<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper published in *Hydrogeology Journal*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Figueiredo, B., Tsang, C-F., Niemi, A., Georg, L. (2016)

Review: The state-of-art of sparse channel models and their applicability to performance assessment of radioactive waste repositories in fractured crystalline formations.

Hydrogeology Journal, 24(7): 1607-1622

<https://doi.org/10.1007/s10040-016-1415-x>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-293596>

A review of the state-of-art of sparse channel model and its applicability to radioactive waste repository in deep fractured crystalline formation

Bruno Figueiredo^{1*}, Chin-Fu Tsang^{1,2}, Auli Niemi¹ and Georg Lindgren³

1. Uppsala University, Villavägen 16, Uppsala, 75236, Sweden

e-mail: bruno.figueiredo@geo.uu.se

2. Lawrence Berkeley National Laboratory, Berkeley, California

3. Swedish Radiation Safety Authority, Stockholm, Sweden

*corresponding author

Abstract: Channelling has been observed in laboratory and field experiments on fractured rock at various scales. However, it is still an open research issue whether a sparse channel network is likely to be a better model than the fracture network model for representing the flow system in tight fractured rock of low transmissivity. The present paper presents a literature study to bring together information useful for addressing this issue. Several key questions are discussed, namely (a) what are the evidences of channelized flow in fractured rock with laboratory and field measurements? (b) what is the relationship between generalized flow dimensions from well test analysis and sparse channel network models? (c) what is the significance of fracture shapes in hydraulic connectivity? (d) how the probability of flow channels encountering a waste canister deposition hole in a nuclear waste repository relates to the characteristics of a sparse channel model? and (e) are there any specific site studies where sparse channel models have been used to model the flow and transport in fractured rock? A summary, a general discussion and some suggestions conclude the paper.

Keywords: Channelized flow · sparse channels · flow dimension · fracture shape · hydraulic connectivity

1. INTRODUCTION

1.1 Modelling flow and transport in fractured rocks

Flow and transport in fractured rock at multiple scales continue to be an active area of scientific research (Neuman 2005; Berkowitz 2002; Sahimi 2011) because of on-going activities in several countries as part of their investigation for the development of nuclear waste repositories in fractured rock deep underground. In particular,

Sweden is planning a nuclear repository in the municipality of Forsmark (SKB 2008), whereas in Finland, a nuclear waste repository is planned to be constructed in Olkiluoto (Posiva 2009 a, b).

There are a number of issues that need to be addressed when modelling flow and transport in fractured rock under field conditions. These include characterization of the fractures in the rock, as well as model parameterization and upscaling of these parameters, from local small-scale measurements to the scale of repository models. All these issues are complicated by a high level of heterogeneity found in fractured rock, including that arising from aperture heterogeneity in individual fractures. Stochastic continuum (SC), discrete fracture network (DFN), and channel network (CN) models (Fig. 1) have been developed and used to describe the flow and transport in fractured rock.

Fig. 1 Models to study groundwater flow and solute transport in fractured rocks (from Selroos et al., 2002)

In stochastic continuum models (Hartley et al. 2006; Follin 2008; Neuman et al. 1987), the fractured rock may be represented as an equivalent homogeneous porous medium with groundwater flow governed by Darcy's law. The hydraulic conductivity of the equivalent system is treated as a random spatial distribution of block/element hydraulic conductivities that represent the spatially averaged properties over the fractures of the block. This approach is applicable at small and relatively large scales, where local scale variability has to be taken into account but the effect of individual fractures can be neglected.

In discrete fracture network models (Long et al. 1982; Cacas et al. 1990 a,b; Berkowitz 2002; Joyce et al. 2009; Sahimi 2011; Hartley and Roberts 2012), the groundwater flow and transport in fractured rocks are assumed to occur primarily within fractures. The resulting fracture networks are converted to three-dimensional networks of essentially one-dimensional pipes (Fig. 2). Fracture networks are thus mostly modelled as consisting of constant aperture open fractures that intersect each other forming a conductive network. Each fracture is assigned with a volume, size and transmissivity and may be simulated as deterministic or stochastic (Dershowitz and Fidelibus 1999). Deterministic representations are used when the location, extent, and orientation of particular fractures are well defined from data. Stochastic representations of fractures are often based on statistical parameters of probabilistic distributions of geometric properties, rather than detailed geometric data themselves. The equations representing the flow and transport in the interconnected fracture system are then solved. The scale of the network simulations is typically limited due to computational constraints.

Fig. 2 Discrete fracture network (DFN) conceptual model (from Selroos et al., 2002)

One of the main drawbacks of these models is that they need a large and very detailed data set on fracture orientations, fracture size distributions and fracture conductivity distributions, plus some major assumptions related to translating the field observations to parameters used in the models, and these can be difficult to validate. Field data can be obtained from borehole transmissivity measurements and observations on fracture widths.

Calibrations can be made with observations in drifts and tunnels. A considerable number of papers on network modeling are referenced in Neuman (2005), who also gave an overview of the difficulties and intricacies encountered in modeling flow and transport in fractured media (see also Tsang, 2005).

Fracture-scale aperture variability can be included within the fracture-network models (Painter 2006; Nordqvist *et al.* 1996), but this further increases computational demands, thus limiting the scale of model for which computation can reasonably be done. Aperture variability within a fracture causes flow channelling, where the water flow is focused in a few channels with least overall resistance and with the remaining areas of the fracture having practically stagnant water (Neretnieks 1993; Tsang and Tsang 1989; Tsang and Neretnieks 1998). The so called “flow wetted surface” is defined as the area of the fractures covered by flowing water apart from the fracture areas covered by essentially stagnant water (Moreno and Neretnieks 1993). In work of Larsson *et al.* (2012a, 2013a), the influence of different degrees of heterogeneity in fracture-aperture distributions (as described by their statistic properties) on solute transport is examined and quantified. This influence is studied by first analyzing one single fracture, and thereafter applying the results to fracture-network modelling. Larsson *et al.* (2012b) presents a systematic study of the dependency between fracture aperture statistics and flow wetted surface in strongly heterogeneous fractures. Larsson *et al.* (2013b) then presents a method to include the effects of fracture aperture variability into the modeling of solute transport in fracture networks.

In channel network models (CN), the flow and contaminants are assumed to be distributed among preferential paths in the fracture plane, or channels (Fig. 3). These channels may intersect in the three-dimensional space, forming a network of channels for the movement and mixing of flowing water. In the channel network model, the equations of flow in each 1-D channel are solved via the finite-difference method. Several theoretical studies considering channelized flow in fractured rocks, have been carried out (Rasmuson and Neretnieks 1986; Neretnieks 1987; Tsang and Tsang 1987, 1989; Moreno and Tsang 1994; Moreno *et al.* 1988, 1990; Tsang *et al.* 1988; Abelin *et al.* 1987; Tsang *et al.* 1991; Moreno and Tsang 1994; Moreno and Neretnieks 1993; Neretnieks 1987, 1994; Black *et al.* 2006). These studies show that channels in fracture networks can lead to major differences for solute transport characteristics compared to other fracture rock models.

As an important subset of channel network models, the sparse channel network model is characterized by flow in long channels separated from each other by large spacing. However, the sets of channels with different orientations can still intersect each other. The sparseness, or the channel spacing being large, can be defined relative to size of the flow domain of interest or tunnel diameter. More discussion of sparse channel network will be given in the next section.

Fig. 3 Conceptual model of a channel network to represent a multiple fracture system (from Cacas et al. 1990b)

1.2 Effect of sorption and matrix diffusion

Different mechanisms are involved in the transportation of solutes in fractured rocks. They include not only the uneven flow distribution, but also interaction between the solutes and the rock. The main interaction mechanisms are sorption and matrix diffusion. An overview of these mechanisms can be found in Retrock (2004). Matrix diffusion is the spread of the solute into the rock matrix driven by the concentration gradient between solute concentrations in the flowing fluid and in water in the porous rock matrix. The solutes may diffuse into and out of the porous rock and the stagnant water and therefore becoming diluted and retarded (Moreno and Neretnieks, 1993). Sorption is defined as the process in which the solute is attached to the surface of a solid phase (Neretnieks, 1993) due to several different causes. For linear sorption, mass adsorbed to the fracture wall is directly proportional to the excess concentration of solute in the fracture. Rock matrix diffusion and sorption are often lumped together and described by one factor called the “material property group”. The rock may also be altered near the fracture and the fracture surfaces may be covered with different mineral coatings, which will influence the access of solutes to the matrix. These are some of the important factors involved in the retarding processes that can substantially slow down transport, especially with respect to long time and large spatial scale flow, such as that in predictions of potential radionuclide transport into the biosphere, as part of a safety assessment of nuclear repositories (Neretnieks, 1980; Tsang, 2005; Tsang et al., 2008).

Further, Xu et al. (2001) showed that the rock properties display a high heterogeneity in the matrix diffusion coefficient, the effect thereof was further investigated by Zhang et al. (2006). Recent observation has also un-

veiled an often occurring zone of altered rock at the interface of the fracture and rock matrix, and this altered zone has a higher diffusivity coefficient (Polak et al., 2003; Widestrand et al., 2007). Effective matrix diffusion coefficients are also found to increase with testing scale (Zhou et al., 2007), and Zhang et al. (2006) examined this effect by numerical simulations. These observations have enhanced our knowledge on the heterogeneous nature of fractured rock.

Matrix diffusion from fractures in networks has been modelled and incorporated in transport codes of radionuclide decay chains (Joyce et al., 2009; Hartley and Roberts, 2012). However, these studies are based on the concept that fractures are either open or closed over the entire fracture plane with the consequences that the flowing fractures have to be assumed very sparse and that the rock between and far from the fractures is not readily accessible by radionuclides during times of interest. The sparse fractures may lead to poor connectivity of the fracture network and can be sensitive to fracture size distribution as has been pointed out by Berkowitz (2002). The fracture size distribution, assessed mainly from observations on outcrops, has a considerable influence on the connectivity of the fracture network.

