Emerging Issues in Fractured-Rock Flow and Transport Investigations: Introduction and Overview

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1. MOTIVATION AND PROBLEM STATEMENT

Field, laboratory, and modeling studies of fractured rock have generated great interest from both fundamental and applied perspectives. Many practical applications of these studies are crucial for the exploitation of petroleum and geothermal reservoirs, the safe environmental management of groundwater, the isolation of radioactive waste in underground repositories, cleanup technologies for other sorts of toxic waste, and site characterization and monitoring. Fluid flow through rock fractures is also important in studying numerous geological processes and geotechnical applications [*Aydin*, 2000; *Menand and Tait*, 2001], as well as hydrocarbon [*Nelson*, 2001] and geothermal reservoirs [*O'Sullivan et al.*, 2001]. Most of the sites tentatively chosen for underground radioactive waste repositories are located in fractured rock [*Bodvarsson et al.*, 1999; *Witherspoon*, 2004].

Over the last three to four decades, a great deal of research in fractured rock hydrogeology has been carried out [*Bear et al.*, 1993; *National Research Council*, 1996; *Faybishenko et al.* 2000b; *Evans et al.*, 2001]. A comprehensive review of recent trends in quantifying flow and transport through fractured rock has recently been given by *de Marsily* [2000] and *Neuman* [2005]. Despite a number of field studies [*Nativ et al.*, 1995; *Faybishenko et al.*, 2000a] and laboratory studies [*Nicholl et al.*, 1993; *Glass et al.*, 2001] concerning the spatial and temporal instabilities of flow in unsaturated media, the physics explaining these phenomena is not completely known. It is also unclear how to optimize related laboratory- and field-scale investigations, or how to explain some paradoxes in unsaturated flow theory [*Gray and Hassanizadeh*, 1991] and scaling phenomena [*Pachepsky et al.*, 2003].

The importance of investigating unstable flow in fractures—in particular, unstable flow and dripping-water phenomena in fractured rock—recently arose from the need to design the proposed high-level nuclear waste repository in unsaturated fractured tuff at Yucca Mountain, Nevada [*Bodvarsson et al.*, 1999]. The possibility of water seepage into tunnels is one of the most critical problems related to the storage of high-level nuclear waste. One of the main difficulties in solving the problem of liquid flow and chemical transport in fractured rock is that flow processes are taking place at many different temporal and spatial scales [*Gale*, 1993; *Pyrak-Nolte et al.*, 1995; *Faybishenko et al.*, 2003; *Neuman and Federico*, 2003], including rock matrix pore structure, microfractures, and fracture networks. Flow and transport in fractured rock usually occurs in non-volume-averaged fashion, as relatively "slow" flow in the rock matrix and "fast" flow along localized preferential pathways in fractures. However, modeling of flow and transport in unsaturated fractured rock currently employs macroscale continuum concepts based on large-scale volume averaging (such as effective continuum, double porosity, dual permeability, and multiple interacting continua models). Such model's are well suited for representing larger-scale fractured rock features, but may be inadequate for resolving spatially localized and time-varying flow phenomena. This poses difficult challenges for mathematical modeling and requires the application of alternative modeling approaches for a given site [*Pruess et al.*, 1999].

After introducing and overview of several emerging trends in fractured-rock flow and transport investigations in this chapter, this monograph presents a collection of 16 selected papers from 90 presentations given by scientists and engineers from 14 countries at the Second International

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Symposium on Dynamics of Fluids in Fractured Rock, which was held at Lawrence Berkeley National Laboratory (Berkeley Lab) February 10–12, 2004. In selecting papers for publication in this monograph, we chose to focus on several emerging approaches to developing models for simulating flow and transport in fractured rock (Section II) and conducting laboratory and field investigations (Section III). This Introduction summarizes the chapters published in this monograph and the extended abstracts published in the Second Symposium Proceedings (citations to these abstracts are given separately at the end of the Reference list).

2. MODELS AND MODELING OF FLOW AND TRANSPORT IN FRACTURED ROCK

More than 40 years of experience in using models [*de Marsily*, 2001; *Neuman*, 2005] resulted in developing multiple approaches to modeling hydrogeological systems [*Barenblatt*, 2004; *Chae et al.*, 2004; *Enzmann et al.*, 2004; *Ezzedine*, 2004; *Faybishenko*, 2004; *Fourno et al.*, 2004; *Lacroix et al.*, 2004; *Liu and Bodvarsson*, 2004; *Moreno et al.*, 2004; *Nikravesh*, 2004; *Painter et al.*, 2004; *Painter*, 2004; *Pan et al.*, 2004; *Shariati et al.*, 2004; *Shimo et al.*, 2004; *Silin et al.*, 2004; *Svensson*, 2004; *Wu and Pan*, 2004; *Zazovsky*, 2004; *Zeng et al.*, 2004; *Zhang and Kang*, 2004]. *Molz et al.* [this volume] presents a useful historical overview of how stochastic models have been used to simulate flow processes in heterogeneous media. The fact that sediment property distributions at sufficiently small scales are irregular, leads to the development of stochastic theory in subsurface hydrology. Gaussian and Lévy-stable stochastic fractals have been applied both in the field of turbulence and subsurface hydrology. However, the results of field measurements do not always follow Gaussian or Lévy-stable probability density functions (PDFs). The authors describe a new stochastic fractal approach for both heterogeneous sediments and fractured rock. The authors present an overview of the origin and development of a new nonstationary stochastic process, called fractional Laplace motion (fLam), with stationary, correlated, increments called fractional Laplace noise (fLan). The *Molz et al.* model is based on the Laplace PDF and does not display self-similarity. For the new stochastic fractal, the PDF family moments remain bounded, and decay of the increment distribution tails vary from being slower than exponential to being exponential, and on to a Gaussian decay as the lag size increases. The authors suggest that the possible generalizations of this approach will help better understand the physics of flow processes.

