In Site Hydro

2017

Review of hydrogeological elements in 2016 RD&D programme of SKB (TR 16-15)

John Black

In Site Hydro

4/28/2017

Issue D1

Preface

The Swedish National Council for Nuclear Waste has contracted me to review the hydrogeologically related elements of the 2016 RD&D Plan of SKB (TR-16-15).

I have been investigating the hydrogeology of poorly permeable rocks, particularly fractured crystalline rocks, in connection with radioactive waste disposal since 1978. I have completed partial reviews of hydrogeological aspects of national programmes for the Swedish regulator, SSM, during 2012 and for the Finnish regulator, STUK, during 2013 and 2014. I also completed a short non-core research project for SKB in 2007 on channel flow (Black et al. 2007). Published work on channel flow since then (Black et al. 2017) has been self-funded reflecting my continuing interest in the hydrogeology of fractured crystalline rock.

I recount this recent history to indicate my specialism but also to state that, since I have not been working recently for SKB, I cannot be expected to be party to the most recent activities of SKB and their research partners. For the most part, I have to rely on the most recent reports that SKB mention in TR-16-15. Some are dated 2015 or 2014 and, given the lag between understanding gained and publication date, some ideas will have progressed a further two or three years: in directions I cannot be aware of.

So, this review is based on my imperfect knowledge of the current status of SKB understanding and also on how I guess future activities, like going underground, will affect that understanding.

Summary

The report reviews the groundwater relevant sections of SKB's 2016 Programme for research, development and demonstration of methods for the management and disposal of nuclear waste. They mainly concern developments to link the excavation process to discrete fracture network (DFN) models, the development of DFN models and understanding glacial processes to improve simulations of ice-sheet dominated futures.

My main concern revolves around my belief that the current versions of DFN models, whilst they may be accurate representations of the fracture systems at Forsmark, are not reasonable representations of the groundwater flow system. The use of equidimensional features in the simulations results in them containing extensive open fractures rendering them impractical for the small scale representation necessary for the excavation process. They also use a size-transmissivity relationship for which the evidence is extremely questionable. This should be investigated thoroughly and established or rejected.

I explain how the concepts underpinning the DFN formulations produce the shortcomings of the models and propose a research effort on alternative conceptual models based around channels. I consequently propose separating structural models from the groundwater network model of the near-field rock that should underpin the safety case.

Further proposals include a greater emphasis on modelling and understanding head variations both related to excavation (i.e. small scale) and of natural variations seen in the Forsmark site investigation boreholes.

The main elements of the programme see progress and increasing complexity as coincident. I fear that adding complexity decreases future demonstability which is supposed to be one of the aims of the programme. Aims and milestones are either woolly or absent from the sections of the report that I have reviewed.

Table of Contents

1. Scope

The scope of this review covers hydrogeological aspects of the "Programme for research, development and demonstration of methods for the management and disposal of nuclear waste" published in 2016 by SKB. These are contained in Sections 5.8 and the first 9 sub-sections of Section 11. The assignment suggests that the review should consider:

- whether the programme omits relevant research internationally
- If other different research is warranted
- If the existing and proposed research is being progressed with sufficient vigour
- The quality of the proposed elements of the programme

Bearing in mind that the next step in the overall project is due to be the start of excavation at Forsmark, a marked change in the type and volume of information available on the hostrock is likely to become available together with the need to make important construction and monitoring decisions on a daily basis. Therefore, it is valid to ask whether the RD&D programme will help to improve understanding and aid decision-making. It is of note that the title of TR-16-15 includes "demonstration" inferring that some practical measurements are expected to confirm or validate some previous concepts or theoretical results.

This review therefore attempts to assess the value and relevance of the hydrogeological aspects of SKB's RD&D 2016 programme from both a medium and long term perspective.

2. Structure of this review

My intention in this review is to summarise what I understand the various sections and subsections of the report to mean. This is partly to indicate my own position of knowledge (or lack thereof) and partly to place the activities in a wider context. This is followed by a summary of where I consider there are shortcomings or omissions about which I give details in appendices. The summary of problems is in turn followed by a set of suggestions about what could be done to deliver a more useful programme. First though, it is useful to consider the state of hard rock hydrogeology in general.