It is to be noted that matrix diffusion is handled in fracture network models in a conceptually correct way, especially when fracture aperture variability is accounted for in the models. In contrast, for stochastic continuum models, matrix diffusion can be calculated as solute exchange between adjacent fast and slow flow lines, which is however an approximation. For channel network models, which represent flow to occur only in channels, matrix diffusion will be calculated as diffusion radially around channels. Care has to be taken that such calculated diffusion includes diffusion into both the rock and the stagnant water adjacent to the channels.

1.3 Structure of the paper

The present paper concerns the relevant implications and open issues related to the application of the concept of sparse channel model in the context of spent nuclear fuel repositories. The specific goals of this literature review are firstly to determine if there is scientific information available that can be used to address key questions regarding the existence and significance of flow in sparse channel networks; and secondly to analyse what further studies could be conducted to gain more knowledge regarding the nature of the flow system and its effects of flow probability and magnitude in channels intercepted by deposition holes in a repository constructed in fractured systems. The following key questions were identified:

- (a) what are the evidences of channelized flow in fractured rocks with laboratory and field measurements?

- (b) what is relationship between generalized flow dimensions from well test analysis and sparse channel network models?
- (c) what is the significance of fracture shapes in hydraulic connectivity?
- (d) how does the probability of flow channels encountering a deposition hole relate to the characteristics of a sparse channel model? and
- (e) are there any specific site studies where sparse channel models have been used and what are the main findings that were found?

In the face of these objectives, this paper is structured in four chapters, of which this introduction is the first one. Chapter 2 entitled *General concept of channel models* presents various concepts inherent to the use of channel models for describing the flow and solute transport in fractured rocks. In this chapter, a channel network model which has been applied in the context of the Swedish repository programme for fluid flow and solutes transport calculations is presented. A discussion is made about the necessary model parameters and how they can be best estimated from field and laboratory data. The main concepts of sparse channel models are presented.

In Chapter 3, entitled *Review of studies addressing some key questions*, the five key questions identified above are motivated and then discussed one by one.

In Chapter 4, a summary and a general discussion are presented together with some suggestions for future work.

2. GENERAL CONCEPT OF CHANNEL MODELS

In this section, a general discussion of channel network model developed by Moreno and Neretnieks (1993) will be presented, followed by a discussion specifically on the sparse channel network.

2.1 The channel network model

The channel network model (Moreno and Neretnieks 1993) has been used to calculate flow and transport of solutes in fractured rocks. The channel network model is a useful tool that has been applied assuming a relatively dense or well-connected channel network system. However, applications to sparse (or somewhat sparse) channel network systems has not been done in a systematic way. The code CHAN3D (Gylling et al., 1997, 1999 a, b) is a computational code that implements the channel network model developed by Moreno and Neretnieks (1993) for the simulation of fluid flow and transport of solutes in fractured rocks. The model assumes that fluid flow takes

place in a network of interconnected and randomly generated flow channels in the rock. A channel may be formed by individual channel members and it may be connected to one, two, three, or even more other channel members. In this code, up to six channels can meet at a grid point (Fig. 4).

Fig. 4 Fracture planes and channel members (from Moreno and Neretnieks 1993)

The channels can have orientations that are not aligned with a regular rectangular grid. This enables the model to represent large heterogeneities of the flow distribution commonly observed and to model solute transport considering advection and matrix diffusion and sorption in the matrix. A hydraulic conductance is assigned to each member of the channel network. The conductance is defined as the ratio between the flow in a channel and the pressure difference between its ends. In applications by Gylling and co-workers, the channel network model is mainly applied not to a sparse network but to a well-connected network. In such cases, objects such as fracture zones, tunnels, and release sources can be incorporated in the model in a simplified manner by modifying the mean conductance of the channels at these locations. In other words, different values are used for the mean conductance, depending on whether the channel member is located, for example, in a fracture zone, a tunnel, or in good rock. Channels located in a fracture zone have larger hydraulic conductivity than if they are in the rock mass. Conductances together with boundary conditions determine the pressures/head field and the flows in the system.

The conductances of the channel members can be assumed to be log-normally distributed, with mean and standard deviation values. The flow is calculated as an electric resistor network problem resolving the distribution of pressure or potential and the solute transport is calculated by using a particle tracking technique (Robinson 1984; Moreno et al. 1988). In the particle tracking technique, many particles are introduced, one by one, into

the calculated flow field at one or more locations. Particles arriving at an intersection are distributed in the outlet channel members with a probability proportional to their exit flow rates or according to stream lines. The former is equivalent to assuming total mixing at the intersections and the latter to no-mixing at the intersections. Each individual particle is followed through the network. The residence time for nonsorbing tracers in a given channel is determined by the flow rate through the channel member and by its volume. The residence time of an individual particle along its whole path is then calculated as the sum of residence times in all channel members that the particle has traversed. The residence time distribution (RTD) is then obtained from the residence times of a multitude of individual particle runs. The mean and standard deviation values for the residence times may be calculated. When dispersion in the channel and/or diffusion into the rock matrix are also considered, different particles in the same channel member will have a range of residence times. In this way, residence times for the particles may be described by a probability density function.

To describe the flow properties of the network the mean channel conductivity and the standard deviation of the channel conductivity are needed. The length distribution is important when the pressure and flow field are calculated. When the solute transport is simulated, additional channel transport properties are needed. For conservative solutes, not subject to sorption and matrix diffusion, the channel volume is needed. The residence-time distribution for conservative solutes may be calculated and compared to tracer tests in order to test the assumptions of the model. For the simulation of the large-time scale transport of sorbing tracers under repository conditions, it turns out that the volumes of the channels are not a significant factor in calculating the residence time distribution. The channel flow wetted surface (FWS) is however an important parameter for the interacting nuclides that are influenced by sorption and diffusion into and out of the rock matrix and depends on the channel length and width. Crawford et al. (2002) presents a method for estimating the flow-wetted surface of the rock mass by observation of the frequency of open fractures intersecting a borehole.

The data needed for a channel model are summarized in Table 1. The values of matrix porosity, effective diffusivity, and sorption constant are needed and can be determined by laboratory tests. It is more difficult to obtain the data for the fracture zones than for the rock mass. This is because of the difficulties in determining, for example, the geometry and hydraulic properties for the fracture zones and their associated variation or range. Table 2 shows an estimate of the importance and uncertainties of various parameters for simulations of fluid flow and solute transport using the channel network model. These estimates and uncertainties were obtained by a qualitative analysis only (Gylling et al. 1999a). To do a quantitative analysis, more research is needed from field and laboratory measurements.

232

Table 1 Summary of the channel network model input data (from Gylling *et al.* 1999a)

Model Input Data	Measurements
Location and geometry of the fracture zones	Regional charting
	Core logs
	Borehole radar
	Spinner tests
Channel conductivity distribution	Hydraulic tests Inflow to tunnels and drifts
Channel length and width distributions	No technique available at present Borehole and tunnel observations may give some indications
Flow-wetted surface	Hydraulic tests in boreholes Inflow to tunnels and drifts Tracer tests with interacting solutes (untested)
Flow porosity	Tracer tests with conservative solutes
Sorption and diffusion data	Laboratory and field tests

233

Table 2 Importance and uncertainty of different parameters for transport of solutes (from Gylling *et al.* 1999a)

Importance	Parameter	Uncertainty
Flow wetted surface

Mean conductivity

Sorption properties

Channel length

Standard deviation in conductivity

Flow porosity

Geometry of zones

Topography

235

236 In order to apply the model to a specific site, additional deterministic data such as dip, extension, and width

237 of major fracture zones are needed. The topography and other site characteristic data, such as, the average pre-

precipitation that might lead to infiltration, which influences the boundary conditions, are also needed. The geometry of the fracture zones can be different from site to site, but parameters like sorption and diffusion properties, on the other hand, may be similar for the same type of rock even if it is obtained from different sites.

2.2 Sparse channel network model

Because of the magnitude of in situ stress component normal to the fractures at depth, the variability of the fractures aperture and the local heterogeneities, it may be possible that many fractures are essentially closed and do not participate in flow and solute transport. In a sparse channel network, flow and transport are assumed to occur in only a few widely spaced 1D channels that are hydraulically active, and the distance between those channels can be significant. Fig. 5 shows an example of sparse and dense channel networks.

Fig. 5 Examples of sparse (left) and dense (right) channel networks (Black et al., 2007)

The main characteristics of sparse channel networks are long channels and low numbers of active channels within a large volume of rock (Black 2011; Geier 2014). When sparse channels interact with underground openings, a “skin” effect is observed. Skin is usually conceived as a region immediately surrounding a borehole or an underground opening whose hydraulic conductivity is different from that of a wider region. Positive skin effect is associated with a decrease in the value of permeability. Skin is usually evaluated using pressure flow measurements and analysis with Theis solutions, by assessing how far the properties near an underground opening, as indicated by early-time pressure data deviating from theoretical values obtained by assuming that the whole region is homogeneous. Field experiments done in Stripa mine (Sweden) enabled to conclude that inflows to the

tunnel are very sparse and converge strongly to the few inflow points available. This is termed hyper-convergence by Black et al. (2006), who developed a sparse channel network model to model the flow towards Stripa Mine. The code HyperConv, developed for this purpose, generates networks of channels on an orthogonal lattice network, applies boundary conditions, calculates flow through the resultant network and ultimately derives values of apparent bulk hydraulic conductivity and skin effect. In contrast to a dense channel model, this sparse channel model was able to produce the hyper-convergence and the positive skin effects that limit the inflows to the tunnel as were observed.

The formation of ‘compartments’, in terms of hydraulic head and water chemistry, is a direct consequence of the dominance of a few low conductance links within the network, the ‘chokes’. Thus where there is flow across a region of sparse channels, the measured heads will seem to occur in ‘patches’ of roughly equal head separated by ‘jumps’ of head where flow is constricted by the ‘chokes’. The ‘chokes’ are then the major site of head loss in the system. The large-scale permeability of such systems is largely determined by a few key connections and their values of conductance (Leung and Zimmerman 2012). In Sawada et al. (2000), in situ tracer migration experiments in fractured granite were carried out which indicated hydraulic compartmentalization and a heterogeneous distribution of conductive fractures.