One of the concepts used by scientists to explain the differences between the results of predictions and field observations is a concept of non-Fickian (or anomalous) transport of contaminants. *Berkowitz and Scher* [this volume] present a review of recent work on the continuous-time random-walk (CTRW) approach [*Berkowitz and Scher*, 2001; *Berkowitz et al.*, 2001; 2002; *Berkowitz*, 2002; *Cortis et al.*, 2004], along with some new results. The CTRW approach is an alternative to various ensemble-average (or homogenization) approaches for modeling of transport through fractured systems using the advection-dispersion equation (ADE). The ADE approach is also shown to be a subset of the CTRW formalism. *Berkowitz and Scher* [this volume] state that non-Fickian transport of contaminants arises naturally, at both laboratory and field scales, for a wide range of fractured and heterogeneous geological formations. *Berkowitz and Scher* also examine how the CTRW approach accounts for the results of observations, which provide the information about the physical nature of contaminant motion, plume geometry, and hydraulic parameters of the fractured formation. Moreover, the authors point out that flow and transport complexity (e.g., highly variable velocity fields) influence groundwater movement because of the superposition of several controlling factors, including fracture-network geometry, physical and/or geochemical interaction between the rock matrix, effects of small- and large-scale roughness of the fracture walls, and the presence of fracture-infilling materials.

Adler et al. [this volume] present a review of recent theoretical research contributions on percolation in discrete fracture networks with porous matrix, and the evaluation of overall percolation flux [*Adler and Thovert*, 1999; *Bogdanov et al.*, 2003a; 2003b]. To simulate flow in fractured rock, *Adler et al.* adopt the general approach of meshing three-dimensional fracture networks and fractured porous media, with the resulting equations discretized by means of a finite-volume technique. They address the problem of assessing percolation properties of fracture networks for mono- and polydisperse fractures for single-phase and two-phase flow systems, taking into account the concept of excluded volume. This approach is also suited for studying the macroscopic permeability of fractured porous media with polydisperse fractures [*Bogdanov et al.*, 2003a], upscaling the properties of fractured porous media, and wave propagation in such media.

To assess fractured-media transport properties, accounting for a preferential fluid-flow process through open fractures, *Wang and Strand* [this volume] implement a pore-scale, percolation model coupled with a continuum model for water vapor diffusion. A simulated tomographic image of water distribution during drying within a rock core indicates that as drying proceeds, the initial, continuous water cluster breaks up into smaller and smaller clusters, with an increasing surface-area-to-volume ratio. Drying times depend on the number and location of boundary surfaces, but the surface-area-to-volume ratio remains approximately the same for a given saturation. By applying a Voigt volume average for the elastic properties of water-filled and air-filled cells, and by introducing the *ad hoc* rule that water-filled pores at the air-water interface are drained, the authors find elastic moduli to be a function of saturation. The authors consider two types of fluid flow through fracture networks: (1) only along fractures, and (2) through both fractures and a porous medium, and also use the concept of excluded volume to improve the numerical model. Note that this concept is in line with the idea of active fracture flow [*Liu et al.*, 1998; *Wang*, 2004], addressing the notion that only part of the fracture network is involved in flow through fractured rock. The results obtained for single-phase flow are then extended for a case of two-phase flow.

Traditionally, flow through rough-walled rock fractures has been modeled using the Reynolds lubrication equation [*Brown*, 1987], which is a two-dimensional simplification of the more fundamental Navier-Stokes equations. The lubrication equation is derived by assuming that the fracture walls are sufficiently smooth, and that the flow rate and local velocity components perpendicular to the nominal fracture plane are sufficiently low. This model also ignores inertial forces. *Al-Yaarubi et al.* [this volume] present the results of using a surface profilometer to measure (at an accuracy of a few microns) fracture profiles every 10 microns over fracture model surfaces of red Permian sandstone. These data are then used as input to two finite-element codes that solve the Navier-Stokes equations and the Reynolds equation. Numerical simulations of flow are carried out for different mean apertures, corresponding to different values of relative roughness. At low Reynolds numbers, the Navier-Stokes simulations yield transmissivity values for the two fracture regions that are closer to the experimental values than those predicted by the lubrication model. In general, the lubrication model overestimate the transmissivity, depending on the relative fracture surface roughness. *Al-Yaarubi et al.* show that for Reynolds numbers from 1–10, the calculated transmissivity values are consistent with those from the "weak inertia" model for porous media developed by *Mei and Auriault* [1991], and with the computational results for a two-dimensional self-affine fracture obtained by *Skjetne et al.* [1999]. For $10 < Re < 40$, both the computed and measured transmissivities could be fit very well to a Forchheimer-type equation, in which the additional pressure drop varies quadratically with the Reynolds number.

