated excessive conservatism is no longer justified by current progress in modeling. Considerable strides are being made in analyzing uncertainty in chemical and geochemical models (Ekberg and Emren, 1996; Ekberg et al., 2000; Najm et al., 2003; Reagan et al., 2004), and such developments should be integrated fully in reactive transport models, so that model outputs will already incorporate output parameter uncertainties.

Sensitivity studies are also a critical part of investigations into barrier design optimization. With the substantial number of design parameters, it is especially important to identify those that can significantly influence radionuclide containment over time, and permit the design to evolve in a manner that not only makes the design safe, but also allows supporting research efforts to focus only on those parameters deemed to be important to the design.

Finally, it should be emphasized that any given simulation of repository behavior describes the system's evolution through a multi-component chemical hyperspace. Without supporting thermodynamic and kinetic analyses, system behavior will not be easily understood, and a constructive approach to model refinement will not be easy. Thus, the use of supplementary activity diagrams to illustrate the distribution of stable and metastable phases at various defined chemical potentials, or suitable Eh-pH diagrams to illustrate redox transformations in the system are essential aids that must be used in conjunction with reactive transport modeling studies. Figure 6-2 illustrates an Eh-pH diagrams in which the stability fields of phases in the system Fe-Ni-S-O-H are displayed. While this diagram would require revision in the light of more recent data, it illustrates the potential complexity of the redox stabilized barrier system, even without the essential addition of Si to the chemical system.

6.6 Conclusions and Recommendations

Current engineered barrier designs for HLRAW repositories do not take full advantage of opportunities for enhancing long-term containment through the use of galvanic protection, or redox buffering. The uses of barrier compositions that allow quasi-thermodynamic stabilization of the waste package materials have not been adequately addressed. Although reactive geochemical transport models incorporating parameter uncertainties remain to be developed, full advantage should be taken of existing state of the art codes to model engineered barrier system behavior, with a view to optimizing the design for long-term containment, consistent with the repository natural geochemical environment, containment requirements to ensure protection of the environment and human life, and realistic costs.

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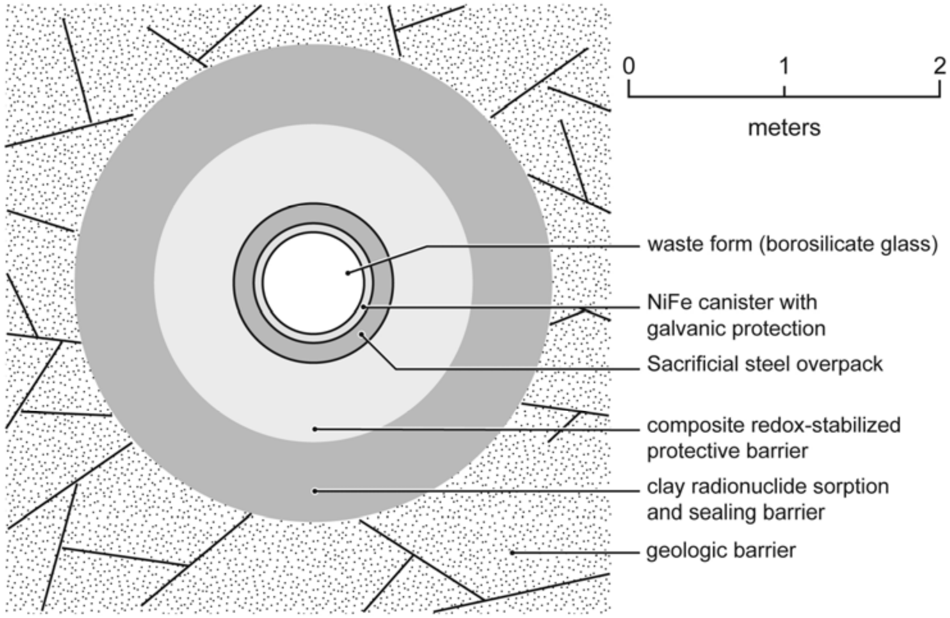

Figure 6-1. Schematic cross section of an engineered barrier system surrounding a high-lebvel radioactive waste container. Scale is approximate, and would depend ultimately on design requirements.

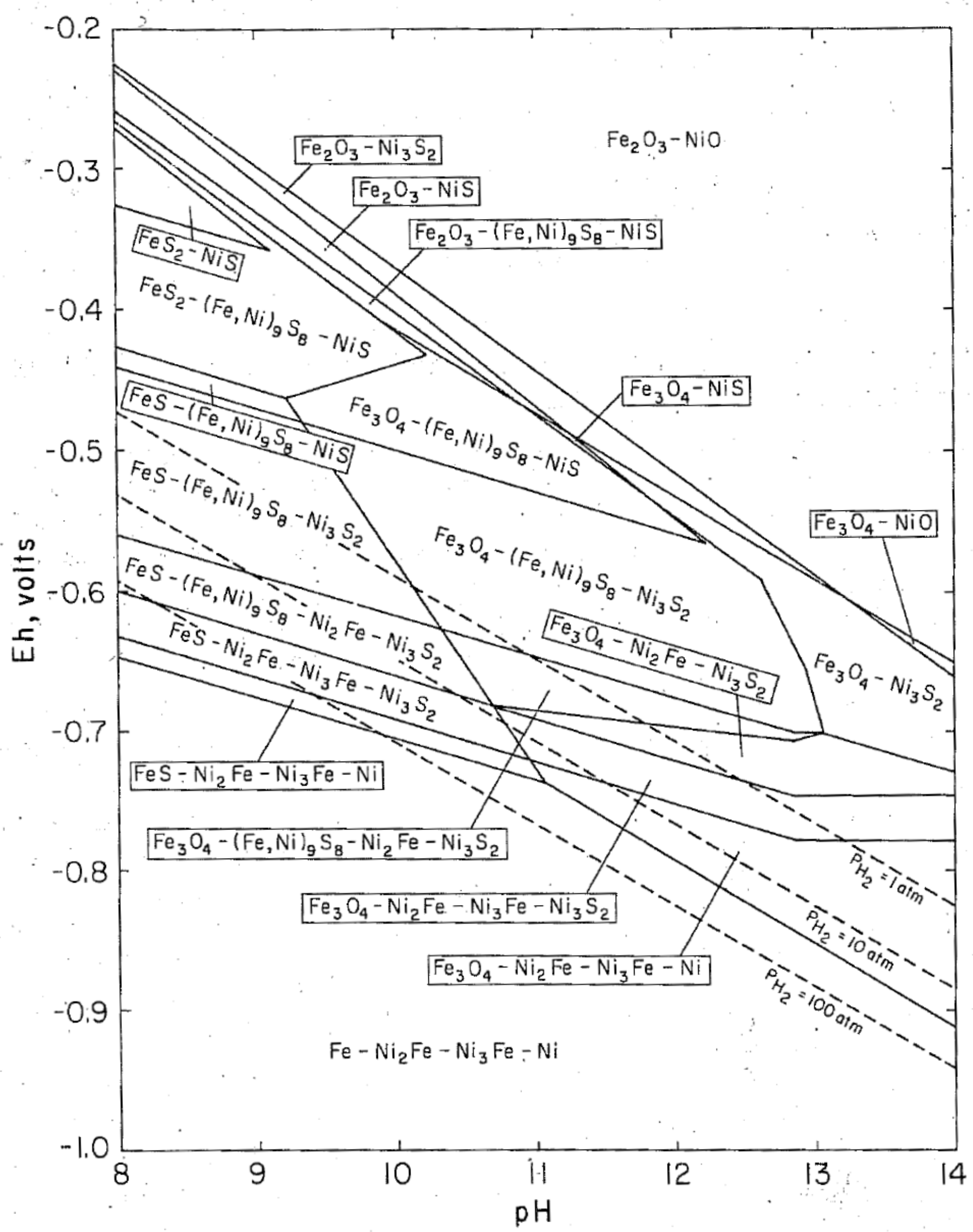

Figure 6-2. An Eh-pH diagram of the System Fe-Ni-S-O-H at 25°C and one atmosphere. Total S concentration is 10-6 molal. (From Apps and Cook, 1981)

7 Evaluation of uncertainties due to hydrogeological modeling and groundwater flow analysis – strategy for characterizing a new site –

7.1 Introduct ion

At the preliminary-site-investigation stage of repository siting, the quantity of available data is generally limited because of the restricted number of boreholes that can be drilled. Nonetheless, it is essential (from the limited data) to identify the parameters important to the safety of nuclear waste disposal and use those data in an iterative modeling study. Among the hydraulic parameters available from borehole tests, it is obvious that permeability and porosity are the most important ones. In the preliminary investigation stage, it is difficult to obtain statistically sufficient permeability data from the limited amount of well tests. Therefore, it is more realistic to use a representative set of permeability values for each hydrogeological unit.

We investigate how uncertainty affects the model outcome when the input values are based on a limited amount of well test data. In this final report, we describe the efforts to construct a "real" site from the most up-to-date data available from the Tono region in Japan. We compare the results of the models (constructed using limited amounts of data) to the results at the "real" site.

We plan various preliminary-investigation configurations and conduct preliminary numerical investigations in a synthetic site constructed by using an available set of real data from an existing domestic characterization site. We then use these preliminary data to construct a model of the "real" site and make predictions of particle travel times to compare against those at the "real" site.

We used an extensive data set from a domestic study site and constructed a "real" rock mass, for which we conducted numerical site characterizations using various drilling scenarios. Based on the data obtained from the boreholes, we constructed site models and made predictions of particle travel times, which we compared to the "real" data.

7.2 Background

The Japan Atomic Energy Agency (JAEA) conducted a multi-national project to investigate the uncertainties involved in the prediction of flow and transport behavior of a fractured rock mass. In the initial stage of the project, known as the CORE Collaborative Study (Oyamada and Ikeda, 1999; Doughty and Karasaki, 1999), several research organizations conducted numerical simulations of tracer transport through a hypothetical fractured rock mass at the 100 m scale. Each group was provided with the same hydrogeological data set and was requested to use the same boundary conditions. The groups' results were compared to identify and quantify uncertainties in model predictions. The study found that discrete fracture network (DFN) models and effective continuum models (ECM) produced comparable results for mean values of flow through the model and tracer travel times, but that DFN models showed greater variability among stochastic realizations than did ECM.

The second stage of the project took a similar approach, but provided site-characterization data for a real field site, a 4 km by 6 km by 3 km region surrounding the MIU site in the Tono area of Gifu, Japan, and left the choice of boundary conditions up to the research groups. The main results of the different groups' models were the predicted particle travel times from specified release points to the model boundary. LBNL developed an ECM and predicted relatively short travel times on the order of tens of years. Our work is summarized in Doughty and Karasaki (2001). There are no comparable field data available to directly validate the models, so, as in the first stage, model uncertainty was assessed by comparing among results of different models (Sawada et al, 2001). Although the general features of the flow paths from the release points to the model boundaries were similar for all the models, travel times varied over a huge range – from 1 to 10,000,000 years. Much of this variation could be attributed to the large range of fracture porosities assumed by the different groups, but direct comparison between models was difficult because of differences in how lateral boundary conditions were assigned.

For additional modeling of the region surrounding the MIU site, JAEA specified a set of common lateral boundary conditions for all the groups to use, so that differences in results could be related directly to the modeling approach and property assignments. In addition to examining steady-state flows and transport, we also did a transient-flow analysis by simulating the Long-Term Pump Test (LTPT), and thermal analysis of steady-flow conditions. It was found that groundwater flow has a large impact on the subsurface temperature distribution and that the thermal analysis proved a valuable means of discriminating between alternative model boundary conditions, which other field observations failed to do. Cooling due to large surface recharge in the closed model produces temperature profiles at odds with the conduction-dominated profiles observed in the field, eliminating the closed model from further consideration This work is summarized in Doughty and Karasaki (2002). Comparison of the results of our isothermal studies with those of the other research groups is presented in Sawada et al. (2003), which concluded that the major source of uncertainty in hydrogeological modeling often lies in the conceptual model rather than the details of numerical simulation. We were the only group to conduct thermal studies.

Subsequent to the LTPT, we analyzed pressure transients collected before, during, and after the LTPT itself. Strong pressure-transients were observed in a number of wells in response to the removal of a packer in well MIU-2, which enabled flow across the Tsukiyoshi fault. We refer to the packer removal and subsequent replacement as the "inadvertent MIU-2 well test" and modeled it numerically by increasing permeability (packer removal) then subsequently decreasing permeability (packer replacement) of the grid block representing the intersection of Well MIU-2 and the Tsukiyoshi Fault. We calibrated the model to observed pressure transients to infer permeability and porosity information for the vicinity of the Tsukiyoshi Fault (Doughty and Karasaki, 2003). A key finding of the study was that pressure responses occur more slowly than our original model predicted, necessitating an increase in model porosity to effectively increase model storativity, and thereby slow model pressure responses. This porosity increase then acted to lengthen predicted tracer travel times by about a factor of ten compared to our previous model.

Next, the lateral domain of the model was increased to 9 by 9 km. This extension enabled lateral boundaries to coincide with geographic features that provide a sound basis for assigning lateral boundary conditions: the eastern and southern boundaries of the model coincide with the Toki River, which is represented as a constant head boundary; the northern and western boundaries of the model coincide with topographic high points (ridge lines), which are modeled as closed boundaries to represent the no-flow symmetry line of a watershed divide. We modeled the steady-state head distribution, groundwater flow, and tracer transport from selected release points. We developed models for a base case and several sensitivity study cases with additional faults included, stochastic distributions of flow properties, or different surface recharge rates. The models were calibrated to steady-state head profiles in several wells, followed by a thermal analysis in which steady-state modeled and observed temperature profiles were compared (Doughty and Karasaki, 2004).

We then investigated representing the fractured rock using a dual-continuum model (DCM), in which each grid block contains two sub-grid blocks, one representing the fracture network and the other representing the intact rock matrix (Doughty et al., 2005). Unlike the ECM, in which fractures and matrix are assumed to be in equilibrium within each grid block at all times, in the DCM, the fracture and matrix components of the model respond to applied perturbations separately. The ECM and DCM produce identical results for steady-state pressure and temperature profiles, but in order to match the pressure transient response to the inadvertent MIU-2 well test, different fracture properties are required for the DCM compared to the ECM. Specifically, because the matrix provides an additional storage term, smaller fracture porosity is required for the high-permeability "sandwich" layers along the Tsukiyoshi fault. Although the pressure-transient data are not very sensitive to the properties of the granite beyond the Tsukiyoshi Fault, one may suppose that the fracture porosity there would also be decreased when a separate matrix continuum is included in the model. This assumption significantly shortens advective travel time through the model. However, the addition of a separate matrix component also allows for diffusion and sorption into the rock matrix, which could greatly slow radionuclide travel through the model as a whole..

In the present study, we take advantage of the available data set from the Tono region and construct a synthetic site, in which we conduct numerical preliminary investigations. The first task is to combine the calibration of the model to the data including steady-state temperature profiles, steady-state head profiles, and transient head responses, in order to use all available data to develop the best possible model of the 9 by 9 km region as the 'synthetic' site. Next, we examine how the data from each borehole contributes to the complete model, by assuming we have to create a model using information from a limited number of boreholes: just three wells, from just six wells, and from just nine wells. Three would be a minimum number of boreholes to be drilled at an actural PI site and nine may be near the maximum number of boreholes, although the ultimate number of boreholes to be drilled at a given PI site would depend on many factors such as the budget and the number of condidate sites. We also examine the impact of key model assumptions on heterogeneity and boundary conditions on choice of well location. Finally, we use the results of this effort to make general recommendations about choosing the locations of wells and the tests to conduct in order to characterize a new site.

7.3 Complete Model of Tono Region

7.3.1 STARTING MODEL

7.3.1.1 GEOLOGICAL REPRESENTATION

We begin with a geological model of the Tono region developed by JAEA in 2005. The model extends from the ground surface (ranging from 100 to 600 masl) to an elevation of -2000 masl. Lateral boundaries are irregular, following local topographic features such as the Toki River along the southern and eastern model boundaries, and ridgelines along the western and northern boundaries. Figure 7-1 shows the surface elevation over the domain of the model.

The model is composed of five geological layers. The bulk of the model is fractured granite, which is underlain by a deep, low-permeability granite and overlain by a weathered, more-intensely fractured granite several hundred meters thick. Over much of the model, the weathered granite is overlain by sedimentary rocks (Mizunami Group sediments overlain by Seto Group sediments). One major fault is included in the model, the east-west striking, sub-vertical Tsukiyoshi Fault. Five additional sub-vertical faults are also included.

We use the numerical simulator TOUGH2 (Pruess et al., 1999) to calculate the steady-state groundwater flow and temperature distributions in the model domain. Large-scale features such as lithologic layering and major fault zones are represented deterministically. Individual fractures are not modeled explicitly. Rather, an equivalent continuum model (ECM) is used for steady flow simulations and both an ECM and dual continuum model (DCM) are used for transient flow studies. Details of the difference between ECM and DCM formulations are given in Doughty et al. (2005).

The computational grid is rectangular, with lateral grid spacing of 100 m. Vertical grid spacing ranges from 50 m in the upper portion of the model, to 100 m over most of the model, to 250 m for the deepest 1000 m. We assign a material from the geological model to each grid block in the TOUGH2 model. Lithologic layers representing the sedimentary rocks, the fractured/weathered granite, and the granite are treated as undulating layers in the model. Figure 7-2 shows a perspective view of the model. The model is locally refined around well MIU-2 as shown in Figure 7-3, to enable more accurate calculation of pressure-transient behavior during the inadvertent MIU-2 well test.

The Tsukiyoshi fault is represented with a planer structure, in which a low-permeability fault core plane is flanked on either side by high-permeability planes (called "sandwich" planes). This structure is suggested by the geological and tectonic nature of the site, and is supported by steady-state and transient-pressure observations (Takeuchi et al., 2001; Doughty and Karasaki, 2003). The location of the fault is adjusted to ensure that it intersects the model locations for the MIU wells at the depths observed in the field. The steep dip of the fault requires that each sandwich plane be at least two grid blocks thick in order to provide continuous flow paths. This continuity requirement implies that the entire fault structure is probably thicker in the model than in reality, hence its intersection with vertical wells cannot be resolved very precisely. The five additional sub-vertical faults are each modeled as a single plane, with an anisotropic permeability to enable large flow within the fault plane but restrict flow across the fault plane. Figure 7-4 shows several views of the model, highlighting the fault structure in relationship to the wells in the vicinity of Well MIU-2.

7.3.1.2 FLUID AND HEAT FLOW PROCESSES

TOUGH2 simulates two-phase (liquid and gas), two-component (water and air) flow, coupled to heat flow. For the natural-state simulations that produce steady head and temperature profiles, fully coupled fluid and heat flow are calculated using the ECM. Because temperature changes occur much more slowly than do pressure changes, for the transient model of the inadvertent MIU-2 well test, which lasts only a few months, we assign a geothermal temperature gradient that is consistent with temperature profiles observed in boreholes in the Tono area (surface temperature near 16^{o}C, gradient 0.022^{o}C/m), but do not solve the conservation of energy equation, so temperatures remain fixed (in previous studies, this was referred to as the uncoupled thermal approach). For transient simulations, we use both the DCM, which enables the fractures and matrix to respond on different time scales, and the ECM, which assumes the fractures and matrix remain in equilibrium, and hence respond on the same time scale.

The bulk of the model remains single-phase liquid, but near the surface a shallow vadose zone develops in some areas.

7.3.1.3 INITIAL AND BOUNDARY CONDITIONS

Initial conditions for the steady-state simulations are chosen as a matter of convenience – they do not affect the final result, just how efficiently the computer reaches it. Usually, the steady-state pressure, temperature, and saturation distributions for a similar problem are used as initial conditions. The results of the natural-state simulation then serves as the initial condition for the transient simulation of the inadvertent MIU-2 well test, which we simulate using both the DCM and the ECM.

The lateral boundaries of the model are chosen based on local geography. Along the western and northern boundaries, the model boundary follows mountain ridge lines and is a closed boundary, to represent the watershed divide. The southern and eastern model boundaries coincide with the Toki River. Here, the model is closed at depth, but is held at atmospheric pressure at the ground surface, allowing exchange between groundwater and river water as governed by hydraulic head conditions. The bottom model boundary is closed to fluid flow and contains a spatially distributed heat source to produce a geothermal gradient of 0.022^{o}C/m throughout the model. This closed boundary condition, although a common practice, is not based on any hard observations, which can be a source of uncertainty in the model. A single grid block represents the Tono Mine, which is held at atmospheric pressure. Table 7.3-1 shows a summary of the boundary conditions imposed on the model.

Table 7.3-1 Summary of the model boundary conditions

<table>
<tr><th colspan="3"></th><th>Flow</th><th>Heat</th></tr>
<tr><td colspan="3">Top Boundary
(Surface)</td><td>Prescribed flow,
Atmospheric</td><td>Fixed Temperature</td></tr>
<tr><td rowspan="3">Lateral</td><td colspan="2">Ridges (North, West)</td><td>No flow</td><td rowspan="3">No flow</td></tr>
<tr><td rowspan="2">River
(South, East)</td><td>Surface</td><td>Open</td></tr>
<tr><td>Depth</td><td>No flow</td></tr>
<tr><td colspan="3">Tono Mine</td><td>Atmospheric</td><td>Fixed Temperature</td></tr>
<tr><td colspan="3">Bottom</td><td>No flow</td><td>Fixed heat flux</td></tr>
</table>

At the top surface of the model, pressure, temperature, and liquid saturation are maintained at fixed values as follows. The gas pressure is maintained at atmospheric pressure. Temperature is maintained at a seasonally-averaged temperature that decreases slightly with surface elevation z ($T = T_0 - 6.38 \cdot 10^{-3} (z - z_0)$, where z_0= 105 m is the minimum surface elevation and T_0=16^{o}C is determined by matching to observed temperature profiles that are linear and hence represent conduction only). Liquid saturation is set such that the desired amount of water recharges or discharges the model, based on a previous calibration to head and temperature profiles (Doughty et al., 2005), as summarized below.

1. Calculate the steady-state flow field for a constant-head boundary condition in which hydraulic head equals surface elevation. That is, the water table coincides with the ground surface (there is no vadose zone).
2. Record the steady-state flow distribution from surface boundary elements into or out of the model. This flow distribution is most sensitive to surface topography and the vertical permeability of the materials composing the top layer of the model.
3. Maintain the surface boundary elements with flow out of the model as constant-head boundaries. Surface boundary elements with flow into the model are converted to constant-flow boundaries. Flow rate is assigned as

1/10th of the constant-head flow, a value chosen by trial and error to best match observed head and temperature profiles.

4. Calculate the steady-state flow field. At inflow locations, the surface head and saturation can vary, enabling a vadose zone to develop. Outflow locations remain water saturated, but as the specified inflow rate decreases, heads adjust so that less outflow occurs as well. This adjustment process implies that the simulation result does not depend strongly on the actual fraction assigned for inflow rate reduction.
5. The resulting steady-state surface conditions (P, T, S) are used as a constant surface boundary condition for further natural-state and transient simulations.

7.3.1.4 MATERIAL PROPERTIES

We begin using permeability and porosity values shown in Table 7.3-2, taken from the final 2005 model (Doughty and Karasaki, 2005), which was calibrated to the inadvertent MIU-2 well test and steady pressure profiles. Note that for sediments and granites "within material" permeability is generally k_{hor} and "between material" permeability is k_{ver}, whereas in faults "within material" permeability is generally k_{ver} and "between material" permeability is k_{hor}.

Table 7.3-2. Properties for starting 9x9 ECM.

Material Type	Porosity	Permeability (m^2)	
		Within materials	Between materials
Seto Group	0.20	$6.3 \cdot 10^{-15}$	$6.3 \cdot 10^{-17}$
Mizunami Group	0.20	$3.2 \cdot 10^{-15}$	$3.2 \cdot 10^{-17}$
Weathered granite	$7.3 \cdot 10^{-03}$	10^{-14}	10^{-16}
Granite	$3.4 \cdot 10^{-03}$	10^{-15}	10^{-17}
Deep granite	$3.4 \cdot 10^{-03}$	10^{-16}	$5 \cdot 10^{-18}$
Tsukiyoshi fault core	$8.4 \cdot 10^{-04}$	10^{-17}	10^{-17}
Tsukiyoshi fault hanging-wall sandwich	$7.6 \cdot 10^{-03}$	$2.7 \cdot 10^{-13}$	10^{-15}
Tsukiyoshi fault footwall sandwich	$7.6 \cdot 10^{-03}$	$2.7 \cdot 10^{-13}$	10^{-15}
Tsukiyoshi fault footwall sandwich, special path to MIU-3	$3.8 \cdot 10^{-3}$	$5.4 \cdot 10^{-13}$	10^{-15}
Other faults	$3.0 \cdot 10^{-03}$	10^{-13}	10^{-16}

The material properties for the starting DCM are shown in Table 7.3-3. Sediment materials are treated as an ECM rather than a DCM. For the fracture component of the

DCM, permeabilities are the same as for the ECM, but porosities are generally smaller. More details on the choice of properties for the DCM are given in Doughty et al. (2005).

Table 7.3-3. Properties for starting 9x9 DCM.

Material Type	Fracture Porosity	Permeability (m^2) Within materials	Between materials
Seto Group	0.20	$6.3 \cdot 10^{-15}$	$6.3 \cdot 10^{-17}$
Mizunami Group	0.20	$3.2 \cdot 10^{-15}$	$3.2 \cdot 10^{-17}$
Weathered granite	$2.3 \cdot 10^{-03}$	10^{-14}	10^{-16}
Granite	$3.0 \cdot 10^{-04}$	10^{-15}	10^{-17}
Deep granite	$3.0 \cdot 10^{-04}$	10^{-16}	$5 \cdot 10^{-18}$
Tsukiyoshi fault core	$3.0 \cdot 10^{-04}$	10^{-17}	10^{-17}
Tsukiyoshi fault hanging-wall sandwich	$2.6 \cdot 10^{-03}$	$2.7 \cdot 10^{-13}$	10^{-15}
Tsukiyoshi fault footwall sandwich	$2.6 \cdot 10^{-03}$	$2.7 \cdot 10^{-13}$	10^{-15}
Tsukiyoshi fault footwall sandwich, special path to MIU-3	$1.3 \cdot 10^{-3}$	$5.4 \cdot 10^{-13}$	10^{-15}
Other faults	$3.0 \cdot 10^{-04}$	10^{-13}	10^{-16}

Matrix properties: porosity 0.005, permeability 10^{-20} m^2

7.3.2 MODEL CALIBRATION PROCEDURE

The starting model was developed by calibrating to steady and transient heads, using a DCM for transient simulations and a refined grid around well MIU-2. For the present studies, we begin by running a steady-state fully-coupled fluid and heat flow natural-state model and compare the results to observed steady head and temperature profiles. We use the ECM (which for steady-state problems gives the same result as the DCM) and remove the grid refinement around MIU-2 to allow bigger time steps. We then modify permeabilities to improve the match (recall that steady-state profiles do not depend on porosity). After several iterations, we use the resulting model (with grid refinement around Well MIU-2 reinserted, and conservation of energy equation not solved) to model the pressure-transient response to the inadvertent MIU-2 well test, using both ECM and DCM formulations. Additional adjustments are made to permeability and porosity to better match the pressure transients. The resulting models are used to model steady-state fully-coupled fluid and heat flow under natural-state conditions, and produce performance measures related to the advective transport of tracers released from various locations within the model. A schematic of the calibration procedure is shown in Figure 7-5

7.3.3 COMPARISON OF STARTING MODEL TO FIELD OBSERVATIONS

7.3.3.1 STARTING MODEL HEAD PROFILES

Figure 7-6 compares the starting model natural-state head profiles to those observed in the field. Steady-state head profiles are available for 11 wells within the 9x9 model area. Nearby similar profiles are combined, resulting in the seven plots shown in Figure 7-6, which are arranged on the page as the wells are distributed in space. Most profiles show constant head with depth, with higher head north of the Tsukiyoshi fault (Wells DH-9, DH-11, and DH-13). Wells MIU-2 and MIU-3 cross the fault, showing ~40 m greater head in the footwall (north of the fault) than in the hanging wall (south of the fault), indicating that the fault provides a significant barrier to fluid flow. The MSB wells show a sharp decrease in head with depth just below the surface: shallow probes in the sediments show normal heads, whereas deeper probes in the weathered granite show anomalously low heads, suggesting a low-permeability interface between these two geologic layers. Nearby, the probes in Well DH-2 (all in the weathered granite) also show very low heads.

Although the model matches are not perfect, most of the key features of the observed head profiles are captured by the model, in particular the 40 m head difference across the Tsukiyoshi fault. The biggest discrepancy is the large over-prediction of the head in Well DH-2 and the lack of head decrease with depth in the MSB wells.

7.3.4 STARTING MODEL TEMPERATURE PROFILES

Figure 7-7 compares the starting model natural-state temperature profiles to those observed in the field. Profiles for a conduction-only case, in which fluid flow has no effect on temperature profiles, are also shown for reference. Steady-state temperature profiles are available for 11 wells within the 9x9 model area. Nearby similar profiles are combined, resulting in the eight plots shown in Figure 7-7, which are arranged on the page as the wells are distributed in space.

When the observed temperature profile falls below the conduction-only profile (e.g., Wells DH-10, DH-13), it indicates that significant recharge of cool surface water is occurring. Conversely, when the observed temperature profile falls above the conduction-only profile (e.g. Well DH-11), upflow of warm water from depth is indicated. An observed temperature profile that coincides with the conduction-only profile indicates that neither significant downflow nor upflow is occurring. Either there is no significant fluid flow at all or flow is primarily horizontal.

Not surprisingly, the largest infiltration occurs at Well DH-10, which is at the highest elevation (see Figure 7-1), where recharge is expected to be greatest. Also, at the location of Well DH-10, weathered granite outcrops at the surface, allowing more infiltration than does the lower-permeability sediment layer that covers much of the model surface.

Upflow is observed at Well DH-11 (and to a lesser extent at Well DH-9), a result of the low-permeability barrier to flow provided by the Tsukiyoshi fault. Wells sited at lower elevations would not be expected to show significant infiltration, and they do not, with the exception of Well DH-4, in which the shallow vertical portion of the temperature suggests localized infiltration into the outcropping weathered granite, whereas the deeper conduction-type profile suggests no infiltration into the underlying granite.

The model generally captures the trends observed in the field data, however model infiltration is not large enough at Well DH-4 or Well DH-10, and it is too large at Well DH-9 and Well MIU-3. The upflow at well DH-11 is not captured at all, with the model showing erroneously large infiltration there.

7.3.4.1 STARTING MODEL TRANSIENT PRESSURE CHANGES

Figure 7-8 compares the starting model pressure transients for the inadvertent MIU-2 well test to those observed in the field. The pressure-transient responses are available for eight wells within the 9x9 model area. Similarly-responding wells can be combined, yielding the six plots shown in Figure 7-8. When the packer was deflated, Well MIU-2 provided a flow connection between the high-head footwall and the low-head hanging wall, so water flowed up the well. Unfortunately the flow rate was not measured but the pressure ditsturbance created by the opening of MIU-2 well was much larger and lasted longer than the designed long term pump tests. Thus came the name of 'inadvertent' well test. Pressure probes in the hanging wall show a pressure increase, whereas probes in the footwall show a pressure decrease. Not every observation depth is plotted, but the full range of responses is shown. For each well, increasing probe number corresponds to a greater probe depth. In Wells MIU-3 and MIU-4 shallow probes show a pressure increase while deep probes show a pressure decrease, bracketing the depth interval where the well intersects the fault.

The model pressure transients generally reproduce the observed ones, but pressure increases are too large initially in the shallow probes of Well MIU-4, too variable in Well SN-3, much too small in the deep probes of well MIU-3, and too small in Well SN-1 and in most of the AN-well probes. Small differences exist between pressure transients calculated by the ECM and DCM, but neither model consistently matches the observed data better.

7.3.5 MODEL CALIBRATION

Before embarking on model calibration, it is useful to visualize the natural-state groundwater flow predicted by the model. This may be done by plotting streamtraces beginning at selected locations (generally wells where natural-state head and temperature data are available). Figure 7-9 shows such a plot for the starting model. Several different sections through the 3D model are shown, and the head, temperature, and permeability fields are shown as background for different plots. The general trend of groundwater flow from northern high elevations toward southern low elevations is apparent in the plan view and y-z plots. The y-z plots also show the characteristic U-shape of a groundwater flow field within closed lateral boundaries, including infiltration at the high elevations and discharge at the low elevations. This trend is interrupted by the Tsukiyoshi fault, which partially blocks lateral flow, diverting fluid up toward the surface just north of the fault. Moreover, this upward flow is focused toward the location (~x = 6000 m, y = -68000 m) where the sedimentary layers are absent and the fault outcrops at the surface, as shown in the plan view and x-z plot. Just south of the fault there is a concentrated infiltration, as evidenced by the deeper penetration of cool temperature. When calibrating the model to the observed head and temperature profiles shown in Figure 7-6 and Figure 7-7, respectively, it is useful to refer back to Figure 7-9 to see the context of the individual profiles.

7.3.5.1 STEADY HEAD AND TEMPERATURE PROFILES

Several variations on the starting model were made, to see their effect on the natural-state head and temperature profiles. These are listed below, along with their motivation and effect, and the judgment on whether to keep the change.

Case CA
Change: Five times higher permeability for granite.
Motivation: Try to increase infiltration Well DH-10 and decrease head in well DH-13.
Effect: Head in DH-13 is lower (better). Most temperature profiles show more infiltration – good for Well DH-13, bad for rest.
Judgment: May be useful, in conjunction with other changes.

Case CB
Change: Other faults have granite properties.
Motivation: Well DH-9, located at one of the other faults, shows too much recharge.
Effect: Head is slightly lower (better) at Well DH-9, most wells show less recharge, which is better.
Judgment: May be useful, in conjunction with other changes.

Case CC
Change: Tsukiyoshi fault sandwich does not extend to surface where granite outcrops (already truncated through sediments); other faults have granite properties.
Motivation: Too much infiltration around Tsukiyoshi fault.
Effect: All heads are a bit higher (better for Well DH-11, others worse). Well DH-10 temperature is unchanged, rest show less recharge (better for all except Well MIU-1 and AN wells, which now show upflow).
Judgment: Keep.

Case CD
Change: Five times higher permeability for granite; other faults have granite properties; Tsukiyoshi fault sandwich does not extend to surface; Tsukiyoshi footwall sandwich has five times lower permeability.
Motivation: Combine good changes from above cases and try to enhance upflow in Well DH-11 by not having upflow localized in footwall sandwich layer.
Effect: Head is lower in wells DH-11 and DH-13 (better), worse in MIU-area wells (too high). Temperature is better in wells DH-2, DH9, DH-11, DH-10. Temperature is different in Wells MIU-2 and MIU-3, not sure if better or worse.
Judgment: Keep these changes in succeeding cases.

Case CE
Change: Increase permeability in weathered granite. Interface permeability between sediments and weathered granite remains low.
Motivation: Try to get lower heads south of Tsukiyoshi fault in Well DH-2 and MSB wells; and try to reproduce non-linear temperature profile in Well DH-4.
Effect: Temperature profiles worse at most wells, too much infiltration. Head profiles little changed.
Judgment: Abandon.

Case CF
Change: Increase sediment permeability by a factor of 10.
Motivation: No specific motivation, want to see sensitivity.
Effect: Too much infiltration, worse heads in most wells.
Judgment: Abandon.

Case CG
Change: Decrease sediment permeability by a factor of 10.
Motivation: No specific motivation, want to see sensitivity.
Effect: Less infiltration – better for most wells.
Judgment: Keep this change in succeeding cases.

Case CH
Change: Increase permeability in weathered granite (see Case CE).
Motivation: With lower sediment permeability, hope to get good communication between Well DH-2 and Toki River to lower Well DH-2 heads, without producing too much infiltration.
Effect: Temperature profiles show too much infiltration at most wells, worse.
Judgment: Abandon.

Case CI
Change: Increase permeability in granite by a factor of 10.
Motivation: With lower sediment permeability and unchanged weathered granite permeability, hope to get good communication between Well DH-2 and Toki River to lower Well DH-2 heads, without producing too much infiltration.
Effect: Too much infiltration.
Judgment: Abandon.

For now, we consider Case CG the best case (with low head at Well DH-2 still not fixed), and use this model to simulate the inadvertent MIU-2 well test.

7.3.5.2 PRESSURE-TRANSIENT CALIBRATION

The changes made for model CG are incorporated into the DCM and used to simulate the inadvertent MIU-2 well test. The biggest change is a much increased pressure change in the deep probes of Well MIU-3, which is a big improvement for the model.

Probe 4 in Well MIU-3, which is in the low-permeability Tsukiyoshi fault core, shows almost no response in the model, whereas in reality it shows a gradual pressure increase, suggesting that it should be in a transition zone near the upper edge of the fault core, where the influence of the hanging-wall is evident. The model is not finely resolved enough to achieve this, so no modifications are attempted to address this mismatch.