3. Current state of the hydrogeology of fractured crystalline rock

SKB is widely recognised as being at the forefront of the hydrogeology of fractured crystalline rock. This results from consistently subsidising research since the 1970s, constructing and operating two underground research laboratories, hosting international co-operative projects and publishing a vast quantity of state-of-the-art reports. They have also embraced the latest technical innovations from outside Sweden including discrete fracture network (DFN) modelling and the Posiva Flow Logging™ (PFL) method. This has resulted in a research programme with considerable momentum of its own, possibly driven by its own goals. Also, within the field of hydrogeology, we have come to the point where only minor technological (i.e. equipment based) advance seems likely or possible.

This is why, the sections in TR-16-15 concerning hydrogeology are almost entirely about developments in modelling.

It should be noted that since the KBS-3 disposal concept uses 'everlasting' copper canisters, the hydrogeology of the hostrock has no safety role in the Safety Analysis Report (SAR) except as an alternative scenario. It is also a widely held belief that in the event of leachate emanating from a breached canister and penetrating the engineered barrier that only the low permeability hostrock in the immediate vicinity would have a safety function before leachate reached the biosphere

4. Summaries of sections relevant to hydrogeology

4.1. Section 5.8 Rock

This section is an introduction to the programmes of work on the geosphere described later in Section 11. It sets out two aims thus:

> *Further development is judged to be able to lead to more effective selection criteria for deposition holes, which in turn means that fewer holes are rejected unnecessarily.*
>
> *The efforts can above all lead to less pessimistic assumptions in the assessment of post-closure safety, i.e. determination of site-specific data with a reduced uncertainty interval should be striven for.*

It can be seen that the broad aim is to reduce uncertainty both in terms of practical decision-making during construction and in the outcome of the eventual safety case. Both are based on modelling fractures in 3D space. For construction, it is likely that this revolves around linking isolated measurements during repository construction within a deterministic model of the fracture system at Forsmark.

The second aim implies that the stochastic model of fractures using ConnectFlow will gradually include more specifically identified fractures and will therefore yield a safety case with less uncertainty than currently.

The rest of Section 5.8 provides no specific aims. In general, the intention regarding hydrogeology is to include more and more processes within the groundwater DFN model (i.e. geochemistry, solute transport, microbial processes etc.) . The aim of using site specific data to reduce uncertainty is repeated.

The aim of the work on seismic risk is again on reducing uncertainty but seems to be based on field studies to derive frequency and effects: an analogue project. The work on seismic impacts is related to the following sub-section on mechanical properties of the hostrock. There is an intention to integrate processes into a so-called thermo-hydro-mechanical (THM) model.

The final sub-section concerns glaciations and its effects on the proposed repository. It is probably fair to say that the Greenland Analogue Project (GAP) has widened the range of possible effects particularly with respect to groundwater/ice sheet interactions. The unstated aim is to set reasonable bounds on the possible impacts of an ice sheet.

Sub-section 5.8.2 reiterates the second aim of reducing uncertainty by including site-specific data within a developed DFN model. However, after mentioning "conditional DFN modelling" it then mentions investigating, "the effect of different conceptual assumptions that serve as a basis for the DFN modelling..". This seems rather fundamental and is not mentioned in the previous summary sub-section on the development of modelling of groundwater flow and transport of solutes.

4.2. Section 11 Rock

4.2.1. Introduction to Section 11

Section 11 is effectively a more detailed version of Sub-section 5.8. and contains 14 sub-sections, of which the first 9 have relevance to hydrogeology. The nine can be seen in the following way:

- 11.1 and 11.2 concern characterisation associated with construction
- 11.3 to 11.6 relate to modelling and the inclusion of many processes within a DFN construct
- 11.7 to 11.9 concern understanding glaciation and its effects

I address them in the above three groups.

4.2.2. Characterisation within construction (11.1 and 11.2)

The characterisation during construction is eventually aimed at identifying the location of deposition holes such that they contain no 'disqualifying' features. A development outlined concerns a fracture visualisation tool intended to identify 'critical structures' (currently identified on the basis of 'size'). This would be deterministic and is part of the overall strategy to include more specified fractures within the DFN modelling underpinning the safety case. However, these 'critical structures' are assigned to three classes (Munier and Mattila 2015) of which, the smallest (Class 3) cannot be accepted to intersect deposition holes. These would appear to be the least well defined and an important hydrogeological proviso is inserted:

> *"the methodology for model-based acceptance of deposition holes, on the basis of hydraulic tests in pilot holes and verifying tests in deposition holes (see Section 11.1.3), must be well tested and functioning prior to detailed design of the deposition areas. This applies also to the methods for measuring small water flows to deposition tunnels and deposition holes, as well as evaluation and modelling techniques."*