It has become evident in recent years that the wealth of experience gained from investigations of porous media is important for a better understanding of flow and transport in fractured rock [*van Genuchten and Schaap,* 2004]. For example, a solution to the problem of laminar flow above a porous surface is essential when investigating phenomena such as erosion, resuspension, or mass transfer between porous media and the flow above it. *Rosenzweig and Shavit* [this volume] simulate flow at an interface between a free-flow region and a porous medium, with emphasis on the choice of a governing model and boundary conditions for the different regions. The authors analyze two models of porous media: a series of parallel grooves and the Sierpinski carpet. The authors show that the interface macroscopic velocity can be modeled by introducing a modification to the Brinkman equation. A moving average approach prove to be successful when choosing the correct representative elementary volume and comparing the macroscopic solution with that for the average microscopic flow. The macroscopic model, developed for 2-D porous media that consisted of multiple parallel grooves, is then applied to 3-D porous media. This model has, in the horizontal plane, the shape of the fractal "Sierpinski carpet." Given porous media properties (e.g., porosity and permeability), flow height, viscosity, and driving force, a complete macroscopic solution for interface flow is obtained. Though a modified Brinkman equation (MBE) was originally developed for steady-state, microscopically unidirectional flow conditions, the Sierpinski carpet flow example shows that the MBE can also be used to describe macroscopically unidirectional flow with negligible inertia effects. The results of this paper could potentially be extended to describe heterogeneous, microscale fluid motion, and the MBE could be applied to flows with negligible inertia; that is, it could be applied to all "non-unidirectional flows," as long as inertia terms are negligible.

One of the central problems facing scientists working on the problem of disposal and containment of CO_2 in deep geological formations is to predict the thermodynamic regime in the presence of the coupled fluid flow and heat-transfer effects during migration of CO_2. *Pruess* [this volume] modeles multiphase flow, including boiling of liquid CO_2, the transition between supercritical and subcritical conditions, phase partitioning between CO_2 and water, and nonisothermal effects. *Pruess* finds that depressurization caused by rising CO_2 creates strong cooling. Thermo-dynamic effects are also associated with conductive heat transfer from the impermeable wall rocks. Pressure and temperature conditions are drawn towards the critical point of CO_2 and the CO_2 saturation line. *Pruess* argues that CO_2 behavior depends on the hydrogeologic properties of the flow pathways, on the thermodynamic regime (temperature and pressure conditions), and on the thermophysical properties of CO_2 and resident aqueous fluids. He also emphasizes the importance of conductive heat transfer across the wall rocks bounding the fault zone. Other important conclusions are related to the tendency towards development of three-phase zones with increasing fracture zone thickness (when CO_2 migrates through thin fracture zones, three-phase zones may not form at all or may form and dissolve in a transient manner). Depending on the fracture zone thickness, permeability and CO_2 discharge rate temperatures may reach the freezing point of water, and water ice and hydrate phases may form. The interplay between multiphase flow in the fracture zone, phase change, and heat conduction may produce nonmonotonic, quasi-periodic variations in thermodynamic conditions and CO_2 discharges across the land surface. These processes could potentially be studied using methods of nonlinear dynamics.

Several types of uncertainties are involved in predictions of flow and transport through soils and fractured rock, such as hydrologic-conceptual-model and hydrologic-parameter uncertainty [*Meyer and Orr*, 2002; *Neuman*, 2002; *Meyer et al.*, 2003; *Neuman and Wierenga*, 2003]. *Sawada et al.* [this volume] introduced another aspect of the uncertainty study—they evaluate the uncertainty associated with site characterization and the development of conceptual models for performance assessment of high-level radioactive waste disposal in fractured granitic rock, at the Tono area of Gifu prefecture, Japan. This chapter presents a comparison of flow and transport predictions performed by five modeling groups, which are provided with site characterization data obtained from the surface-based investigations at and around an underground research laboratory (URL) construction site. The groups were tasked to develop their own conceptual models and use their software for predictions of flow and transport. The results of numerical simulations performed by the five research groups vary greatly, showing that a major source of uncertainty arises from different interpretation of site characterization data and conceptual model development. Modeling results are especially impacted by uncertainties associated with the determination of advective flow porosity, which controls travel time, and the hydraulic conductivity field (created in this instance by the Tsukiyoshi fault running through the study area), which controls flow direction around the fault. To reduce the uncertainty of predictions, the authors recommend collecting additional site characterization data, such as the hydraulic properties of the Tsukiyoshi fault, effective porosity, the lineament structure, and boundary conditions. Thus, the results summarized in this chapter confirm that the major source of uncertainty in hydrogeological modeling lies in the interpretation of site characterization and monitoring data—used for the development of a conceptual model—rather than in the details of numerical simulation.