3. REVIEW OF STUDIES ADDRESSING SOME KEY QUESTIONS

Several key questions in the context of nuclear waste repository performance have been identified, and in this section, they are addressed based on a literature study.

The first question is: *what are the experimental evidences of channelized flow in fractured rocks?* Such evidences provide insight to characteristics of channelled flow and basis to build up suitable channel network models for simulating flow and transport in tight fracture rock formations.

The second question is: *what is the relationship between generalized flow dimensions from well test analysis and sparse channel network models?* Because of the sparseness, flow from a borehole intercepted by a channel will initially have dimension one, which then increases as the channel is intercepted by other channels to allow the flow to spread in space. Pressure tests data allow the possibility of identifying the flow dimension and potentially provide information related to channel network characteristics. For example, in fractured rocks, the flow dimension may vary from one-dimension, in case of channels, to fully three-dimensional, in case of spherical flow. Because of heterogeneities, the flow is restricted in space and therefore, the flow can have a fractional dimension smaller than the respective value for the homogeneous medium. This question will be addressed by

summarizing the studies that have been done to show how pressure tests data can be used to assess the existence of channelized flow.

The third question is: *what is the significance of fracture shapes in hydraulic connectivity?* The long channels in a channel network model, depends on hydraulic connectivity defined by the intersections of those successive fractures. The probability of intersections in fracture rock depends in turn on their shape, e.g. circle, ellipse. This question will be addressed by summarizing the studies that have been done to analyse the influence of the fracture shapes on the hydraulic connectivity of the channels.

The fourth question is: *how the probability of flow channels encountering a deposition hole relates to the characteristics of a sparse channel model?* In a channel network model, the channels may intersect a waste canister deposition hole. The probability of this occurrence is of importance to the safety analysis of a spent nuclear fuel repository, because the water flow from the channel entering the deposition hole may drive piping erosion during open repository conditions and buffer erosion under saturated conditions, which eventually may lead to radionuclide releases.

The fifth question is: *are there any specific site studies where sparse channel models have been used to model flow and transport in fractured rocks?* To answer this question, the main studies where sparse channel models have been applied to model flow and solute transport in fractured rocks are summarized below, and the results that were obtained were compared with those obtained by using discrete fracture network models.

3.1 What is the experimental evidence of channelized flow in fractured rocks?

Channeling has been observed in small and large scale laboratory experiments in centimetres to tens of centimetres samples with natural or induced fractures, in large laboratory experiments, in field experiments with scale of meters to 100s of meters, and on walls of drifts and tunnels where water is seen to emerge in less than centimetres to tens of centimetres wide channels. The experimental observations also show the flow-rate distribution is very large among channels. Tsang and Neretnieks (1998) give an overview of a large number of experiments in which channeling is observed, conceived and interpreted.

Bourke (1987) selected several fractures in the Cornish granite in England and drilled five boreholes in the plane of one fracture with a length of about 2.5 m. Because the fracture plane undulates to a small extent, the five holes did not lie entirely in the fracture. Water was pressurized in one hole, and the adjacent holes were divided into 7-cm intervals by the use of packers, for measuring the pressure responses at different locations along these boreholes. It was found that many of the packed intervals in the five boreholes did not communicate

with each other. Fig. 6 shows a sketch of the connected flow pathways inferred from the measurements. The figure shows that the flow areas occupy only about 20% of the fracture surface. This is mainly due to the fracture apertures not being uniform and the two fracture surfaces not being parallel plates. Rather, the aperture varies over the fracture plane, and pressurized water takes the easiest pathway from one drill hole to the other, resulting in channelized flow paths as shown.

Fig. 6 Flow channeling in the plane of a single fracture (from Bourke 1987). The five boreholes are drilled in the fracture plane. Flow channels are labeled A, B, C and D. Numbers on the histograms are flows from adjacent holes

A much more sophisticated and detailed field experiment at a similar scale was performed by Abelin et al. (1988, 1990). In the so-called channeling experiment a fracture in granitic rock was selected in the Stripa iron mine in central Sweden, 360 m below ground level. Two parallel boreholes 1.95 m apart were drilled in the fracture plane. Five different tracers were injected into 5-cm sections of one hole and their emergence in packed intervals in the others, were observed. Results show a tracer transport pattern between the two boreholes (Fig. 7), with breakthrough curves at different locations in the observation hole (Fig. 8). Channelized flow was apparent, and the breakthrough curves showed multiple peaks and long tails.

337

338

339 **Fig. 7** Diagram of tracer flow from one borehole (hole 7) to another (hole 12) in the same fracture plane based

340 on data of responses between packed intervals of the boreholes (from Abelin et al. 1990)

341

342

343 **Fig. 8** Tracer breakthrough curves at various points in the pumping hole 12 (from Abelin et al. 1990)

344

The Stripa 2D experiment by Abelin et al. (1985) was a larger-scale field experiment than the channeling experiment. Two fractures in granitic rock were identified in one of the tunnels, or drifts, in the Stripa mine. A number of holes were drilled from the drift to intercept these fractures at points 5-10 m from the drift (Fig. 9a). A tracer was deposited at the intersections bracketed by packers emplaced in these holes. The tracer flowed through the fracture plane toward the drift, emerging at the drift along the fracture trace on its ceiling and walls. The emergence of the tracer into the drift was not uniform along the fracture trace; rather, both the flow rate and the tracer concentration were highly variable (Fig. 9b).

Fig. 9 (a) Experimental setup of the Stripa 2-D experiment (b) Water and tracer emergence points along fracture traces in the Stripa 2-D experiment illustrating strong channelization (from Abelin et al. 1985)

Novakowski et al. (1985) conducted an experiment in a single fracture in a monzonitic gneiss rock body at Chalk River, Ontario, Canada. A pulse of conservative tracer was injected in a steady state dipole flow field using an injection well and a pumping well separated by 10.6 m. The tracer breakthrough curve did not display multiple peaks, and they were able to fit it with a solution of the advective dispersive equation. Another set of

five experiments were made in a single fracture in the same rock (Raven et al. 1988) involving both injection-pumping dipole flow field and radial convergent flow field. It was found that the breakthrough curves displayed long tails that could not be fitted by the advective dispersive equation. A much better fit was obtained by considering a "transient solute storage model" that includes a highly mobile flow path and adjacent stagnant or very slow water volumes with tracer exchange between them.

Laboratory tracer tests in a core with natural fractures in granite cores were carried out by Neretnieks et al. (1982) and Moreno et al. (1985). The traced solution was injected at one end of the core and collected at the other. The breakthrough curves that were shown show a plateau. This concluded that the water does not flow uniformly through the system but flows through channels.

In the Stripa 3D experiment, a tunnel of about 100 m was constructed with three boreholes of 75 m in length, each drilled into the ceiling of the tunnel (Abelin et al. 1987). Nine high transmissivity intervals were identified in the three boreholes, from which different tracers were injected. The tunnel ceiling and walls were covered by 375 rectangular plastic sheets of 1 m x 2 m in dimension. The tracer emergence in to the tunnel was studied by measuring and analyzing the flow into these plastic sheets. It was found that the tracer does not emerge uniformly over the whole tunnel surface but rather emerges at very selected locations. Both the flow rates and the tracer concentrations at different locations were found to have a large degree of variability.

Field experiments at a scale of 100 m or more were conducted at the Finnsjön site in Sweden and at the Underground Research Laboratory (URL) in Pinawa, Manitoba, Canada. At the Finnsjön site (Andersson et al. 1988, 1989, 1990), two fracture zones were identified in a granodioritic formation. The deeper one, zone 2, with a thickness of about 200 m located at 100-260 m below the ground surface, was chosen for tracer experiments. Typical behavior of channeling flow is observed for the breakthrough curve, which is characterized by a long tail and one or several peaks. The other large-scale tracer experiments were carried at the URL in Canada (Thompson and Simmons 1995). At that site three fracture zones were identified in the granitic Lac du Bonnet batholith. In two-well injection-withdrawal tests in one of the fracture zones, multiple peaks were observed in tracer breakthrough curves at short transport distances (about 20 m), while for large transport distances a single well-dispersed peak was obtained (Frost et al. 1992). For tests in another of the fracture zone, tracers were injected in wells in the radially converging groundwater flow field surrounding the URL shafts and they were collected at groundwater seepage locations in the main and ventilation shafts of the URL. Of the more than 30 breakthrough curves obtained, 12 display multiple peak behavior, and many have early sharp rise and long tail features, both of which indicate the possible effects of flow channeling.

Large-scale observations in drifts and tunnels have also shown clear effects of channelized flow. At the Final Repository for Reactor Wastes site at Forsmark, more than 14000 m² of tunnel wall surfaces were surveyed for water effluent spots, and their widths and flow rates were measured (Neretnieks 1994). Strong variability in the measured flow rates was found.

Abelin et al. (1994) presents channeling experiments that were designed to study the transmissivity and aperture variations in fractures in crystalline rock at a depth comparable to high-level waste repository depths. These experiments were performed in the Stripa experimental mine. Two types of experiments were designed. In the single-hole experiments a hole was drilled > 2 m into the plane of the fracture and injection flow-rates were measured in 5-cm sections using a specially designed injection packer. Photographs were also taken inside the hole along the fracture to determine the visible fracture aperture and to obtain other information such as fracture intersections and fracture infilling. In the double-hole experiment two parallel holes were drilled in the plane of the same fracture at a center distance of 1.95 m. Hydraulic tests and tracer tests were made between the two holes to obtain information on connections in the plane of the fracture and to obtain information on residence time distributions in different paths (channels).

Brown et al. (1998) presents laboratory observations of channel structures in a natural fracture under various flow conditions. A method for obtaining precise replicas of real fracture surfaces using transparent epoxy resins was developed, allowing detailed study of fluid flow paths within a fracture plane. Clear and dyed water were injected into the aperture between fracture surfaces, allowing examination of the flow field. Digitized optical images were used to observe wetting, saturated flow, and drying of the specimen. Both video imaging and nuclear magnetic resonance imaging techniques showed distinct and strong channeling of the flow at the submillimeter to several-centimeter scale. It was found that channels have complex geometries and a wide range of scales. It was found that fluid velocities measured simultaneously at various locations in the fracture plane during steady state flow range over several orders of magnitude, with the maximum velocity a factor of 5 higher than the mean velocity. Due to channeling, then, the breakthrough velocity of contaminants can significantly exceed the mean flow.