All the probes of Well MIU-4 still show too big a response; the upper three in the hanging wall and the lower two in the Tsukiyoshi fault core. To attempt to lessen the pressure responses, the granite porosity is doubled and the permeability in the fault core is decreased by a factor of two. These changes cause a modest improvement in the match to the observed pressure transients. When they are applied to the natural-state modeling, they have only a small effect on head profiles and no noticeable effect on temperature profiles, so they are retained.

7.3.6 FINAL MODEL

7.3.6.1 COMPARISON TO OBSERVED DATA

The comparison of the final model to the observed data is shown in Figure 7-10**,** Figure 7-11, and Figure 7-12. Comparing steady head profiles for the starting model and final model (Figure 7-6 and Figure 7-10, respectively) shows that the final model match is better for wells DH-9, DH-11, and DH-13, but a little worse for the MIU wells and AN wells, which showed a pretty good match to the observed heads in the starting model, but too high heads in the final model. It is hoped that when the large head decrease required for Well DH-2 and the MSB wells is achieved, it will lessen the head for the MIU and AN wells also.

Comparing steady temperature profiles for the starting model and final model (Figure 7-7 and Figure 7-11, respectively) shows that the final model match is better for Wells DH-9, DH-10, DH-11, MIU-2, and MIU-3. The matches for the other wells are little changed.

Comparing transient pressure changes for the starting model and final model (Figure 7-8 and Figure 7-12, respectively) shows that the final model match is better for all wells except MIU-4, where it is slightly worse. In particular, the slower recovery of each pressure pulse for the final model matches the field behavior much better than did the starting model. Although the matches for the ECM and DCM differ in some details, it is not possible to say that one or the other consistently produces a better match to the observed data.

The properties for the final ECM and DCM simulations are shown in Table 7.3-4 and Table 7.3-5, respectively. Note that only the porosities differ between the two models.

Figure 7-13 shows streamtraces for the final ECM. Generally, these are similar to those for the starting model (Figure 7-9). However, there is less infiltration around the Tsukiyoshi fault, as evidenced by the smaller penetration of cool water there. Also, the streamtrace direction is less impacted by the other faults. As in the starting model, there is a focusing of upflow toward the location where the Tsukiyoshi fault outcrops. It would be of (academic) interest to look at field data to see if there are surface springs in this location.

7.3.6.2 PERFORMANCE MEASURES

Performance measures, consisting of path lengths and travel times for streamtraces beginning at six wells and the main shaft location, are compared for the starting models (Table 7.3-2 and Table 7.3-3) and the final models (Table 7.3-4 and Table 7.3-5) in Figure 7-14. Because the ECM and DCM differ only in porosity, the same streamtraces are obtained in each case. However, since tracer velocity is inversely proportional to porosity, average velocity and travel time for each streamtrace differ between the two models, with the smaller fracture porosity of the DCM producing higher velocities and correspondingly shorter travel times. Note however, that the travel times shown are advective travel times. Delays due to diffusion or sorption of radionuclide are not included. Since these processes can significantly retard radionuclide travel, and since their dynamics will differ significantly between ECM and DCM, the advective travel times may greatly underestimate actual travel times.

Figure 7-14 indicates that changes made between the starting model and final model do not produce large differences in performance measures. The porosity increase for the granite tends to lengthen travel time (in the starting model travel times as short as one-half year were obtained, whereas for the final model the minimum travel time for any streamtrace is 30 years). The moderate increase in granite permeability coupled with the moderate decrease in fault-core permeability makes the fault more of a barrier, hence the streamtraces originating at Well DH-10 are diverted around the fault, making them much longer (compare Figure 7-9 and Figure 7-13).

Table 7.3-4. Properties for final 9x9 ECM (values changed from starting model shown bold).

Material Type	Porosity	Permeability (m^2)	
		Within materials	Between materials
Seto Group	0.20	**$6.3\cdot10^{-16}$**	$6.3\cdot10^{-17}$
Mizunami Group	0.20	**$3.2\cdot10^{-16}$**	$3.2\cdot10^{-17}$
Weathered granite	$7.3\cdot10^{-03}$	10^{-14}	10^{-16}
Granite	**$6.8\cdot10^{-03}$**	**$5\cdot10^{-15}$**	10^{-17}
Deep granite	$3.4\cdot10^{-03}$	10^{-16}	$5\cdot10^{-18}$
Tsukiyoshi fault core	$8.4\cdot10^{-04}$	**$5\cdot10^{-18}$**	**$5\cdot10^{-18}$**
Tsukiyoshi fault hanging-wall sandwich	$7.6\cdot10^{-03}$	$2.7\cdot10^{-13}$	10^{-15}
Tsukiyoshi fault footwall sandwich	$7.6\cdot10^{-03}$	**$5.4\cdot10^{-14}$**	10^{-15}
Tsukiyoshi fault footwall sandwich, special path to MIU-3	$3.8\cdot10^{-3}$	$5.4\cdot10^{-13}$	10^{-15}
Other faults	$3.0\cdot10^{-03}$	**10^{-15}**	**10^{-15}**

Table 7.3-5. Properties for final 9x9 DCM (values changed from starting model shown bold).

Material Type	Fracture Porosity	Permeability (m^2)	
		Within materials	Between materials
Seto Group	0.20	**$6.3\cdot10^{-16}$**	$6.3\cdot10^{-17}$
Mizunami Group	0.20	**$3.2\cdot10^{-16}$**	$3.2\cdot10^{-17}$
Weathered granite	$2.3\cdot10^{-03}$	10^{-14}	10^{-16}
Granite	**$7.5\cdot10^{-04}$**	**5.10^{-15}**	10^{-17}
Deep granite	$3.0\cdot10^{-04}$	10^{-16}	$5\cdot10^{-18}$
Tsukiyoshi fault core	**$7.5\cdot10^{-5}$**	**$5\cdot10^{-18}$**	**$5\cdot10^{-18}$**

Tsukiyoshi fault hanging-wall sandwich	$2.6\cdot10^{-03}$	$2.7\cdot10^{-13}$	10^{-15}
Tsukiyoshi fault footwall sandwich	$2.6\cdot10^{-03}$	**$5.4\cdot10^{-14}$**	10^{-15}
Tsukiyoshi fault footwall sandwich, special path to MIU-3	$1.3\cdot10^{-3}$	$5.4\cdot10^{-13}$	10^{-15}
Other faults	$3.0\cdot10^{-04}$	**10^{-15}**	**10^{-15}**

Matrix properties: porosity 0.005, permeability 10^{-20} m^2

7.3.7 OUTSTANDING ISSUES

One aspect of the observed data is not at all well matched by the present model. South of the Tsukiyoshi fault, in Well DH-2 and the lower depths of the MSB wells, observed heads are much lower than modeled heads. Probes located in the weathered granite show the low heads, whereas probes in the sediments show normal heads. There are no probes below the weathered granite for these wells. The Toki River has lower head than the probes in Wells DH-2, suggesting that there is especially good communication between this well and the river, by virtue of a higher than usual permeability in either the weathered granite, the granite, or both. Sensitivity studies have shown that weathered granite and granite permeability cannot be increased throughout the model, because increased permeability enables too much deep infiltration of surface water. Thus, we must hypothesize a local area between Well DH-2 and the Toki River with larger permeability in the weathered granite or granite or both. Additionally, property changes that improved the pressure-transient match for most wells worsen the match for Well MIU-4, suggesting that there is a localized variation in properties in that vicinity. A conceptual model including deterministic heterogeneity at the kilometer scale would be useful for improving the match to observed data, along with a revisiting of the grid-block scale (100 m) stochastic heterogeneity employed in the past.

7.4 Using a Subset of Wells for Site Characterization

Next, we compare site characterization using all available information with that obtained from only a subset of wells. In other words, we evaluate models resulting from various preliminary investigation strategies by comparing model predictions to the ‘real’ data (that are generated by running simulations in the 'real' model). The procedure consists of starting with a 'real' model, which has been created using all available information. Then, different sets of well locations are chosen and the properties of the real model are sampled at those locations, i.e., conduct PIs using different strategies. Porosity and permeability distributions are generated stochastically based on these samples. We thus create an SDM (Site Descriptive Model), or a trial model for each PI strategy represented by a set of well locations. Natural-state simulations are run in each trial model to generate performance measures, which are then compared to performance measures obtained with the real model, to judge the value of the trial well locations (and numbers).

7.4.1 SIMPLIFIED REAL MODEL

To expedite the procedure, several simplifications to the final model described in the previous section are made, to create a simplified real model from which TRIAL MODELs will be created. The simplifications are as follows:

1. An ECM is used. This choice is made because we assume that the initial stages of site characterization, when only a few wells have been drilled, will not include detailed matching of pressure-transient data as was done in the analysis of the inadvertent MIU-2 well test.
2. The Tsukiyoshi fault is the only fault included, and it does maintain its sandwich structure with a low-permeability core flanked by two high-permeability sandwich layers.
3. The two sedimentary materials are combined into one sedimentary material type.
4. Stochastic permeability and porosity distributions are used. A log-normal permeability distribution for each material is assumed, with the mean log-permeability taken from the "within material" column of Table 7.3-4. Standard deviation of log-permeability is assumed to be 1.5 for granite and weathered granite, 0.5 for the sedimentary material, and 1.0 for all other materials, based on distributions of properties from boreholes in the Tono region. After log-permeability for a grid block is drawn from the normal distribution for the material of that grid block, grid-block porosity is calculated by multiplying the mean porosity for the material of the grid block (Table 7.3-4) by the cube-root of the difference between grid-block permeability and the mean permeability for that material (Table 7.3-3). In this way, the stochastic permeability and porosity distributions are correlated with one another rather than being considered independent distributions. Furthermore, the form of the correlation is intended to take into account the fractured nature of the rock.

Table 7.4-1 compares the statistics of the porosity and permeability distributions created for the simplified real model with the constant values employed in the final model. Mean log-permeabilities agree well, but mean porosities are consistently higher for the simplified real model, a consequence of the technique used to generate them. The larger porosity will tend to slow tracer transport, therefore, one should not expect tracer travel times for the simplified real model to match those obtained for the real model. Note that porosity standard deviation is also quite large; to avoid unphysical porosities (less than zero or greater than one), stochastically-determined porosities are bounded by user-specified limits of 1E-5 to 0.8.

5. The surface boundary condition is simplified – rather than allowing a vadose zone to develop, fully-saturated liquid conditions are assumed, but permeability in the top layer of the model is decreased by an amount comparable to the average relative permeability of the partially-saturated vadose zone obtained for the complete model**.** Figure 7-15 shows the distribution of vertical flow into and out of the top surface for the final version of the complete model and for the simplified real model. Although there are small differences between the two flow distributions, the main features are the same: inflow and outflow are strongly correlated to surface topography (Figure 7-1), with the largest inflows at the highest elevations in the northern portion of the model, and the largest outflow at the lowest elevations along the southern and eastern model boundaries, which coincide with the Toki River. Large outflow also occurs near the middle of the model (x = 65000 m, y = -68,000 m), where the Tsukiyoshi fault is not overlain by sediments (Figure 7-2, top frame).

6. The Tono Mine is not represented in the model.

Table 7.4-1. Comparison of properties for final model and simplified real model.

Material	Porosity			$\log_{10}$(permeability in m^2)		
	Final model	Simplified real model		Final model	Simplified real model	
		Mean	Std dev		Mean	Std dev
Sediments	0.20	0.21	8.5E-2	-15.2, -5.5	-15.33	0.49
Weathered granite	7.3E-3	1.4E-2	2.4E-2	-14.0	-13.99	1.50
Granite	6.8E-3	1.3E-2	2.2E-2	-14.3	-14.30	1.51
Deep granite	3.4E-3	4.6E-3	4.2E-3	-16.0	-16.00	1.00
Fault Core	8.4E-4	1.3E-3	9.5E-4	-17.3	-17.27	0.97
Hanging-wall sandwich layer	7.6E-3	1.0E-2	9.9E-3	-12.6	-12.55	1.02
Footwall sandwich layer	7.6E-3	9.9E-3	9.9E-3	-13.3	-13.29	0.97

A fully-coupled fluid and heat flow simulation of natural-state conditions for the simplified real model is run and performance measures are generated. Figure 7-16 shows several views of the natural-state head, temperature, and permeability distributions, as well as streamtraces illustrating tracer travel pathways from the vicinities of three hypothetical repository locations. Comparison with results of the final model (Figure 7-13) shows that the main features of the final model are preserved in the simplified real model. Streamtraces generally flow from north to south, illustrating groundwater downflow at higher elevations in the north and upflow at lower elevations in the south. The head and temperature distributions both illustrate this regional groundwater flow as well. The Tsukiyoshi fault impacts the streamtraces by diverting some toward the surface and others around the fault to the east, but some streamtraces do cross the fault itself. Note that the addition of heterogeneity causes the streamtraces to be less smooth, as fluid flows preferentially through high-permeability grid blocks.

7.4.2 CREATION OF TRIAL MODELS

To create trial models, we pick well locations either at random or systematically representing different PI strategies, as summarized in Table 7.4-2 and illustrated in Figure 7-17, and sample properties from the simplified real model at these locations. For the randomly-chosen well locations, three well locations are chosen at random (Case 1, Cases 11-15). Then, Case 2 considers six wells, and Cases 3 and 16 consider nine wells each.

For the systematically-chosen well locations, three approaches are taken. The first approach (Case 4) is to site three wells close to one another, as if interference hydrologic testing were to be conducted. The second approach (Case 5) assumes that a major structure such as the Tsukiyoshi fault is known ahead of time from existing geological studies, and three wells are sited close to this feature, in order to investigate its effect. The third approach (case 6) is to site three wells far apart, so that their locations span the extent of the region being studied. Then Cases 7-10 consider various combinations of systematic three-well placements.

Table 7.4-2. Well locations under different PI strategies

Case	Number of Wells	Method for choosing well location	Fault Included
1	3	Random	No
2	6	Random (combine Cases 1 and 11)	No
3	9	Random (combine Cases 1, 11, 12)	Yes
4	3	Systematic: close together	No
5	3	Systematic: close to Tsukiyoshi fault	Yes
6	3	Systematic: far apart	No
7	6	Systematic: close together and close to fault (combine Cases 4 and 5)	Yes
8	6	Systematic: close together and far apart (combine Cases 4 and 6)	No
9	6	Systematic: close to fault and far apart (combine Cases 5 and 6)	Yes
10	9	Systematic: close together, close to fault, far apart (combine Cases 4, 5, 6)	Yes
11	3	Random	No
12	3	Random	No
13	3	Random	No
14	3	Random	Yes
15	3	Random	No
16	9	Random (combine Cases 13, 14, 15)	Yes

For each trial model, we look at the pressure and temperature profiles from the set of wells, and decide if there is evidence of the Tsukiyoshi fault: a jump in the head profile at the elevation the well intersects the fault. If there is not, the trial model does not include a fault; it contains four materials: sedimentary rock, weathered granite, granite, and deep granite, which follow the same undulating layers as in the real model. If there is evidence of the fault, then three additional materials are included in the model: a low-permeability fault core, and the higher-permeability sandwich layers on either side of the core. These materials occur at the actual location of the Tsukiyoshi fault in the real model. Thus, there are two main classes of trial models, those including a major fault, and those without one, as indicated in Table 7.4-2.

Figure 7-18 illustrates this procedure by showing the head profiles for the trial models with systematic well locations (Cases 4-10 in Table 7.4-2). Most of the head profiles show sharp gradients near the surface, but are reasonably uniform over the remainder of their length. The sharp jumps in head for Case 5 at elevations of -1000 m and -1500 m are interpreted as the intersection of the well and the fault plane, so Case 5 includes a fault whereas Cases 4 and 6 do not. Additionally, any combination case that contains Case 5 includes a fault.

Permeability and porosity are assigned stochastically to the trial models, using a log-normal distribution for permeability and a normal distribution for porosity for each material. The means and standard deviations for log-permeability and porosity are determined material by material, based on sampled values from the real model. For log-permeability, a 300 by 300 m^2 neighborhood of each well is used as the basis for determining mean and standard deviation, as though long-term well tests had been conducted. For porosity, only the porosities sampled along the wells themselves are used. Because well-only sampling produces a relatively small number of porosity values for each material, the standard deviation can easily be unrealistically large. Therefore, if the standard deviation is greater than one-third of the mean porosity, it is set to one-third of the mean porosity, thus limiting porosity variability to a reasonable range. If any porosities are less than zero or greater than one, they are bounded by user-specified limits of 1.e-5 to 0.8, as was done for the simplified real model.

All trial models use the same boundary conditions as the simplified real model. Initial (T, P) conditions for the trial models consist of the final (T, P) conditions for the simplified real model. Natural-state simulations with the trial models include fluid flow only; that is, temperature is not allowed to vary (but distributed) and heat flow is not modeled. This greatly expedites the computations, but should not have a significant effect on the final results, because the overall groundwater flow patterns are similar for the real and trial models. Hence, the temperature distribution obtained with the real model is a reasonable approximation for what would be obtained for the trial model if fully-coupled heat and fluid flow simulations were done. The results of the 16 trial models are illustrated in Figure 7-A-1 through Figure 7-A-16 in the appendix 7-A. Although there are differences in the details of the streamtraces among the different trial models, the general features are quite consistent.

Comparison of the heterogeneous permeability distributions for the real model (Figure 7-17) and for the trial models (Figure 7-A-1 through Figure 7-A-16) shows that they share the same character. Although permeability varies greatly (by six or seven orders of magnitude), the correlation length (the grid block size of 100 m) is small compared to the model domain (9 km). Hence there are no long-range trends in permeability, except for those introduced deterministically (the layering and Tsukiyoshi fault). A well located anywhere in the model will typically encounter the full range of properties for the granite materials.

7.4.3 PERFORMANCE MEASURES

The performance measures of the simplified real model and the 16 trial models are the mass flow rate across three control volumes representing hypothetical repository sites, and streamtrace path length and travel time for release points located in the center of these control volumes. Figure 7-17 shows the locations of the control volumes; one is just south of the Tsukiyoshi Fault, one is just north of it, and one is far to the north. All are located at elevations of -1000 masl, and are 1 km by 1 km in lateral extent. Control-volume flows provide a means of quantifying the amount of groundwater that could potentially contact waste canisters; they depend on model boundary conditions and the hydraulic conductivity (permeability/viscosity) distribution. Streamtrace path length is the length of the path traveled by a tracer from its release point to whichever model boundary it first encounters; it identifies the direction of groundwater flow and also depends on model boundary conditions and the hydraulic conductivity distribution. Streamtrace travel time is the time it takes the tracer to reach the model boundary considering advective transport through the fractured rock; it depends on the porosity distribution encountered by the tracer as it travels along the streamtrace, in addition to model boundary conditions and the hydraulic conductivity distribution. Because diffusion and sorption of radionuclides by the rock matrix may significantly slow advective travel time, the streamtrace travel times presented represent lower bounds on actual travel times expected.

Table 7.4-3 and Figure 7-19 show the control-volume flows for the trial models, and Table 7.4-4 and Figure 7-20 show path lengths and travel times of streamtraces originating at the center of the control volumes.

Table 7.4-3. Material properties and control-volume flows for real and trial models.

Case	Fault or no-fault	# Wells	Granite Properties				Control Volume Flow (kg/s)		
			$\log_{10}$(k in m^2)		Porosity		South	North	Far North
			Mean	Std dev	Mean	Std dev			
Real	F		-14.30	1.51	1.32E-2	2.17E-2	0.81	0.55	0.44
Trial									
1	N	3	-14.26	1.62	1.08E-2	3.60E-3	0.64	0.32	0.26
2	N	6	-14.30	1.61	1.07E-2	3.57E-3	0.46	0.31	0.28
4	N	3	-14.31	1.54	1.90E-2	6.33E-3	0.46	0.42	0.31
6	N	3	-14.28	1.53	1.45E-2	4.83E-3	0.59	0.39	0.32
8	N	6	-14.29	1.54	1.64E-2	5.47E-3	0.58	0.32	0.46
11	N	3	-14.34	1.60	1.06E-2	3.53E-3	0.67	0.40	0.29
12	N	3	-14.33	1.57	1.12E-2	3.73E-3	0.63	0.31	0.23
13	N	3	-14.31	1.51	1.59E-2	5.30E-3	0.77	0.47	0.40
15	N	3	-14.26	1.51	1.00E-2	3.34E-3	1.04	0.41	0.59
3	F	9	-14.32	1.48	1.17E-2	3.90E-3	0.55	0.20	0.26
5	F	3	-14.47	1.46	1.11E-2	3.70E-3	0.56	0.25	0.26
7	F	6	-14.38	1.51	1.50E-2	5.00E-3	0.60	0.38	0.35
9	F	6	-14.36	1.50	1.28E-2	4.27E-3	0.64	0.26	0.31
10	F	9	-14.34	1.51	1.47E-2	4.90E-3	0.56	0.54	0.42
14	F	3	-14.5	1.47	8.51E-3	2.84E-3	0.47	0.26	0.16
16	F	9	-14.35	1.48	1.17E-2	3.90E-3	0.54	0.28	0.43

Table 7.4-4. Stream trace results for z = -1000 m (hypothetical repository elevation) for real and trial models.

Case	Fault or no-fault	# Wells	Streamtrace Path Length (m) South	North	Far North	Streamtrace Travel time (yr) South	North	Far North	Average Streamtrace Velocity (m/yr) South	North	Far North
Real	F		2078	3237	6627	1060	1890	3590	2.0	1.7	1.8
Trial											
1	N	3	2141	2448	6047	321	973	3091	6.7	2.5	2.0
2	N	6	2285	2634	3596	247	1947	2512	9.2	1.4	1.4
4	N	3	2534	4733	6612	728	3314	19,686	3.5	1.4	0.3
6	N	3	2135	6398	10,231	790	5793	17,190	2.7	1.1	0.6
8	N	6	2208	3331	11,307	491	3515	13,987	4.5	1.0	0.8
11	N	3	2200	2774	7386	475	945	10,170	4.6	2.9	0.7
12	N	3	1774	4188	10,175	571	2684	9985	3.1	1.6	1.0
13	N	3	2043	4228	4513	1238	3512	11,742	1.6	1.2	0.4
15	N	3	2367	2709	7167	110	1088	10,724	21.5	2.5	0.7
3	F	9	2003	6353	10,570	331	1908	5344	6.0	3.3	2.0
5	F	3	2041	2852	6837	553	1383	21,105	3.7	2.1	0.3
7	F	6	2143	2987	6948	1053	2415	8564	2.0	1.2	0.8
9	F	6	2034	4397	8192	397	2795	8442	5.1	1.6	1.0
10	F	9	2487	2161	5076	1744	389	2957	1.4	5.5	1.7
14	F	3	2054	2151	6113	620	1881	5302	3.3	1.1	1.2
16	F	9	2382	3491	6348	1590	977	1308	1.5	3.6	4.8

In addition to the control-volume flows, Table 7.4-3 also shows trial model statistics for the granite material, since that is the main rock type in which the streamtraces leaving the hypothetical repository locations at -1000 m elevation are found. Note that sampling permeability over a 300 by 300 m^2 area around each well produces a very good estimate of the real-model permeability, even when only three wells are available. In contrast, far fewer porosity observations are available, hence porosity distributions vary more between trial models. Recall that control-volume flow and streamtrace path do not depend on porosity, but streamtrace travel-time does. Consequently, one would expect less variability among control-volume flows for the trial models (Figure 7-19) than for streamtrace travel times (Figure 7-20).

Figure 7-19 indicates that control-volume flows do not differ significantly among the trial models. This finding remains true even when too few wells are used to identify a major feature like the Tsukiyoshi fault – Figure 7-19 shows that there is no systematic difference between fault and no-fault cases. In all cases, flow through the southern control volume is slightly greater than flow through the other two control volumes, a consequence of the shape of the model, which narrows in the primary direction of groundwater flow (north to south). Hence, we find that reasonable representation of the magnitude of groundwater flow can be obtained by using a minimal number of wells for site characterization, because for the present style of heterogeneity with short correlation length, the magnitude of groundwater flow depends strongly on model topography and boundary conditions.

Figure 7-20 shows streamtrace travel time as a function of streamtrace path length for the real model and each trial model. In addition, linear fits to the travel time versus path length points provide a measure of the average tracer velocity along streamtraces from the various control volumes (average tracer velocity is the reciprocal of the slope of the fitting line). Figure 7-20 indicates that average tracer velocity along a streamtrace decreases slightly as one goes from south to north to far north control volume**.** Figure 7-16 and the Figure 7-A-1through Figure 7-A-16 show that the farther north the -1000 masl streamtraces originate, the greater the fraction of their path is spent at large depths, where groundwater flow is slower, explaining this trend. Similarly, Figure 7-20 indicates that no-fault average tracer velocity is slightly slower for the release-points north of the Tsukiyoshi fault and slightly faster for the release-point south of the fault, compared to the with-fault average tracer velocity. The reason is that the fault acts to divert groundwater upward north of the fault and downward south of the fault, and whenever tracer moves shallower it tends to go faster. Hence, the direction of groundwater flow does depend on whether or not enough wells are used to identify the presence of the fault, but the resulting change in tracer velocity is rather small relative to the range of velocities obtained for different release points. Table 7.4-4 verifies that tracer velocity does not show a significant dependence on the number of wells used for site characterization – porosity is so variable and sampling so sparse that whether one samples from three or nine wells does not change the character of the porosity distribution.

In summary, we find that, for the most part, our understanding of the regional groundwater flow and advective tracer transport does not improve significantly as more and more wells are used for site characterization. These measures are controlled by surface topography, surface and lateral boundary conditions, and the permeability and porosity distributions. For the present short-correlation property distributions, using one well for site characterization provides as much information about material properties as using many wells does. On the other hand, observing head profiles in more wells does increase the probability that large-scale features such as the Tsukiyoshi fault can be identified, and the presence or absence of such a fault does have a noticeable effect on streamtrace properties including the destinations of streamtraces.

7.4.4 IMPACT OF KEY ASSUMPTIONS ON CHOICE OF WELL LOCATIONS

The trial models described in the previous section all had different permeability and porosity distributions, but they shared a number of other features that may also strongly impact performance measures, including the constant-head surface boundary condition, the closed lateral boundary condition, and heterogeneity with short-range correlations. In this section, we vary the choices make for these features, and investigate the implications for choosing optimal well locations.

7.4.4.1 AMOUNT OF SURFACE INFLOW AND OUTFLOW

The 50-m vertical resolution of the model is too coarse to accurately model near-surface processes such as precipitation, evaporation, runoff, spring discharge, stream-groundwater interaction etc. Thus, the distribution of surface inflow and outflow in the model must represent the net result of all these processes, ultimately determining the amount of water that moves through the deep groundwater flow system. In the complete model of the Tono site (Section 7.3), a vadose zone is included, which limits the amount of surface inflow and outflow compared to a fully-saturated medium. In the creation of the simplified real model (Section 7.4.1), no vadose zone is allowed to develop and surface flow is limited by decreasing the permeability of all the elements in the uppermost layer of the model: multiplying all permeabilities by 0.1376 is comparable to a model with a vadose-zone liquid saturation of 0.7 and no permeability reduction. Here we consider a case with no permeability reduction, which results in higher surface inflows and outflows, and a case with a greater permeability reduction (a permeability reduction factor of 0.1376-squared or 0.0189), which results in lower surface inflows and outflows.

Figure 7-21 illustrates the surface inflow/outflow distributions for the simplified real model and these two additional cases. Although the spatial distribution of inflow and outflow remains about the same for all three cases, the magnitude of both inflow and outflow decreases as surface permeability decreases. Figure 7-19 shows control-volume flows for the three cases. As expected, higher surface flows lead to higher control-volume flows, but the effect is rather small. Figure 7-22 shows streamtrace travel time versus path length for the three cases. The high surface permeability (high surface flow) case shows slightly shorter travel times, consistent with the larger control-volume flows. However, for the low surface permeability (low surface flow) case, there is no consistent trend for travel time.

Figure 7-23 shows head and temperature profiles for four hypothetical well locations (near the upgradient model boundary, near the middle of the model, near the Tsukiyoshi fault, and near the downgradient model boundary) for the three values of surface permeability. Head profiles are most sensitive to surface permeability near the downgradient model boundary, but even there, the effect is small. Temperature profiles are most sensitive to surface permeability near the Tsukiyoshi Fault, with the high-permeability case indicating more infiltration (a more concave-up temperature profile) and the low-permeability case indicating less infiltration (a more linear temperature profile). The small magnitude of head and temperature changes is consistent with the small difference in control-volume flow shown in Figure 7-19 for the different values of surface permeability.

In conclusion, the quantity of water moving through the deep groundwater flow system does change as surface inflow/outflow changes, but the magnitude of the change is rather small – when surface permeability varied by a factor of 50, control-volume flow only varied by a factor of 1.3. Consequently, head and temperature profiles are not very sensitive to this variation.

7.4.5 CLOSED VERSUS OPEN LATERAL BOUNDARIES

The simplified real model considers all lateral boundaries to be closed (no-flow) boundaries, based on the concept that lateral model boundaries represent watershed lines across which groundwater flow does not occur (i.e., groundwater enters and exits the model only through the surface layer, which represents the Toki River along the southern and eastern model boundaries, and surface precipitation/discharge elsewhere). As an alternative conceptualization, the lateral boundaries are assumed to be open, and are modeled as constant-pressure, constant-temperature boundaries. Pressure is specified by atmospheric pressure at the ground surface and a hydrostatic profile below, and temperature is specified by a conductive geothermal gradient. Hence, there is no upflow or downflow at the model boundaries, but lateral inflow or outflow to the model can occur. The concept underlying these boundary conditions is that local topography does not control deep groundwater flow. In other words, the 9 km by 9 km model is merely part of a much more extensive groundwater flow system.

Figure 7-24 compares the distributions of surface inflow/outflow for closed and open lateral boundaries. For the open case, less infiltration occurs in the high-elevation region near the upgradient model boundary and less upflow occurs in the low-elevation region near the downgradient model boundary. Figure 7-19 shows the control-volume flows for the simplified real model with closed lateral boundaries and the case with open lateral boundaries. The effect is striking – far more flow moves through the model for the open lateral boundaries. Figure 7-25 shows streamtrace travel time versus path length for closed and open lateral boundaries. Again the effect is striking – travel times are far shorter for the open lateral boundaries. Figure 7-26 shows several views of the streamtraces themselves for the case with open lateral boundaries. In contrast to the streamtraces for the simplified real model (Figure 7-16), the vertical cross-sections show none of the U-shape typical for models with upgradient infiltration and downgradient discharge. Furthermore, the plan view shows streamtraces exiting the model in an entirely different location.

Figure 7-27 compares head and temperature profiles at four hypothetical well locations for closed and open lateral boundary cases. Wells near the middle of the model do not differ appreciably between the two cases, but wells near the upgradient and downgradient boundaries of the model certainly do. For the open boundary case, the head profiles show a much greater range (the high-head profile gets higher and the low-head profile gets lower), and the temperature profiles are much more linear, clearly indicating the lack of infiltration near the upgradient model boundary and the lack of discharge near the downgradient model boundary.

In conclusion, the large impact that lateral boundary conditions have on all aspects of flow and transport makes it clear that for effective site characterization, one must have a good understanding of lateral boundary conditions. If boundary conditions are not known by regional studies of topography and regional groundwater flow, wells can be located near the presumed upgradient and downgradient boundaries of the site, and their head and temperature profiles can be examined to look for the characteristics of closed and open systems illustrated in Figure 7-27.

7.4.5.1 HETEROGENEITY WITH LONG-RANGE CORRELATION

The stochastic porosity and permeability distributions used for the simplified real model and the trial models are not correlated between grid blocks. Hence the effective correlation length for these distributions is the extent of the grid blocks themselves, 100 m. Under these conditions, we have seen that trial models constructed by taking porosity and permeability from only a few wells perform just as well as trial models constructed using more wells. To examine the situation for property distributions with longer-range correlations, four property distributions with an idealized long-range correlation were created. The simple algorithm employed is to divide the 9 km by 9 km model into quadrants: a northeast (NE), northwest (NW), southwest (SW), and southeast (SE) quadrant. Then the original stochastic permeability distribution is modified quadrant by quadrant by multiplying all permeabilities within each quadrant by a factor.

Figure 7-28 through Figure 7-31 shows the permeability distributions and streamtrace patterns for four cases, in which each of the four quadrants has its permeability decreased by a factor of ten. It is clear that the tracer travel paths are greatly affected as water bypasses the low-permeability quadrants. Figure 7-19 shows the control-volume flows. The FN control volume is in the NE quadrant, the N control volume is in the NW quadrant, and the S control volume is in the SW quadrant. Control-volume flows are sharply lower for each case in which the control volume is in the low-permeability quadrant. Figure 7-32 shows the streamtrace travel time as a function of path length for the four quadrant-heterogeneity cases. Whenever the control volume that serves as the streamtrace release point is in the low-permeability quadrant, the travel time is significantly longer.

Figure 7-33 shows the head and temperature profiles at four hypothetical well locations for the four quadrant-heterogeneity cases. In general, head and temperature profiles only differ between cases when the well location is in the low-permeability quadrant. For example, for the well located near the upgradient boundary (red curves in Figure 7-33), head and temperature profiles are nearly the same for all cases except when the NE quadrant, where the well is located, has low permeability (short dash). Then, the temperature profile changes drastically, from a strongly concave-up profile indicating substantial infiltration of cool water, to a near-linear profile indicating a negligible amount of vertical groundwater flow. Similarly, for the well located near the downgradient boundary in the SW quadrant (blue curves in Figure 7-33), when the SW quadrant has low permeability (long dash), the concave-down temperature profile, which indicates upflow of deep warm water, becomes nearly linear, indicating no vertical flow.

In conclusion, if the permeability distribution has long-range correlations then a small number of wells are not as likely to provide a representative sample of rock properties, nor a true picture of the regional groundwater flow.

7.5 Recommended Sequence of Developing an SDM for a New Site

Based on the findings of the present study, we propose the following general procedure for prioritizing borehole drilling locations when conducting preliminary investigations at a new site and constructing an SDM of the site.

1. Study regional groundwater flow, including topography, surface geology, meteorological and stream flow data, data from existing wells, and satellite data, to begin to develop a regional groundwater flow model.

2. Choose lateral and depth boundaries for the model—this choice is important, for it ensures that the model has defensible, readily implemented boundary conditions.

3. Conduct surface geophysical surveys (preferably 3-D seismics if sedimentary rocks) to explore disqualifying conditions and to identify subsurface structures, such as lithology and faults.

4. Drill the first characterization borehole in the vicinity of the middle of the investigation area (after priority boreholes to explore disqualifying conditions are exhausted). If a large-scale feature such as a fault is suspected, try to intersect it. Do conventional logging, including temperature logging, fluid logging, and core analysis. Conduct large-scale (one puckered-off section per lithology), long-term pump tests. Update the conceptual model for groundwater flow if necessary. Instrument with multipackers and continue pressure monitoring while drilling additional wells.

5. Site the second borehole near the upgradient boundary of the site. Drill and log the second borehole, conduct large-scale pump tests, instrument with multipackers, Update conceptual model for groundwater flow if necessary. Continue pressure monitoring while drilling additional boreholes.

6. Site the third borehole near the downgradient boundary of the site. Drill and log third borehole, conduct large-scale pump tests, instrument with multipackers. Update conceptual model for groundwater flow if necessary. Continue pressure monitoring while drilling additional boreholes.

7. Optional additional boreholes: (1) if there is evidence of major heterogeneity between the first three wells, drill borehole(s) to try to intersect it; (2) drill boreholes to estimate the lateral boundary conditions, and (3) drill boreholes close enough together to do interference testing. Continue to update the conceptual model of regional groundwater flow as each borehole is drilled, siting new boreholes to provide information on least-constrained regions. Modify boundary conditions if necessary.

Steady head and temperature profiles provide information on regional groundwater flow direction, which determines where radionuclides will go if they escape a repository. Large-scale, long-term hydraulic testing provides spatially integrated permeability values, which impact how fast groundwater moves. At the preliminary stage of site characterization, these are the most valuable data to collect, and well-established techniques for data collection and analysis are in wide use.

Unfortunately, a number of the other factors that also impact radionuclide transport time through fractured rock are very difficult to assess at the regional scale required for repository performance assessment. These factors include the porosity of the fracture network, the fracture/matrix interaction area, and the capacity of the matrix for diffusion and sorption. At present, there are no well-established means for determining these properties at the regional scale.

7.6 Conclusions

Instead of fabricating a “real” model based on a synthetically generated set of data, we chose to take advantage of the extensive data set available from the Tono area collected by JAEA under their geosciences program, although the Tono area would never be considered as one of the actual preliminary sites. A synthetic data set may contain a combination of features and/or parameters that may never exist in reality. In contrast, by using the actual data set in the “real” model, we are able to construct and investigate preliminary strategies of greater credibility.