3. FIELD AND LABORATORY INVESTIGATIONS

Section III of this monograph presents several case studies describing the results of multiscale investigations of flow and transport in fractured media, including chemical and microbial transport, and investigations of geochemical reservoirs. This section demonstrates the wealth of data collected at various field sites around the world, data that could be helpful in developing conceptual models, and for building confidence in existing flow and transport models for hydrogeological systems.

3.1. Multiscale Investigations of Flow and Transport in Fractured Media

Field investigations in support of site characterization for different practical purposes have been performed at many sites throughout the world: for example, Yucca Mountain, USA [*Bodvarsson et al.*, 1999; *Salve*, 2004; *Trautz and Flexer*, 2004; *Wang*, 2004], Grimsel, Switzerland [*Vomvoris et al.*, 2004], the Apache Leap Research Site, Arizona [*Neuman et al.*, 2001], and the Negev Desert, Israel [*Nativ*, 2004; *Weiss et al.*, 2004]. The history of the development of underground research laboratories for radioactive waste isolation is given by *Witherspoon* [2004]. *Kurtzman et al.* [2004] and *Bernstein et al.* [2004] presented the results of multiscale field hydraulic and tracer tests. *Kaneshiro* [2004] discussed the lessons learned from field studies designed for the evaluation of groundwater inflow into tunnels intersecting fractured rock. Chapters 11—13 of this volume present three case studies from multi-scale hydrogeologic and geochemical field investigations, including the results of modeling, which are related to radioactive waste management programs.

Holt et al. [this volume] present the results from investigations of fracturing in the Culebra Dolomite of the Permian Rustler Formation, in the vicinity of the U.S. Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico. The WIPP is the U.S. Department of Energy's deep geological repository for transuranic and mixed wastes, which is the world's first underground repository licensed to safely and permanently dispose of transuranic radioactive waste left from the research and production of nuclear weapons. Because of the high degree of fracture variability within the Culebra Formation, aquifer transmissivity (T) varies over 6 orders of magnitude, with higher T ($\log T$ (m^2/s) > -5.4) within zones of well-interconnected fractures. The authors develop, test, and then refine a conceptual model for predicting fracture zones within the Culebra. The conceptual model includes three types of regional-scale controls on fracturing—the dissolution of salt from below the Culebra; the presence of halite above and below the Culebra; and overburden thickness. The model also includes two types of local-scale controls on Culebra fracture zones—fracture-filling cements and localized deformation caused by ductile flow of the mudstone underlying the Culebra. Although the spatial distribution of the regional-scale controls is generally predictable from the site characterization data, the influence of local controls can only be identified through hydraulic testing. The chapter presents an insightful discussion of the relationship between transmissivity and dissolution, overburden stress release, and depositional facies in a fractured formation, which are needed for long-term predictions of the potential impact of a nuclear waste repository.

The Äspö site, in Sweden, is one of the most thoroughly characterized and well-documented sites in the world. Using the Äspö site characterization data, *Grenier et al.* [this volume] aim to build a bridge between site characterization (SC) models and performance assessment (PA) models for a potential deep geologic repository. The authors show that SC models are usually complex, incorporating detailed physical and geochemical properties, and are calibrated on or constrained by short-term and small-scale field experiments. In contrast, PA models are usually simpler, reflecting only the main physical processes needed to address the range of possible predictions for much longer time and spatial scales. This study focuses on the evaluation of one of these processes—radionuclide retention affected by diffusion into a low-permeability formation, i.e., into the porous matrix fracture-infilling materials, or dead end pores with insignificant flow. Retention processes in fractured rock cause a temporal diversion of a certain fraction of the plume from primary flow paths [*Neretnieks*, 1980]. The tracer tests, using nonsorbing and moderately sorbing tracers, are carried out to assess breakthrough curves under fully saturated flow conditions within the Äspö block. *Grenier et al.* simulate flow at two scales: (1) a single fracture, extending roughly 10 m (the Tracer Understanding Experiment, TRUE-1), using the fracture statistical parameters determined from field measurements, and (2) a semisynthetic 200 m block (TRUE Block Scale project), consisting of different types of fracturing—from roughly 1 m to 100 m. Finally, the authors develop a model suited to performance assessment for single-fracture geometry and present a smeared-fracture approach to model radionuclide transfer within a fractured block.