To summarize, channeling effects in fractured rocks, as represented by relatively narrow and fast flow paths and tracer breakthrough curves with early arrival, long tail and possible multiple peaks, have been well observed at multiple scales, from laboratory measurements to field observations. Flow channeling may occur in the fracture plane because of strong variability in fracture aperture or in a fracture network composed of fractures with a wide range of transmissivities, or in general in a strongly heterogeneous porous medium system.

3.2 What is the relationship between generalized flow dimensions from well test analysis and sparse channel network models?

Flow dimension refers to the number of space coordinates required to describe flow. In 3D homogeneous media, the flow dimension is expected to be 3. If the flow occurs in a plane, the flow has a dimension of 2. If the flow is along a line, the flow dimension is 1. However, because of heterogeneities, the flow is restricted in space and therefore, the flow can have a fractional dimension smaller than the value for the homogeneous medium, i.e., a dimension that is a fraction smaller than 3, 2 or 1 for the heterogeneous 3D, 2D or 1D space respectively. For the 1D case, the smaller-than-1 dimension occurs if the 1D flow channel reduces in width.

Black et al. (1981, 1986) proposes a method for determining the hydrogeological parameters based on a prescribed sinusoidal pressure being applied to an “excitation” borehole. This test consists of observing the propagation of a pressure perturbation in the formation of interest and interpreting the test by fitting the observations with an idealized flow model. Equations are derived which describe the dependence of pressures and phase lags outside the excitation borehole on distance, signal frequency, specific storage, hydraulic conductivity, and flow rates. These cover two distinct configurations: that of a point source deep within a water-saturated elastic formation and that of a line source totally penetrating a confined aquifer. It was shown that if the fracture density is large and the system is isotropic, then a three-dimensional spherical flow geometry might be considered appropriate. If the fracture density is low or the system is very anisotropic, a one or two-dimensional flow model would probably be preferred.

Barker (1988) presents the generalized radial flow (GRF) model. This model used the flow dimension to describe how the cross-sectional area of flow changes with radial distance from the pumped well. In this approach, the flow dimension may have also non-integer values, but within a framework of average radial flow and homogeneity. There are some difficulties in applying this model: (a) the flow dimension is not a rock property and is likely to be scale dependent, (b) an ideal three-dimensional spherical flow geometry cannot be realized, and (c) anisotropy cannot be included. In addition, the physical interpretation of the flow dimension is unclear, although it is conjectured that the model represents dispersion in a fracture network. This author presents some analytical expressions for the constant rate, constant head and sinusoidal pressure tests.

Doe and Geier (1990) present three complementary methods to determine the geometry and connection between existing fractures from borehole tests. The first method uses the evidence of boundary effects in the well test to determine the distance to and the type of fracture boundary. The second method uses the flow dimension of the borehole test to infer about the fracture system. In the third method, the spacing and transmissivity distri-

bution of individual conductive fractures are extracted from fixed-interval-length borehole tests. These methods were applied to data obtained at 360 m below surface of the Stripa mine (Sweden). It was found that the influence of the boundary effects in the well test results is small. This suggests that the fracture system is well connected, but a significant variation in the spatial dimension of the well tests data was found, ranging from sub-linear (fractures which decrease in conductivity with distance from the hole) to spherical, for three-dimensional fracture systems. Also, it was found that during some pressure tests, the flow dimension changed with time.

In Doe (1991), the generalized dimension approach is applied to the interpretation of constant-pressure well tests. It is shown that the flow dimension cannot be uniquely interpreted because the flow geometry is related with local heterogeneities. This was pointed out as a limitation of the GRF method. Thus, the flow dimension needs to be combined with knowledge provided by geologic, geophysical and hydrologic methods, to construct a reliable model of the fracture network.

In Geier et al. (1996), transient flow data obtained from constant-head injection tests in Äspo Hard Rock Laboratory site were analysed using the GRF model. The analyses provided estimates of flow dimensionality, conductivity, and transmissivity which can be used in the development and validation of conceptual models, and to assess the quality of the existing Äspo conductivity database. Because of low flows indicating tight rock sections, half of the tests in a 3 m packer section and one third on the tests in 30 m section were not interpretable. Results of other interpreted tests showed a flow dimension ranging between 1 (or less) to 3. This author discusses the implications of dimensionality and transmissivity among the main fractures on choosing an appropriate conceptual model.

Walker and Roberts (2003) and Walker et al. (2006) discuss how system geometry and heterogeneities can influence the flow dimension of a fractured rock through analysis of constant-rate hydraulic tests. In Walker and Roberts (2003) it is shown that for a leaky aquifer, the flow dimension is a function of time and leakage factor. For a radial flow system with a linear constant-head boundary, the flow dimension tends to 3 asymptotically. Numerical analysis showed that a stationary transmissivity field with a modest level of heterogeneity has a stable flow dimension of 2. For a non-stationary field, the flow dimension depends on the form and magnitude of the non-stationarity. In Walker (2006), the flow dimension of stochastic models of heterogeneous transmissivity is determined. Results suggest that the flow dimension may be useful for selecting models of heterogeneity and their parameters.

Kuusela-Lahtinen et al. (2002) apply the general solution for n-dimensional flow obtained by Barker (1988) to study the possibility of using the flow dimension from constant pressure injection tests to characterize the

hydraulic conditions of fractured media. Results show a flow dimension of 1 (or less) can be clearly distinguished from a flow dimension larger than 2. But, in many cases, some difficulties were encountered in distinguishing the flow dimension equal to 2, 2.5, and 3 from each other, because of experimental difficulties in achieving the ideal conditions required by the Barker's solution. In non-unique cases the higher dimensions typically correspond to higher, sometimes unrealistically high, values of specific storage and to the less reliable and less representative early part of the experiment. In this way, most of the observations of a flow dimension equal to 3 can be excluded, leaving the majority observations of the flow dimension equal to 2 and 2.5.

In the work of Kuusela-Lahtinen and Poteri (2010), several data sets provided by constant pressure tests are analysed with the purpose of evaluating the flow channelling in the scale of a single fracture and the fracture network. The tests have been carried out at the Onkalo site in Finland by using a 2 m test interval approximately at the depth of the planned repository of the nuclear waste (400 - 450 m). One of the test intervals is intersected by a filled fracture. The flow dimension was found to be 1.5 or 2.0, where the dimension of 2 means that the flow occurs in the fracture and the dimension of 1.5 may indicate the possibility of narrow flow paths. The other analysed test interval is intersected by three filled fractures. The flow dimension ranged between 2.5 and 3, which implies a behaviour related to a fracture network (homogenous porous media). Flow dimension was also analysed by performing simulated constant pressure tests for different borehole locations over an artificial heterogeneous fracture. The channelling of flow was not demonstrated by the analysis of the flow dimension. Most of the cases showed a similar behaviour that can be represented by a flow dimension of two. Thus, the single-hole testing is probably more sensitive to the connectivity of the fracture network and partitioning of the flow to multiple flow paths through connected fractures than on the channelization of the flow. Hydraulic single-hole testing activates a limited volume of rock around the tested interval. If the tested volume is mainly limited to the fracture that intersects the borehole, it is more likely to separate channelized from two dimensional flow. If a larger volume of fracture network is activated by the hydraulic test, the transient hydraulic response can be used to distinguish possible channelized flow compared to the cylindrical or spherical pressure field of the test.

Follin et al. (2011) studies the discrepancies due to analysis method with or without GRF concept on the results of single-hole transmissivity values in the Forsmark site characterization using data from constant-head injection testing. Data were obtained with two methods: the Pipe String System (PSS method) and difference flow logging with the Posiva Flow Log (PFL method). The analysis showed that the transmissivities derived with standard constant-head injection well test analysis methods and with the GRF concept are similar provided that the dominating flow geometry during the testing is radial. A difference in the results obtained with the PSS

and PFL methods were found and it is because the measurements with the PFL method were done after several days of pumping, while the measurements with the PSS method were obtained 20 minutes after test interval perturbation. It is noted that a test interval intersecting a finite “dead-end” fracture or network may produce a flow in the early time period of the PSS test, but record a reduced or no flow by the much later time of running of PFL tool.

To conclude, flow dimension analysis can show effects of heterogeneity that flow is not simple three dimensional or two dimensional. However, its interpretation is ambiguous since the results are also sensitive to flow boundaries and channel intersections, as well as testing time. In the latter, different testing times represent testing of different sizes of rock region around the testing borehole. Thus, when flow dimension analysis shows a simple one dimensional flow over an initial testing period, it can be inferred that channelized flow occurs only over the test volume corresponding to this initial time period.

3.3 What is the significance of fracture shapes in hydraulic connectivity?

The importance of fracture shapes in hydraulic connectivity of channels was explored in Black et al. (2006, 2007) and was discussed in Black (2011, 2012) in a previous review of SKB’s hydrogeological models for Forsmark. They examined how the shape of a transmissive planar feature affected its probability of intersecting other fractures. The evaluation was for two nearby discs and two nearby ellipse of gradually increasing aspect ratio (Figs 10 and 11). This analysis concluded that when equidimensional features cease intersecting, non-equidimensional features continue to intersect even though with a small probability.

According to Black’s work, the intersection of two fractures is not a measure of network performance, whereas continuous connection across the entire network, percolation, is a key indicator. The percolation threshold of ellipses with different values of aspect ratio was estimated by several authors. In Garboczi et al. (1995), analytical predictions were made by using results from lattice models obtained by numerical modelling with ellipsoids of varying aspect ratio. In Robinson (1984), numerical simulations of uniformly distributed square fractures in 3D space were made. De Dreuzy et al. (2000) analyses the intersection of 3D random ellipses with widely scattered distributions of eccentricity and size but within the context of networks with ‘power law’ size distributions.