In Sub-section 11.1.3 SKB intend new modelling methodology to be developed and envisage:

> *"… continued integrated deterministic modelling in 3D. …. linked to the stochastic description of fractures (DFN), see Section 11.3, in the rock mass between the deterministically modelled deformation zones."*
>
> *Some initially stochastically described fractures/structures are expected to gradually obtain such informational underpinnings that they can be (re-)interpreted as deterministic structures, mainly in the description of the deposition areas on a tunnel scale.*

The important aspect here is the intention to address fractures and 'flow features' at a 'tunnel scale' which means in the order of a few tens of metres. They talk of continued development of "discipline-specific modelling methodology" apparently tested at Äspö HRL, Forsmark and Onkalo. I assume this includes hydrogeological modelling in addition to the geological and hydrogeochemical which they say is already developed.

4.2.3. Developments in modelling (11.3, 11.4, 11.5 & 11.6)

The first sub-section, 11.3, concerns DFN models for hydrogeological purposes and divides roughly into two sections. The first describes again, but in more detail, the inclusion of deterministic fractures into a DFN model using an approach developed by Srivastava (2002) (a report of Ontario Power Generation which I couldn't obtain but I did obtain Srivastava 2005). The Srivastava approach concerns large scale features such as lineaments. SKB claim to have modified and used the approach for rejecting/accepting deposition hole positions as presented by Selroos et al. 2015. Selroos et al. 2015 is a non peer-reviewed abstract for an AGU conference of about 300 words without significant information. I have not found a subsequent report.

The next section of 11.3 concerns a fracture generation approach originating in France (Davy et al. 2010; 2013) based on how fractures form and spread. The basic rule is that initial fractures are unconstrained and can become large; later fractures are smaller and essentially inhibited by the pre-existing larger ones. It seems that faults form a different power law distribution of sizes than joints. I wonder if that is inconsistent with the all-sizes single truncated power law currently employed in the safety cases. The simulations are based on circular fractures.

Uncertainty is also addressed by a project examining the propagation of error into the DFN representations and thereby on to the safety case based on the natural geometric uncertainty arising when a 76 mm diameter borehole intercepts a non planar fracture surface.

What seems to be the most ambitious project concerns the use of 'massively parallel computing' to model rough fractures within a reasonably sized DFN (Hyman et al. 2015) thus examining the role of channelling in concentrating flow. Again it assumes roughly circular fractures derived I assume from the various structurally related measurements originating from the site investigations. This same model system is intended to form the framework for adding geochemistry to the fluid flow modelling.

In general SKB describe a multi-faceted programme of research to improve the realism of DFN models and add more and more processes into the models rather than running separate process specific models.

Within the sub-section on hydrochemistry and solute transport, SKB describe research to include the controls on salinity, density, pH and redox properties within the flow models of DarcyTools and ConnectFlow. A further development is envisaged that calculates a K_d value that changes within the flow field with time. Including the complexities of colloid transport and matrix diffusion is also mentioned. The programme then lists a wide range of processes where,

> *"Efforts are also required concerning advective transport, dispersion, electromigration, gas transport, X-ray microtomography and colloidal transport to gain a better understanding of transport processes and provide input to the calculation tools. In order to reduce the uncertainty in transport parameters, new measurements should be carried out under relevant and well-defined conditions and on site-specific material."*

This is an incredibly wide ranging programme though it is not clear whether specific model development is intended or simply some form of improved understanding. It is also not clear how much experimentation is involved and whether it is field or laboratory based. There then follows further mentions of work on electromigration (I assume this is to speed up laboratory experiments), matrix diffusion, gas transport and radial diffusion within the lattice model Chan3D.

The next sub-section concerns the link between the deep and near-surface groundwater systems and their models (DarcyTools and ConnectFlow for deep, MikeShe for shallow). The intention is to link the two systems together and particularly to replace the method of particle-tracking with actual water flows containing nuclides. This would enable near-surface dilution and dispersion to yield better (and probably lower) estimates of dose to exposed populations.

The final sub-section in this modelling group is titled 'Development of hydrogeological calculation tools'. It appears to be a gather-up of the modelling methods that are intended to enable the developments outlined in the previous three sub-sections.