Further development of the model at the Tono region has produced improved matches to steady head and temperature profiles, and to the pressure-transient responses to the inadvertent MIU-2 well test. We consider this the most complete 9 km × 9 km model of the Tono site developed to date, using the data set available as of 2005. The changes made in the final model have relatively small impact on the performance measures of path length and travel time from specified release points to the model boundary. Most significantly, a porosity increase made to better match the long tail of the pressure-transient response to the inadvertent MIU-2 well test produces slightly longer streamtrace travel times.

We find that, for the most part, our understanding of regional groundwater flow and advective tracer transport does not improve significantly as ever more boreholes are drilled. These measures are mostly controlled by surface topography, surface and lateral boundary conditions, the permeability and porosity distributions, and the property of faults, if they exist. (In Japan, faults exist ubiquitously.) For the short-correlation property distributions in the present study, using information from only a few boreholes for site characterization provides as much information about material properties as using many boreholes does, provided that large-scale, long-term pump tests can be successfully conducted. On the other hand, observing head profiles in more boreholes does increase the probability that large-scale features such as the Tsukiyoshi fault can be identified, and the presence or absence of such a fault does have a noticeable effect on streamtrace properties. In particular, the locations where streamtraces manifest are greatly affected by faults. An additional caveat is that if the permeability distribution has long-range correlations, then a small number of wells are not as likely to provide a representative sample of rock properties, nor does a true picture of regional groundwater flow emerge.

Lateral boundary conditions have a large influence on all aspects of flow and transport . Thus, a very good understanding of lateral boundary conditions is essential. If boundary conditions are not known by regional studies of topography and regional groundwater flow, boreholes should be located near the presumed upgradient and downgradient, and peripheral boundaries of the site. Their head and temperature profiles should be examined, to look for characteristics of closed and open groundwater flow systems.

In summary, the parameters that influence, to the greatest extent, model predictions of particle trajectories and their travel times—and the parameters most difficult to estimate through field investigations—are: (1) effective porosity, (2) boundary conditions, and (3) fault properties. The overall average permeability does affect advective transport time, but it is less uncertain and easier to measure than the other parameters. Although one would find highly variable permeability at small scales, the overall average permeability is what is needed at the preliminary investigation stage, and is best estimated by conducting large-scale pump tests. Of the three parameters mentioned above, effective porosity is especially difficult to estimate. The current state-of-the-art characterization techniques are not adequate to reliably estimate the effective porosity of a large rock mass. Therefore, we recommend against conducting tracer tests, which are time consuming and expensive. Instead, we recommend conducting large-scale pump tests and observing steady-state pressure and temperature distributions, to narrow down the uncertainties in boundary conditions and fault properties.

7.7 References

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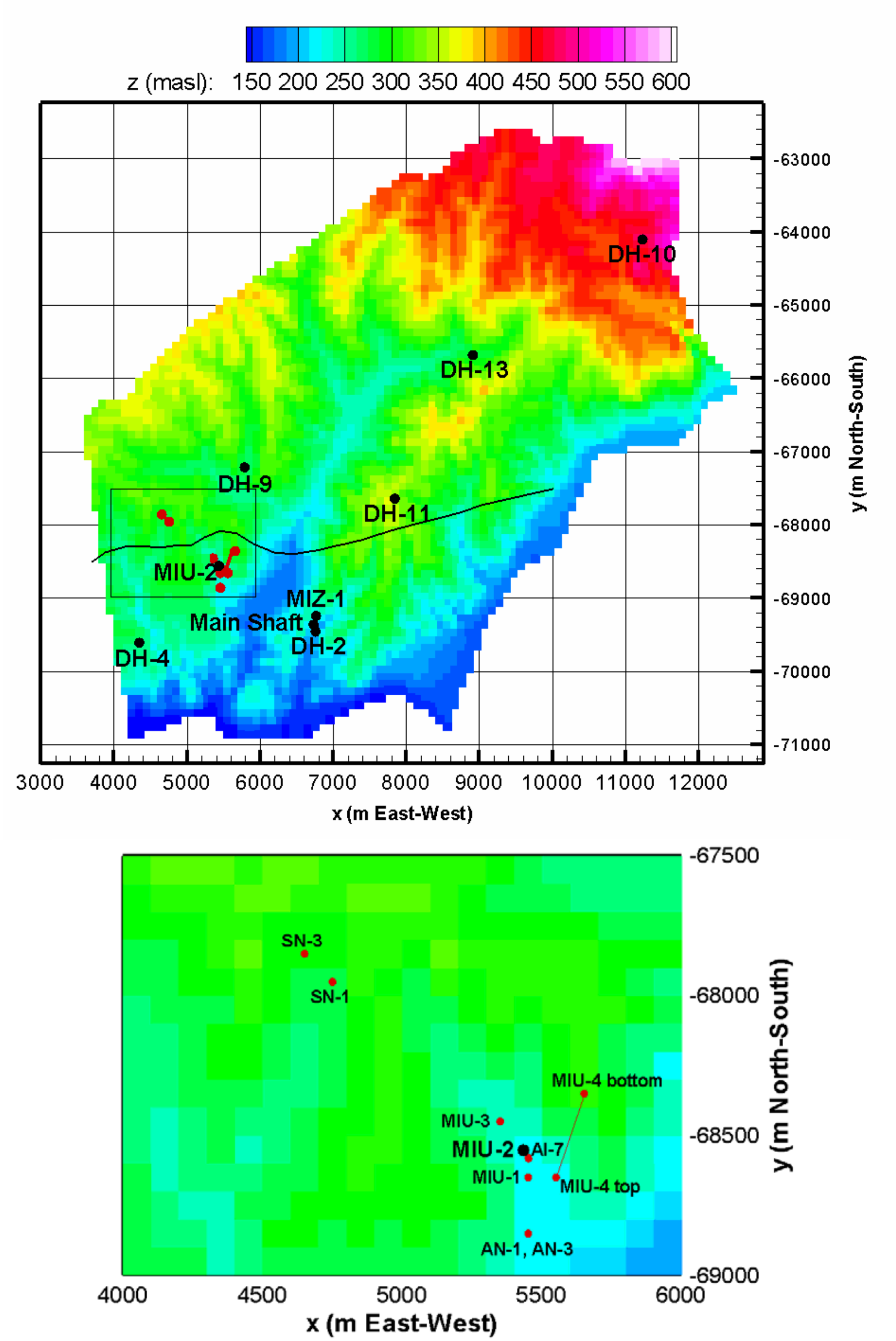

Figure 7-1. Surface elevations of the 9x9 TOUGH2 model. Surface locations of wells with steady pressure data or steady temperature data or both are shown as black dots. Zoomed-in region shows wells with pressure-transient data as red dots.

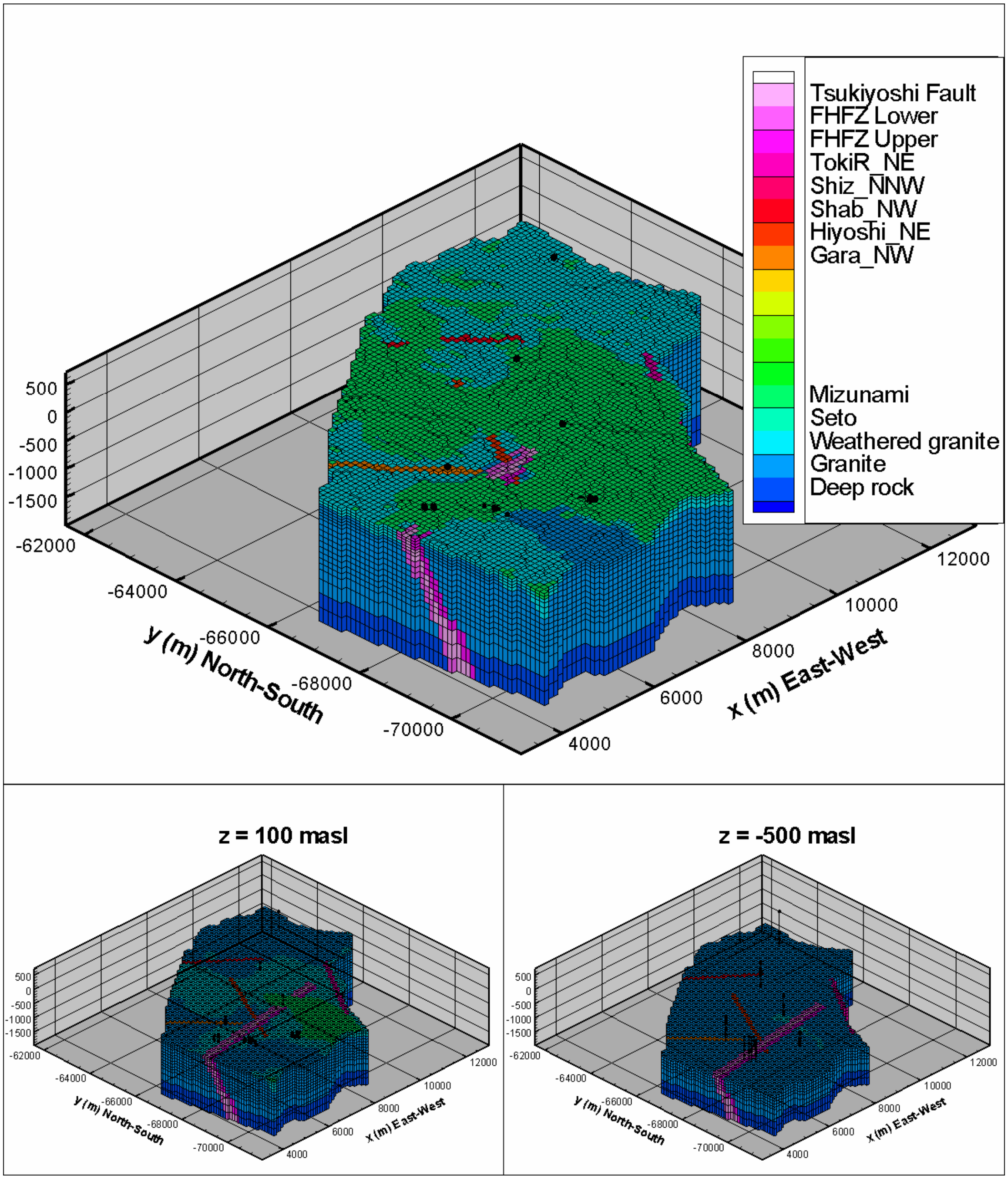

Figure 7-2. Top: Perspective view of the entire 9x9 TOUGH2 model showing different material types; bottom: same model but with grid blocks above depths of 100 or -500 removed, to better illustrate fault structure.

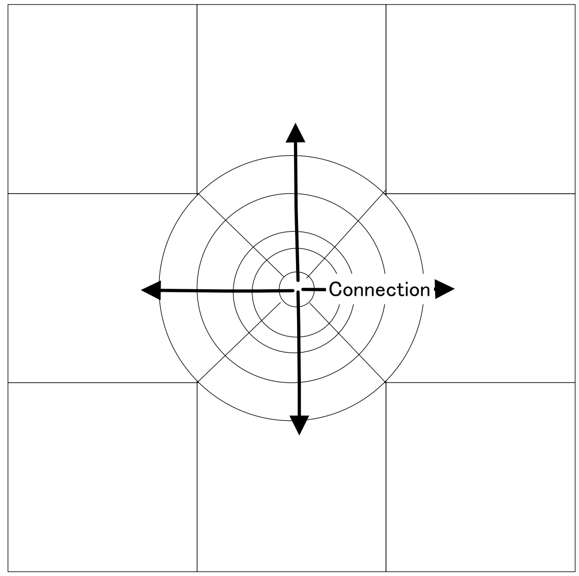

Figure 7-3. Schematic of local grid refinement around Well MIU-2 (plan view). This refinement was done in all layers of the model.

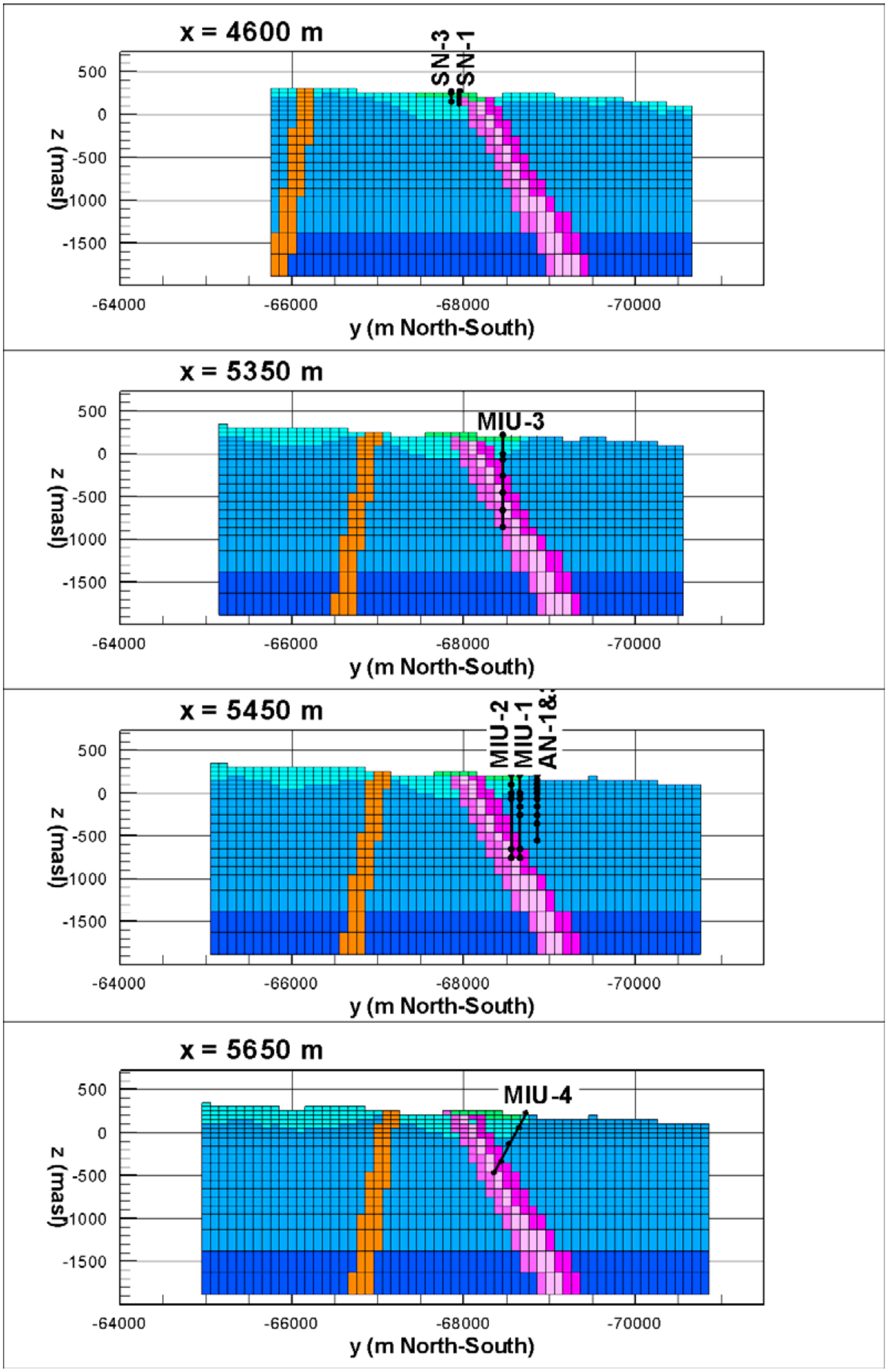

Figure 7-4. North-south cross-sections of TOUGH2 model showing Tsukiyoshi fault location with regard to wells used for calibration to pressure transients.

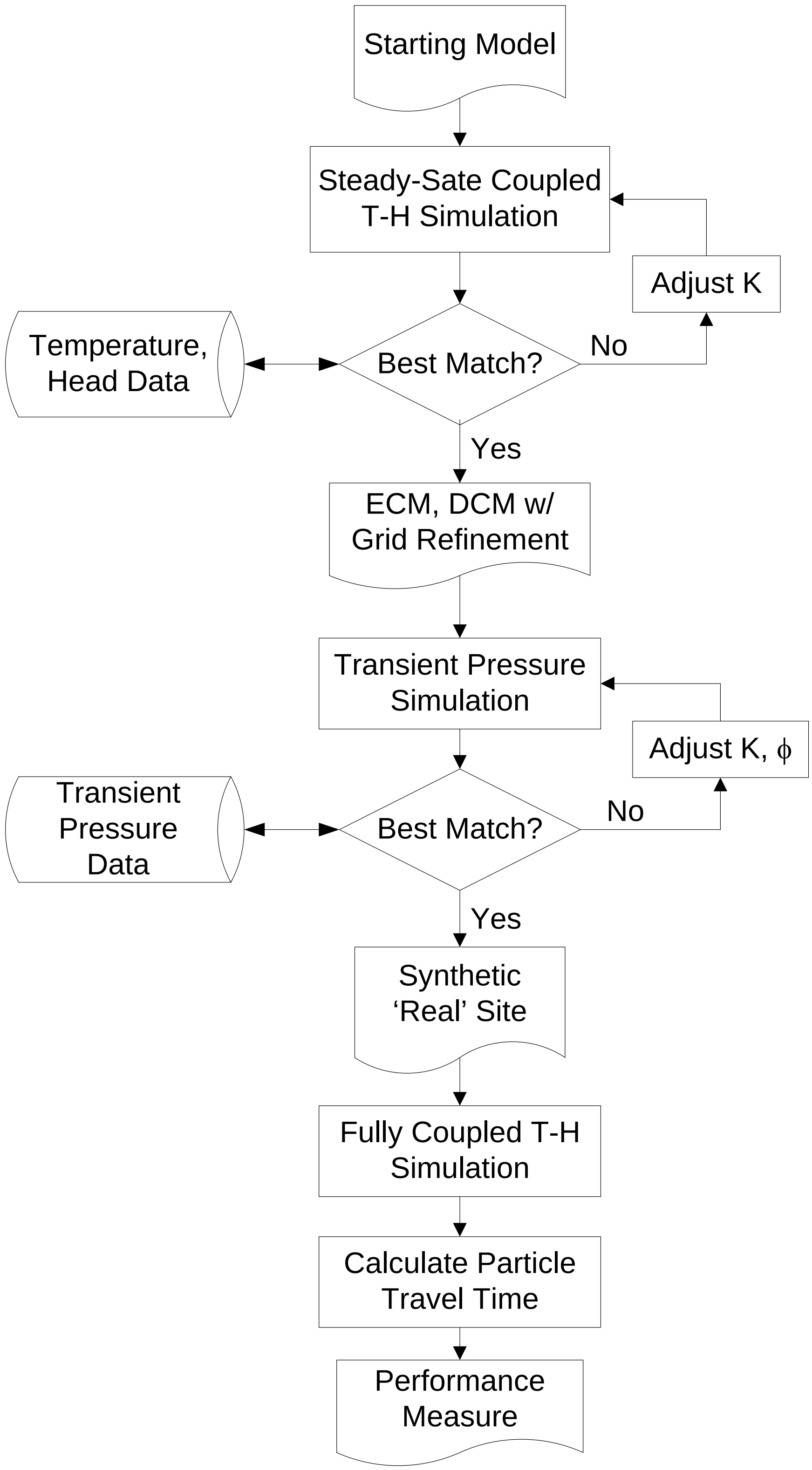

Figure 7-5. Schematic of the calibration procedure to produce the 'real' site and the performance measure.

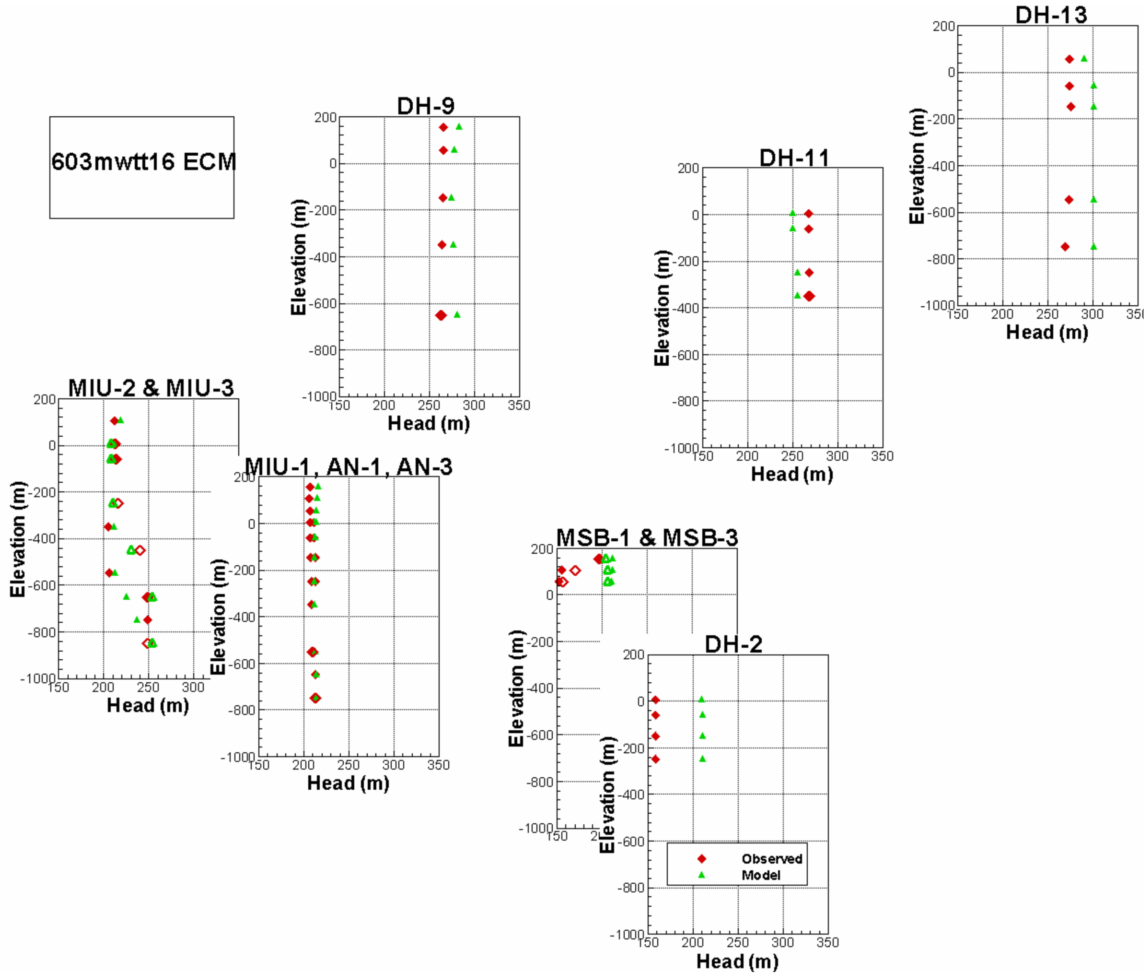

Figure 7-6. Natural-state head profiles for the starting model. The MSB wells are located in the vicinity of the point labeled Main Shaft in Figure 7-1. The arrangement of plots on the page roughly corresponds to the locations of the wells.

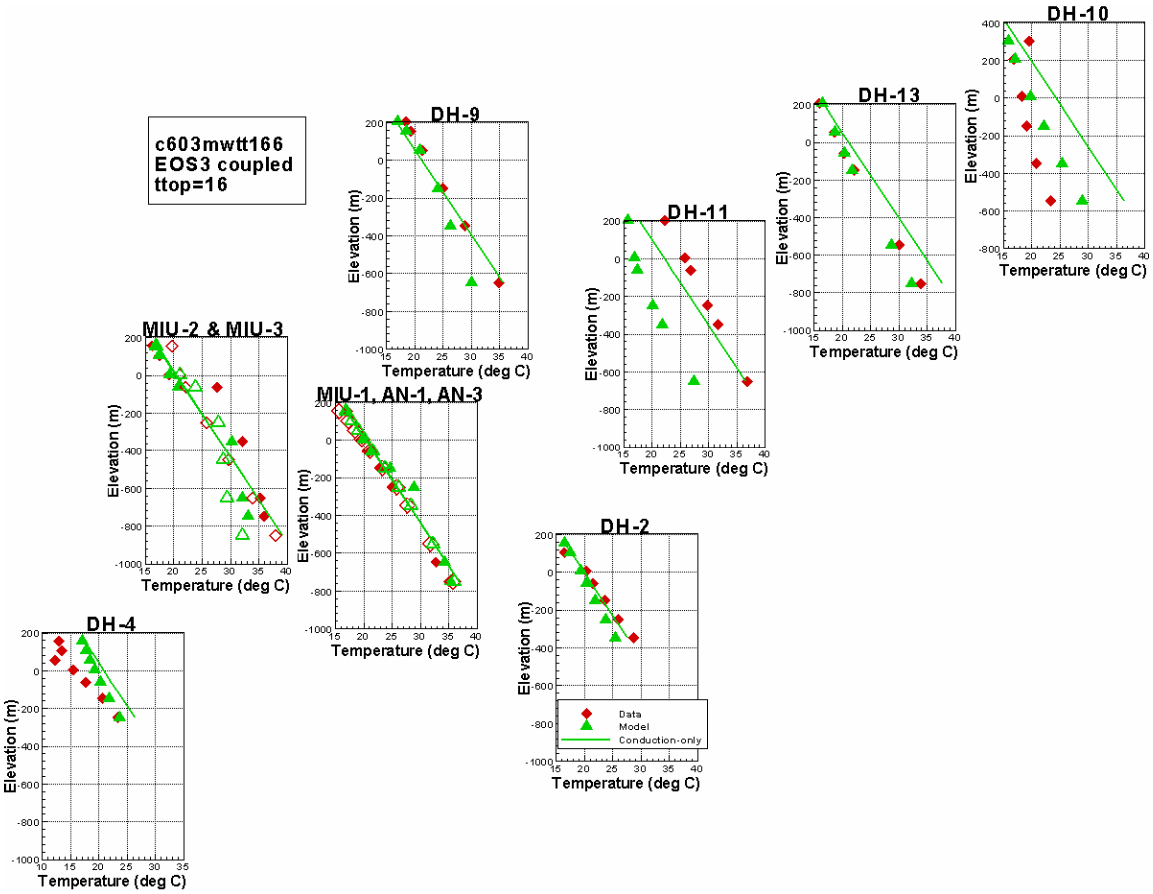

Figure 7-7. Natural-state temperature profiles for the starting model. The arrangement of plots on the page roughly corresponds to the locations of the wells.

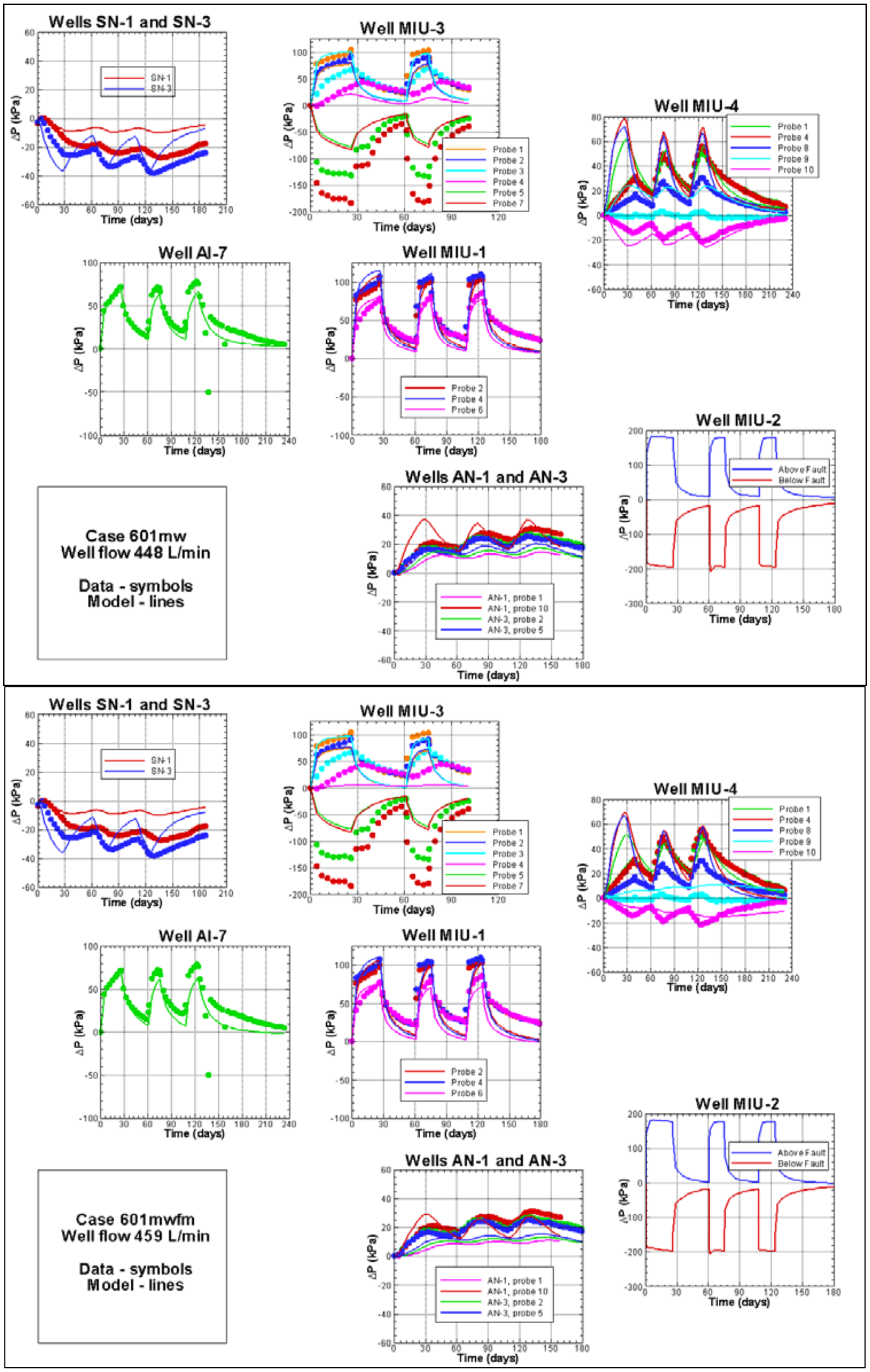

Figure 7-8. Pressure-transient response to inadvertent MIU-2 well test for the starting ECM (top) and DCM (bottom). The arrangement of plots on the page roughly corresponds to the locations of the wells.

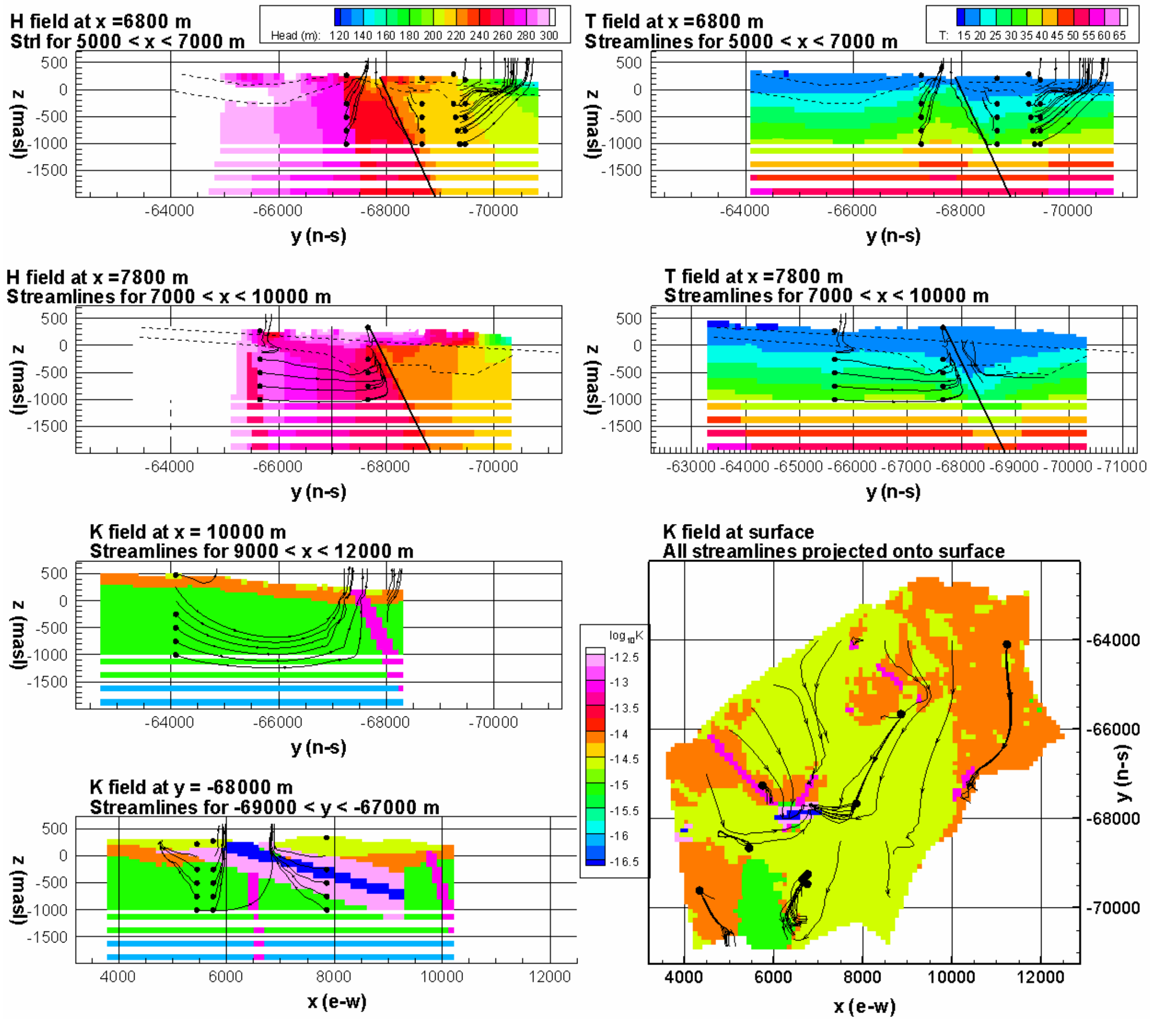

Figure 7-9. Visualization of groundwater flow field for starting model. Locations with observation data are shown as black dots; these points and selected other locations are used to initiate streamtraces that follow the groundwater flow field. For the plots with head and temperature as a background, the Tsukiyoshi fault trace is shown as a heavy black line and the boundary of the weathered granite is shown with dashed lines.

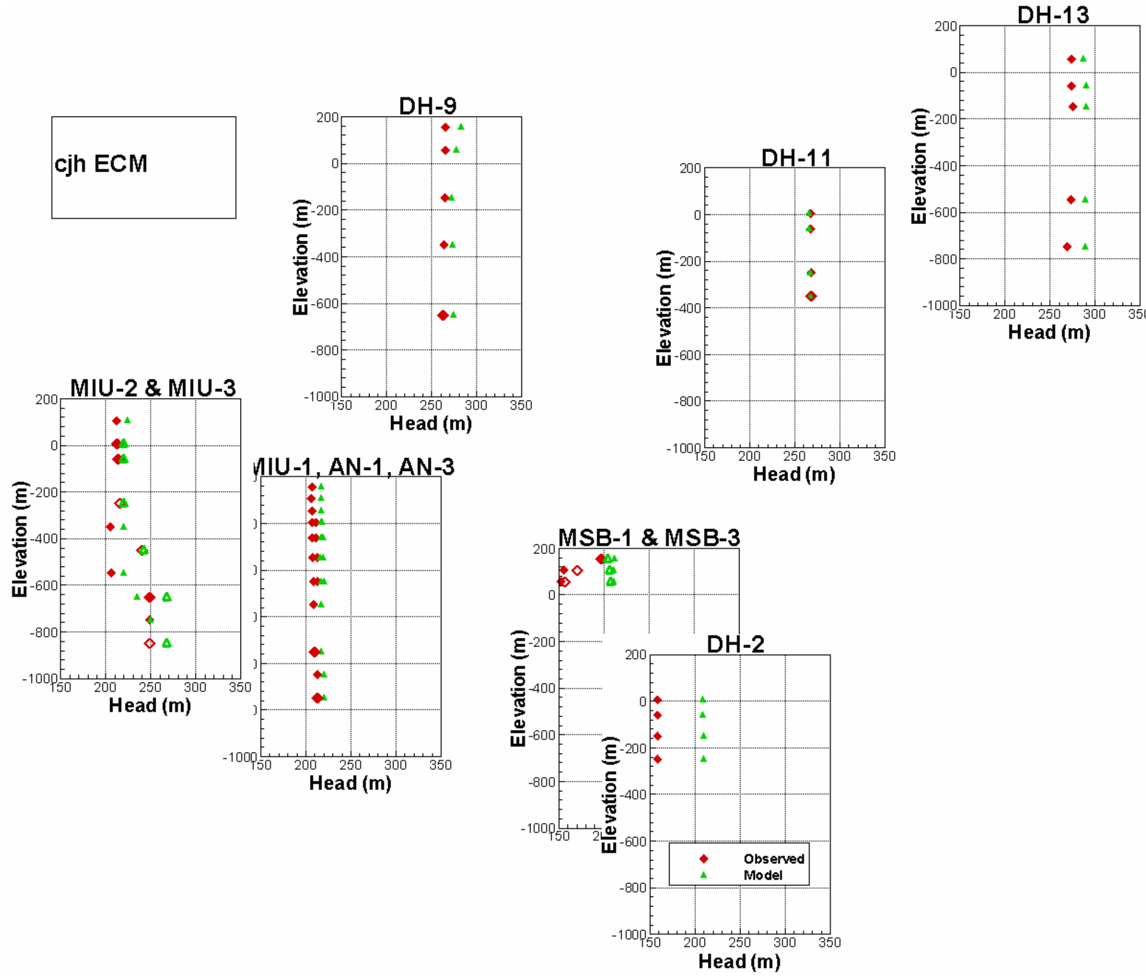

Figure 7-10. Natural-state head profiles for the final model.