2 identical ellipses

distance between centres = R

each of negligible thickness

area = $\pi a b$

aspect ratio = a/b

each ellipse has area = π

Fig. 10 Intersection of circular discs and ellipses with different aspect ratio (Black et al., 2007)

Fig. 11 Probability of intersection of two identical ellipses as a function of their scaled separation for ellipses of different aspect ratios (Black et al., 2007)

Fig. 12 shows a compilation of the various results. The results presented by Black (2011, 2012), Garboczi et al., (1995) and Robinson (1984), are consistent with other, and show that as the aspect ratio of the features in-

creases the area per volume density of the network required for percolation decreases. The value of percolation threshold reduces markedly beyond an “aspect ratio” of about 3 or 4. As aspect ratio increases from 1 towards 50 so the feature density required for percolation drops by an order of magnitude. The percolation threshold for the same size of equidimensional objects lies between 0.15 and 0.5. In order to percolate, disc-shaped fractures require about twice the area density as elliptical fractures of the same area but with a major axis length of about 2 to 3 disc diameters. This shows that equal size discrete fracture network (DFN) models need to have an overestimated density of fractures to percolate and that such DFN models may be a poor representation of reality. In other words, DFN model using fractures with an aspect ratio greater than one are in some cases more realistic. In sparse channel networks, the flow percolates at lower values of area per volume density than networks of equidimensional fractures.

Fig. 12 Estimated percolation threshold as a function of aspect ratio (Black, 2011)

The results presented by De Dreuzy et al. (2000) are also included in Fig. 12 and they show that the percolation increases as aspect ratio of the ellipses increases from 1 to about 3, reaches a peak at an “aspect ratio” of 4, and whatever the distributions of length and eccentricity, the values of percolation threshold remain restricted to a range of less than one order of magnitude. This shows almost no dependence of the percolation on the aspect ratio of the ellipses. Black et al. (2007) point out that the results presented by De Dreuzy et al. (2000) look “anomalous and unlikely” and Black (2015) points out some problems with this numerical study.

In Fig. 13, the percolation probability as a function of channel length and channel density is presented (Black, 2011). The channel length is represented by units of sub-channels. The figure shows that using assemblages of 100 realizations, percolation occurred in 100% of cases at lower values of density as channel length increased. The figure shows that the onset of percolation is more abrupt as channel length decreases. This explains why channel networks should be the predominant mechanism for flow in fractured rocks.

Fig. 13 Percolation probability as a function of channel length and channel density (Black, 2011)

In Mourzenko et al. (2004), the fracture network permeability is investigated numerically by using a three-dimensional model of plane polygons uniformly distributed in space with sizes following a power-law distribution. The influence of the parameters of the fracture size distribution, such as the power-law exponent and the minimal fracture radius, on the permeability of the fracture network is analysed. In Mourzenko et al. (2005), a numerical study of the influence of the fracture domain size, the flow dimension, and the fracture shape on the percolation threshold of fracture networks, is made. The work reported in these two papers, together with the work reported in De Dreuzy et al. (2000), concluded that the fracture shape is of secondary importance when it comes to hydraulic fracture connectivity.

To summarise the effect of fracture shape on percolation through sparse channel network is likely to be important. The different conclusions from alternative analyses could be due to the different constraints used in the analyses such as power law size distribution and use of different types of calibration data.

3.4 How does the probability of flow channels encountering a deposition hole relate to the characteristics of a sparse channel model?

The deposition holes can be intersected by fractures with channels of flowing water. The flowrate around a deposition hole and around tunnels control the rate of transfer of corrosive agents and of escaping nuclides to the biosphere. An escaping nuclide will reach the flowing water in the channel and be transported further into the channel network, mixing with water from other channels at some channel intersections or dividing into several outflowing channels at other intersection.

Geier (2014) presents an assessment of the SKB's conceptual model for flow through the fractured rock at Forsmark together with a set of relevant supporting analyses, in response to questions raised by SSM. In this work, four types of models are discussed. Two of these models are DFN models that include heterogeneity in terms of fracture intensity. Possible consequences of using these models include a moderate increase in the number of deposition holes with high flow rate and an increase up to an order of magnitude of the maximum flow rates. Also, a clustering of deposition holes that are subjected to high flow rates, can be obtained. The two other types of models that were discussed include some degree of channelized flow: variable-aperture DFN model and sparse channel network model. A very simplified variable aperture DFN model was also used in a limited assessment in support of Finland's repository programme. The model assumed that the fractures are non-transmissive on randomly distributed patches occupying some specified fraction of its area, with no larger-scale correlations. Results showed an increase of a few percent in the number of deposition holes that are connected to the flowing fracture network. Some discussion was presented on the sparse-channel network model, but it has not been considered in this work to estimate flows to deposition holes in a repository. This type of models was applied only to simulate flow around open tunnels and to explain the so-called "tunnel skin" effects, due to the effects of flow convergence in a sparsely fracture network (Black et al., 2006).

Summarizing, no literature was found on a systematic study of the impact of a sparse channel network on potential flow into deposition holes as a function of sparse channel parameters. Further investigation along this line may be required.

3.5 Are there any specific site studies where sparse channel models have been used to model flow and transport in fractured rocks?

The channel network model (Moreno and Neretnieks 1993) was used to simulate a long-term pumping and tracer test (LPT2) (Gylling et al. 1994, 1998, 1999a) performed at Äspo Rock Laboratory and to predict tracer

tests carried out within a 30 m cube scale experiment (Tracer Retention Understanding Experiment-TRUE) (Gylling et al. 1999a).

The goal of the LPT2 tests was to investigate the site and to test possible models to be used in safety assessment of a repository. These tests included three major parts: several pumping tests, tracer test experiments, and tracer dilution experiments. The channel network model which was used to simulate the LPT2 tests has $1000 \text{ m} \times 700 \text{ m} \times 700 \text{ m}$ and included the most of the boreholes in the LPT2 experiment. The channel network model was used to predict the experiments without calibration to reproduce the field observations. The simulation required the knowledge of the geometry of fracture zones and boreholes, the conductance distribution of the channels, flow-wetted surface area, tracer and rock interaction properties, and appropriate boundary conditions. The channel frequency, conductivity distribution and flow-wetted surface were obtained by interpretations of hydraulic packer tests. The mean and standard deviation values of the conductance for channels located in fracture zones were calculated from the analysis of distributions of the transmissivity data taking into account the channel length used in the model and the width of the fracture zones estimated from field data. The flow-wetted surface area was determined through the intersection frequency between boreholes and channels in the rock. The values of the flow porosity, pore porosity and effective diffusivity were not known and were obtained from Stripa data (Birgersson et al. 1992). The main tracer experiment was in reasonably good agreement, while other tests were overpredicted by the model.

The tracer tests within the TRUE project were performed at a depth of about 400 m. In the first stage, interference tests, dilution tests, flow loggings, pressure build-up tests, and preliminary tracer tests, were carried out. From the field studies, two fractures (A and B) were identified. Fracture A was found to intersect other fractures. Radially converging tracer tests were performed in this fracture by using nonsorbing tracers with steady-state pumping. In addition, a dipole experiment and tests with sorbing tracers were carried out. Results of these experiments were used to improve the channel network model that was used to predict all these tracer tests.

In the modelling, the geometry and boundary conditions were considered and the resulting flow distribution was then used in the transport calculations. This flow model includes a tunnel with the niche, all the boreholes, and fractures A and B. The size of the modeled rock volume was $30 \times 30 \times 40 \text{ m}$ in the longitudinal direction to the tunnel, the horizontal direction, and the vertical direction, respectively. The mean transmissivity values for the different fractures were assigned from the experimental data. In the transport calculation, the solutes were treated as non-sorbing species. The tracer transport mechanisms in one single channel is by advection together with diffusion into the matrix. The dispersion of the solute occurs because of the heterogeneity of the flow field

when the solute is transported with different velocities in the channel network. The tracers were injected as a decaying pulse. From the injection curves and the volumes at the injection points, the injection flow rates and the total injection mass were calculated. Using the available information to calibrate the model, the radial convergent test was well predicted. However, for two of the tests no recovery was obtained within the duration time for the experiment, whereas the simulations, it was predicted some loss of tracers to the tunnel for these two cases, but not as much as the experiment showed.

Dershowitz and Klise (2002) present three studies to study the transport of tracer tests by using the channel network model. These studies were focused on three different aspects of the TRUE Block Scale Hypothesis (Winberg et al. 2000) and addressed key issues regarding (a) transport properties based on conservative and sorbing tracer tests, (b) the possibility of special flow and transport properties at fracture intersection zones (FIZ), and (c) the possibility to improve the project hydro-structural model through minor changes in connectivity and transmissivity. It was found that the advection-dispersion-diffusion concept for transport within fracture networks is reasonably consistent with both hydraulic and transport observations and most of the observed hydraulic and transport responses can be explained by the model.

Selroos et al. (2002) present a comparison of the results for fluid flow and solute transport from the waste canister to the biosphere at Äspo site (Sweden), obtained with a stochastic continuum, a discrete fracture network and a channel network models. This comparative study was done in the context of the alternative models project (AMP) conducted by the Swedish Nuclear Fuel and Waste Management Company (SKB) as part of the SR97 project (SKB, 1999). SR97 is a comprehensive performance assessment of three hypothetical repositories for nuclear waste disposal, located at real sites in Sweden. The main goals of the AMP are to (1) illustrate the impacts of using alternative approaches for modelling groundwater flow and advective transport in fractured rock; and (2) determine the appropriateness of using a single approach to groundwater flow modelling in a performance assessment for nuclear waste disposal. In order to get useful comparison of the alternative modelling approaches, in the three cases, the same modelling domain, boundary conditions, repository layout, and definition of more parameters, were considered. This results in model applications that are similar in most respects, including similar discharge locations and median performance measures. In each modelling approach, the spatial variability of the rock mass was considered by mean of Monte Carlo simulations. The realizations are summarized by the statistics of three simplified measured of geosphere performance: travel time, transport resistance, and canister flux. Results show that the three approaches predict similar median travel times and median canister fluxes, but dissimilar variability. Similar values were obtained for the minimum travel time and maximum canis-

ter flux, as well as similar locations for particles exiting the geosphere. Results obtained with the stochastic continuum model show the highest variability of all three approaches considered. Results obtained with the channel network model show the lowest canister flux variance, indicating that this channel network application simply has a lower inferred spatial variability. Some of the differences in the results obtained with the various modelling approaches are caused not only by pure conceptual differences, but also by differences in modelling strategy and the compilation of performance measure statistics, such as the interpretation of underlying hydraulic conductivity data, the representation of tunnels and disturbed zone in the models, the number of canisters considered in the analysis and the number of realizations.