4.2.4. Glaciation and its effects (11.7, 11.8 and 11.9)

The first sub-section (11.7) concerns the impact of ice load on the flow and transport properties of the rock beneath a future ice sheet. The first paragraph appears to misunderstand the process on infiltration beneath a wet-based ice sheet and fails to mention the important role that bulk-rock compressibility plays in defining amounts of recharge under the ice. It proposes the application of a THM model to bound the consequences of ice sheet cover but it seems to focus on changed rock properties rather than any resulting change in direction or quantity of the contained groundwater. The particular THM model to be used is not specified but I note in Hökmark et al. (2010) that they use the code 3DEC which is a block model.

The second sub-section (11.8) is mostly about the near surface groundwater system and intends to undertake experiments within the framework of the Greenland analogue surface project. It is intended to gain a better understanding of the various shallow processes (particularly seasonal changes and permafrost) occurring in the vicinity of the edge of an ice sheet.

The last sub-section (11.9) about the glacial impact on hydrochemistry and transport is a re-iteration of sub-section 11.4 in the context of glacially induced changes in properties but mainly groundwater chemistry.

4.3. Overall impressions of the programme

The lack of clearly stated aims and objectives either for the whole set of hydrogeologically related programmes or the individual elements gives me the impression that the programme is only loosely focused on the overall aims of the project . A minor symptom of this is the repetition of the same initiative under different headings suggestive of multiple non-communicating authors without overall guidance.

It seems to me there is also a philosophical dilemma between the desire to increase model complexity to improve 'realism' and the need to 'demonstrate' understanding as in 'Research, Development and Demonstration'. Almost all the modelling initiatives involve the aim to include more and more processes within the basic DFN flow model. The outcome of this policy is exemplified by the DFNWORKS suite based at Los Alamos using the massively parallel subsurface flow and reactive transport finite volume code PFLOTRAN. Whilst its simulations may be more realistic than the current approach, can they ever be checked or 'demonstrated' and can enough realisations be run using such a complex code within the context of a necessarily probabilistic safety case?

5. Concerns

5.1. Introduction

I have two concerns about SKB's programme in general which is reflected in the absence of research effort on two significant aspects.

The first is any significant effort on alternative conceptual flow models to the one that underlies the DFN flow modelling encapsulated in ConnectFlow.

The second is the lack of effort in trying to understand variations in head in background fractured rock (the so-called Hydraulic Rock mass Domain [HRD] of Rhén et al. 2007) , either in the vicinity of underground openings or in the deep boreholes at Forsmark.

The issue of measuring and understanding head variations is important because there are only two practical measures against which one can verify, or at least gain confidence in, flow model simulations. They are head and groundwater chemistry. The distribution of transmissivity is of secondary value as it is within the model formulation. To date, the SKB programme has justified its groundwater flow modelling on the basis of appearing to match flow distributions in boreholes and groundwater chemistry. Groundwater chemistry varies very slowly and reflects large scale processes, hence its central role in understanding past glaciations and simulating a very long time into the future. Head on the other hand reacts quite quickly to subsurface activities and has been measured and interpreted extensively within the fracture and fault zones (the so-called Hydraulic Conductor Domains [HCDs] of Rhén et al. 2007). Head variations in the background fractured rock are going to be the most telling hydrogeological measurements emanating from the construction phase yet there is no history of trying to understand head variations around underground openings within the SKB and DFN modelling has (to the best of my knowledge) never successfully addressed the near-field, background rock environment.

I explain the reasons for my concerns below.

5.2. The problems underlying the current DFN modelling

5.2.1. The underlying concepts

It should be borne in mind that DFN models are structural models to which hydraulic characteristics are attached. The structural (geometric) model envisages flat planes in space and has four descriptors. They are flow feature size and shape and network density and organisation.

The concept is simple; that flow in fractured rocks occurs via the fractures. Thus, if one can represent all the fractures, one can calculate overall flow. Since the location, orientation and size of every fracture is unknowable, the process has to be done stochastically via the use of well-established geological procedures of structural interpretation. This is based on mapping fracture traces on outcrops and logging fractures intersecting boreholes. Crucially, it depends on assuming all fractures are equidimensional (Appendix A) in order to render a unique interpretation of fracture size distribution. This interpretation underpins all DFN models.

The 3D structural model that results is the so-called Geo-DFN model and contains all fractures both open and closed. Based on logging ‘open’ and ‘closed’ fractures in boreholes, the Geo-DFN model is ‘thinned’ to leave a network of supposedly open fractures, the Hydro-DFN model. When compared to hydraulic measurements in boreholes, this ‘open’ fracture network always yields too many fractures that should be flowing so the network is ‘thinned’ again. This second and final thinning effectively reduces the area density (often termed ‘intensity’ by DFN modellers and measured in m^2/m^3) of the model to the same value of area density of flow-features as measured in the boreholes of the site investigation. At the end of these ‘thinning’ procedures, it is hoped that the model is capable of percolating. That is, that there are a sufficient number of fracture-to-fracture intersections to enable at least one continuous pathway across the region under consideration.