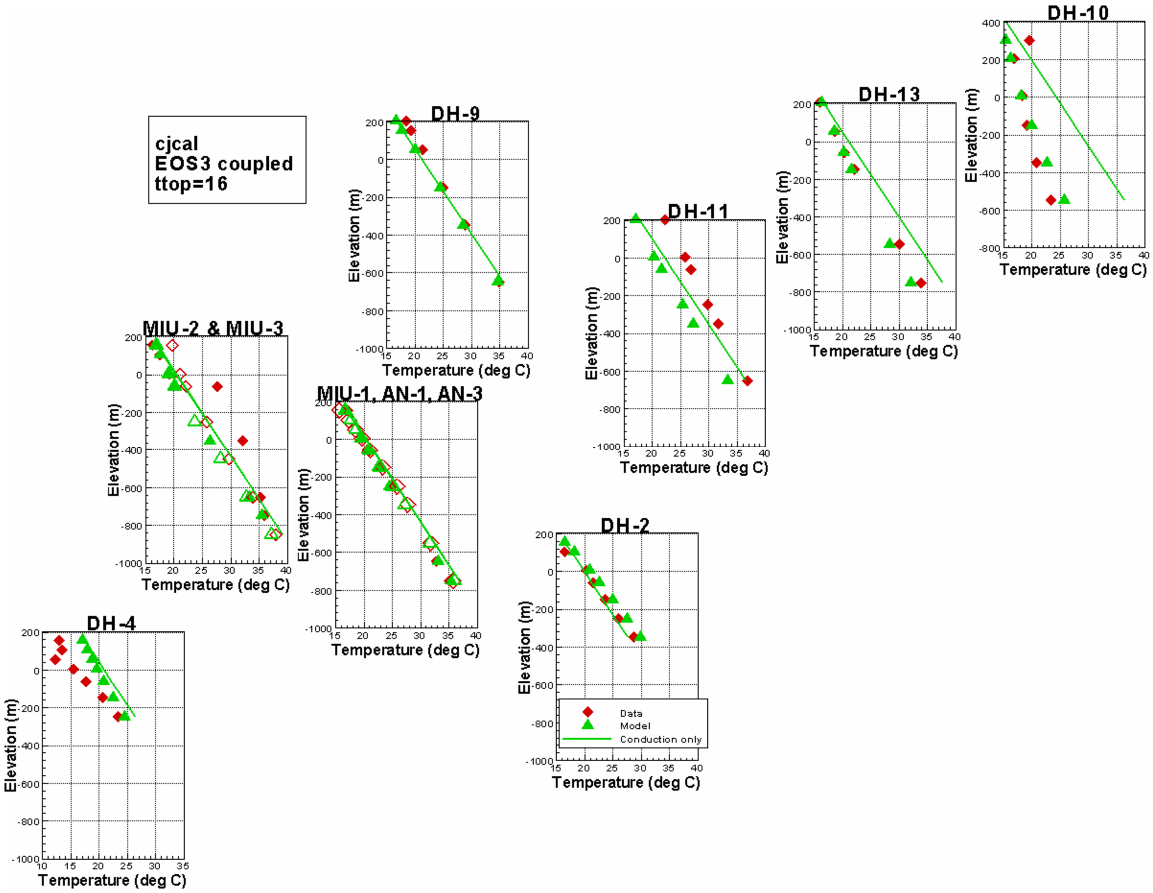

Figure 7-11. Natural-state temperature profiles for the final model.

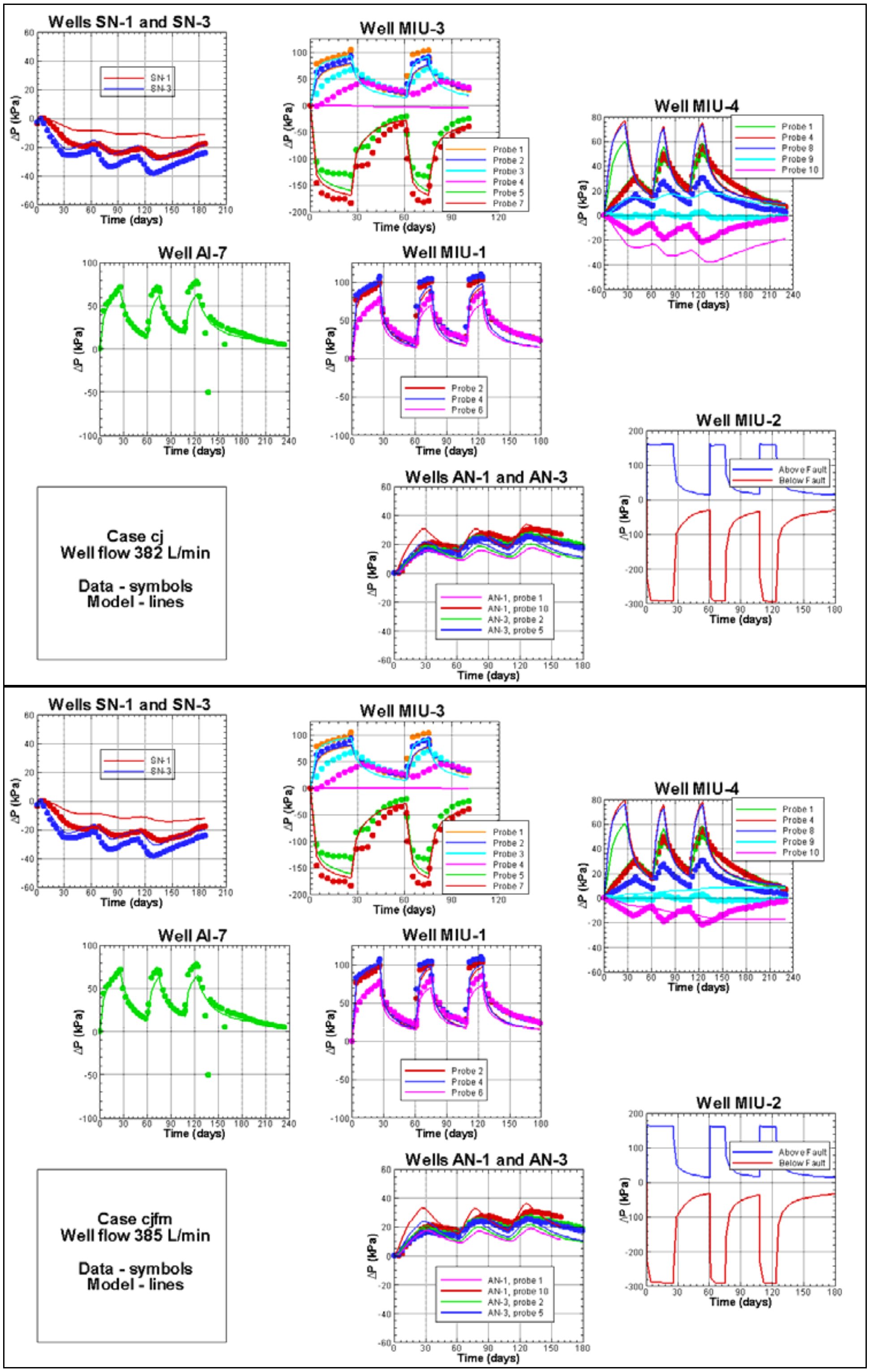

Figure 7-12. Pressure-transient response to inadvertent MIU-2 well test for the final ECM (top) and DCM (bottom).

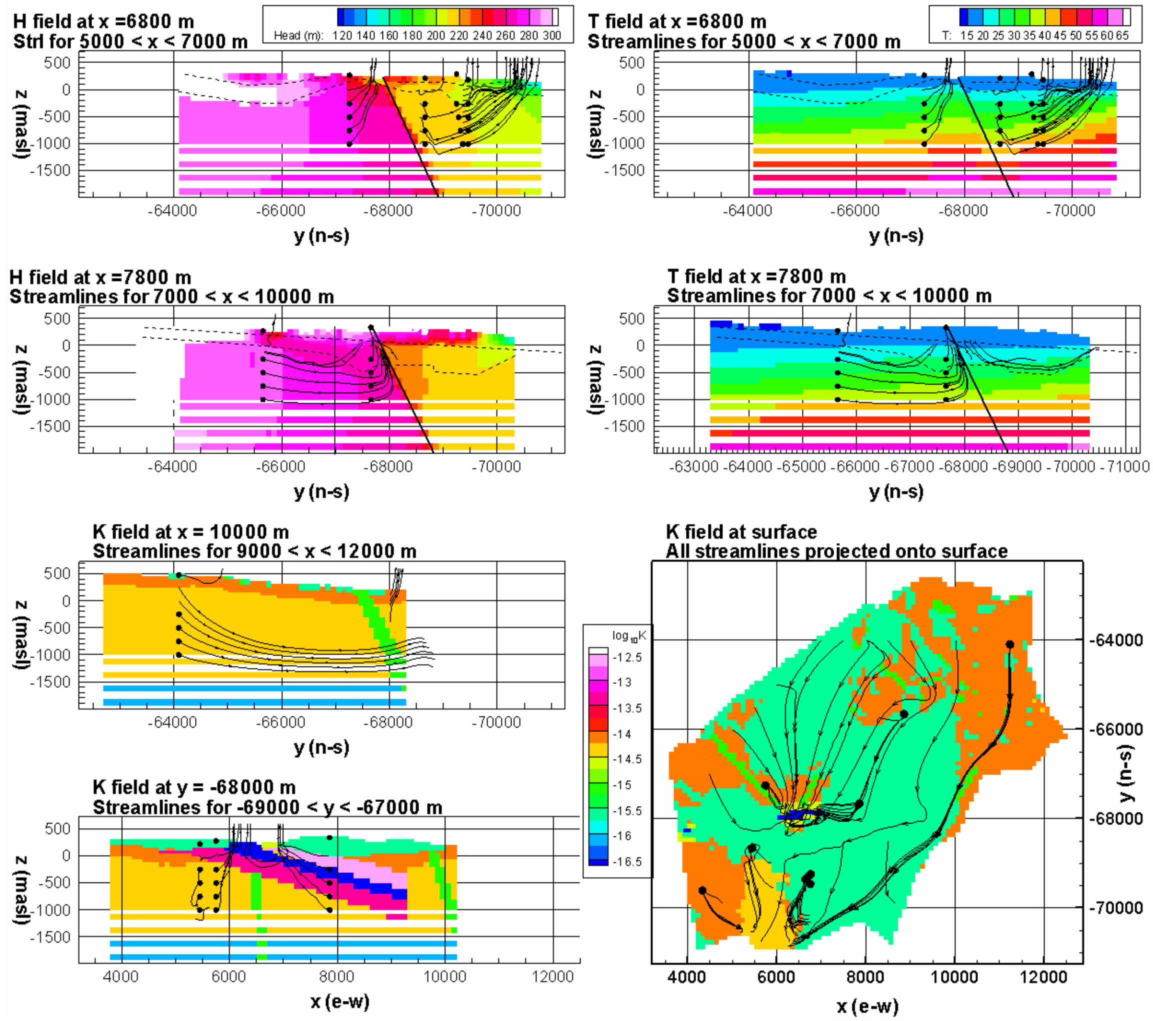

Figure 7-13. Visualization of groundwater flow field for final model.

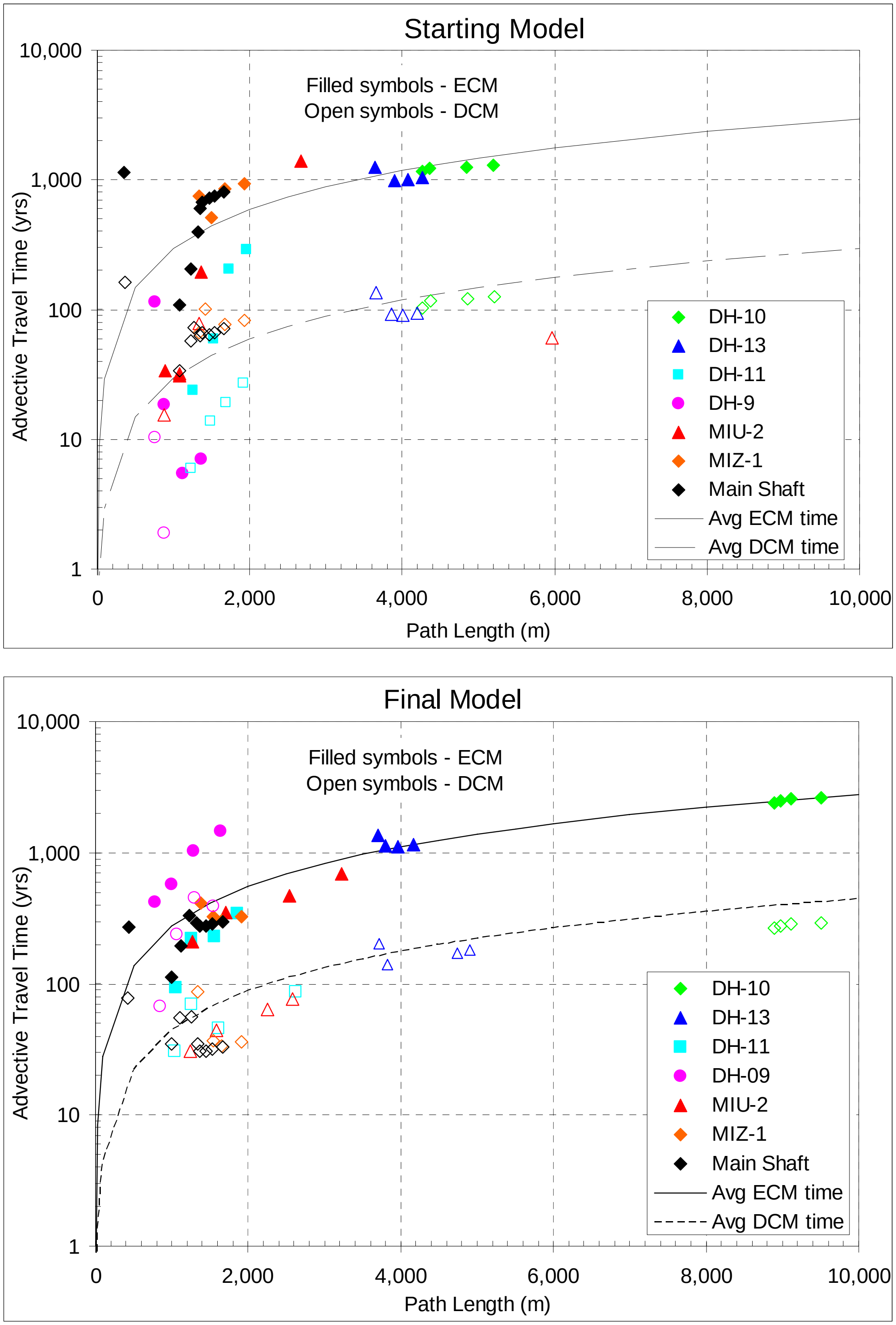

Figure 7-14. Advective travel time and path length for streamtraces originating at four depths between 250 and -1500 masl in six wells and at nine depths between 0 and -800 masl in the main shaft, for the starting model (top) and for the final model (bottom).

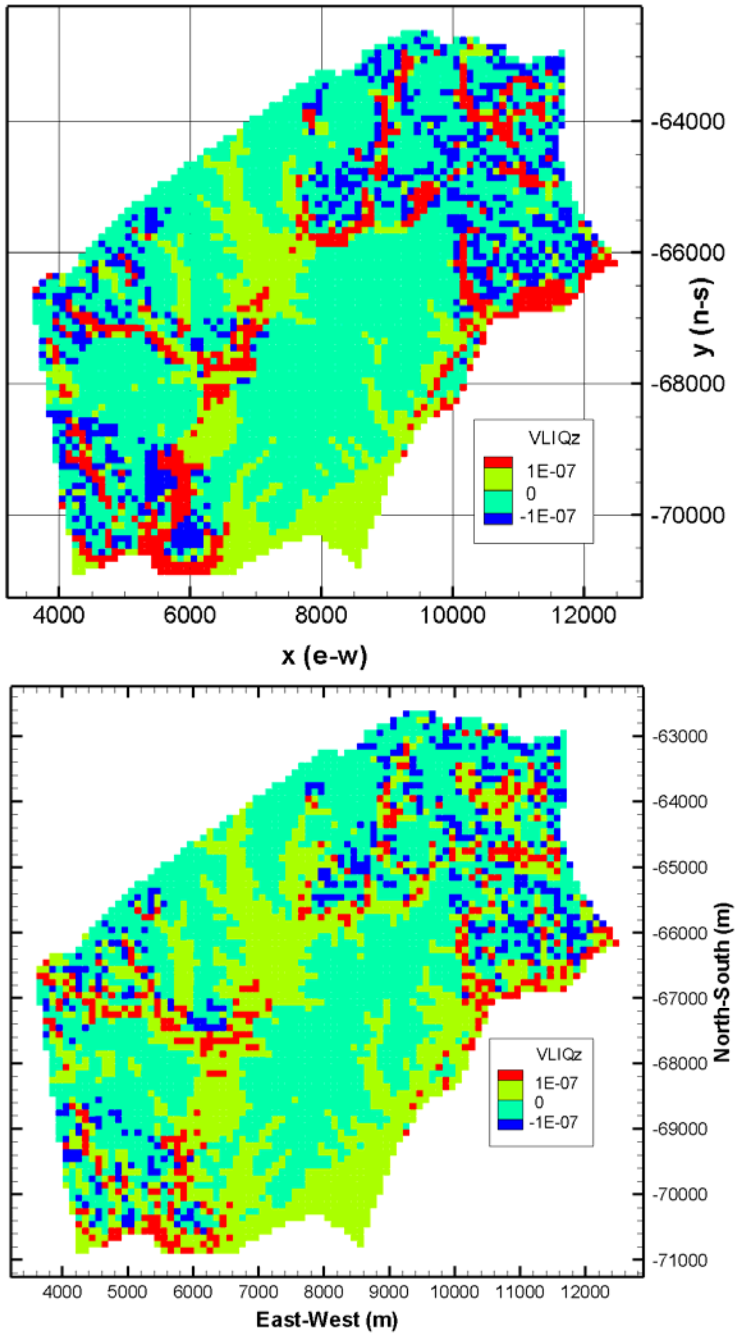

Figure 7-15. Distribution of surface flow into (negative) and out of (positive) the model for the final version of the complete model (top) and the simplified real model (bottom).

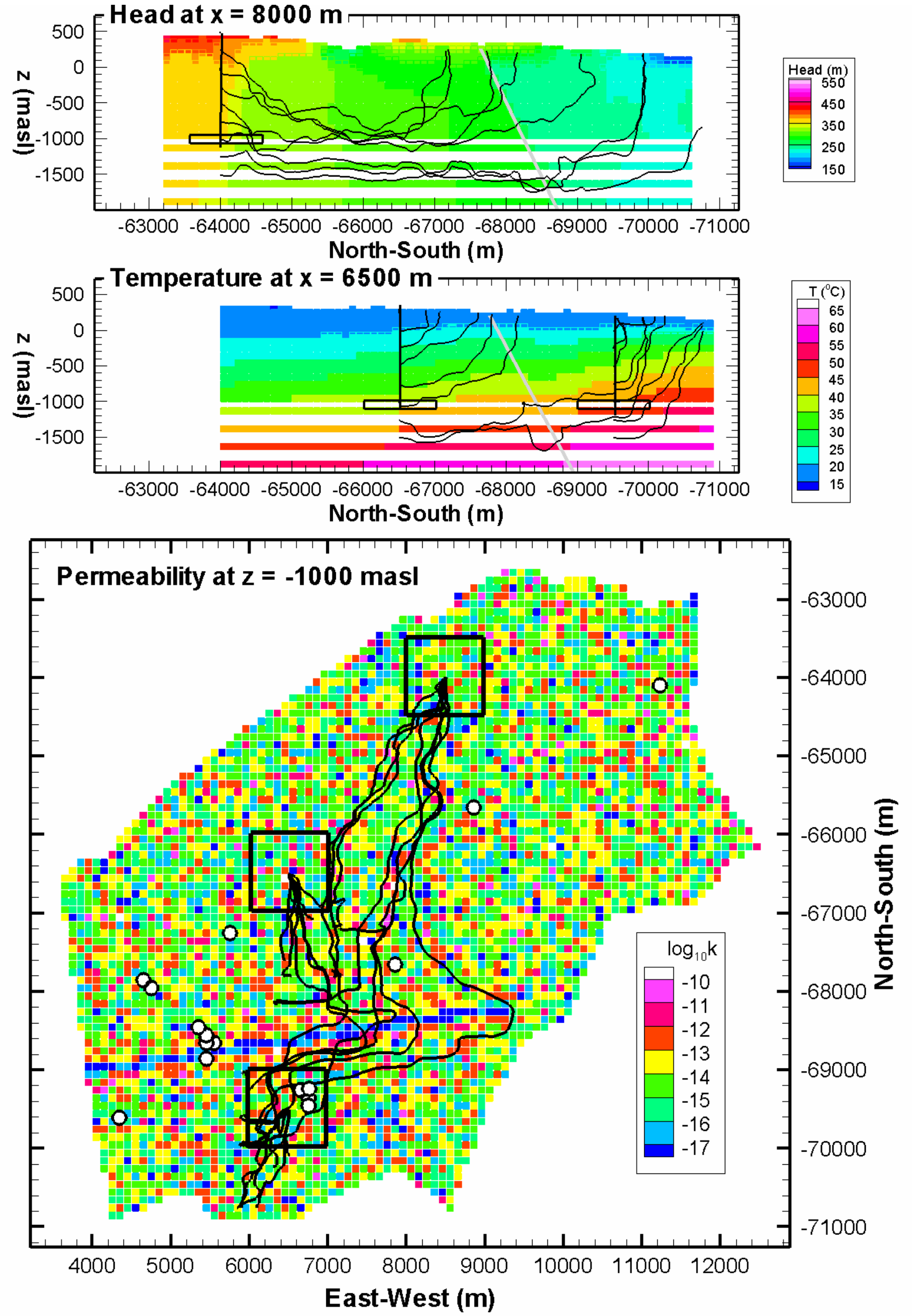

Figure 7-16. Results of coupled fluid and heat flow natural-state simulation of the simplified real model. Hypothetical repository sites are shown as black-outlined boxes. White dots on the plan view show locations of all wells where pressure or temperature data were collected.

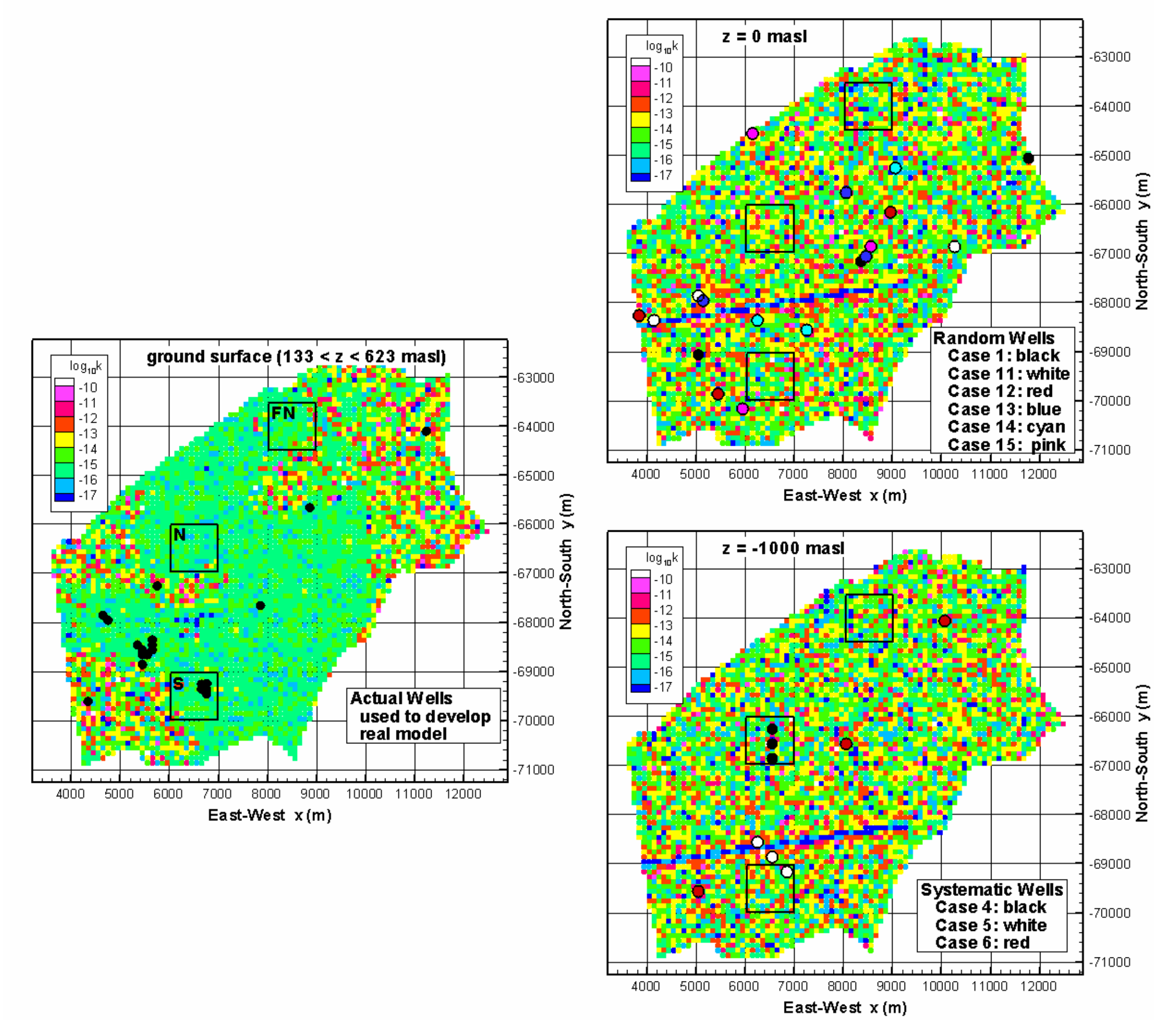

Figure 7-17. Plan view of the simplified real model showing the permeability distribution at several depths, three hypothetical repository locations identified as S for south, N for north, and FN for far north, and the random and systematic well locations used to generate the trial models. Although shown at all three depths, the repositories only extend from -900 to -1000 masl.

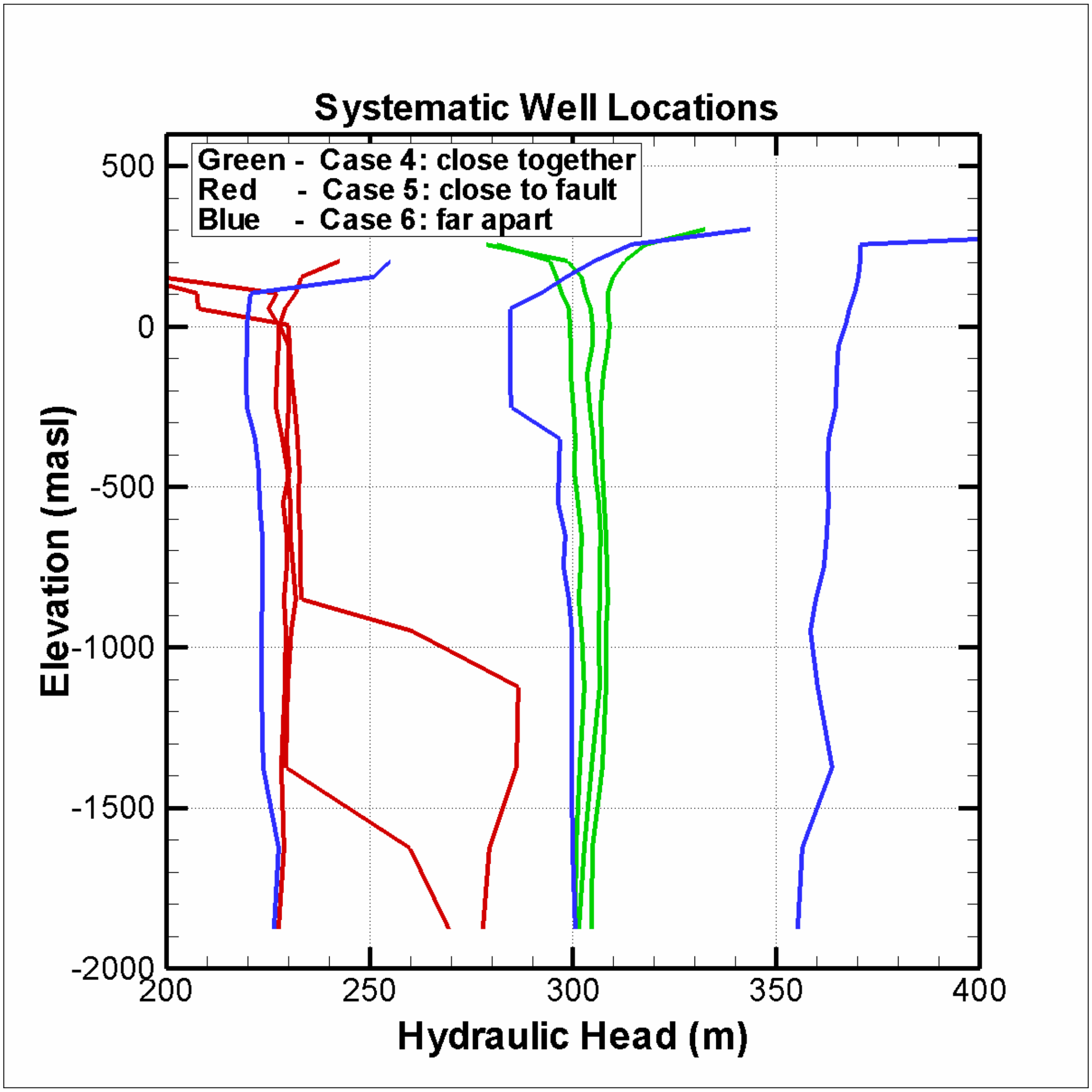

Figure 7-18. Modeled head profiles for trial models with systematic well locations. The jumps in head at elevations of -1000 masl and -1500 masl identify the intersection of the well and the fault plane.

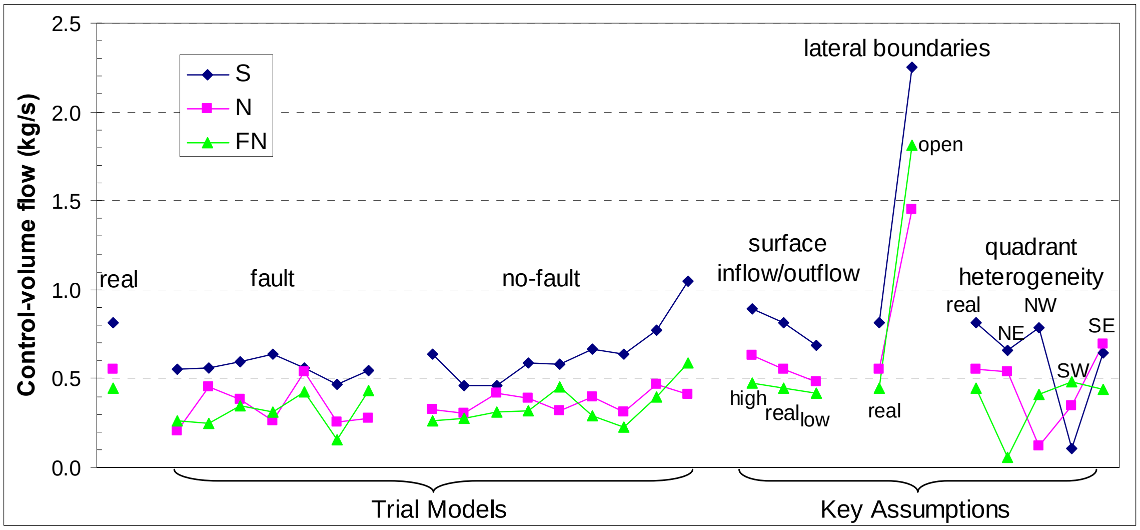

Figure 7-19. Control-volume flows for simplified real model, trial models, and variations on the real model to test key assumptions. Control volumes are labeled S for south, N for north, and FN for far north (see Figure 16 for exact locations).

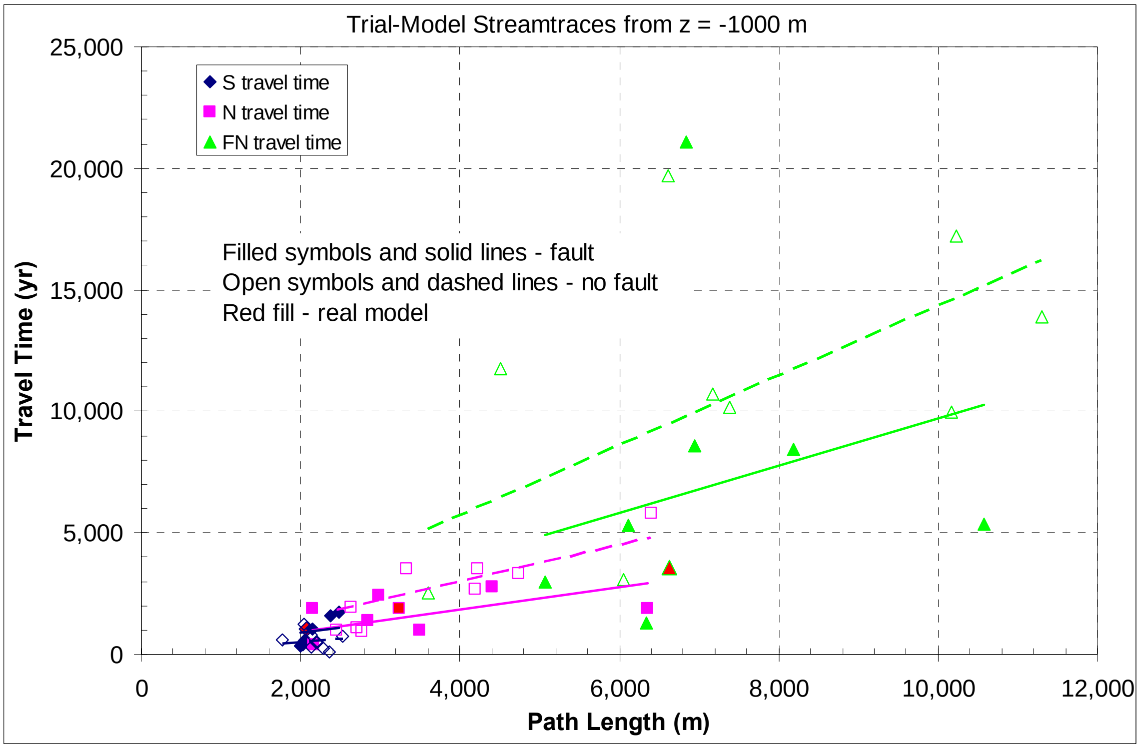

Figure 7-20. Advective travel time as a function of path length for streamtraces originating at the S, N, and FN control volumes for the trial models. The lines show least square fits to various subsets of trial models.