Liu and Neretnieks (2006) integrated the channel network model with a near field model to follow a nuclide from any leaking canister to the effluent points at the ground surface. The channel network model was used to calculate the flow rate in the channels near the deposition holes. By using those flow rates, the near field model was used to calculate the rate of transport of corrosive agents and the release of nuclides from a canister through different pathways into the near field of a repository. Then, the channel network model was used to calculate the paths of the nuclides from the canister through the network by particle tracking.

In Liu et al. (2010), safety assessment calculations for the Forsmark site were performed using a code that couples the channel network model and a near-field model. A site model was developed that includes most of the fracture zones of the Forsmark site. Deterministic data were used for tunnels, deposition holes, and shafts, while stochastic data were used for existing fractures. The simulations were carried out for 90 different canister locations, which were randomly chosen. The performance of the simulations was assessed through the F-ratio and the water travel time distributions. The results that were obtained were compared with those published in Joyce et al. (2009). Although the results cannot be compared directly, a reasonably good agreement was obtained for the F-ratio.

4. SUMMARY, DISCUSSION AND CONCLUSIONS

This paper presents a literature study bringing together information useful for addressing the questions of when a sparse channel network is likely to be an appropriate representation of the flow system in fractured rocks, and what are the implications of a sparse channel network model on some important issues related to the performance of nuclear waste repositories.

Several key questions are discussed in the foregoing sections based on literature survey: (a) what are the evidences for channelized flow in fractured rocks from laboratory and field measurements; (b) what is the rela-

708 tionship between generalized flow dimensions from well test analysis and sparse channel network models; (c)
709 what is the significance of fracture shapes in hydraulic connectivity; (d) how the probability of flow channels
710 encountering a deposition hole relates to the characteristics of a sparse channel model; and (e) are there any site
711 specific studies that have been carried out using channel network models?

712 Field and laboratory experiments, done at various scales, show that in fractured rocks, the flow and solute
713 transport occurs preferentially through channels in the fracture planes. However, what constitutes sparse channel
714 to be representable by sparse channeling model is not well defined. Whether a site-specific flow system in frac-
715 tured rock constitutes a sparse channel network depends on the size of channel spacing as compared with the
716 observation or sampling scale and with the size of flow domain of interest.

717 Conceptually, a flow channel occurs with flow dimension one when an initial flow path segment from a flow
718 source or pressure injection (or pumping) point is joined to only one downstream flow segment, and each of the
719 later flow segments is connected only with one upstream (inflow) segment and one downstream (outflow) seg-
720 ment. Multiple flow channels in parallel without intersection with each other will behave still with flow dimen-
721 sion of one. Deviation from flow dimension of one occurs when the downstream outflow segments are more than
722 one, which happens when two channels intersect each other (or when a fracture is intersected by more than one
723 inflow and one outflow fractures). Thus flow dimension is a measure of the characteristics of channel intersec-
724 tions as a function of flow distance. In particular, flow dimension of less than one can occur if several parallel
725 independent flow channels coalesce into one channel. With this conceptual picture, it is clear that flow dimen-
726 sion can be a function of scale. Thus, flow dimension may be one near an injection well in a region without
727 channel intersections, as seen by early pressure data, but may become more than one in late-time pressure data
728 covering a larger region where many channels begin to intersect each other. The value of flow dimension de-
729 pends on how intersections are distributed as a function of distance from the borehole where injection or pump-
730 ing is imposed. On the other hand, the special case of a persistent flow dimension of one may represent a long
731 flow channel or several parallel non-intersecting channels over an extended distance.

732 A sparse channel model by definition is, then, a channel network in which the channel spacing is large rela-
733 tive to the observation scale (e.g., tunnel diameter), or is not too many times smaller than the size of the flow
734 domain of interest. The determination of appropriateness of representing an in situ flow system by a sparse
735 channel network model through site characterization data is not straightforward and deserves further studies. For
736 example, how the different types of site characterization data, ranging from tunnel wall seepage observations to
737 pressure and tracer tests, can be used to characterize the channel network needs careful study. As pointed out

earlier, the occurrence and density of channel or fracture intersections are important in understanding the flow properties of channel network. Recent work showed that the intersection density is a significant factor in determining the effective permeability of fractured rock (Leung and Zimmerman, 2012). Thus this quantity may also be a useful parameter to be estimated in site characterization. In addition, the study may need to include a clear view towards the ultimate uses of the channel network model thus developed. These uses may be for addressing some issues of concern related to waste repository performance. Hence it is recommended that a generic and systematic study should be done to develop a site characterization approach to obtain parameters of a channel network model as a function of the average channel spacing; i.e., from a situation of a dense to that of a sparse channel network.

The relationship and consistency of the characteristic of the channel network in fractured rock with its rock mechanical properties and the local stress field at depth are an area of research that have largely been neglected so far. The fact is that they are intimately related. Rock fractures at the deep subsurface are under large normal stress with the result that there will be closures with zero apertures over large areas of the fracture plane, giving rise to flow channelling. Also, given the rock mechanical properties, the local aperture and permeability over the fracture plane of each of the fractures or channels, with its own orientation and shape, need to be consistent with the local 3D stress field. Furthermore, if there are changes in pore pressure or local stress field due to, e.g. its location near an excavated tunnel, water desaturation and resaturation, or overland glacier movements, the fracture apertures may deform giving rise to changes in the geometry of the channel network.

Sparse-channel network models have been applied only to simulate flow around open tunnels, and the channel model developed by Moreno and Neretnieks (1993) has been applied with “non-sparse” parameters to model flow and solute transport experiments at Äspo. It may be very useful to apply the channel network model to the same site, but as a function of channel spacing or sparseness (properly calibrated against field data) to see the impact of repository-relevant issues as the channel network becomes more and more sparse.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Swedish Radiation Safety Authority (SSM), for providing financial support to research reported in this paper.

REFERENCES

- Abelin H, Birgersson L, Agren T, Neretnieks I (1988) A channelling experiment to study flow and transport in natural fractures. Proceeding Scientific Basis of Nuclear Waste Management XII, edited by L. Lutze and R. C. Ewing, Mater. Res. Soc. Symp. Proc., vol. 127. pp. 661-668, Elsevier Sci., New York.
- Abelin H, Birgersson L, Gidlund J, Moreno L, Agren T, Widen H, Neretnieks I (1987) 3-D migration experiment in sparsely fractured crystalline rock, Proceedings Scientific Basis of Nuclear Waste Management, XI, Mater. Res. Soc. Symp. Proc., vol. 112, edited by M. J. Apted and R.F. Westerman, pp. 199-207, Elsevier Sci., New York.
- Abelin H, Birgersson L, Widen H, Agren T, Neretnieks I (1994). Channelling experiments in crystalline fractured rocks, J. Contam. Hydrol. 15(3): 129-158.
- Abelin H, Birgersson L, Wilén H, Agren T, Moreno L, Neretnieks I (1990) Channelling experiment. Stripa Project Tech. Rep. 90-13, Nuclear Fuel Safety Project, Sweden Nuclear Fuel and Waste Manage. Co., Stockholm.
- Abelin H, Neretnieks I, Tunbrant S, Moreno L (1985). Final report of the migration in a single fracture - experimental results and evaluation, Stripa Project, Report 85-103, SKB-Nuclear Fuel and Waste Management Company, Stockholm.
- Andersson P, Bygard J, Dershowitz W, Doe T, Hermanson J, Meier P, Tullborg EL, Winberg A (2002) TRUE block scale project final report 1: Characterization and model development, Technical Report TR-02-13, Swedish Nuclear Fuel and Waste Management Company-SKB, Stockholm.
- Andersson JE, Ekman L, Gustafsson E, Nordqvist R, Tiren S (1989) Hydraulic interference tests and tracer test within the Brändan Area, Finnsjön study site: The fracture zone project phase 3, Progress Report 89-12, Swedish Nuclear Fuel and Waste Manage Company-SKB, Stockholm.
- Andersson P, Eriksson CO, Gustafsson E, Ittner T (1990) Dipole tracer experiment in a low-angle fracture zone at the Finnsjön site, central Sweden-Experimental design and preliminary results, Progress Report 90-24, Swedish Nuclear Fuel and Waste Manage Company-SKB, Stockholm.
- Andersson JE, Ekman L, Winberg A (1988) Detailed investigations of fracture zones in the Brändan Area, Finnsjön study site: single hole water injection tests in detailed sections: analysis of conductive fracture frequency, Project Report 88-08, Swedish Nuclear Fuel and Waste Manage Company-SKB, Stockholm.
- Barker JA (1988) A generalized radial flow model for hydraulic tests in fractured rock, Water Resour. Res. 24: 1796-1804.

796 Berkowitz B (2002) Characterizing flow and transport in fractured geological media - a review, *Adv. Water*
797 *Resour.* 25: 861-884.

798 Birgersson L, Widén H, Agren T, Neretnieks I (1992) Tracer migration experiment in the Stripa Mine 1980–
799 1991. Stripa Project Technical Report 92-25, Swedish Nuclear Fuel and Waste Management-SKB, Stock-
800 holm.

801 Black JH (2011) Recognition and parameterization of SCNs, Presentation to Deep Hydrogeology Workshop.

802 Black JH (2012) Selective review of the hydrogeological aspects of SR-Site, SSM Report 2012:37.

803 Black JH (2015) Private communication to CFT.

804 Black JH, Barker JA, Noy DJ (1986) Crosshole investigations: the method, theory and analysis of crosshole
805 sinusoidal pressure tests in fissured rock, Stripa Project, Internal Report 86-03, Swedish Nuclear Fuel and
806 Waste Management-SKB, Stockholm.