Löfman and Mészáros [this volume] present a synthesis of investigations related to the design of a spent nuclear fuel repository in Finland conducted by Posiva, the expert organization on nuclear waste management in Finland. The variations in water-table drawdown, deep saline-water upconing, and tunnel inflow that might result from the construction and operation of the underground rock characterization facility (ONKALO) are assessed by site-scale finite-element simulations. ONKALO, which is in a construction phase now, will consist of an 8,500 m long and 520 m deep system of tunnels, to be potentially extended with the repository drifts. Groundwater drawdown is calculated by employing the free-surface approach, open tunnel inflow is obtained from the state of equilibrium, and salinity distribution evolution is simulated using a model of transient, coupled flow, and salt transport. Most of the inflow (330–1,100 L/min) would enter the tunnel through the conductive subhorizontal fracture zones intersected by the drifts. The water table could sink to a 200 m depth, and the depressed area could extend over the Olkiluoto Island. Simulations show that the water table depression could be confined with tight grouting to the immediate vicinity of the ONKALO, the maximum drawdown of the water table remain around 10 m, and the total inflow to the tunnels is about 20 L/min. Moreover, upconing of the saline water remain moderate. Because the repository temperature could rise several tens of degrees, heat generation could induce an increase in upward groundwater flow and groundwater salinity in the vicinity of the repository. To reduce the uncertainty in hydrogeological predictions, the authors recommend updating both conceptual and numerical models periodically by comparing predictions to observations, as new data become available [*Posiva*, 2003].

Significant progress has been achieved in the past years in the area of small-scale imaging of flow in fractures, exploiting cutting-edge imaging technologies. These studies are essential for better understanding the physics of flow and transport in fractures and quantification of liquid-rock contact area, aperture distribution, permeability, and fracture-matrix interaction [*Enzmann et al.*, 2004; *Fuentes and Faybishenko*, 2004; *Polak et al.*, 2004; *Yamamoto et al.*, 2004]. *Gale and Seok* [2004] used a large (1 m^3) laboratory scaling-up experiment on a single fracture plane in a granite sample to investigate the process of degassing and scaling relationships. *Dragila and Weisbrod* [2004] conducted a series of experiments to study flow across an unsaturated fracture intersection, which revealed that flow invasion dynamics may depend on fracture and fluid properties (such as liquid surface tension), the relationship of the advancing contact angle to the intersection angle, and the effect of fracture texture and sorption on the creation of liquid bridges and the sustainability of rivulets. Unstable flow dynamics were also studied by *Wang et al.* [2004] and *Ghezzehei* [2004].

Various field and laboratory techniques have been employed for evaluating the hydraulic properties of both saturated and unsaturated fractured rock. It is important to emphasize that many researchers have investigated phenomena of the temporal evolution of rock hydraulic properties [*Brown et al.*, 2004; *Kessel et al.*, 2004; *Kunkel*, 2004; *Lunati et al.*, 2004; *Murdoch et al.*, 2004; *Neuman*, 2004; *Song et al.*, 2004; *Tokunaga et al.*, 2004; *van Genuchten and Schaap*, 2004; *Wellman and Poeter*, 2004]. *Gale and Seok* [2004] highlighted several reasons for the observed disagreement between the results of laboratory and field estimation of rock permeability at different spatial scales; and they also indicated the need for the development of well-documented databases from multiscale, controlled flow and transport experiments, which are essential to test various single and multiphase fracture flow and solute transport concepts and models.

An emerging area of research is the application of different geophysical methods and numerical interpretation of the results of geophysical tomography for the evaluation of hydrogeological parameters of fractured rock [*Berge*, 2004; *Doughty and Tsang*, 2004; *Chen et al.*, 2004; *Gritto and Majer*, 2004; *Pedler et al.*, 2004; *Takeuchi et al.*, 2004].

Further investigations are needed to build models for hydrogeologic systems with small-scale heterogeneities.

3.2. Coupled Processes of Solute Transport and Chemical Processes

Considerable progress has been achieved in the area of investigations of chemical transport and coupled processes. *Sonnenthal and Spycher* [2004] investigated coupled thermal, hydrological, and chemical processes in unsaturated fractured rock at Yucca Mountain, including the effects of mineral precipitation in fractures, water chemistry, and gas composition. Competition among flow, dissolution, and precipitation in fractured rock could lead to very complex flow patterns [*Singurindy and Berkowitz*, 2004]. *Spiegelman* [2004] argues that some features of magma flow may be considered as analogues for a better understanding of fluid flow in brittle media; for example, preferential flow phenomena are likely to be caused by a combination of chemical and mechanical mechanisms that are responsible for the observed localization in magmatic systems.

One of the most interesting problems related to fracture flow is the evaluation of episodic and fast liquid and solute flow through fractures. *Weisbrod et al.* [this volume] have contributed towards a better understanding of this problem. They describe the results of field, laboratory, and modeling studies aimed at investigating the mechanism by which surface-exposed fractures could be a source of aquifer salinization in low-permeability fractured formations under arid conditions. The authors describe the mechanism underlying the cycle of summer evaporation followed by winter precipitation events, resulting in the annual loading of solutes in the underlying aquifer. This mechanism consists of gas-phase convection within a fracture that promotes an elevated rate of evaporation, possibly drawing pore water and salt from the matrix toward fracture surfaces. This process culminates in the precipitation of salt on the fracture surfaces. Moreover, this combined mechanism of liquid evaporation and salt precipitation could result in pulses of high salt concentration towards groundwater during rainfall events, with liquid flow through fractures that is substantially faster than through the adjacent porous matrix.