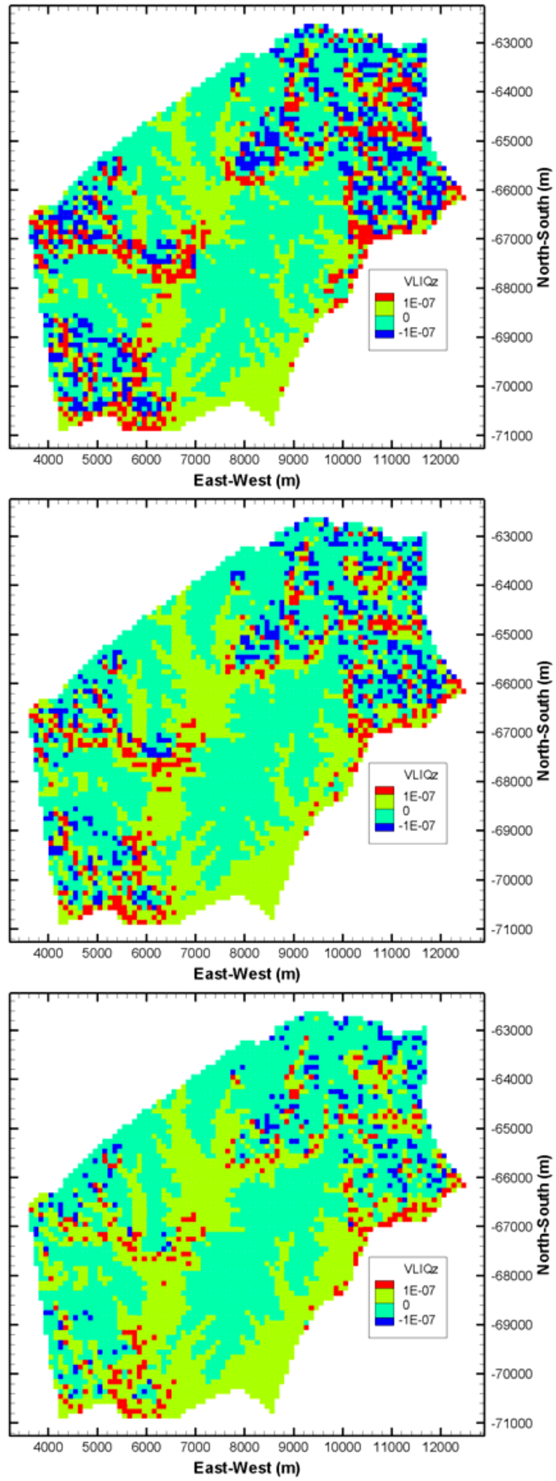

Figure 7-21. Distribution of surface inflow (negative) and outflow (positive) for no surface permeability reduction (top), the simplified real model (middle), and larger surface permeability reduction (bottom).

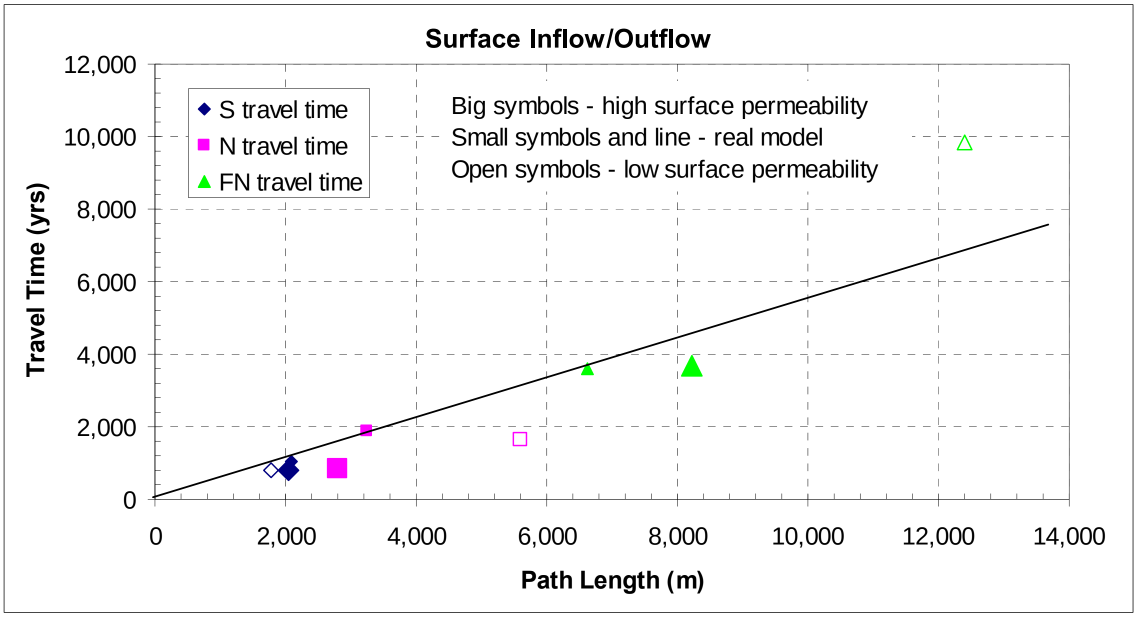

Figure 7-22. Advective travel time as a function of path length for streamtraces originating at the S, N, and FN control volumes for different values of surface permeability.

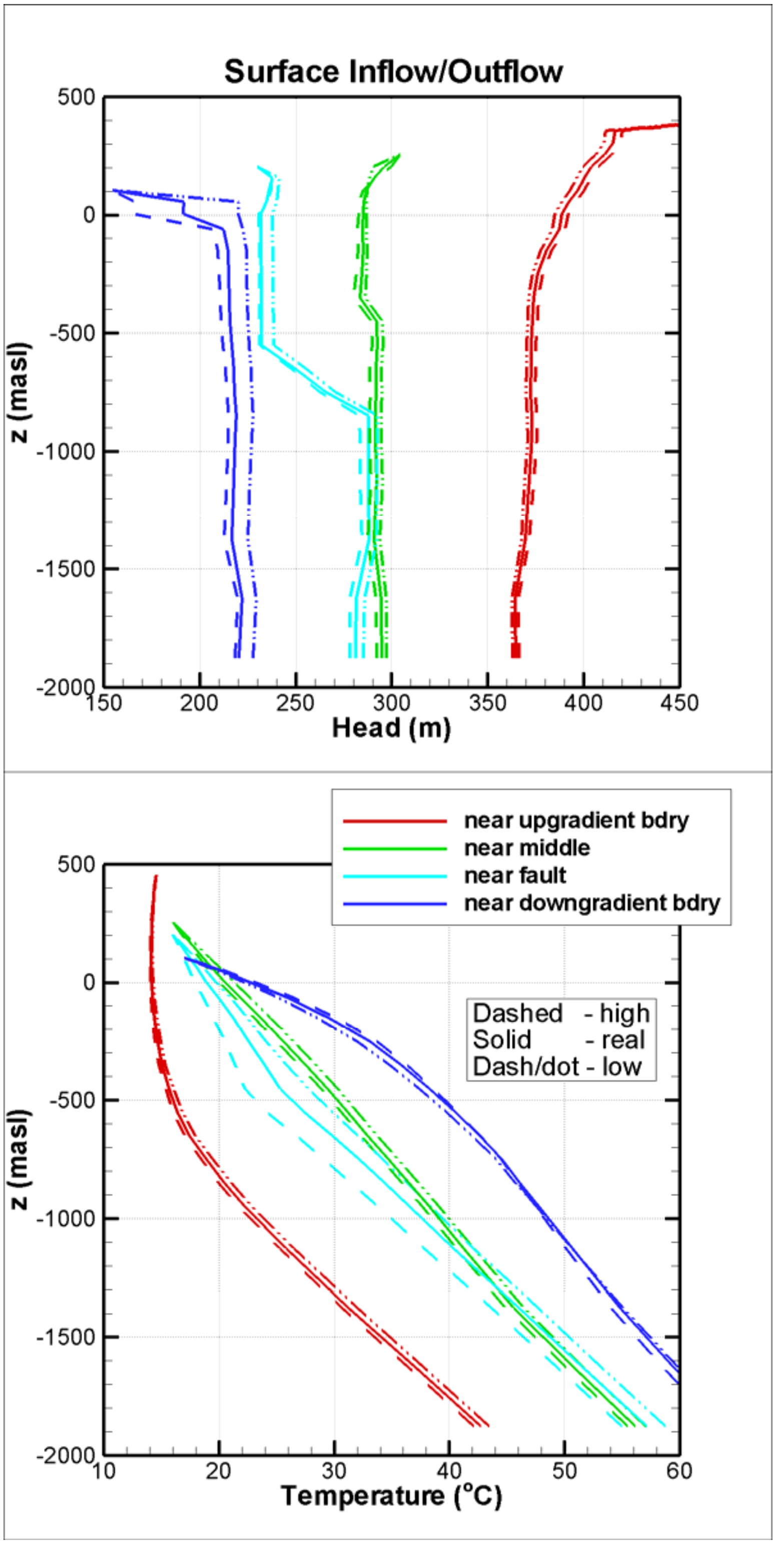

Figure 7-23. Head (top) and temperature (bottom) profiles at four hypothetical well locations (different colors), for different values of surface permeability (different line styles).

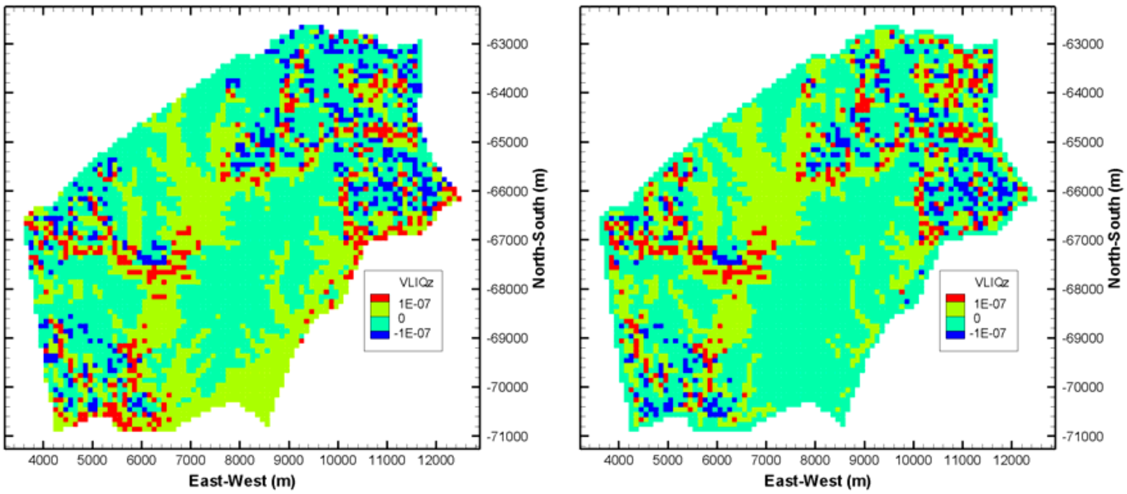

Figure 7-24. Distribution of surface inflow (negative) and outflow (positive) for the simplified real model (left) with closed lateral boundaries, and the case with open lateral boundaries (right).

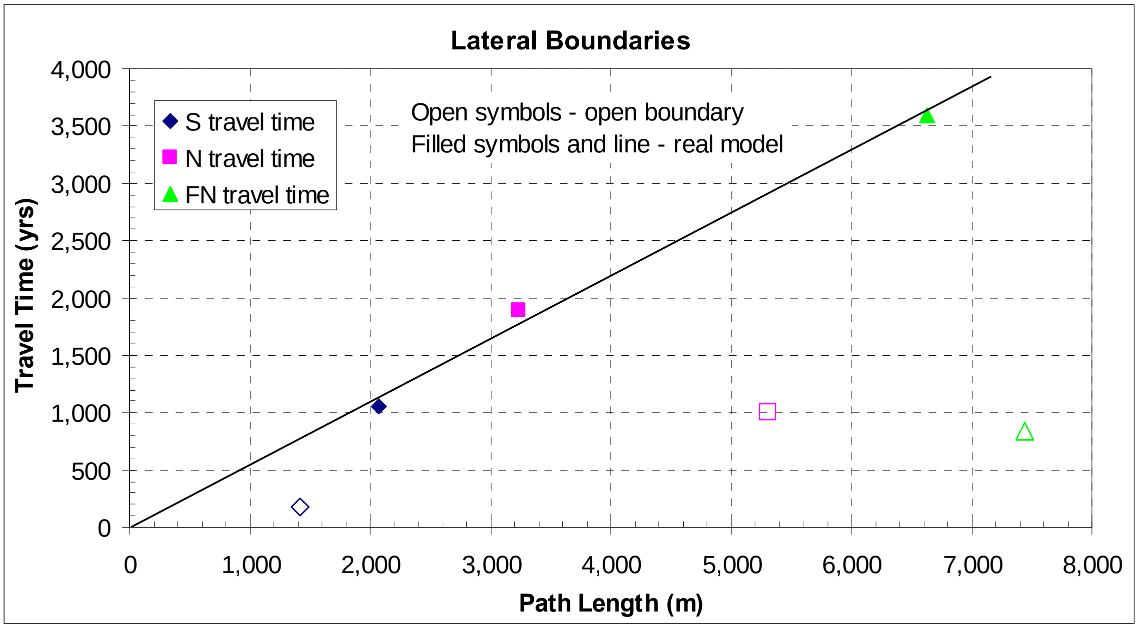

Figure 7-25. Advective travel time as a function of path length for streamtraces originating at the S, N, and FN control volumes for the simplified real model with closed lateral boundaries, and the case with open lateral boundaries.

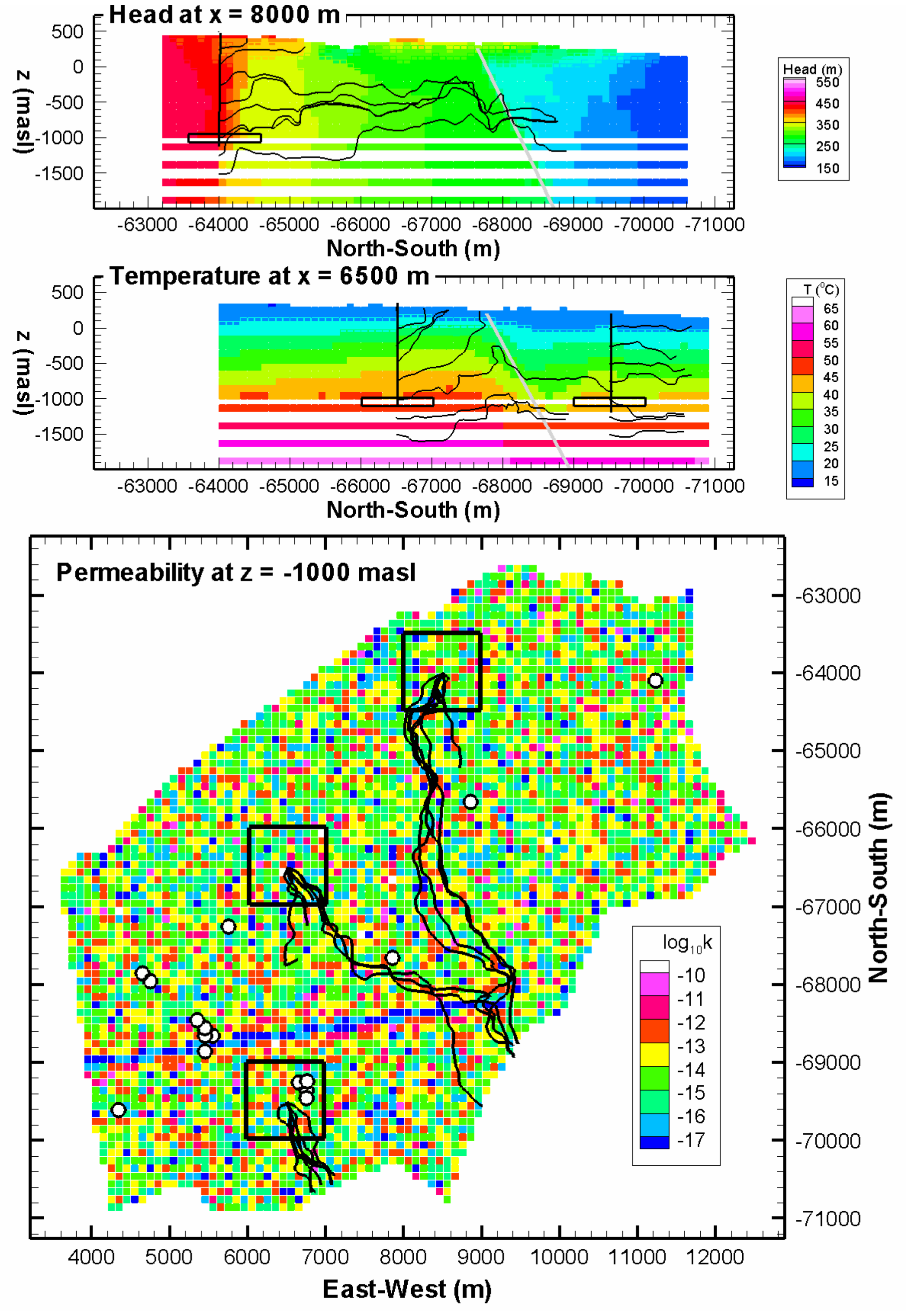

Figure 7-26. Results of coupled fluid and heat flow natural-state simulation of the model with open lateral boundaries.

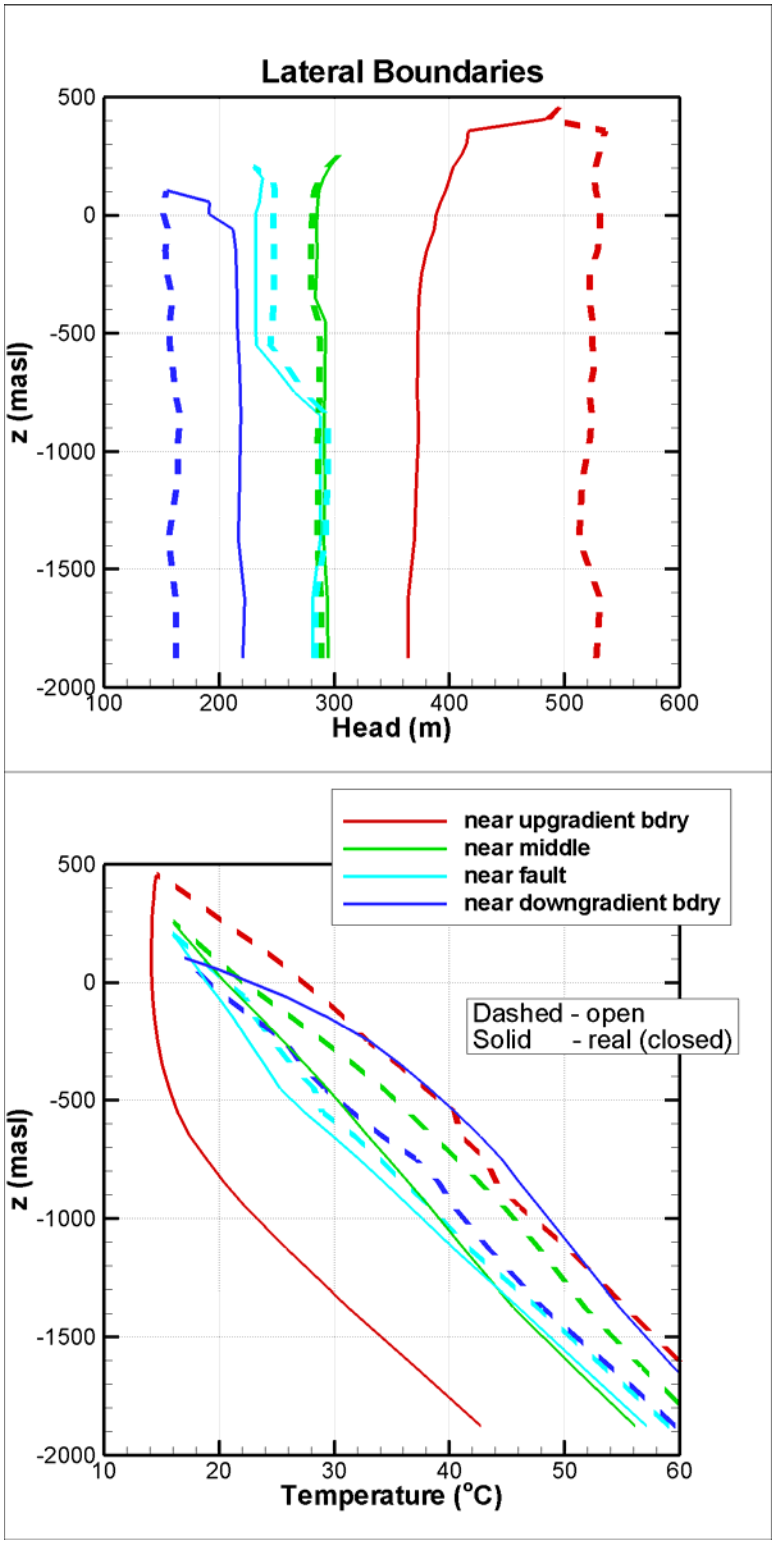

Figure 7-27. Head (top) and temperature (bottom) profiles at four hypothetical well locations (different colors), for closed (simplified real model) and open lateral boundaries (different line styles).

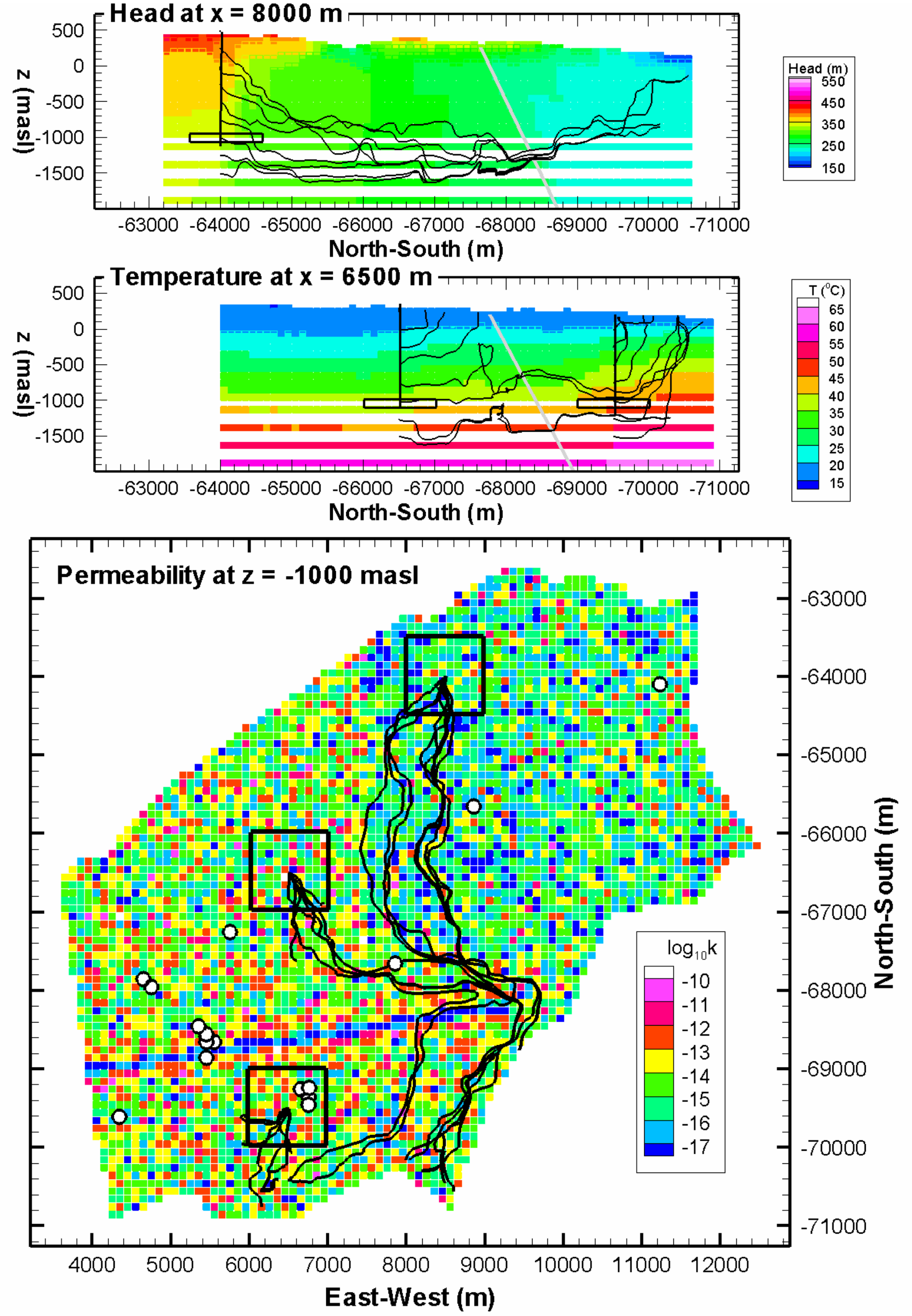

Figure 7-28. Results of coupled fluid and heat flow natural-state simulation of the model with ten times lower permeability in the NE quadrant.

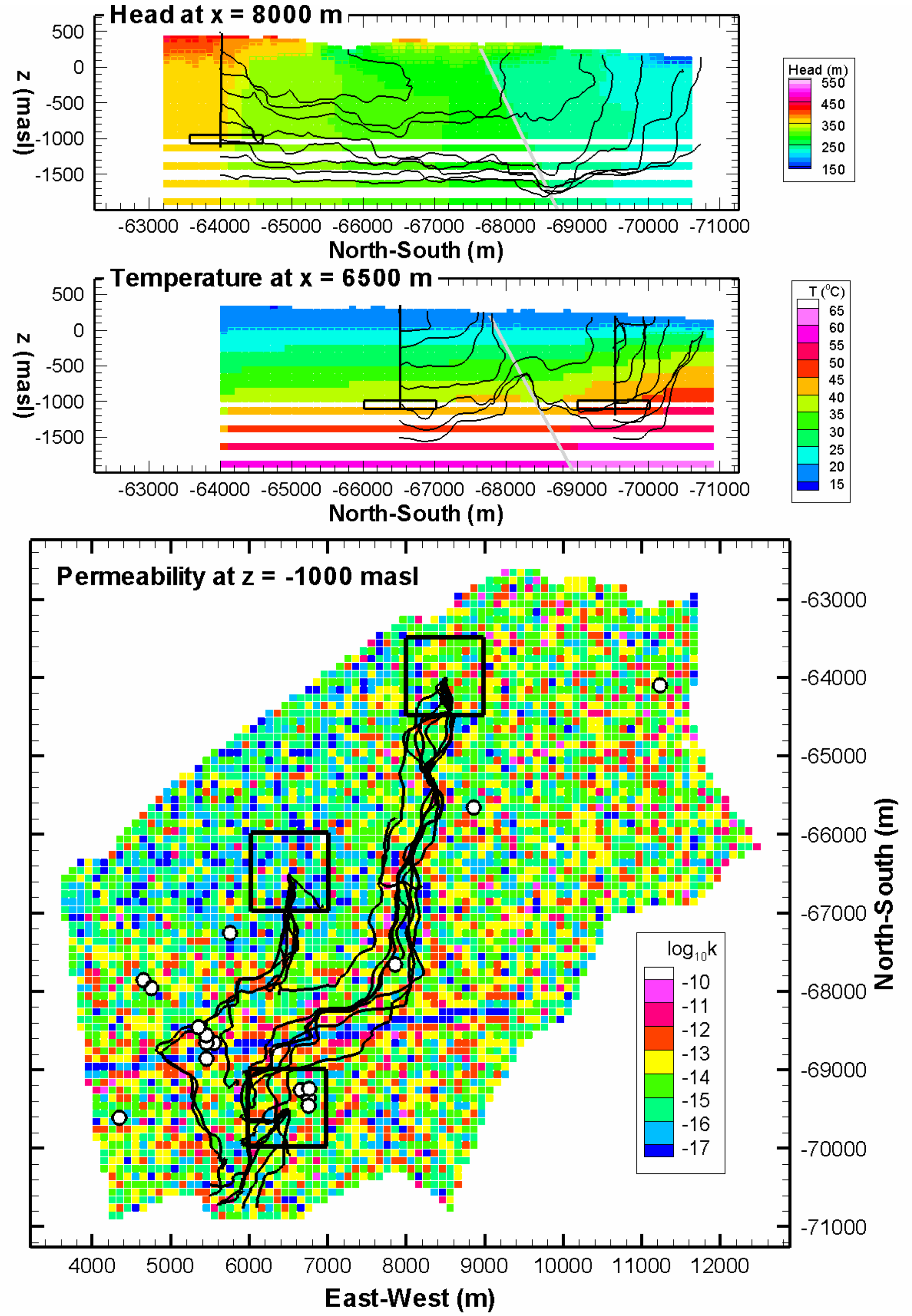

Figure 7-29. Results of coupled fluid and heat flow natural-state simulation of the model with ten times lower permeability in the NW quadrant.

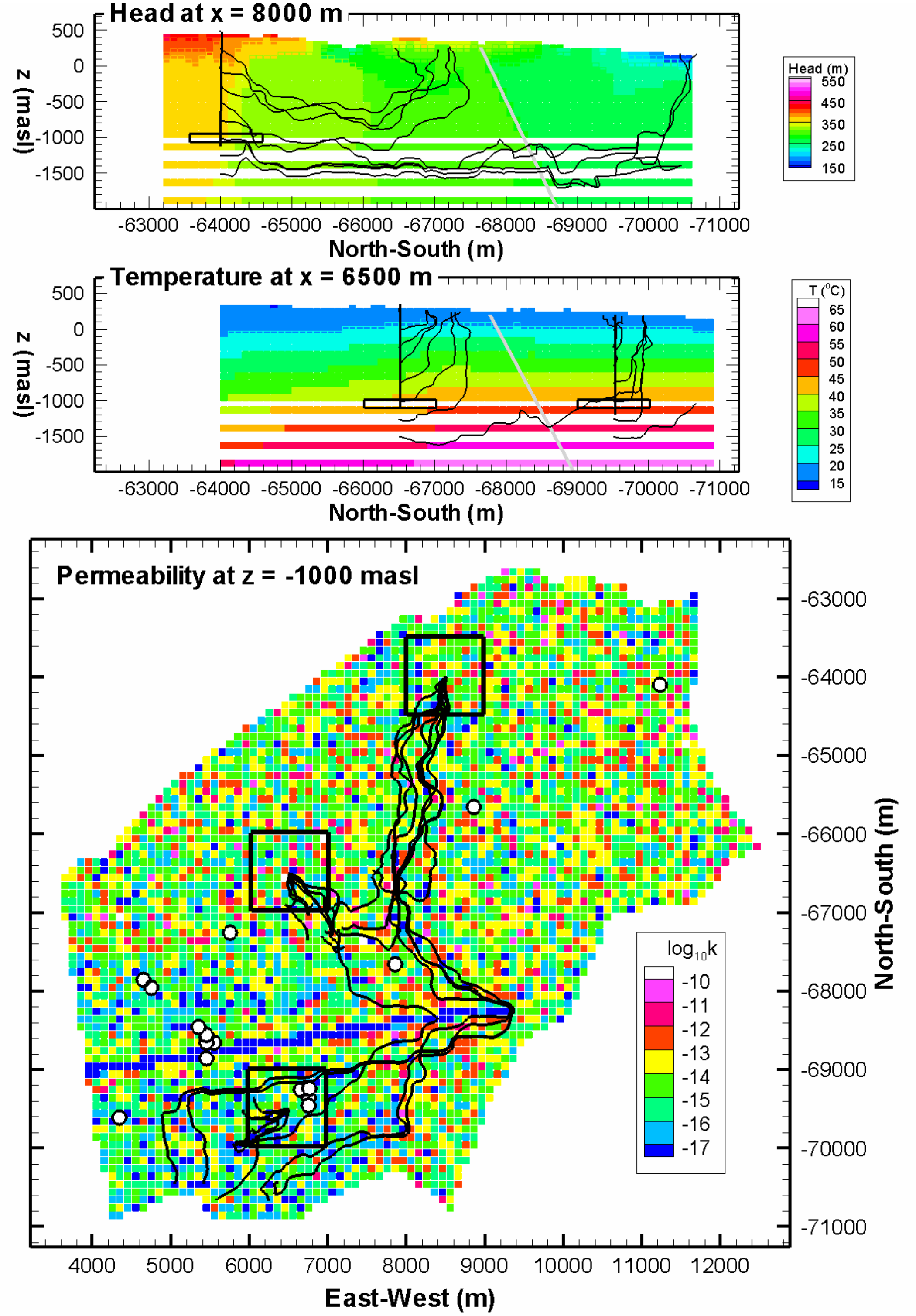

Figure 7-30. Results of coupled fluid and heat flow natural-state simulation of the model with ten times lower permeability in the SW quadrant.

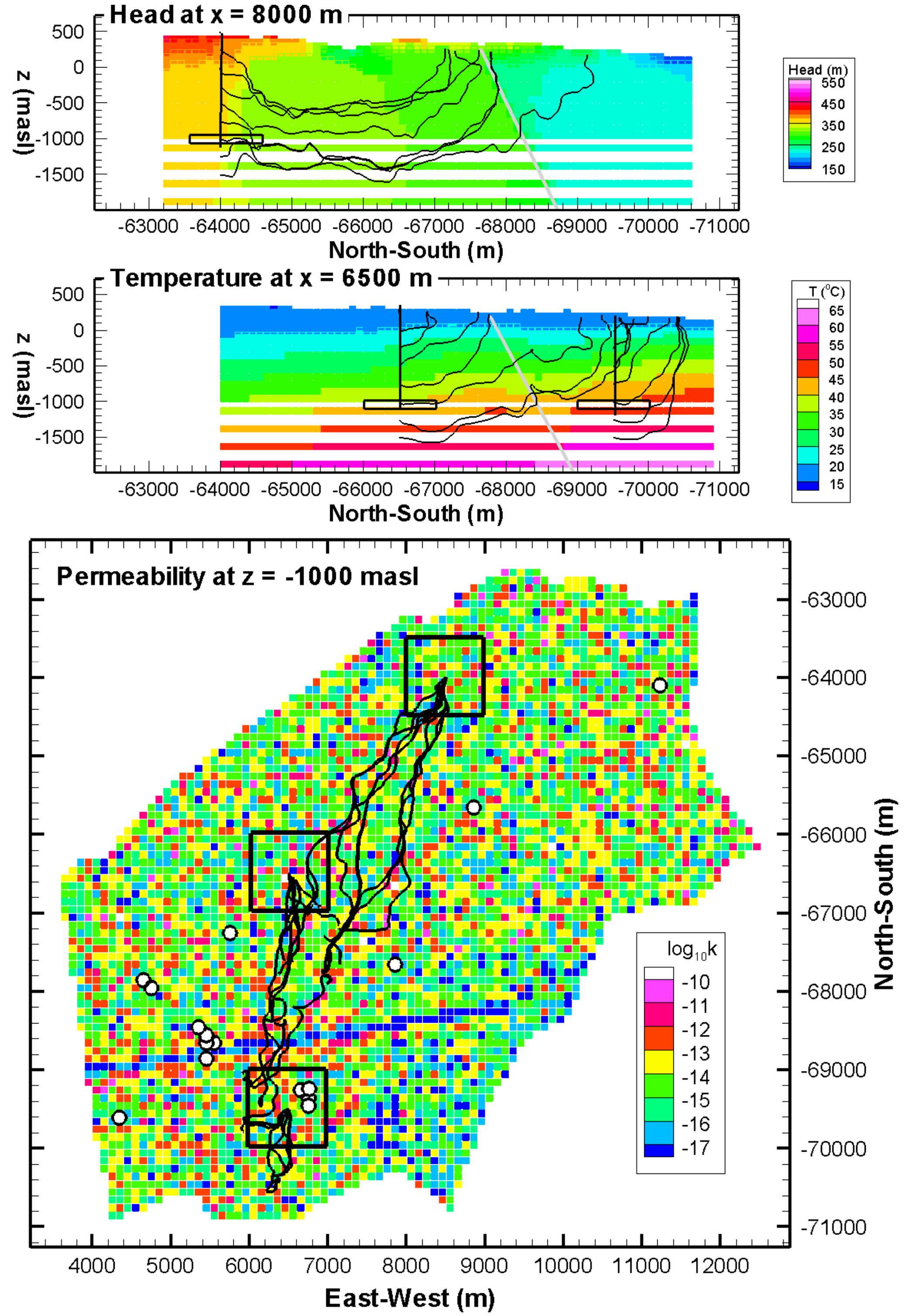

Figure 7-31. Results of coupled fluid and heat flow natural-state simulation of the model with ten times lower permeability in the SE quadrant.