807 Black JH, Barker JA, Woodman N (2007). An investigation of ‘sparse channel networks’ – characteristic, behav-
808 iours and their causes, Research Report R-07-35, Swedish Nuclear Fuel and Waste Management-SKB,
809 Stockholm.

810 Black JH, Kipp KL (1981) Determination of hydrogeological parameters using sinusoidal tests: a theoretical
811 appraisal, *Water Resour. Res.* 17 (3): 686-692.

812 Black JH, Robinson PC, Barker JA (2006). A preliminary investigation of the concept of hyper-convergence,
813 Research Report, R-06-30, Swedish Nuclear Fuel and Waste Management-SKB, Stockholm.

814 Bourke PJ (1987). Channelling of flow through fractures in rock, paper presented at GEOVAL-87 International
815 Symposium, Swedish Nuclear Power Inspection (SKI), Stockholm, April 7-9.

816 Brown S, Caprihan A, Hardy H (1998) Experimental observation of fluid flow channels in a single fracture, *J.*
817 *Geophys. Res.* 103: 5125-5132.

818 Cacas MC, Ledoux E, Marsily G, Barbreau A, Calmels P, Gaillard B, Margrita R (1990b) Modelling fracture
819 flow with a stochastic discrete fracture network: Calibration and validation, 2: the transport model, *Water*
820 *Res. Res.* 26(3): 491-500.

821 Cacas MC, Ledoux E, Marsily G, Tillie B, Barbreau A, Durand E, Fueva B, Peaudecerf P (1990a) Modeling
822 fracture flow with a stochastic fracture network: calibration and validation, 1: the flow model, *Water Res.*
823 *Res.* 26(3): 479– 489.

824 Crawford J, Moreno L, Neretnieks I (2002) Determination of the flow-wetted surface in fractured media, *J. Con-*
825 *tam. Hydrol.* 61: 361-369.

826 De Dreuzy JR, Davy P, Bour O (2000) Percolation parameter and percolation-threshold estimates for three-
827 dimensional random ellipses, *Phys. Rev. E*. Vol. 62 (5).

828 Dershowitz WS, Fidelibus C (1999) Derivation of equivalent pipe network analogues for three-dimensional
829 discrete fracture networks by boundary element method, *Water Res. Res.* 35, 2685–2691.

830 Dershowitz W, Klise K (2002) Evaluation of fracture network transport pathways and processes using the Chan-
831 nel Network approach. International Progress Report IPR-02-34, Swedish Nuclear Fuel and Waste Manage-
832 ment-SKB, Stockholm.

833 Doe T (1991) Fractional dimension analysis of constant-pressure well tests. *Soc. Petrol. Eng. J. SPE* Pg. 22702,
834 461 - 467.

835 Doe T, Geier J (1990) Interpretation of fracture system using well test data. Stripa Project Technical Report 91-
836 03. Swedish Nuclear Fuel and Waste Management Company-SKB, Stockholm.

837 Follin S (2008) Bedrock hydrogeology Forsmark. Site descriptive modelling, SDM-Site Forsmark, Report R-08-
838 95, Swedish Nuclear Fuel and Waste Management Company-SKB, Stockholm.

839 Follin S, Ludvigsson J, Levén J (2011) A comparison between standard well test evaluation methods used in
840 SKB's site investigations and the generalized radial flow concept, Report P-06-54, Swedish Nuclear Fuel and
841 Waste Management Company-SKB, Stockholm.

842 Frost LH, Scheier NW, Kozak ET, Davison CC (1992) Solute transport properties of a major fracture zone in
843 granite, in *Tracer Hydrology*, edited by H. H6tzl and A. Werner, pp. 313-320, A. A. Balkema, Brookfield,
844 Vt.

845 Garboczi EJ, Snyder KA, Douglas JF, Thorpe MF (1995) Geometrical percolation threshold of overlapping
846 ellipsoids, *The American Physical Society, Phys. Rev. E*, Vol. 52/1: 819-828.

847 Geier J (2014) Assessment of flows to deposition holes, SSM report 2014:05 ISSN: 2000-0456.

848 Geier J, Doe TW, Benabderragmane A, Hassler L (1996) Generalized radial flow interpretation of well tests for
849 the SITE-94, Report 96:4, Swedish Nuclear Power Inspectorate-SKI, Stockholm.

850 Gylling B (1997) Development and applications of the channel network model for simulations of flow and solute
851 transport in fractured rock, PhD thesis, Royal Institute of Technology, Stockholm, Sweden.

852 Gylling B, Biergersson L, Moreno L, Neretnieks I (1998) Analysis of a long-term pumping and tracer test using
853 the channel network model, *J. Contam. Hydrol.* 32: 203-222.

854 Gylling B, Moreno L, Neretnieks I (1999a) The channel network model-a tool for transport simulations in frac-
855 tured media, *Ground Water* 37 (3), 367-375.

856 Gylling B, Moreno L, Neretnieks I (1999b) SR97 – alternative models project: channel network modelling of
857 Åberg: performance assessment using CHAN3D, Report R-99-44, Swedish Nuclear Fuel and Waste Man-
858 agement Company-SKB, Stockholm.

859 Gylling B, Moreno L, Neretnieks I, Birgersson L (1994) Analysis of LPT2 using the channel network model,
860 International Cooperation Report ICR 94-05, Swedish Nuclear Fuel and Waste Management Company-SKB,
861 Stockholm.

862 Hartley L, Hunter F, Jackson P, McCarthy R (2006) Regional hydrogeological simulations using CONNECT-
863 FLOW, Preliminary site description. Laxemar subarea – version 1.2. Report R-06- 23, Swedish Nuclear Fuel
864 and Waste Management Company-SKB, Stockholm.

865 Hartley L, Roberts D (2012) Summary of discrete fracture network modelling as applied to hydrogeology of the
866 Forsmark and Laxemar sites, Report R-12-04, Swedish Nuclear Fuel and Waste Management Company-
867 SKB, Stockholm.

868 Hermanson J, Doe T (2000) March '00 structural and hydraulic model based on borehole data from KI0025F03,
869 International Progress Report IPR-00-34, Swedish Nuclear Fuel and Waste Management Company-SKB,
870 Stockholm.

871 Kuusela-Lahtinen A, Niemi A, Luukkonen, A. (2002) Flow dimension as an indicator of hydraulic behavior in
872 site characterization of fractured rock, Groundwater 41 (3): 333-341.

873 Kuusela-Lahtinen A, Poteri A (2010), Interpretation of flow dimensions from constant pressure injection test,
874 Working report 2010-35, Posiva Oy, Finland.

875 Joyce S, Simpson T, Hartley L, Applegate D, Hoek J, Jackson P, Swan D, Marsic N, Follin S (2009) Groundwa-
876 ter flow modelling of periods with temperate climate conditions-Forsmark, Report R-09-20, Swedish Nuclear
877 Fuel and Waste Management Company-SKB, Stockholm.

878 Larson M (2012a) Heterogeneity-induced channelling flow-wetted surface, and modelling of transport in frac-
879 tured rock, PhD thesis, Uppsala University.

880 Larsson M, Doughty C, Tsang CF, Niemi A (2013a) Understanding the effect of single fracture heterogeneity
881 from single well injection withdrawal (SWIW) tests, Hydrogeol. J. 21 (8): 1691-1700.

882 Larsson M, Niemi A, Tsang CF (2012b) A study of flow-wetted surface area in a single fracture as a function of
883 its hydraulic conductivity distribution, Water Res. Res. 48: W01508, doi: 10.1029/2011WR010686.

884 Larsson M, Odén M, Niemi A, Neretnieks I, Tsang CF (2013b) A new approach to account for fracture aperture
885 variability when modeling solute transport in fracture networks, Water Res. Res. 49(4): 2241-2252.

886 Leung CT, Zimmerman RW (2012) Estimating the hydraulic conductivity of two-dimensional fracture networks
 887 using network geometric properties, *Transport Porous Med* 93: 777-797.

888 Liu L, Moreno L, Neretnieks I, Gylling B (2010) A safety assessment approach using coupled NEAR3D and
 889 CHAN3D-Forsmark, Report R10-69, Swedish Nuclear Fuel and Waste Management Company-SKB, Stock-
 890 holm.

891 Liu L, Neretnieks I (2006) Coupling the near and far field models for performance assessment of repositories for
 892 spent nuclear fuel, American Geophysical Union, Fall Meeting 2006.

893 Long JCS, Remer JS, Wilson CR, Witherspoon PA (1982) Porous media equivalents for networks of discontinu-
 894 ous fractures, *Water Res. Res.* 18 (3): 645-658.

895 Moreno L, Neretnieks I (1993) Fluid flow and solute transport in a network of channels, *J. Contam. Hydrol* 14:
 896 163-192.

897 Moreno L, Neretnieks I, Eriksen T (1985) Analysis of some laboratory tracer runs in natural fissures, *Water Res.*
 898 *Res.* 21 (7): 951-958.

899 Moreno L, Tsang CF (1994) Flow channelling in strongly heterogeneous porous media: A numerical study,
 900 *Water Res.* 30(5): 1421-1430.

901 Moreno L, Tsang YW, Tsang CF, Hale FV, Neretnieks I (1988) Flow and tracer transport in a single fracture - a
 902 stochastic model and its relation to some field observations, *Water Res. Res.* 24 (12): 2033-3048.

903 Moreno L, Tsang CF, Tsang YW, Neretnieks I (1990) Some anomalous features of flow and solute transport
 904 arising from fracture aperture variability, *Water Res. Res.* 26: 2377-2391.

905 Mourzenko VV, Thovert JF, Adler PM (2004) Macroscopic permeability of three-dimensional fracture networks
 906 with power-law size distribution, *Phys. Rev. E*, Vol. 69, 066307.

907 Mourzenko VV, Thovert JF, Adler PM (2005) Percolation of three-dimensional fracture networks with power-
 908 law size distribution, *Phys. Rev. E* 72, 036103.

909 Neretnieks I (1980) Diffusion in the rock matrix: An important factor in radionuclide retardation, *J. Geophys.*
 910 *Res.* 85 (B8): 4379-4397.