An important area of research is the evaluation of migration of industrial chemicals, especially nonaqueous phase liquid (NAPL) transport. Many field, laboratory, and modeling techniques were used to study these processes (*Falta*, 2004; *Sekerak and Dickson*, 2004; *Su and Javandel*, 2004; *Ezra et al.*, 2004]. *Falta* [this volume] addresses the important issue of aquifer remediation in the presence of dense nonaqueous phase liquids (DNAPLs) in fractured geologic media. DNAPL chemicals (such as chlorinated solvents) are capable of penetrating through fractures and rapidly diffusing into the porous matrix, because of steep concentration gradients. Contaminants retained in the porous matrix can serve as a long-term source of groundwater contamination. Using a discrete fracture model with a finely discretized porous clay matrix, *Falta* has built a robust two-dimensional numerical model for simulations of DNAPL distribution in clay aquitards overlying water-supply aquifers. The simulation results show that in the absence of any chemical decay in the clay matrix, the process of fracture flushing may take hundreds to thousands of years to reduce the matrix contaminant concentrations, depending on the fracture aperture. However, if even a moderate amount of chemical decay occurs in the clay matrix, these time scales are reduced to tens or hundreds of years. A simple analytical function is shown to approximately reproduce the time-dependent fracture discharge to an underlying aquifer. This analytical function is then used to assign the boundary condition in a reactive advection-dispersion model of an underlying porous aquifer. The author finds that small fractures (<30 μm aperture) appear to be less likely to result in large groundwater plumes in nearby aquifers, but larger fractures (~100 μm aperture) in contaminated clay aquitards can produce large groundwater plumes that persist for decades or more.

3.3. Geothermal Reservoirs

Case studies related to geothermal areas in Japan and Canada were presented by *Tamanyu* [2004], *Ioannou and Spooner* [2004], and *Nakao et al.* [2004]. *Pritchett* [this volume] shows that, in many geothermal fields around the world, the vertical distribution of fluid pressure in the undisturbed reservoir is approximately hydrostatic. However, when a well is drilled into the reservoir and fluid is withdrawn, the enthalpy (or steam fraction) of the stable fluid discharge is often anomalously high, sometimes by itself causing the well-steam discharge. This apparent paradox cannot be explained unless the reservoir is highly heterogeneous on a local scale, with a sharp permeability contrast between the relatively impermeable rock matrix and the fracture zones that provide channels for fluid flow. Also, anomalous wellhead discharge enthalpies will not be observed unless two-phase, water/steam mixture flow is distributed deep into the reservoir. This so-called excess enthalpy effect is inherently transient in character, and discharge enthalpies will eventually decline over the period of several years. The chapter presents two examples of these phenomena from geothermal fields in Japan.

3.4. Microbial Transport

The two final chapters of this monograph are concerned with a fairly new area of research—microbial transport in fractured rock. *Kinner et al.* [this volume] summarize investigations carried out by the Bedrock Bioremediation Center of the University of New Hampshire, Durham, New Hampshire. This study documents the presence of a diverse array of prokaryotes (Eubacteria and Archaea) and some protists. The prokaryotes appear to live in both small, diffusion-dominated microfractures and larger, more conductive open fractures. Some of the prokaryotes are associated with the surfaces of the host rock and mineral precipitates, while other planktonic forms are floating/moving in the groundwater filling the fractures. Studies indicate that the surface-associated and planktonic communities are distinct, and their importance in microbially mediated processes occurring in the bedrock environment may vary, depending on the availability of electron donors/acceptors and nutrients needed by the cells. In general, abundances of microbes are low compared with other environments, because of the paucity of substances transported into the deeper subsurface. To obtain a complete picture of the biomass and microbe metabolic activity, we must sample formation water from specific fractures (using, for example, boreholes) and fracture surfaces (using, for example, cores). The authors caution that the chemistry in the microfractures, where biological processes are ongoing, may be different from the chemistry of rapidly flowing pore water. Moreover, microbial activities in rocks could impact abiotic and biotically mediated rock mineral oxidation [*Sidborn and Neretnieks*, 2004]) and change fractured rock transmissivity [*Arnon et al.*, 2004].

The final chapter, by *Arnon et al.* [this volume], includes results from investigations on the effect of microbial activity on flow and transport of 2,4,6-Tribromophenol (TBP) in naturally fractured chalk cores. The chapter contains data from a long-term (~600 days) laboratory study on the biodegradation of TBP in low-permeability fractured-chalk. The authors evaluated the impact of residence time, oxygen concentration, and chalk pore size on TBP biodegradation, as well as the relationship between microbial activity and fracture transmissivity. The authors find that the main limiting factor in TBP biodegradation is oxygen availability within the fracture void space. Although the chalk appears to provide an excellent environment for biodegradation activity, TBP removal is very slow under conditions similar to those of natural attenuation in a contaminated aquitard. Approximately 90% of the TBP removal occurs within 10 cm from the source, even when the residence time is reduced from 305 to 8 minutes and the fracture transmissivity decreased by up to two orders of magnitude. As one would expect, the results of simulations of *in situ* bioremediation, by increasing oxygen concentration within the fracture and creating a faster flow rate, would significantly enhance TBP removal. The results of this study could be used to test conceptual and numerical models for designing *in situ* bioremediation scenarios.