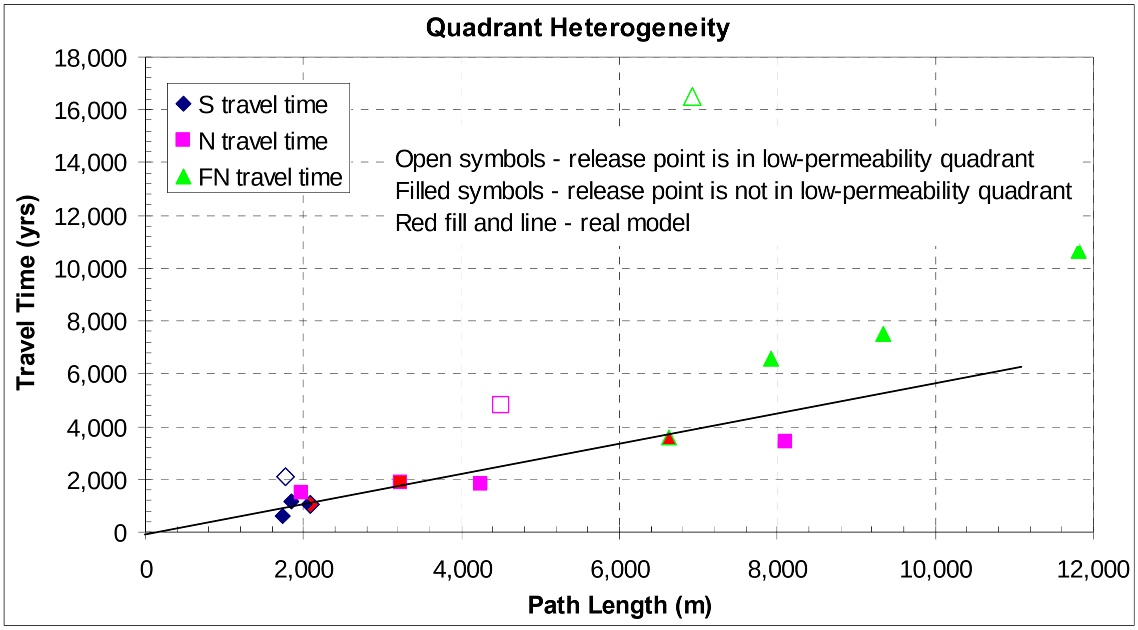

Figure 7-32. Advective travel time as a function of path length for streamtraces originating at the S, N, and FN control volumes for heterogeneity distributions with one low-permeability quadrant.

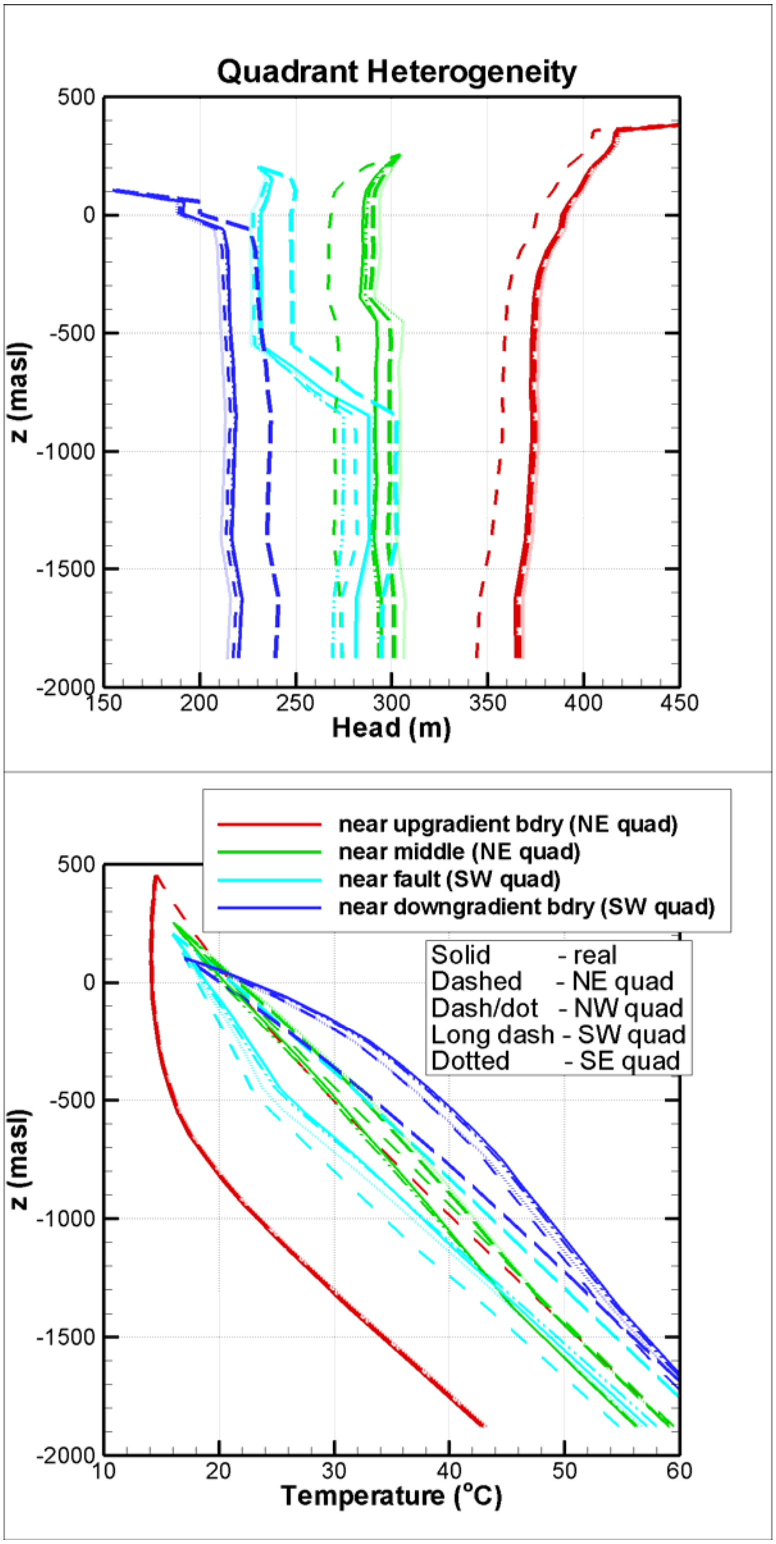

Figure 7-33. Head (top) and temperature (bottom) profiles at four hypothetical well locations (different colors), for the four quadrant-heterogeneity cases (different line styles). The legend identifies which quadrant has ten times lower permeability.

Appendix Figures

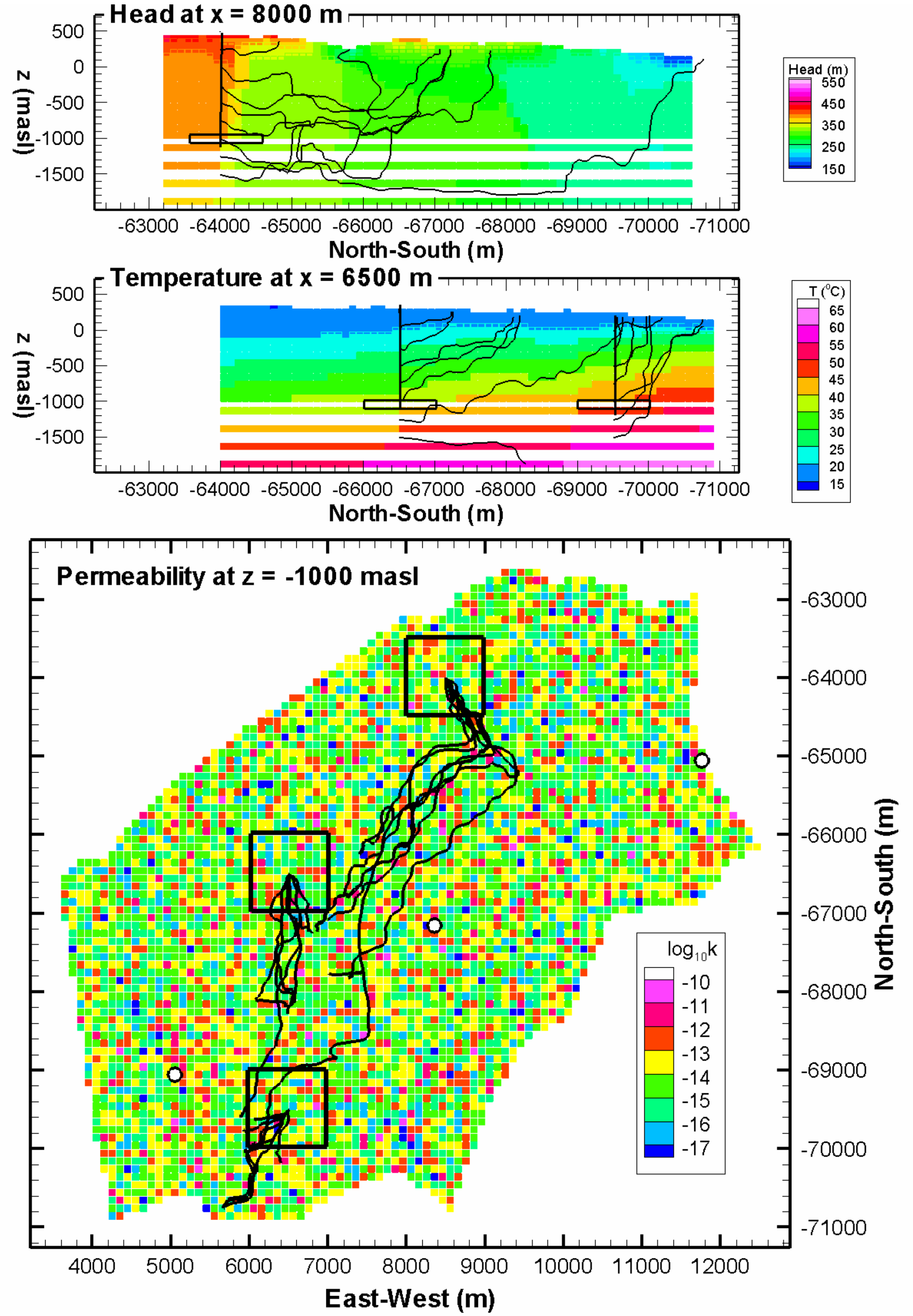

Figure 7-A-1. Case N01: three random wells, no fault.

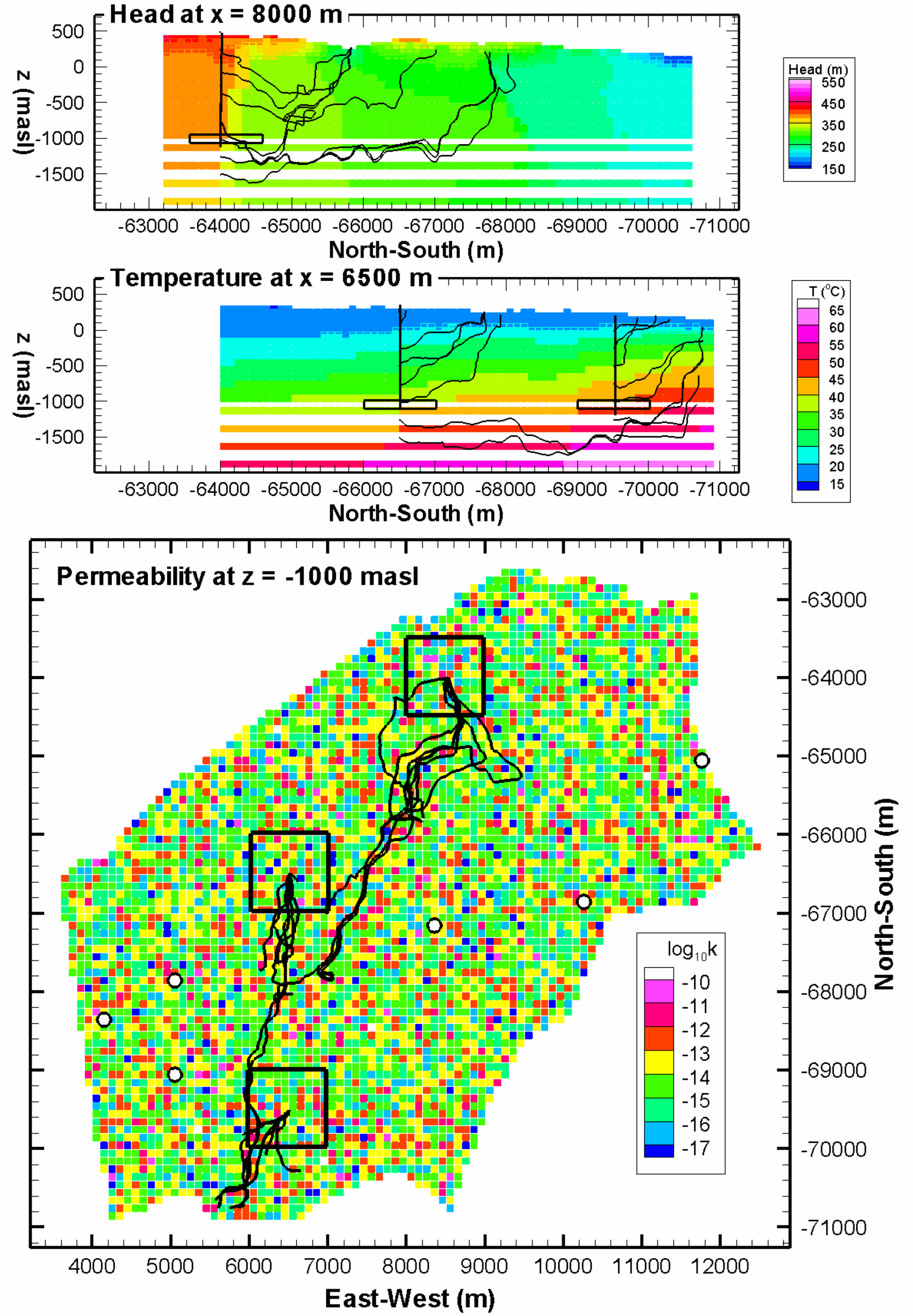

Figure 7-A-2. Case N02: six random wells, no fault.

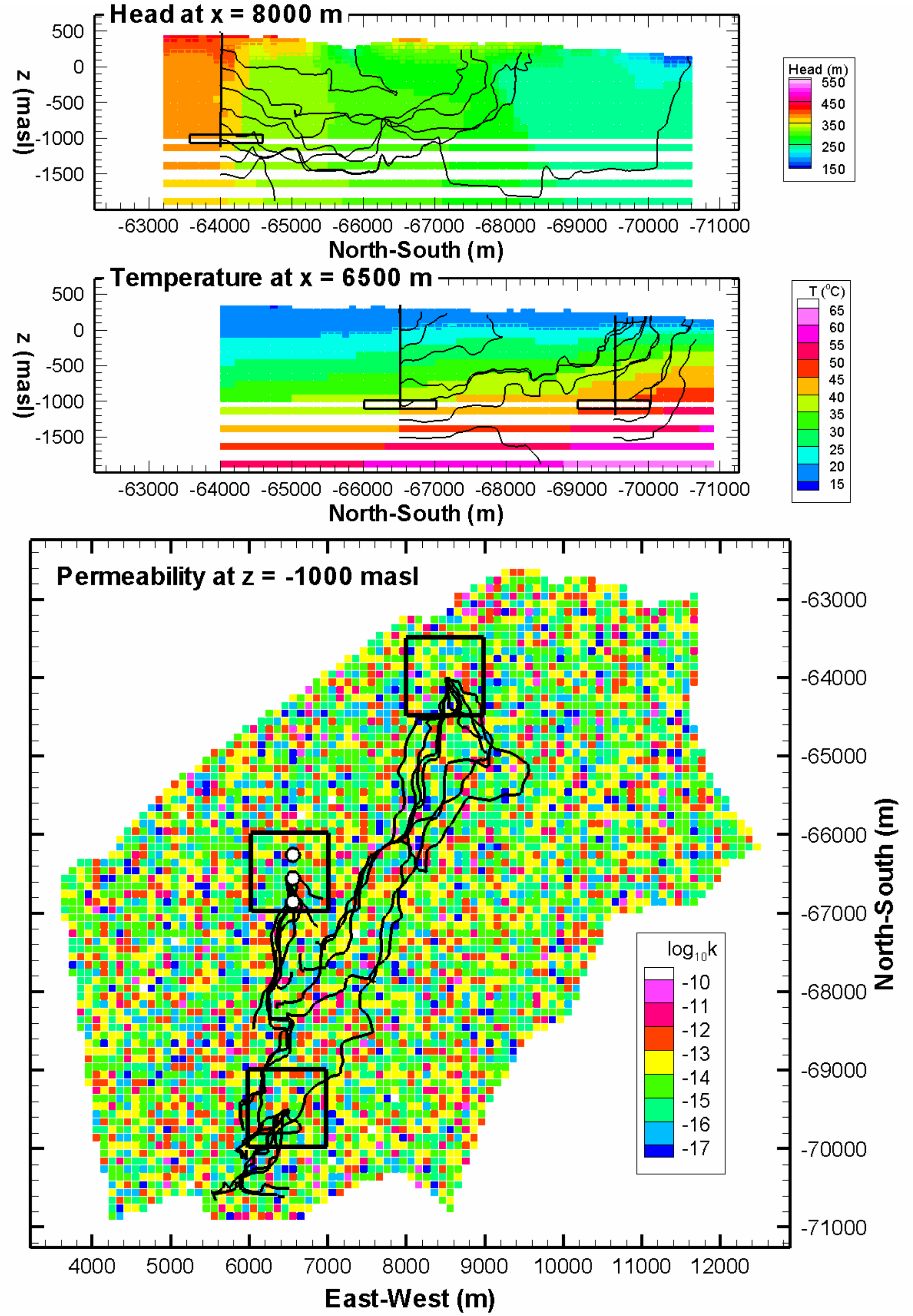

Figure 7-A-3. Case N04: three systematic wells (close together), no fault.

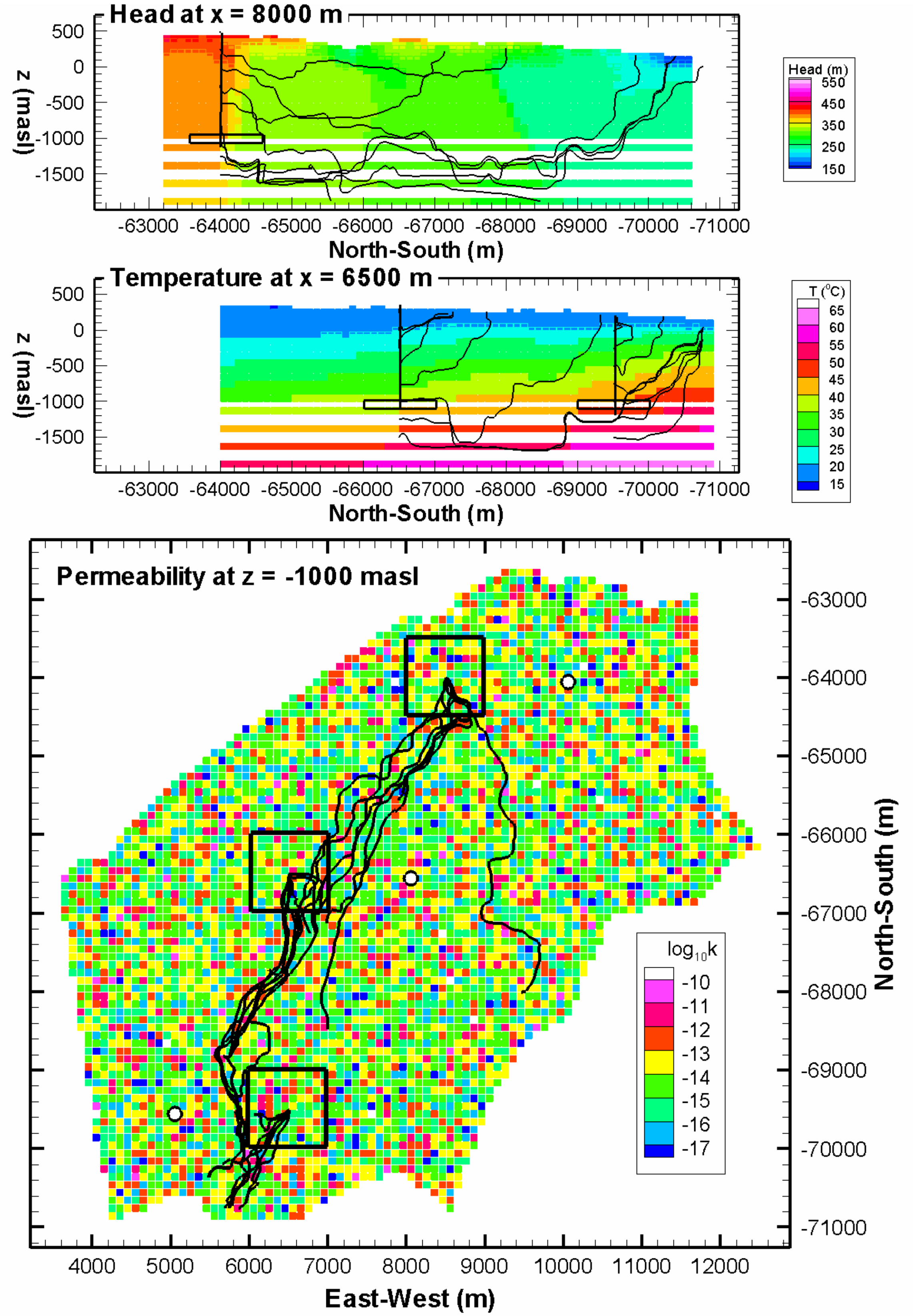

Figure 7-A-4. Case N06: three systematic wells (far apart), no fault.

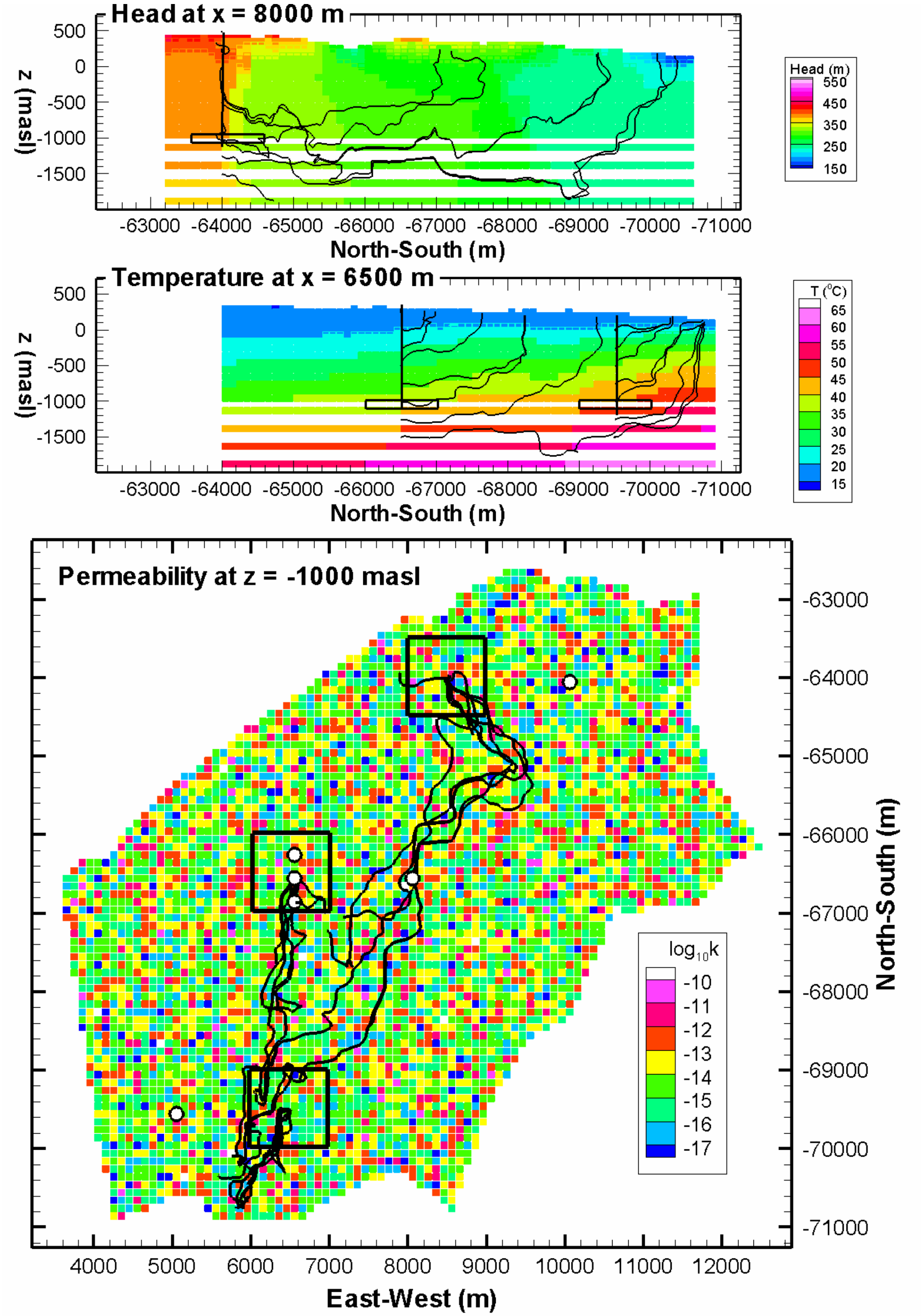

Figure 7-A-5. Case N08: six systematic wells (three close together and three far apart), no fault.

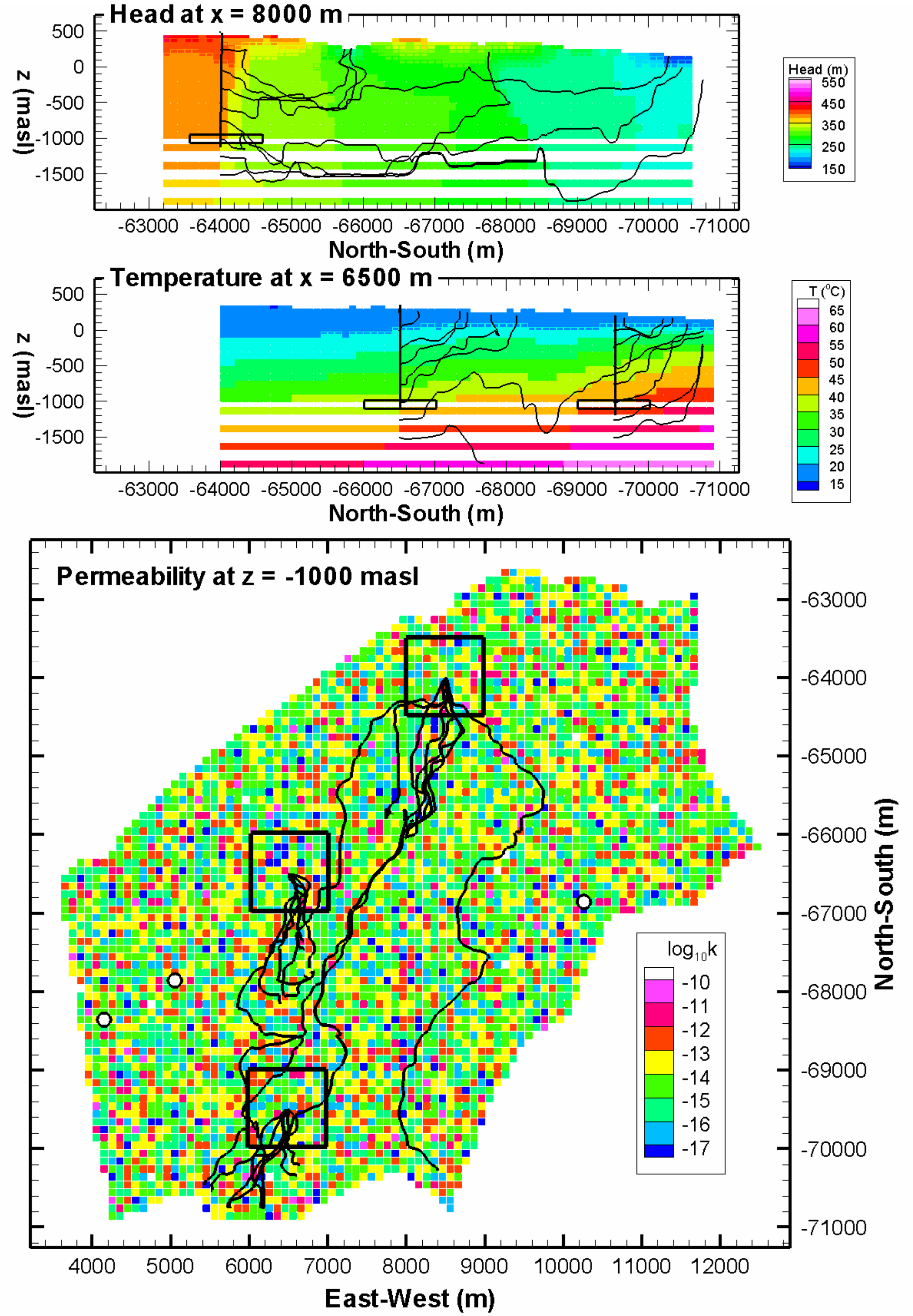

Figure 7-A-6. Case N11: three random wells, no fault.

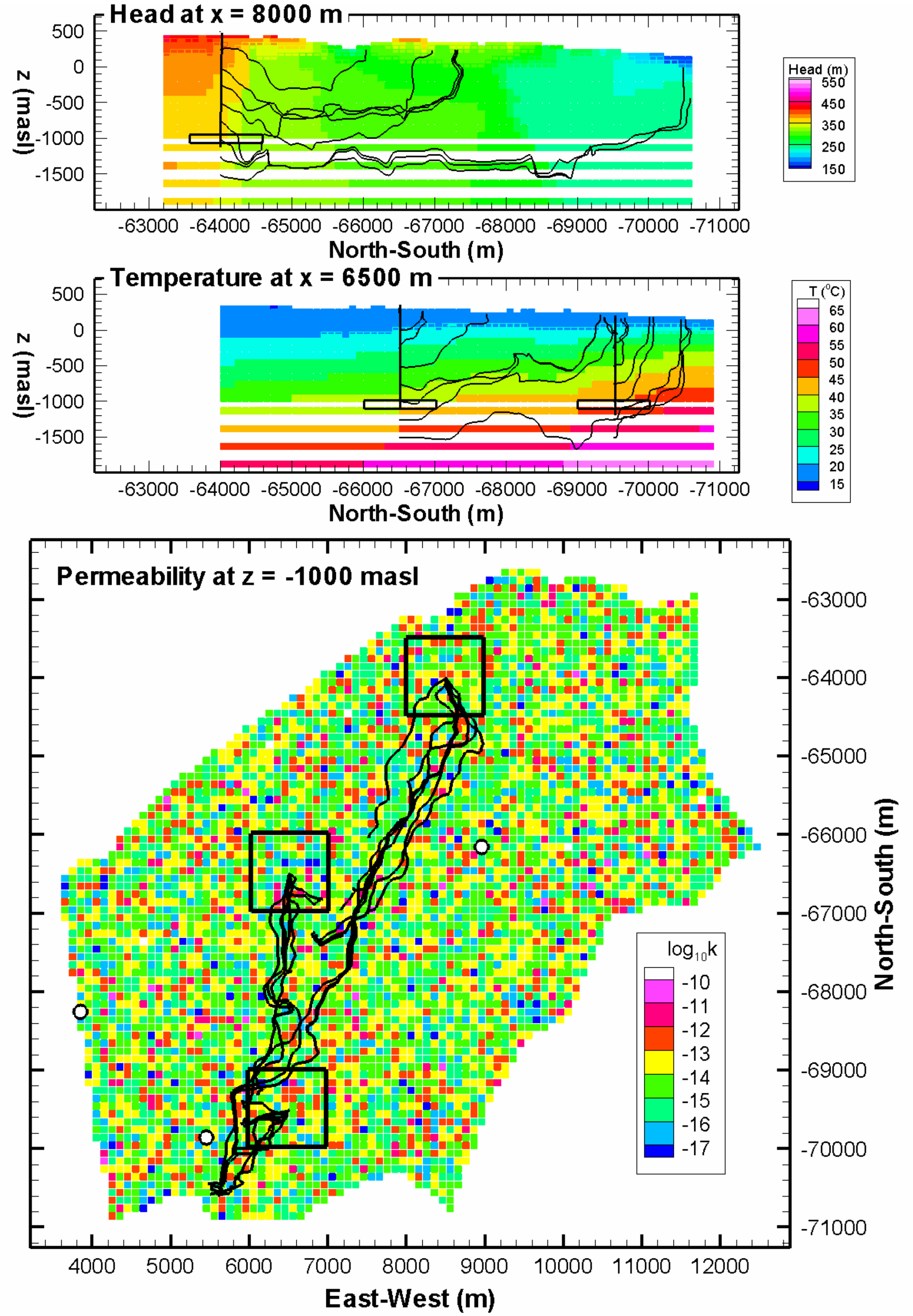

Figure 7-A-7. Case N12: three random wells, no fault.

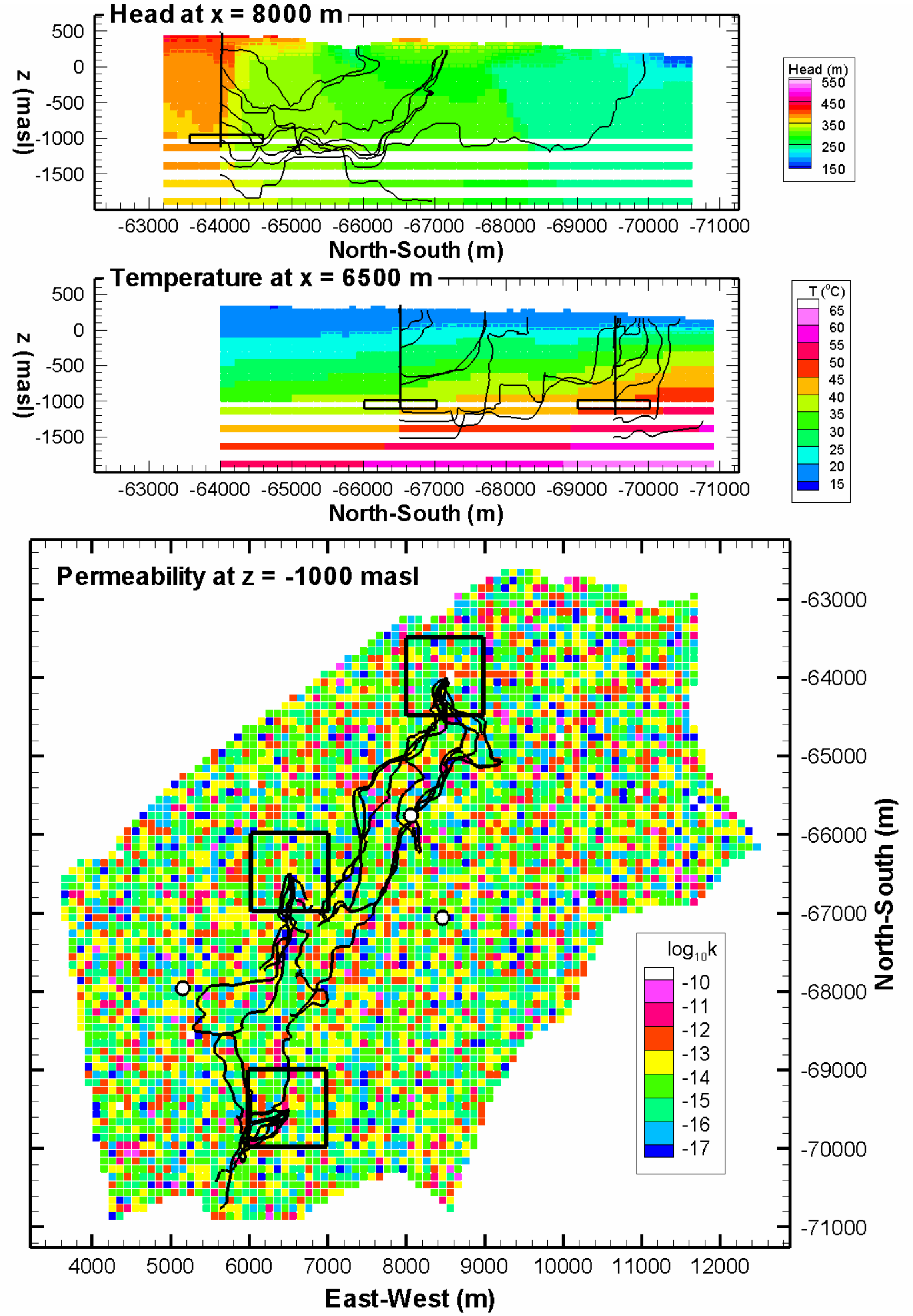

Figure 7-A-8. Case N13: three random wells, no fault.