911 Neretnieks I (1987) Channelling effects in flow and transport in fractured rocks--Some recent observations and
 912 models, paper presented at GEOVAL-87 International Symposium, Swedish Nuclear Power Inspection
 913 (SKI), Stockholm, April 7-9.

914 Neretnieks I (1993) Solute transport in fractured rock: applications to radionuclide waste repositories. In Bear J,
 915 Tsang CF, de Marsily G (eds) Flow and contaminant transport in fractured rock, Academic Press, San Diego:
 916 39-127.

917 Neretnieks I (1994) Nuclear waste repositories in crystalline rock-an overview of nuclide transport mechanisms,
 918 paper presented at MRS Meeting on Scientific Basis for Nuclear Waste Management, Mater. Res. Soc.,
 919 Kyoto, Japan, October 24-26.

920 Neretnieks I, Eriksen T, Tahiten P (1982) Tracer movement in a single fissure in granitic rock: some experi-
 921 mental results and their interpretation, Water Res. Res. 18 (4): 849-858.

922 Neuman SP (1987) Stochastic continuum representation of fractured rock permeability as an alternative to the
 923 REV and fracture network concepts, In: Rock Mechanics: Proceedings of the 28th US Symposium, I. W.
 924 Farmer, J. J. K. Daemen, C. S. Desai, C. E. Glass, and S. P. Neuman, 533-561, Rotterdam: A. A. Balkema.

925 Neuman S (2005) Trends, prospects and challenges in quantifying flow and transport through fractured rocks,
 926 Hydrogeology J. 13: 124-147.

927 Nordqvist AW, Tsang YW, Tsang CF, Dverstorp B, Andersson J (1992) A variable aperture fracture network
 928 model for flow and transport in fractured rocks, Water Res. Res. 28(6): 1703-1713.

929 Nordqvist, AW, Tsang YW, Tsang CF, Dverstorp B, Anderssoon J (1996) Effects of high variance of fracture
 930 transmissivity on transport and sorption at different scales in a discrete model for fractured rocks, J. Contam.
 931 Hydrol. 22: 39-66.

932 Novakowski KS, Evans GV, Lever DA, Raven KG (1985) A field example of measuring hydrodynamic disper-
 933 sion in a single fracture, Water Res. Res. 24(8): 1165-1174.

934 Painter S (2006) Effect of single-fracture aperture variability on field-scale transport, Technical report R-06-25,
 935 Swedish Nuclear Fuel and Waste Management Company-SKB, Stockholm.

936 Polak A, Grader AS, Wallach R, Nativ R (2003) Chemical diffusion between a fracture and the surrounding
 937 matrix: Measurement by computed tomography and modelling, Water Res. Res. 39 (4): 1106, doi:
 938 10.1029/2001WR000813.

939 Posiva (2009a) Olkiluoto Site Description 2008-Part 1, Posiva Report 2009-01. Posiva Oy, Finland, ISBN 978-
 940 951-652-169-8.

941 Posiva (2009b) Olkiluoto Site Description 2008-Part 2, Posiva Report 2009-01. Posiva Oy, Finland. ISBN 978-
 942 951-652-169-8.

943 Rasmuson A, Neretnieks I (1986) Radionuclide transport in fast channels in crystalline rock, *Water Res. Res.* 22
 944 (8): 1247-1256.

945 Raven KG, Novakowski KS, Lapcevic, PA (1988) Interpretation of field tracer tests of a single fracture using a
 946 transient solute storage model, *Water Res. Res.* 24(12): 2019-2032.

947 Retrock (2004) Treatment of geosphere retention phenomena in safety assessments, scientific basis of retention
 948 processes and their implementation in safety assessment models (WP2), Report R-04-48, Swedish Nuclear
 949 Fuel and Waste Management Company-SKB.

950 Robinson PC (1984) Connectivity, flow and transport in network models of fractured media, Ph.D. thesis, St.
 951 Catherine's College, Oxford University.

952 Sahimi M (2011) Flow and transport in porous media and fractured rock: from classical methods to modern
 953 approaches, Wiley, New York.

954 Sawada A, Uchida M, Shimo M, Yamamoto H, Takahara H, Doe T (2000) Non-sorbing tracer migration experi-
 955 ments in fractured rock at the Kamaishi mine, Northeast Japan, *Dev. Geotech. Eng.* 84: 83-104.

956 Selroos JO, Walker DD, Anders S, Gylling B, Follin S (2002) Comparison of alternative modelling approaches
 957 for groundwater flow in fractured rock, *J. Hydrol.* 257: 174-188.

958 SKB (2008) Site description of Forsmark at completion of the site investigation phase, SDM-Site Forsmark,
 959 Technical Report TR-08-05.

960 Thompson P, Simmons G (1995) Underground laboratories-A site characterization tool for nuclear fuel waste
 961 Disposal in Canada, Proceedings of the Sixth Annual International Conference on High Level Radioactive
 962 Waste Management, American Nuclear Society, Las Vegas, Nevada, April 30-May 5.

963 Tsang CF (2005) Is Current Hydrogeologic Research Addressing Long-Term Predictions?, *Ground Water* 43 (3):
 964 296–300.

965 Tsang CF, Doughty C, Uchida M (2008) Simple model representations of transport in a complex fracture and
 966 their effects on long-term predictions, *Water Res. Res.* 44(8), doi: 10.1029/2007WR006632.

967 Tsang CF, Neretnieks I (1998) Flow channelling in heterogeneous fractured rocks, *Rev. Geophys* 36(2): 275-
 968 298.

969 Tsang YW, Tsang CF (1987) Channel model of flow through fractured media, *Water Res. Res.* 23 (3): 467-479.

970 Tsang YW, Tsang CF (1989) Flow channelling in a single fracture as a two-dimensional strongly heterogeneous
 971 permeable medium, *Water Res. Res.* 25(9): 2076-2080.

972 Tsang CF, Tsang YW, Hale FV (1991) Tracer transport in fractures: analysis of field data based on a variable-
 973 aperture channel model, *Water Res. Res.* 27(12), 3095-3106.

974 Tsang YW, Tsang CF, Hale FV, Dverstorp B (1996). Tracer transport in a stochastic continuum model of frac-
 975 tured media, *Water Res. Res.* 32: 3077-3092.

976 Tsang YW, Tsang CF, Neretnieks I, Moreno L (1988) Flow and tracer transport in fractured media: A variable
 977 aperture channel model and its properties, *Water Res. Res.* 24(12): 2049-2060.

978 Walker D, Cello P, Valocchi A, Loftis B (2006) Flow dimensions corresponding to stochastic models of hetero-
 979 geneous transmissivity, *Geophys. Res. Lett.* 33 (7): L07407, doi: 10.1029/2006GL025695.

980 Walker D, Roberts R (2003) Flow dimensions corresponding to hydrogeological conditions, *Water Res. Res.*
 981 39(12): 1349, doi: 10.1029/2002WR00151.

982 Widestrand H, Byegård J, Cvetkovic V, Tulborg EL, Winberg A, Andersson P, Siitari-Kauppi M (2007) Sorbing
 983 tracer experiments in a crystalline rock fracture at Äspö (Sweden): 1. Experimental setup and micro-scale
 984 characterization of retention properties, *Water Res. Res.* 43, W10413, doi: 10.1029/2006WR005277.

985 Winberg A, Andersson P, Hermanson J, Byegård J, Cvetkovic V, Birgersson L (2000) “Final report of the first
 986 stage of the tracer retention understanding experiments”, Technical Report TR-00-07, Swedish Nuclear Fuel
 987 and Waste Management Company, Stockholm.

988 Xu S, Wörman A, Dverstorp B (2001) Heterogeneous matrix diffusion in crystalline rock – implication for geo-
 989 sphere retardation of migrating radionuclides, *Journal of Contaminant Hydrology* 47 (24): 365-378.

990 Zhang Y, Liu H, Zhou Q, Finsterle S (2006) Effects of diffusive property heterogeneity on effective matrix dif-
 991 fusion coefficient for fractured rock, *Water Res. Res.* 42: W04405, doi: 10.1029/2005WR004513.

992 Zhou Q, Liu HH, Molz FJ, Zhang Y, Bodvarsson GS (2007) Field scale effective matrix diffusion coefficient for
 993 fractured rock: Results from literature survey, *Journal of Contaminant Hydrology* 93: 161-187.

994

List of figures:

- Fig. 1** Models to study groundwater flow and solute transport in fractured rocks (from Selroos et al., 2002)
- Fig. 2** Discrete fracture network (DFN) conceptual model (from Selroos et al., 2002)
- Fig. 3** Conceptual model of a channel network to represent a multiple fracture system (from Cacas et al. 1990b)
- Fig. 4** Fracture planes and channel members (from Moreno and Neretnieks 1993)
- Fig. 5** Examples of sparse (left) and dense (right) channel networks (Black et al., 2007)
- Fig. 6** Flow channeling in the plane of a single fracture (from Bourke 1987). The five boreholes are drilled in the fracture plane. Flow channels are labeled A, B, C and D. Numbers on the histograms are flows from adjacent holes
- Fig. 7** Diagram of tracer flow from one borehole (hole 7) to another (hole 12) in the same fracture plane based on data of responses between packed intervals of the boreholes (from Abelin et al. 1990)
- Fig. 8** Tracer breakthrough curves at various points in the pumping hole 12 (from Abelin et al. 1990)
- Fig. 9** (a) Experimental setup of the Stripa 2-D experiment (b) Water and tracer emergence points along fracture traces in the Stripa 2-D experiment illustrating strong channelization (from Abelin et al. 1985)
- Fig. 10** Intersection of circular discs and ellipses with different aspect ratio (Black et al., 2007)
- Fig. 11** Probability of intersection of two identical ellipses as a function of their scaled separation for ellipses of different aspect ratios (Black et al., 2007)
- Fig. 12** Estimated percolation threshold as a function of aspect ratio (Black, 2011)
- Fig. 13** Percolation probability as a function of channel length and channel density (Black, 2011)

List of tables:

- Table 1** Summary of the channel network model input data (from Gylling et al. 1999a)
- Table 2** Importance and uncertainty of different parameters for transport of solutes (from Gylling et al. 1999a)