It is quite obvious that much more research is needed to obtain a better understanding of microbial processes in fractured rock environments.

4. CONCLUDING REMARKS

Characterization of the dynamics of fluid flow, heat, and chemical transport in geologic media remains a central challenge for geoscientists and engineers worldwide. Investigations of fluid flow and transport within rock relate to such fundamental and applied problems as environmental remediation; NAPL transport; exploitation of oil, gas, and geothermal resources; disposal of spent nuclear fuel; and optimization of field and modeling studies in fractured rock.

The chapters collected in this monograph present emerging trends in the areas of modeling, field, and laboratory studies. They contain a wealth of data collected at various field sites around the world in both saturated and unsaturated zones. We believe that these data could be helpful for other sites in developing conceptual models, and for building confidence in existing fracture-rock flow and transport models for hydrogeological systems. We expect that this monograph will provide valuable information for many aspects of fractured-rock investigations, and will help solve a variety of fundamental problems in the earth sciences.

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Berge, P.A., Modeling poroelastic earth materials that exhibit seismic anisotropy, pp. 293-294.

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Chae, B.-G., Y. Ichikawa, and Y. Kim, Homogenization analysis for fluid flow in a rough fracture, pp. 295-299.

Chen, J., S. Hubbard, and J. Peterson, A comparison between hydrogeophysical characterization approaches applied to granular porous and fractured media, pp. 421-427.

Doughty, C. and C.-F. Tsang, Hydrologic characterization of fractured rock using flowing fluid electric conductivity logs, pp. 383-387.

Doughty, C. and K. Karasaki, Constraining a fractured-rock groundwater flow model with pressure-transient data from an inadvertent well test, pp. 319-324.

Dragila, M. and N. Weisbrod, Flow across an unsaturated fracture intersection, pp. 27-32.

Enzmann, F., M. Kersten, and B. Kienzler, Microscale modeling of fluid transport in fractured granite using a Lattice Boltzmann Method with x-ray computed tomography data, pp. 300-304.

Enzmann, F., M. Kersten, and M. Stampanoni, Synchrotron-based microtomography of geologic samples for modeling fluid transport in real pore space, pp. 114-119.

Ezra, S., S. Feinstein, I. Bilkis, E. Adar, and J. Ganor, The fate of industrial-organo bromides in a fractured chalk aquifer, pp. 169-173.

Ezzedine, S.M., Modeling flow and transport in fractured media using deterministic and stochastic approaches, p. 305.

Falta,R., The potential for widespread groundwater contamination by the gasoline lead scavengers ethylene dibromide and 1,2-dichloroethane, pp. 57-62.

Faybishenko, B.A., Modeling of hydrogeologic systems using fuzzy differential equations, pp. 306-309.

Fourno, A., C. Grenier, F. Delay, E. Mouche, and H. Benabderrahmane, Qualification and validity of a smeared fracture modeling approach for transfers in fractured media, pp. 195-200.

Fuentes, N.O. and B. Faybishenko, Rimaps and variogram characterization of water flow paths on a fracture surface, pp. 120-123.

Gale, J.E. and E. Seok, Using fracture pore space geometry to assess degassing and scaling relationships in fractured rocks, pp. 25-26.

Ghezzehei, T.A., Constraints on flow regimes in unsaturated fractures, p. 369.

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Kaneshiro, J.Y., Groundwater inflow into tunnels—Case histories and summary of developments of simplified methods to estimate inflow quantities, pp. 388-389.

Kessel, W., R. Kaiser., and W. Gräsle, Hydraulic test interpretation with pressure dependent permeability—Results from the continental deep crystalline drilling in Germany, pp. 407-414.

Kunkel, J.R., A probabilistic analytical method to calculate dispersion coefficients in fractured rock, pp. 248-252.

Kurtzman, D., R. Nativ, and E.M. Adar, A fractured-chalk field laboratory for flow and transport studies on the 10- to 100-m scale, pp. 19-24.

Lacroix, S., P. Delaplace, and B. Bourbiaux, Numerical simulation of air injection in light oil fractured reservoirs, pp. 272-277.

Liu, H.H. and G.S. Bodvarsson, Possible scale dependency of the effective matrix diffusion coefficient, pp. 310-313.

Lunati, I., W. Kinzelbach, and I. Sørensen, Effects of pore volume variability on transport phenomena, pp. 33-35.

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Murdoch, L.C., T. Schweisinger, E. Svenson, and L. Germanovich, Measuring and analyzing transient changes in fracture aperture during hydraulic well tests: Preliminary results, pp. 129-132.