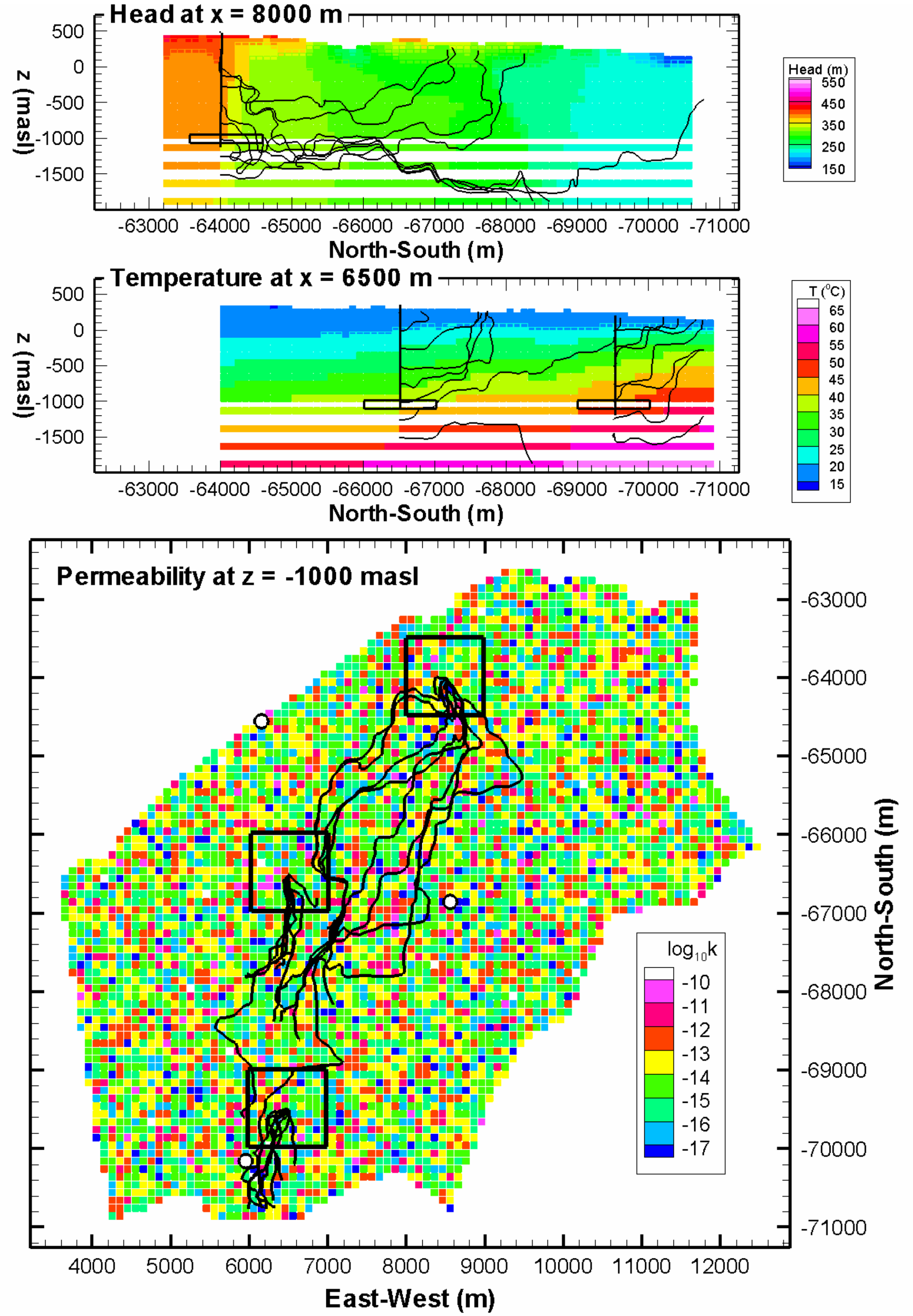

Figure 7-A-9. Case N15: three random wells, no fault.

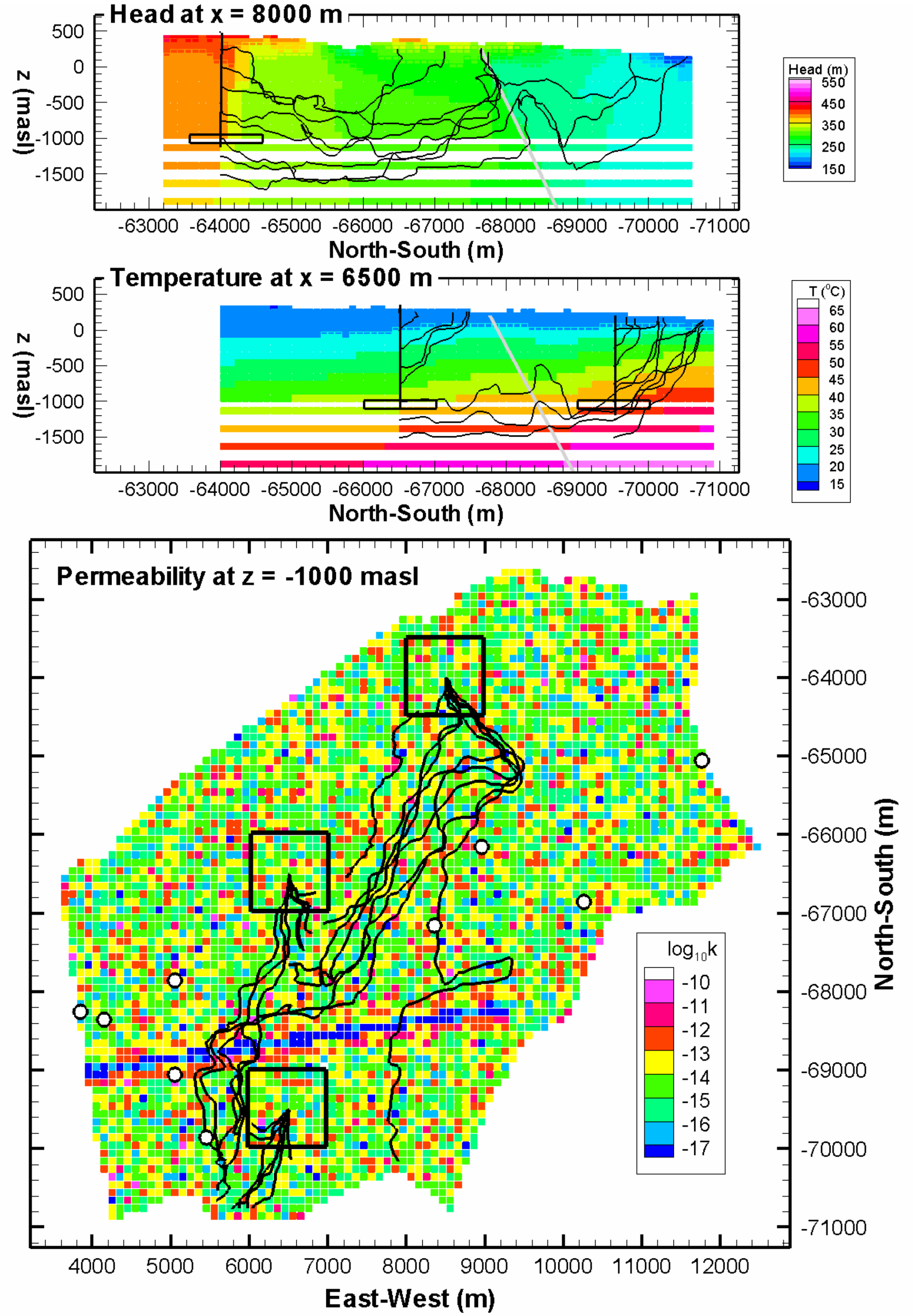

Figure 7-A-10. Case F03: nine random wells, fault.

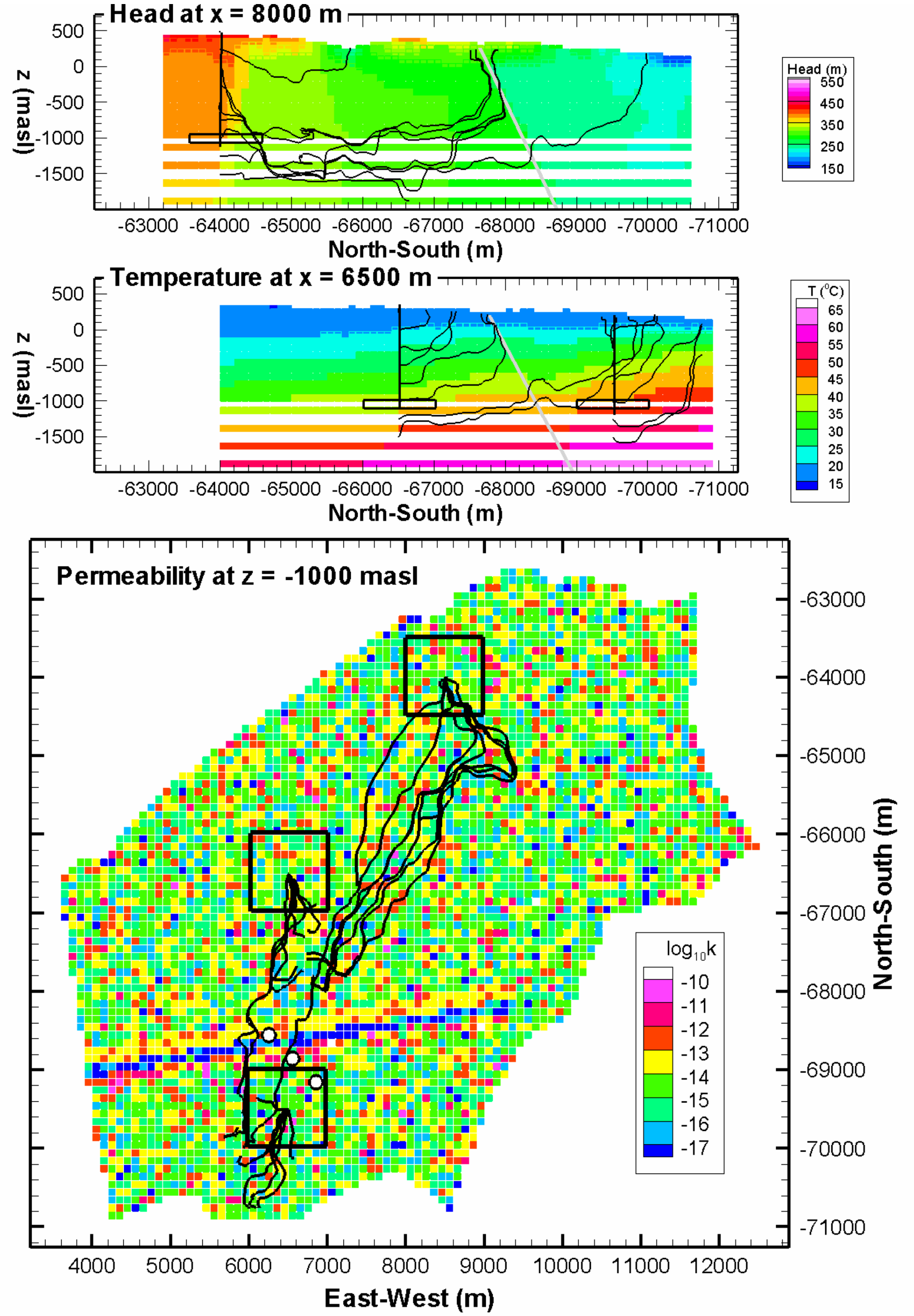

Figure 7-A-11. Case F05: three systematic wells (close to fault), fault.

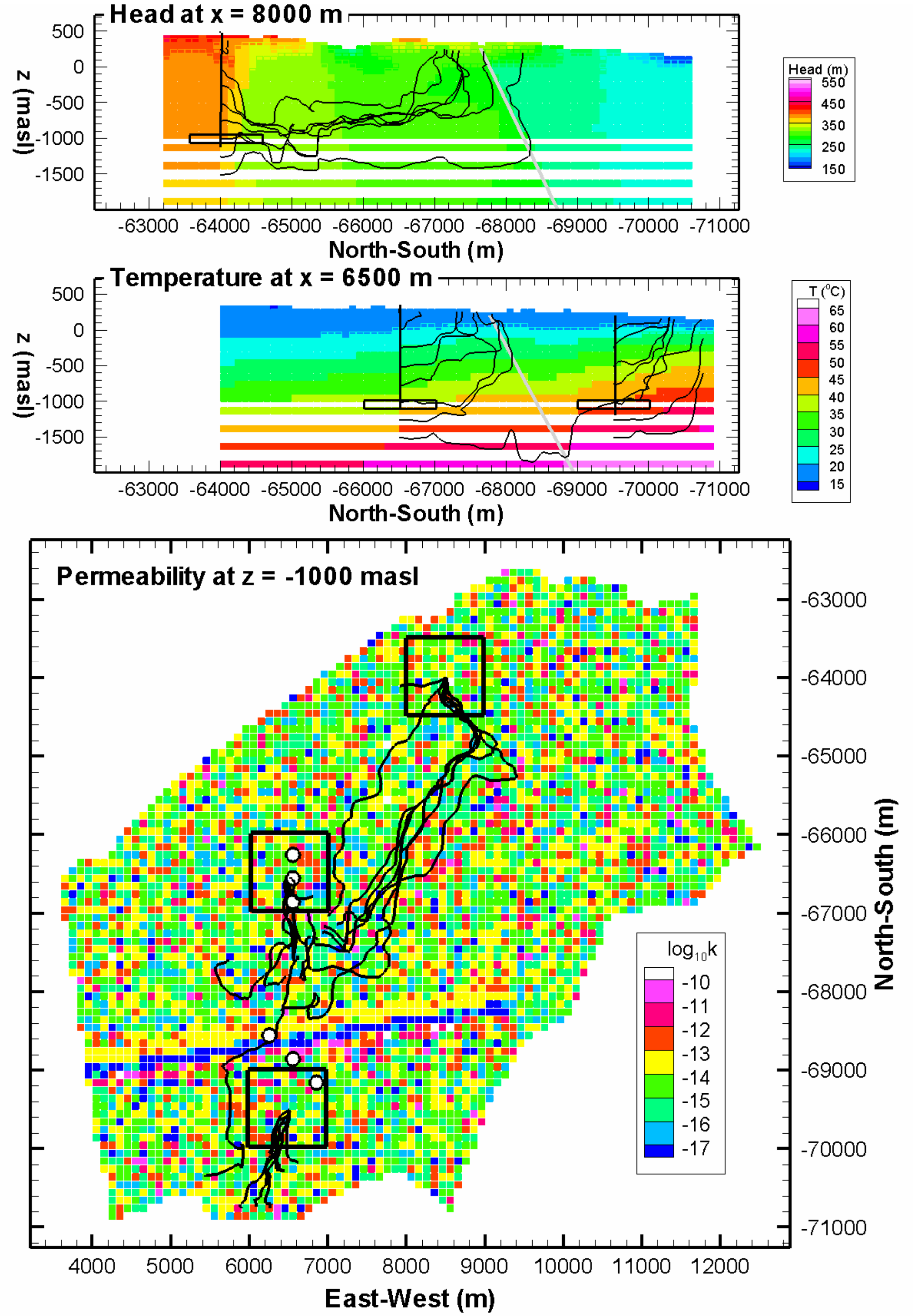

Figure 7-A-12. Case F07: six systematic wells (three close together, three close to fault), fault.

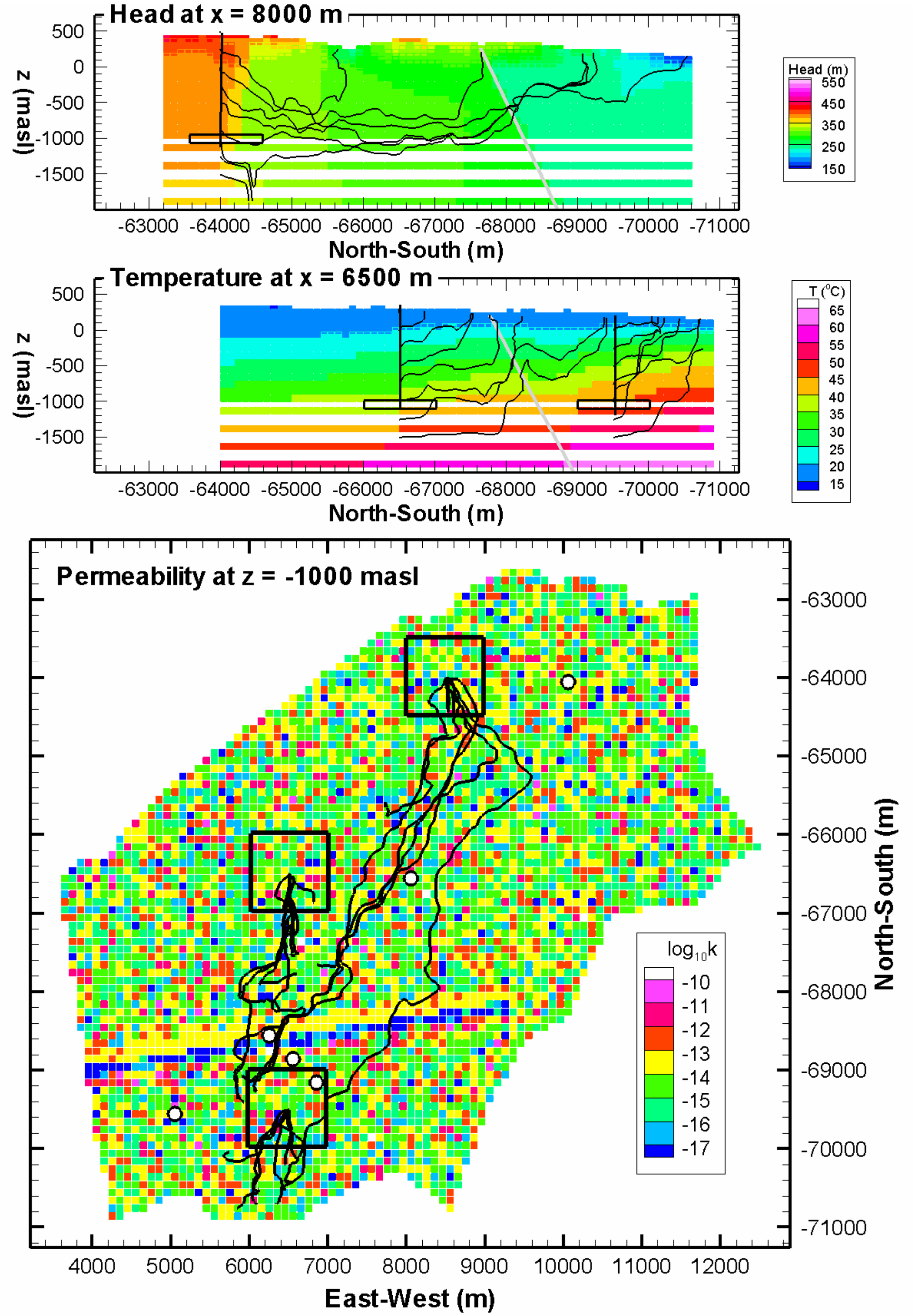

Figure 7-A-13. Case F09: six systematic wells (three close to fault, three far apart), fault.

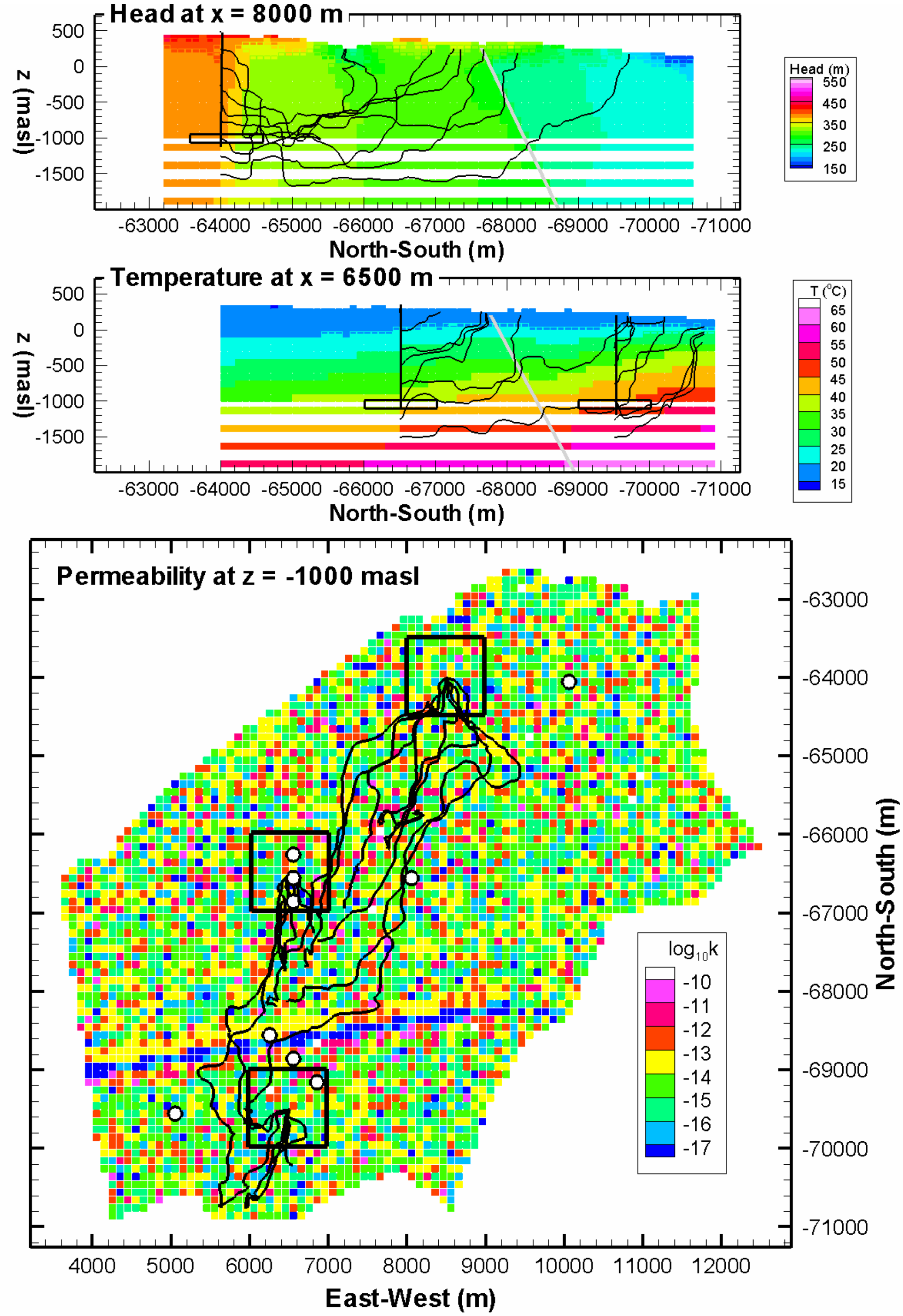

Figure 7-A-14. Case F10: nine systematic wells (three close together, three close to fault, three far apart), fault.

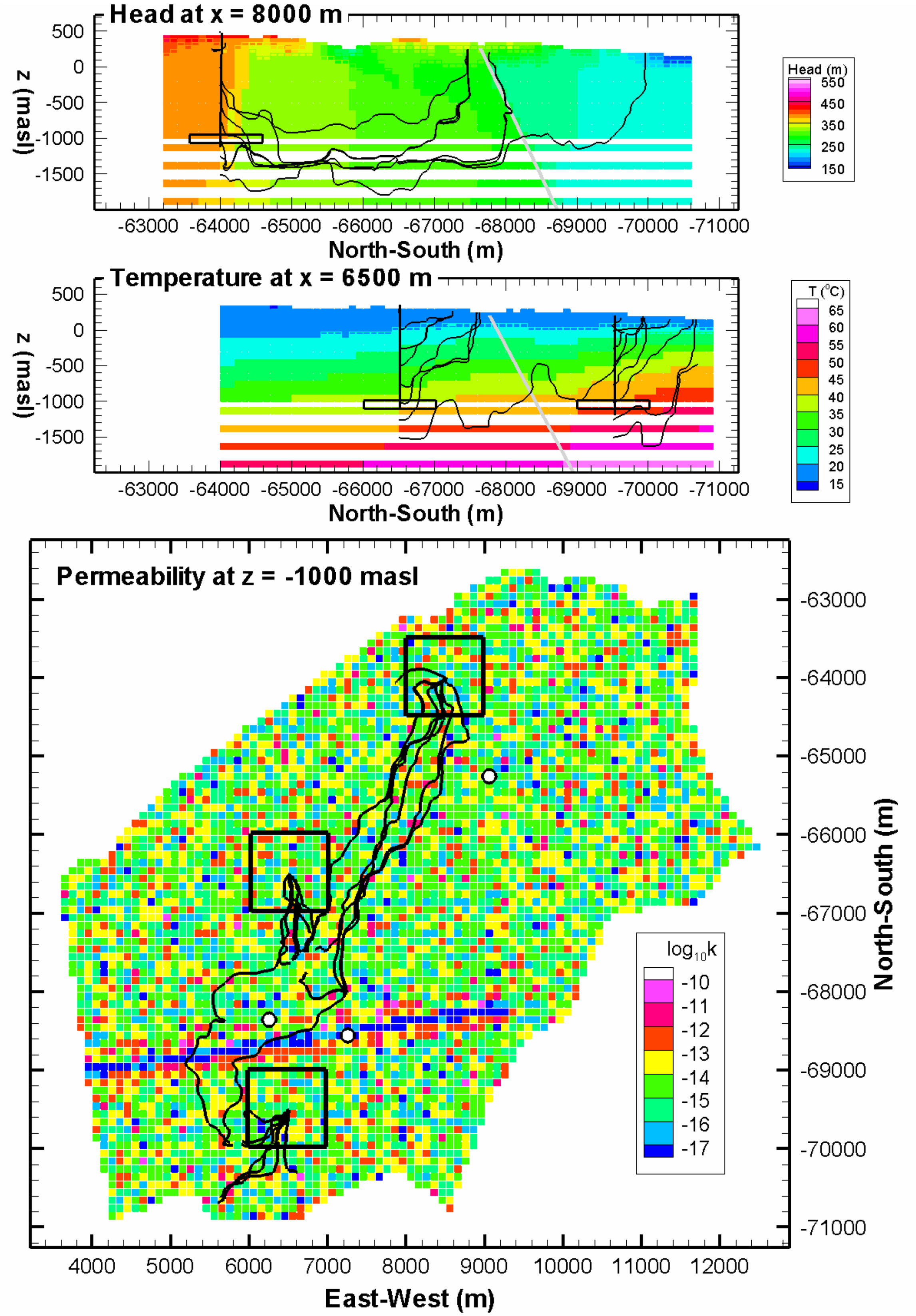

Figure 7-A-15. Case F14: three random wells, fault.

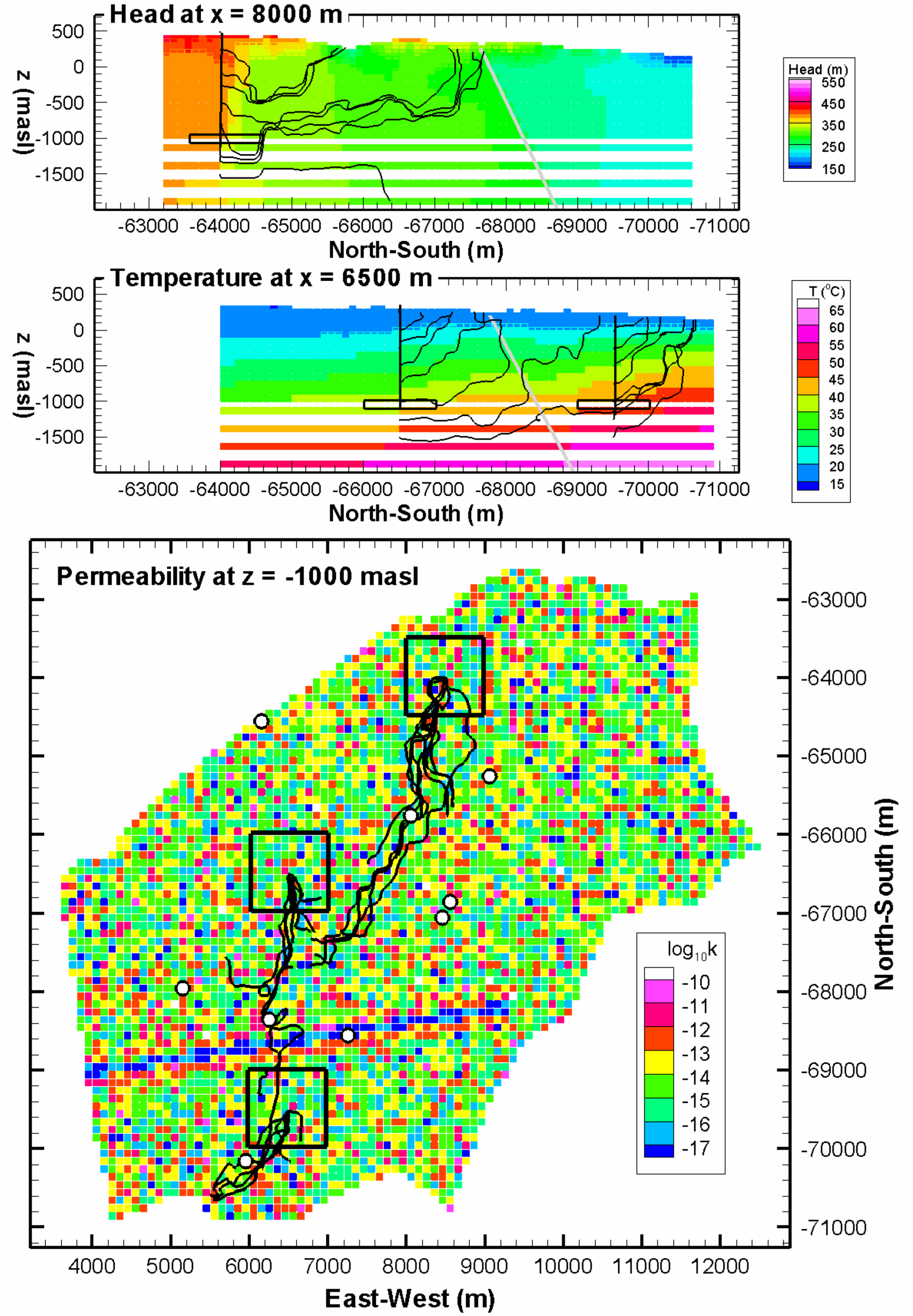

Figure 7-A-16. Case F16: nine random wells, fault.

8　概要調査地域に於ける調査の最適化について

概要調査地区での調査は、精密調査地区を選定するために必要なデータを取得するのが主目的である。従って概要調査段階では、対象地域の地質環境を完全に理解するために必要な全てのパラメータを取得することや、不確実性を限りなく低減させる為に費用や労力を多大に費やすことは不要かつ非現実的である。万一、不適格とされる要因が存在すれば概要調査の早い段階での発見が望ましい。一方、概要調査地区の何れかは精密調査地区に選定される筈である事を鑑みると、概要調査段階での調査は将来の精密調査段階での調査との整合性を考慮したものでなければならない。例えば概要調査の為に掘削する孔井の配置や孔内で行う試験の設定が精査段階でも有利に利用できることが望ましく、少なくとも精密調査の支障にならないようにする事が肝要である。一方、精密調査段階でなされるべき調査を概要調査で行うのは無駄である。

第２章, 第３章、および第７章でも触れたが、概要調査段階で最も特性評価が必要かつ、可能な重要パラメーターは境界条件、および断層の性状である。特に我が国に於いては、断層は地殻変動環境の影響によりほぼ普遍的に存在する。従って、概要調査の対象となり得る地域、地層に於いても例外なく断層が存在すると考えられる。断層は多くの場合、その周辺の水理を大きく左右するが、断層によっては遮水的であったり、逆に極めて透水性があったり、また、両方の特性を兼ね備えている場合があり、一義的にその特性を予測するのは困難である。従って、処分候補地においては、断層の特性を正確に評価する調査が極めて重要となる。

第７章では、実データをベースにした仮想の“実サイト”を構築し、コンピューターモデル内で種々の計画を用いてサイトの“概要調査”を行った。その調査データを元にサイトモデルを構築し、パーティクルトラッキングによる移行速度を計算し、“実サイト”での移行速度と比較した。その結果、境界条件の設定と断層が移行経路や速度に大きな影響を及ぼすことが分かった。概要調査で不適格要因の探査の次に最重要ターゲットとすべきは境界条件の把握、断層の性状の調査、大きなスケールの平均透水係数であることが分かった。実サイトに特徴的な大きなトレンドや構造が無い限り、モデルの予測結果はボアホールの本数や配置にはあまり影響されないことが明らかになった。

本章では本研究のまとめとして概要調査段階でのサイトの特性評価の為の最適な現地調査の方法や取り組み方について検討する。第２章で記したように、各国の処分プログラムで重要で普遍的なパラメータやプロセスは概ね共通である。第７章の仮想サイトでの“概要調査”の比較研究の結果を元に、最適な現地調査手法の組合せや仕様について検討し、概要調査のアプローチについての提言を行う。特に概要調査に於いて最もコストが掛かるボアホールの掘削やボアホール試験の最適化に焦点を当てる。

8.1　概要調査の取り組み方

概要調査地域に於ける最優先課題は不適格要因の探査である。文献調査により不適格要因が存在する事が明らかである地域は既に除外されているはずであるが、概要調査の基本的な取り組み方としては、文献調査では特定できなかった不適格要因が存在する可能性があるとの前提を置き、それを発見する為の調査が最優先されるべきである。合理的に可能な手段を尽くした後にそれでも不適格要因が発見されない事が、その地域が次

のステップ（精査）へ進める為の必要条件となる。無論、（次のステップへ進む為の）十分条件は、候補地の数に左右される。例えば、候補地が２箇所であれば、両方とも自動的に精査段階へ進むが、一方、候補地が多数ある場合はランキングが必要となる。従って概要調査の第２番目の目的はサイトの大まかな特性評価である。核燃料サイクル開発機構の H17 取りまとめ（JNC, 2005）は、我が国で考えられる地質環境において、不適格要素さえ回避すれば、安全な処分場の建設は場所によらず可能と報告している。ランキングの項目は地球科学的要素を始め経済的、社会的条件等の要素等、多岐に及ぶ。実際は、海外の例を見るまでもなく実務的、社会経済的要素がランキングを最終的に大きく左右するが、本編では地球科学的要素以外の条件は考慮しないものとする。

8.1.1 不適格要因の探査

サイトが不適格となりうる主な要因は

a. 活断層が存在する
b. 火山が近傍に存在する
c. 著しい隆起侵食
d. 鉱物資源が存在する

等が挙げられるが、これらの要因は、現地調査に進む前の文献調査段階で概ね存在しないことが確認されていると考えられる。そこで、実際の現地での概要調査において最も現実的に発見され得る要因として考えられるのは伏在活断層であろう。伏在活断層の探査は困難であるが、考えられる手法としては（4.1.2.1 を参照）、

- 反射法、屈折法等の地震探査
- 微小地震モニタリング
- 地表面変位の観測
  - GPS
  - 高精度傾斜計モニタリング
  - 衛星搭載干渉合成開口レーダー（InSAR）
- その他の物理探査手法
  - 電磁波
  - 比抵抗
  - 自然電位
  - 重力

等が挙げられる。特に 3 次元地震探査は堆積岩質の地下の構造を推定するのに極めて有効な手段であり、堆積岩での調査では必ず行われるべきである。3 次元地震探査のコストは米国に於いては 50 フィート立方の精度で 1 平方マイルにつきおよそ 25,000 ドルである。10km 四方の概要調査地域であれば、約 1 億円の計算になる。つまり、ボーリング孔 1 本を掘削するコストと同等か、より安いコストで探査が可能であるので、堆積岩環境であれば、掘削するボーリング孔数を 1 本減らしてでも行うべきである。ただし、

花崗岩のような結晶岩質の地質では弾性波探査はあまり有効でないと言われている。また、表層の被りが厚いと地震波が減衰し良好なデータを取りにくい。また、表面の高低が激しい地域では複雑な補正が必要となり、解析の不確実性が増すので事前の検討が必要である。3 次元地震探査が困難と考えられる場合はボーリング孔を使った疑似３次元 VSP（Vertical Seismic Profiling）を行うことが考えられる。一般に VSP ではボアホールの深度程度の半径(1km の深度のボアホールであれば、最大 1km のオフセット)の逆円錐体の範囲の地下構造の判定が可能である。

8.1.3 で触れるが、InSAR による地表面の観測は安価に広域のデータが得られる利点がある。候補地が決定次第、バックグラウンドデータを取得し地表面変位データの解析を始める事が肝要である。加えて高精度傾斜計の設置も考慮すべきである。ただし、これらの手法は直ちに活断層の発見には繋がらない。長期間のモニタリングが肝要である。

8.1.2 概念モデルの構築

調査の初期段階から地域水理場の概念モデルの構築を始める事が肝要である。最初は文献調査に基づいた極めて大まかな地質構造の概念から始まる。地表踏査や地表面からの物理探査などのデータの解析に伴って概念モデルが複雑化していくが、それに平行して、どういった情報や調査結果により、モデルがどういう理由で、どう修正されていったのかの記録を残すことが非常に重要である。これにはシステマティックな Rivision Control System (RCS) の導入が望ましい。加えて、仮定と調査に基づいた入力データとの差別化を図る必要がある。例えば、概念モデルに於いては一般的に下面の境界条件は、さしたる根拠も無く不透水境界条件に設定されるが、調査の段階で不透水性を示すデータが得られない限り、あくまで仮定である事を忘れてはならない。こういった境界条件はモデル予測の結果を大きく左右し、不確実性に大きく寄与する。

概念モデルは、「どのくらいの量の地下水が、何処から来てどのくらいの速さで何処に行くのか」というサイトに関する最も基本的で重要な知識の根拠となるものであり、当初からそれらの疑問の解明を調査目的とすべきである。

8.1.3 バックグラウンドデータの取得、長期モニタリングの開始

概要調査を行う地域が決定次第、初頭からバックグラウンドのモニタリングを開始するのが肝要である。既設の GPS が存在すればそのデータが利用も可能であるが、複数点での観測が望まれる。また、InSAR などのリモートセンシングデータに関しても調査開始前のデータを確保するべきである。さらに、高精度傾斜計の設置も考慮すべきである。GPS や InSAR データと併用する事で解析の信頼性と精度が増す。また、微小地震観測ネットワークを設置するのが望ましい。その他、温度等の環境データ、河川、海水サンプルの定期的な採取プログラムを開始する必要がある。また、既存の井戸があれば、可能な限り利用し、水位等の記録計を設置するべきである。要はサイトにボーリング孔の掘削といった人的な影響を与える前の段階（バックグラウンド）のデータを押さえておく必要がある。

バックグラウンドデータは精査の段階で重要になってくるもので、概要調査期間中に著しい変化が認められない限り、バックグラウンドデータが概要調査から精査段階に進

む際の評価基準になるとは考えにくいが、概要調査地域の何れかは精査段階に進むので少なくとも有力候補地でのバックグラウンドモニタリングは早期に始めるべきである。

8.2 ボーリング孔

8.2.1 目的

概要調査でボーリング孔を掘削する第一目的は 3 次元震探等の非侵襲的な物理探査手法によって不適格要素の存在が疑われる箇所があった場合、その存否の確認である。第二には、処分場建設に適すると予測されるボリュームの地層の性状のおおまかな調査である。精査に進んだ段階で概要調査段階で掘削したボーリング孔を使って詳しい調査を行うことが可能なので、再取得不可能なデータ以外の必要以上のデータの取得は避けるのが時間的にもコスト的にも経済的である。例えば、詳細な圧力試験やトレーサー試験、フラクチャーのロギング等は概要調査段階では不必要と考える。

一方、我が国では 500m~1km の深度のボーリング孔を掘削すれば、殆ど例外なく断層が確認される。第 7 章の結論からも明らかなように、断層の性状が周辺の水理場を大きく左右するので、断層の性状の把握が重要である。従って概要調査段階ではボーリング孔を掘削する主目的は地質データ取得に加えて主要断層の性状の調査と境界条件を把握する為と考えるべきである。

8.2.2 位置

ボーリング孔の位置はリモートセンシング、3 次元地震探査等の物理探査や地表踏査の解析結果に基づいて決定されるべきである。実際の掘削地点は用地の買収に関する要件やアクセスなどの要因にも左右されるであろうが、基本的には 3 次元地震探査等の物理探査に基づいて以下をターゲットとするべきである。

a. 不適格要素の存在が疑われる地点や断層

b. 処分場建設に十分な容積が取れる岩体

c. 上流、下流、側方境界付近

ボーリング孔は可能な限り、複数同時に掘削しない事が肝要である。スケジュールが許す限り、先に掘ったボーリング孔から得られるデータに基づいて次の孔井の掘削地点を決定するのが望ましい。先に掘ったボーリング孔は次の掘削による水理影響の観測井として使うことができる。掘削のみならず、ボーリング孔を使った一通りの調査を行った後にその結果を加味して次のボーリング孔の位置を決定して掘削をするのが理想的である。ただし、掘削地点が数キロメートル離れていればお互いに干渉しないと考えられるので同時に掘削を進行させても問題はない。

8.2.3 本数

概要調査でボーリング孔を何本掘れば良いかは、他に候補地が幾つあるか、予算、スケジュール、その他の要因に左右される。地球科学的な見地から言えば、地層の特性が

ある法則を持った分布をしている事が既知でない限り、何本のボーリング孔を掘ればその地域の特性がどの程度把握できるか前もって予測することは不可能である。また、概要調査の段階でどの程度の詳しさと確からしさで特性を把握しなければならないかという問題も、前出の要因に左右される相対的な問題である。無論ボーリングの本数が多いほど、より多くの断層等の地質学的特徴をサンプルできることは明らかであるが、1孔数億円のコストが掛かり、精密調査段階に進むのは数箇所の概要調査地域の内 2 箇所程度である事を考えると、概要調査のそれぞれの候補地で数多くのボーリング孔を掘削するのは現実的でない。第7章の研究では、（少なくとも東濃地域のような地層では）ボーリング孔３本のデータを使ったモデルと９本のデータを使ったモデルで予測結果に大きな違いは見られなかった。

各概要調査地区に付き、例えば、ボーリング孔 10 本を目安にすると、その 10 本を上記の a, b, c 間でどういう風に割り振るかが課題となるが、先ずは、不適格要素の存否の確認と断層の性状調査の為のボーリング孔数を最優先するべきである。健常なホストロックの性状と連続性の概要調査には多くの本数は必要がなく、多くても 3 本のボーリング孔で足りると思われる。残りの本数は上流、下流の境界条件の調査のためのボーリング孔を調査地域の境界付近に掘削する必要がある。

一般に特別な地質学的特徴（大きな断層など）をボーリング孔が貫通するかそれらの極めて近傍にない限り（上記 a 目的のボーリング孔）、ボーリング孔内で実行可能な調査から候補地を大きく差別化するデータが得られるとは考えにくい。また、第 7 章の研究からも明らかなように、文献調査のふるいを通った後の、我が国で考えうる地質条件においては物質移行の予測結果を大きく左右するパラメーターは断層の性状、有効間隙率、透水係数、ならびに境界条件である。これらの内、有効間隙率の推定は非常に困難であり、未だ研究の域を出ておらず、概要調査の段階では意味のある確からしさで特定する事は不可能である。よって、概要調査でのターゲットにするべきではない。無論、精査の段階では、可能な限りの手段を尽くして有効間隙率の推定に努力するべきである。これらの内、比較的推定しやすいと考えられるのは平均透水係数である。細かいスケールでの透水係数分布を特定しようとすれば、多くのボアホールと孔井試験が必要となるが、概要調査の段階では広域の平均透水係数が推定できれば良く、数多くの本数は不要である。

8.2.4 深度

掘削深度は処分場のターゲット深度より最低 500m 以深に掘削する事が望ましい。例えば、堆積岩で 500m の処分場深度であれば、1000m のボーリング深度が望ましい。結晶岩質では 1000mのターゲット深度を想定すれば、1500m 程度の深度まで掘削するのが望ましいと考える。

8.3 掘削

8.3.1 ログ

ボアホール掘削中のドリルログは掘削の進捗や地質状況の速報の役割としてのみに終わる事が多いが、実は掘削中の逸水や掘削速度等のデータは地層の水理特性の大雑把な

推定に役立つ。特に逸水データから高透水性ゾーンの位置が推定でき、後の水理テストの設計の重要な参考になる。コアボーリングをしない場合は地質の専門家を常駐させてカッティングのログを取る必要がある。また、掘削中の環境モニタリングを忘れてはならない。さらに、掘削水に SF6 等のトレーサーを混入させて掘削水による地層水の汚染をマークする必要がある。これは、後に採取する地層水サンプルの地球化学データの信頼性評価の為に重要である。

8.3.2 傾斜掘り

傾斜掘りは垂直に近い断層やフラクチャーをボアホールでサンプルする為に有用であるが、垂直孔に比べてコストが掛かる。概要調査の段階では、傾斜（dip）が鉛直に近いフラクチャーをサンプルする為のみの理由で傾斜孔を掘削することは不要であると考える。第 3 章でも触れたが、フラクチャーの統計的データや幾何学データは少なくとも概要調査段階では全く使えないと言っても過言ではない。しかし、周辺地域の水理場を支配しているであろうと思われる主要な断層に直交して貫通させる目的で傾斜孔を掘削するのはそれなりの意味がある。

8.3.3 コアボーリング

核廃棄物処分場候補地の特性評価の為のボーリング孔掘削で全孔コアボーリングをする事は内外の処分プログラムでも慣例となっているが、コアを採取しない場合に比べ、遥かに費用と時間が嵩む。実際、コア採取からコア貯蔵の施設の費用まで含めると膨大なコストとなる。無論、岩石の強度試験や地化学データを得るためにコアは欠かせないが、実際に実験用に使われるコアはほんの一部に過ぎない。予算が許せば全てのボーリング孔を全孔コアボーリングするには越したことはないが、コストの最適化の観点から見れば、コアボーリング孔 1 本と同じコストで 2 本のボーリング孔が掘削できれば、長い目でどちらが有効かは意見の分かれるところであろう。コアが得られない代わりに 2 地点で圧力データや、水質データが得られ、全孔のコアを取るほど詳細ではないがドリルログや検層から連続した地質データも取得可能である。特に、水頭圧や水質サンプリングの為に調査地域の境界周辺に掘削するボーリング孔ではコアボーリングはさほど重要でないと考える。同じ予算であれば、もう 1 本、ボアホールを掘削したほうがより重要なデータが収集できると考える。折衷案として考えられるのは、場所によっては全孔コアボーリングの代わりに、地質が変わる毎や一定区間毎にコアを採取し、掘削後にボアホールイメージングログ（可視又は音波）で代用する方法も視野に入れるべきである。

8.3.4 ボーリング孔径

口径が大きい程掘削コストが高くなる。従来はロギングツールを上下させたり、センサーを多数の深度に設置するためには、ボーリング径がある程度大きい必要があったが、近年の MEMS、スマートセンサーやデジタル転送技術の発達（4.2.2 参照）に伴い、計測装置の大きさが格段に小さくなってきている。加えて径 5-3/4 インチ程度の slim borehole (Hough, 2000)や 3 インチ以下の microhole（4.2.1 参照; DOE, 2006）の掘削技術が発達してきており、コスト削減の為にも小孔径のボアホールの掘削を考慮すべきである。ある試算によれば、径が半分になれば掘削コストは 40~50%になる。掘削コストのみな

らず、掘削に必要な用地は約 1/4 で済み、リグが小さくて済むため検層コストやモニタリングコストも低減できる。

8.3.5 掘削水

掘削の際にはビットの冷却やカッティングを搬出させる為に水を循環させる必要がある。加えて泥岩などの軟岩では崩壊を防ぐ為にベントナイト等を加えた比重の重い泥水を循環させる必要がある。しかし、この水が地層水を地化学的に汚染してしまう恐れがある事や、光学的ボアホールビデオログの妨げになることから、清水や純水を使って掘削した例が国内外でみられる。しかしながら、清水や純水でも地層水とは地化学成分が異なるので成分比の汚染は避けられない。従って概要調査の段階ではコストが嵩むわりには利点は少ないと考えられるので最も掘削しやすい方法で掘削するのが望ましい。ただし、前出のように、掘削水に SF6 等のマーカートレーサーを混入させることは重要だと考える。一方、ヤッカマウンテンの不飽和領域での掘削では掘削水そのものが飽和度を変えてしまう恐れがある事から空気掘削技術を開発した経緯がある。無論、日本の調査では空気掘りをする必要はない。

8.4 検層

掘削後は検層サービス会社が提供するスタンダードなワイヤーラインの孔内検層（比抵抗、音波、温度、放射能、圧力、キャリパー等、4.1.2.2 を参照）を行うのは言うまでもないが、加えて、純水で孔内水を置換する電気伝導度検層(Flowing Fluid Conductivity Log, 4.1.3.1.1.3 参照)を行い、孔井の深度に沿った相対透水性の分布を把握するのが望ましい。ただし、FEC Log は裸孔である必要があり、花崗岩のような結晶質岩では裸孔を保てるが、軟弱な堆積岩ではケーシングの設置が必要となるので掘削直後に FEC Log を行う必要がある。FEC Log から得られる相対透水性の分布情報はキャリパーと併せて、パッカー配置を計画する際に役立つ。概要調査段階では細かい透水性の深度分布の情報は不必要であるが、検層を終えたボアホールには水頭の違う地層間の短絡を防ぐ目的と圧力や温度のモニタリングの為に複数のパッカーを設置する必要があり、パッカーをなるべく最適な深度に必要最低限の個数で配置する事が望まれる。一旦パッカーを掛けると再び開孔するには時間とコストが掛かるので慎重に計画したい。

深度方向の温度分布の情報は広域地下水理の推定に寄与するが、掘削直後に行う温度検層は掘削の影響が残っており、しかも開孔状態ではボアホール内の水の流れによる動的な温度分布しか観測できない。動的な温度分布は地層間の相対圧力と温度の違いによって起きるので有用ではあるが、静的な状態の温度分布を求めるにはパッカーの設置が必要で掘削後かなりの時間を要する。

8.5 ボアホール試験

ボアホール試験は、コア試験に比較して大きなスケールで試験が可能であり、地下深部の特性を直接的に評価する目的で行う。概要調査段階で行うべきボアホール試験は、物理探査と水理試験である。ボアホール試験を行った後に、モニタリングの為のセンサーを設置することになる。

8.5.1 ボアホール物理探査

8.5.1.1 弾性波探査

概要調査に必要で取得可能な地震波探査データは前に述べた 3 次元地震探査ですでに取得されているのが望ましいが、地表付近の被りが厚く、表層で地震エネルギーが大きく減衰してしまうと 3 次元地震探査では質の良いデータが取得できない恐れがある。そういった場合は孔井を使った物理探査が有効である。孔間弾性波トモグラフィーは比較的スケールの小さい地質性状の解明に寄与するが、概要調査段階では小さいスケールの情報は必要でない。従って、孔間トモグラフィーを行うことを目的に孔井間隔を近距離にするべきではない。一方 Vertical Seismic Profiling (VSP)は孔井間トモグラフィーに比較すると解像度が低いが単一孔で実行可能であり、ボアホールを中心に放射状に側線を取ることで 3 次元的なデータを取ることが可能である。サイトの適性に関るような性状の断層の存在が疑われる際に近傍にボアホールを掘削した場合は VSP が有効な手段と言える。

8.5.1.2 ボアホールレーダー

スウェーデンやスイスなどの花崗岩のサイトでの特性調査ではフラクチャーの検出にボアホールレーダーが用いられた例が幾度かあるが、セクション 3.5 でも述べたようにフラクチャーの頻度と透水性に相関性が見られた例は過去に殆どなく、特に概要調査の段階では細かい亀裂情報は不要であるのでボアホールレーダー調査の必要はないと考える。

8.5.2 力学試験

ホストロック中の応力場に極端な異方性があれば処分場建設に困難をきたす事が考えられるのでターゲット深度で水圧破砕などの手法を使って孔内応力測定試験を行うのが望ましい。またボアホールのブレークアウトから応力方向や非等方性が推定できる他、弾性波との相関性を仮定すれば一軸強度の分布の推定も可能である。後に述べるコアサンプルの強度試験も必要となる。

8.5.3 地下水サンプリング

地下水の地化学的情報は大きなスケールでの水理場の解明に寄与する。地層区分にも拠るが、ボアホールの貫いている基盤岩の浅部、処分場のターゲット深度、孔底の 3 箇所程度の深度から地下水のサインプルを採取するべきである。ガスの存在が確認されれば、ガスのサンプル採取も行う。採取をする際、揚水する必要があるが、マーカートレーサーの濃度が十分低くなるまで（例えば、<1%）汲み出した後のサンプルを採取する必要がある。ヤッカマウンテンでは当初、地質調査用、物理探査用、水理学用、地化学用とそれぞれ別のボアホールを掘削したが、無駄が多すぎた。地下水サンプル採取は次に述べる揚水試験と組み合わせて行うのが効率的である。

8.5.4 揚水試験

概要調査のボアホール試験の中で最も重要な試験の 1 つが揚水試験である。揚水試験はコア試験に比べてはるかに大きなスケールで地層の水理性状の推定が可能である。内でも、定流量の揚水試験が最も有効な手段である。しかしながら、我が国では断層が遍在するので、処分場建設に適すると目されるホストロックをターゲットに掘ったボアホールでの揚水試験でも、断層の存在を抜きにした解析は考えにくい。

揚水試験が不可能な程に透水係数が低ければ圧入試験や圧力降下試験という方法も考えられるが、両者とも地下水サンプルが採取できない上に、後者は影響半径が限られるので大きなスケールについての特性は明らかにならない。もっとも、揚水試験ができない程透水係数が低ければ、少なくともそのボアホールに於いては、透水係数に関しては概要調査の目的がすでに達成されたと考えても良いであろう。何故なら、透水係数が低い事自体、サイト特性としては好条件であるからである。

8.5.4.1 試験期間

揚水期間が長ければ長いほど、大きなスケールでの平均の透水係数が推定できる。概ね、倍のスケールを達成するためには 4 倍以上の揚水時間が必要である。よって、概要調査では、環境に悪影響を及ぼさない範囲で可能な限り長期揚水試験を行うべきである。ただし、周辺の井戸の水位や、水質によっては汲み上げた地下水の処分に注意する必要がある。揚水井での圧力が定常になるまで、揚水を続けるのが理想である。また、揚水停止後の圧力回復のモニタリングを欠かしてはならない。2 ヶ月の揚水期間であれば、さらに最低 2 ヶ月の回復期間をあてがえたい。

いずれにしろ、試験期間はできる限りフレキシブルにする必要がある。スケジュールを守るためだけの試験を行って、結局得られたデータは使い物にならなかったケースは過去に多々ある。信頼性の低い数多くの試験をするより、1 回でも信頼度の高い長期テストを行うほうがはるかに重要である。

8.5.4.2 揚水レート

直感的には揚水レートが大きいほど、大きなスケールの試験ができると考えがちであるが、実際には影響される岩体のスケールは揚水レートに依存しないので、揚水レートを制限することによって環境への影響を低減し、コストも抑える事が可能である。一方、揚水量が大きいほど圧力変化が大きくなるので遠隔にある観測井で実際の圧力干渉とノイズとを差別化して捉え易いという利点がある。そこで、実際の現場で種々の要因を加味して揚水レートを決定すべきである。掘削時の逸水データや事前の Fluid Logging やドリルステムテスト（DST）等がレートを決める参考になる。いずれにしろ、観測にはできるだけ高精度、高感度のセンサー（例えば、Paroscientific 社製の Digiquartz）を使うことが肝要である。

8.5.4.3 試験区間

概要調査でもっとも必要なパラメータの1つはできるだけ大きなスケールの平均透水係数である。よって、試験区間を細かく区切って、数多くの試験を行う必要は無い。基盤岩を地質構造と区間長に基づいて大きく 3 区間程度に分けて試験をすればよいと考える。例えば、200m以深が基盤岩の 1000m深度のボアホールなら、1区間長が平均 300m程度で十分と考える。大事なのは、上述のように試験期間を可能な限り長く取る事である。4 区間で 1/4 の長さの試験を 4 回行うより、全区間を 1 回の試験で 4 倍の長さの試験をした方がより良いデータが得られる。

8.5.5 トレーサー試験

トレーサー試験は一般に有効間隙率、マトリックス拡散や吸着性を評価する目的で行われるが、概要調査段階では行う必要が無いと断言できる。その理由は、トレーサー試験はコストや時間が嵩むわりに意思決定の基準となるデータがまず得られないからである。有効間隙率の推定やマトリックス拡散は物質移行時間の計算に不可欠であるものの、未だに決め手となる調査手法が存在せず、概要調査段階で行うことができるトレーサー試験では信頼性のある値が得られない。また、我が国で考えられる地質では、マトリックス拡散や有効間隙率の違いが精査に進むがどうかの要素とはならないと考えられるからである。さらに、トレーサー試験結果を正しく解析する為には流れの場のジオメトリーが既知である必要があるが、特にフラクチャーの卓越した岩盤では、流れの場が不明であることが多く、不確実要素が大きい。また、孔間トレーサー試験を行うには近接した(100m 以下) 2 本以上のボアホールが必要であるが、概要調査段階ではよほど予算と時間に余裕が無い限り、近接して複数のボアホールを掘削するべきでない。2 本のボアホール間でトレーサー試験を行うことができ、解析が可能であったとしても、推定される有効間隙率は 2 点間の特性でしかない。以上のことから、概要調査段階では有効間隙率の測定を調査の対象にするべきでなく、トレーサー試験を行う必要はないと考える。

8.6 コア試験

概要調査段階でのコア試験で最も必要なのは力学強度試験であろう。ホストロックに処分場建設に十分な強度があることをコア試験で確認する必要がある。また、我が国において、有望な鉱物資源が存在するとはまず考えられないが、この点も確認しておく必要があるのでサンプル的に鉱物組成を調べる必要がある。また、コアから採取される地下水やガス成分の分析を行っておく必要がある。一方、コアの透水試験はほぼ必要無い。何故なら、ボアホール試験で確認される透水係数はほぼ例外なくコア試験の値より大きな値を示すうえに、より大きなスケールを代表する値であり、より信頼性が高い。再取得が不可能なデータについては抑えておく必要があるが、その他のコア試験も概要調査の段階ではさして重要でなく、コアの状態の保存に留意すれば精査段階に先送りして問題ない。

8.7 モデリング

概要調査の段階で性能評価の計算まで必要かは意見の分かれるところであるが、少なくとも、どのくらいの量の地下水が何処から来てどこを通ってどの位の速さでどこに出

て行くかを予測推定できる水理地質構造モデルが必要である。しかしながら、実際にはこの一見、基本的で簡単な問題を細かく正確に解明するのは困難を極める。特に概要調査の段階で完全に解明するのは不可能と言える。そこで、必要かつ調査可能なパラメーターを把握することを概要調査の目的とすべきである。

第 7 章の研究からも明らかになったように、水理地質モデルの予測結果を最も左右するのは、以下の 4 つであるが、

1）平均有効間隙率

2）境界条件

3）断層の性状

4）平均透水係数

1）の有効間隙率の正確な同定は現在の技術では極めて困難であり、概要調査の段階での計測は不可能である。精査が終わる段階までにある程度の幅を持って推測できれば良しとすべきであり、今後の技術開発が期待される。２）の境界条件の同定もかなり困難である。涵養量、下方、側方境界を決定するには慎重で詳しい調査が必要であり、前出のように境界条件の推定の為のボアホールを掘削する必要がある。３）の断層の性状は概要調査でかなりの確からしさで把握されるべきであるが、断層の調査手法も未だに確立されていないのが現状である。４）の平均透水係数に関しては、ボアホール水理試験に加えて、モデル全体の水収支やエネルギーバランス、地化学データなどからある程度の確からしさで把握できると考える。

概要調査段階でのモデリングの目的はサイトの特性の理解を具現化するものであり、その理解がどういった調査データを使ってどういう風に変遷して行ったかのトレース(証拠)を残す為のものである。また、モデリング結果を以後の調査計画に反映させるのも重要な目的である。現実的には、概要調査地域間のモデリング結果の違いが複数の概要調査地域の中から精査地域を選出する根拠や決定要素になるとは考えにくい。サイト間の特性の違いそのものより、個々モデルの入力データの不確実性の幅が遥かに大きいと考えられる。

ここで強調したいのは、概要調査段階では不適格要因が存在しないことがある程度の確からしさで確認されれば、サイト特性のパラメータに関して不確実性が大きくても良いと考えるが、精査の段階では不確実性を低減するための調査と技術開発の努力を惜しんではならない。

8.8 まとめ

本章で述べてきた概要調査の流れの略図を Figure 8-1 に示す。図中ではすべてのボアホールの掘削を終えた後にボアホール試験を行うことになっているが、ボアホールの距離が離れている場合はボアホール掘削毎に試験を行っても問題ないと考える。また、両方向の矢印は調査と概念モデルの間の相互のフィードバックを示す。最後に重ねて強調されるべきは、調査手法もモデリング技術も今後、大きく発展する必要性と余地が残されており、サイトの特性調査に関してはフレキシビリティを保ちつつ、その時点毎に入手可能なベストな手法の選択を続けるのが良策と考える。

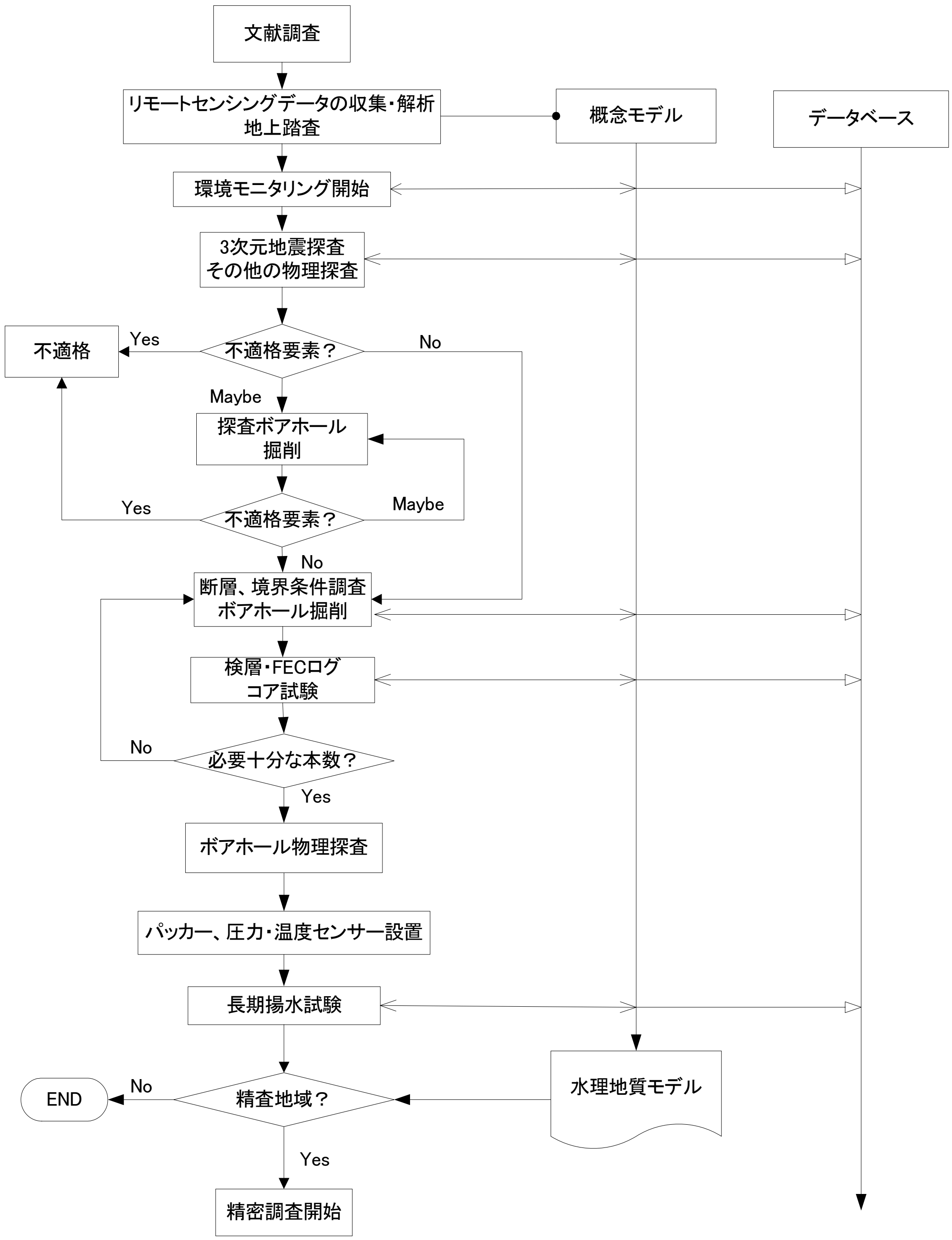

Figure 8-1: 概要調査の流れ

8.9 References

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Appendix 1

NUMO-LBNL Collaboration on Feature Detection, Characterization and Confirmation Methodology
-Implementation plan (Revised)-

Task A: Survey of Site Characterization Programs

Objectives:

The objectives of this task are to identify key and common site parameters important for safe disposal of nuclear wastes, to identify and evaluate existing and emerging field testing technologies to obtain such parameters, and to compile the know-how's based on the experiences from the countries with an active site characterization program.

Approach:

Task A-1: Identification of Important Parameters

In this task data from Japan, U.S. and other international investigations will be evaluated to identify key parameters that are important for site characterization for a nuclear waste repository. At the preliminary investigation stage it is not necessary or practical to exhaust all the parameters that are needed to describe the site completely. Site description will have to be made using available data. Such data will come from surface investigations, hydraulic and geophysical tests and surveys in a limited number of boreholes and trenches. The task will initially focus on examining a list of key and common parameters from site investigations elsewhere. Such sites may include, but not limited to, Yucca Mountain (USA), Äspö (Sweden), Olkiluoto (Finland) and the sites being characterized in Japan. We will compose lists of key parameters at various sites from the U.S. and other international investigations including Japan and identify key parameters that are common to majority of the sites.

Task A-2: Compilation of Site Characterization Know-how's

In this task we will analyze the success and failure stories and extract lessons learned from various site characterization programs from the world. We will then compile essential know-how's of site characterization strategy.

Task A-3: Evaluation of Site Characterization Technology

In this task, available and emerging field investigation technologies in the US and other international investigations including Japan will be reviewed. Their merits and limitations will be evaluated as well as their applicability to site characterization. The study will encompass geological, geophysical, hydrological, geochemical and geotechnical testing, monitoring and analysis technologies. Initially the emphasis will be on those that can be used at preliminary investigation areas. As the siting process advances progressively through stages and time, it is reasonable to expect that there will be a continuing improvement of field testing technologies that can be applied for site characterization. Thanks to various technological advancements, it is becoming possible to acquire data at ever higher resolutions and wider dynamic ranges, and in some cases it is even possible to collect a new set of parameters that has been previously unattainable. Such technologies available in the US include: (1) technology to estimate the heterogeneity structure much like the seismic tomography by measuring minute pressure changes at a very fast sampling rate during a cross-borehole hydraulic test, and by inverting the pressure arrival times and (2) automated wireless data acquisition technology applicable for borehole-based monitoring. Existing field investigation and exploration technologies available in the US, Japan and elsewhere including geological, geophysical, hydrological, geochemical, and geotechnical testing, monitoring and analysis techniques will be surveyed. Their usable ranges, accuracies, and their applicability to site characterization will be analyzed. New and emerging site investigation technologies including geological, geophysical, hydrological, geochemical, and geotechnical testing, monitoring and analysis techniques will be evaluated based on accessible information. Their prospective performance and future applicability to site characterization will be examined.

Task A-4: Investigation of Uncertainties

Uncertainties exist in every aspect of site characterization. They can be associated with the data obtained during site investigation, data interpretation, the assumptions and parameters in the numerical model that uses the data as input, and the numerical technique itself. For example, the permeability of a formation, which is one of the most important parameters in site characterization, and is commonly estimated by conducting hydraulic tests in boreholes, can be wrongly evaluated due to various causes including equipment malfunctions, noises, limitations in the test configuration, mismatched interpretation technique, as well as the assumptions used in the model. Many interpretation techniques assume ideal test conditions based on analytical solutions. Detection of the location and depth of faults, a most important feature to be identified during preliminary investigation stage, are often attained by using geophysical techniques, which are not free of uncertainties. Furthermore, there has been no established technique for accurately estimating the hydrologic properties of faults to this day. In this task we will evaluate the uncertainties involved with the data obtained in the field and with the characterization results using the data. We will identify the causes of the uncertainties associated with the key parameters and quantify the degree of uncertainties. In addition, we examine the uncertainties due to the use of mismatched analysis techniques.

Schedule and Deliverables: (Table 1)

Task A-1:

We conduct this task in the first and second half of FY 2005. The first half will focus on the U.S. program and the latter will examine the programs elsewhere. An interim report will be made at the end of July. The annual report available at the end of the fiscal year will summarize the whole task.

Task A-2:

We conduct this task in the first and second half of FY 2005. The first half will focus on the U.S. program and the latter will examine the programs elsewhere. An interim report will be made at the end of July. The annual report available at the end of the fiscal year will summarize the whole task.

Task A-3:

We conduct this task in the first and second half of FY 2005. A summary of the existing technologies and equipment will be made in the first half and in the latter half we will examine new and emerging technologies as well as the usable ranges, accuracies, and the applicability to site characterization of the technologies. An interim report will be made at the end of July and the annual report will be available at the end of the fiscal year.

Task A-4:

We initiated this task in the latter of FY 2005. Interim results will be summarized in the annual report in March, 2006 and the overall results will be summarized in the final report in December, 2006.

Task B: Geohydorlogical Modeling and Analysis

Objectives:

The objectives of this task are to reconfirm the list of important parameters identified in Task A, to examine the effects of the types, configurations, combinations and specifications of the tests and the model parameters on the test results and interpretation, and to evaluate the uncertainties involved in site characterization by constructing a geohydrological model and performing numerical analyses.

Approach:

Task B-1: Modeling and Analysis of Hypothetical Site

In this subtask, we will construct a hypothetical geohydrological model using an actual set of data available in Japan. Through the iterative process of model construction and update, we will reconfirm the important parameters identified in Task A-1. The effects of the types, configurations, combinations and specifications of the field tests and the model parameters have on the test results and interpretation will be investigated. The TOUGH2 family of codes developed at LBNL will be utilized. We will elicit those data that are important but may be missing and those that are important and already included in the set but are associated with some uncertainty.

Task B-2: Evaluation of Uncertainties

In this subtask, we will conduct sensitivity analyses of the key parameters using the model constructed in Task B-1. We examine the effects of the uncertainties in the parameters used in the model on the model outcome.

Schedule and Deliverables: (Table 1)

Task B-1:

This task will be performed in the first and second half of FY 2005, and in the first half of FY 2006. In the first half of FY 2005, a preliminary modeling is performed (head distribution, flow path and travel time). In the following periods, the model will be updated with additional data and the key parameters will be evaluated. The interim results are summarized in the report in July 2005, and the overall results will be reported in the annual report at the end of the fiscal year.

Task B-2:

This task will be initiated in the last half of FY 2005 and the interim report will be made in March 2006. The overall results will be summarized in the final report in December 2006.

Task C: Summary and Reporting

Objectives:

Based on the findingx in Task A and B, we develop an optimum investigation approach that describes the types of tests, test configurations, and test durations to be conducted for site characterization. The design should allow measurement and collection of a set of data to be used for a preliminary performance assessment and for the design of an underground facility.

Approach:

Task C: Recommendations for Optimum Characterization Strategy

The main objective of the field tests at the preliminary investigation sites is to collect data to determine which sites are suitable for detailed investigation. Therefore, at the preliminary investigation stage it is not necessary or practical to expend large costs and efforts to examine all the parameters for complete site description, or to decrease the uncertainties to the absolute minimum. However, it is desirable to detect the existence of any disqualifying conditions at the early stage. Given that at least one of the preliminary investigation sites is to be chosen for further detailed investigation, the field activities at the preliminary sites should be compatible with the future detailed investigations. For example, the locations of the boreholes and the test configurations during the preliminary stage should not compromise future investigations, if they are not directly usable. In this task, we will investigate the most optimum field investigation strategy for site characterization at the preliminary investigation stage. Specifically, the key and universal parameters and processes identified in Tasks A and B are to be investigated by using the most suitable technologies also identified in Task A. The optimum combination and specifications of the site investigation technologies will be examined with the assessment of the expected degree of uncertainty. Recommendations will be made for the optimum site characterization approach.

Schedule and Deliverables: (Table 1)

Task C:

This task will be initiated in the beginning of calendar year 2006 to reflect the results form Task A and B. An interim report will be made in March 2006. The final report will be made available at the end of December, 2006.

Table 1: Task Schedule

	JFY 2005	JFY 2006
Task A-1	Apr → Jul Nov → Feb	
Task A-2	Apr → Jul Nov → Feb	
Task A-3	Apr → Jul Nov → Feb	
Task A-4	Nov →	→ Sep
Task B-1	Apr → Jul Nov →	→ Sep
Task B-2	Nov →	→ Sep
Task C	Feb →	→ Dec
	△ Interim Report △ Annual Report	△ Final Report