Nakao, S., T. Ishido, and Y. Takahashi, Pulse testing analysis for fracture geothermal reservoir—A case study at the Uenotai Geothermal Field, Japan, Addendum, pp. A-14-18.

Nativ, R. and E. Adar, The porous fractured chalk of the Northern Negev Desert: Lessons learned from ten years of study, pp. 390-395.

Neuman, S.P., Advective porosity tensor for flux-weighted, pp. 377-382.

Nikravesh, M., Reservoir characterization and management using soft computing, pp. 269-271.

Painter, S., Comparison between dual and multiple continua representations of nonisothermal processes in the repository proposed for Yucca Mountain, Nevada, pp. 343-348.

Painter, S., V. Cvetkovic, and J.O. Selroos, Upscaling discrete fracture network simulations of solute transport, pp. 225-231.

Pan, L., Y. Seol, and G.S. Bodvarsson, Improved estimation of the activity range of particles: The influence of water flow through fracture-matrix interface, pp. 339-342.

Pedler, W., R. Jepsen, and W. Mandell, Laboratory and numerical evaluation of borehole methods for subsurface horizontal flow characterization, pp. 132-142.

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Rosenzweig, R. and U. Shavit, Theoretical, numerical, and experimental study of flow at the interface of porous media, pp. 260-266.

Salve, R., Preferential flow in welded and non-welded tuffs: observations from field experiments, pp. 143-147.

Sekerak, B. and S. Dickson, Development of an interfacial tracer test for DNAPL entrapped in discrete fractured rock, pp. 75-80.

Shariati, M., L. Talon, J. Martin, N. Rakotomalala, D. Salin, and Y.C. Yortsos, Fluid displacement between two parallel plates: A model example for hyperbolic equations displaying change-ff-type, p. 325.

Shimo, M., H. Yamamoto, and K. Fumimura, Equivalent heterogeneous continuum model approach for flow in fractured rock—Application to regional groundwater flow simulation at Tono, Japan, pp. 326-333.

Sidborn, M. and I. Neretnieks, Abiotic and biotically mediated rock mineral oxidation, pp. 163-164.

Silin, D.B., T.W. Patzek, and G.I. Barenblatt, On damage propagation in a soft low-permeability formation, pp. 334-338.

Singurindy, O. and B. Berkowitz, Competition among flow, dissolution and precipitation in fractured carbonate rocks, pp. 81-85.

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Sonnenthal, E. and N. Spycher, Progress toward understanding coupled thermal, hydrological, and chemical processes in unsaturated fractured rock at Yucca Mountain, pp. 49-53.

Spiegelman, M., Plumbing the depths: Magma dynamics and localization phenomena in viscous systems, pp. 54-56.

Su, G. and I. Javandel, DNAPL invasion into a partially saturated dead-end fracture, pp. 165-168.

Svensson, U., Modeling flow and transport in a sparsely fractured granite: A discussion of concepts and assumptions, pp. 221-224.

Takeuchi, S., M. Shimo, C. Doughty, and C.-Fu Tsang, Identification of the water-conducting features and evaluation of hydraulic parameters using fluid electric conductivity logging, pp. 349-354.

Tamanyu, S., Fluid flow patterns calculated from patterns of subsurface temperature and hydrogeologic modeling: Example of the Yuzawa-Ogachi Geothermal Area, Akita, Japan, pp. 90-94.

Tokunaga, T.K., and J. Wan, Comparing unsaturated hydraulics of fractured rocks and gravels, pp. 253-254.

Trautz, R. and S. Flexser, Determination of moisture diffusivity for unsaturated fractured rock surfaces, pp. 148-154.

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Vomvoris, S., W. Kickmaier, and I. McKinley, Grimsel Test Site: 20 years of research in fractured crystalline rocks—Experience gained and future needs, pp. 14-18.

Wang, J.S.Y., Active flow path evaluation in the unsaturated zone at Yucca Mountain, pp. 11-13.

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Weiss, M., Y. Rubin, R. Nativ, and E. Adar, Fracture and bedding plane control of groundwater flow in a chalk aquitard: A geostatistical model from the Negev Desert, Israel, pp. 396-399.

Wellman, T.P., E. Poeter, Evaluating hydraulic head data as an estimator for spatially variable equivalent continuum scales in fractured architecture, using discrete feature analysis, p. 267.

Witherspoon, P.A. Development of underground research laboratories for radioactive waste isolation, pp. 3-7.

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Yamamoto, T., J. Sakakibara, and T. Katayama, Imaging permeability structure in fractured rocks: Inverse theory and experiment, pp. 42-46.

Zazovsky, A., Propellant fracturing demystified for well stimulation, pp. 367-368.

Zeng, J., Y.C. Yortsos, and D. Salin, On the Brinkman Correction in uni-directional Hele-Shaw flows, p. 370.

Zhang, D. and Q. Kang, Lattice Boltzmann simulation of flow and solute transport in fractured porous media, pp. 206-213.