Flow is calculated by assigning hydraulic properties to each fracture according to various rules whilst trying to match measured flow characteristics.

The process involves several premises that need to be borne in mind because they have important influences on the eventual form of the model and its outcomes. They are:

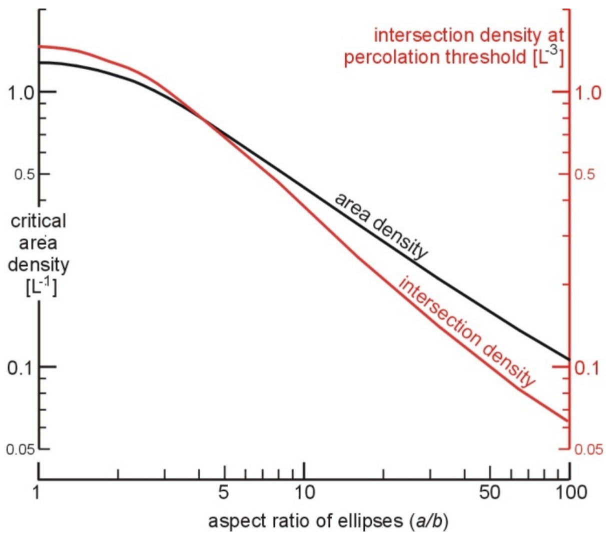
- Fractures are equidimensional, essentially planar and of varying sizes
- A limited fraction of all available fractures forms the network of flow-features (transmissive fractures) that enable percolation, and of those, the entire surfaces of the fractures allow flow

- Flow divides at every fracture intersection. Follin et al., (2014) state that, *"Flow is assumed to take place in the plane of each fracture with exchange of mass between fractures taking place at their intersections……"*
- The transmissivity of flow-features is linked to their extensiveness

It should be borne in mind that the only available measurement of flow-features, as opposed to fractures, is their density as seen as 'flowing zones' in boreholes. It is often assumed that the groundwater in fractured rocks is close to the percolation threshold. A review by Berkowitz (2002) cites four authors favouring this view and it seems very likely in the case of background fractured crystalline rocks. Indeed, Black et al. (2017) propose that some behaviours often observed in such rocks only occur near the percolation threshold. If this is the case, then the measurements of flow-feature density are of a value of area density close to the percolation threshold (also termed the 'critical density'). It is then important to know which of the remaining three network descriptors, flow feature shape, flow-feature size and network organisation affect the critical density of a network, and by how much.

5.2.2. The effect of flow-feature shape on the value of critical density

The effect of flow-feature shape on critical density has been evaluated by many authors with mixed results and a few have applied the same approach using networks of same-size discs that evolve into same-size ellipses of increasing aspect ratio but retaining the same area (de Dreuzy et al. 2000; Yi and Tawerghi 2009; Barker in press). Uniquely, Barker (in press) has developed general formulae that unite almost all previous results and apply to any mixture of shapes and sizes (Figure 1).



Based on general formulae of Barker (in press) for identical ellipses of area, *A* and perimeter *P*

$$A_{vc} = A\,n_c = \frac{\rho_c}{A^{k-1}P^{3-2k}}$$

$$I_{vc} = \frac{n_c^2\,A\,P}{4}$$

where A_{vc} = critical area density
n_c = critical number density
ρ_c = dimensionless critical number density
I_{vc} = critical intersection density
$\rho_c \approx 8.14$ for $1 < \alpha < 16$
and $\rho_c \approx 8.14[1+0.0023(\alpha-16)]$ for $16 < \alpha < 128$
where α = aspect ratio
and $k = 0.774$

Figure 1 Variation with aspect ratio of the critical area density and the critical intersection density for ellipses of area 1 m^2.

Figure 1 is a key result since it shows that networks of discs (i.e. equidimensional features) require the highest values of area density in order to percolate. In other words, that ellipses with even quite moderate aspect ratios would percolate at values of density less than a tenth of the value for discs.

5.2.3. The effect of flow-feature size on the value of critical area density

The general formula in Figure 1 can also be used to see the effect of flow-feature size on the value of critical area density (Figure 2).

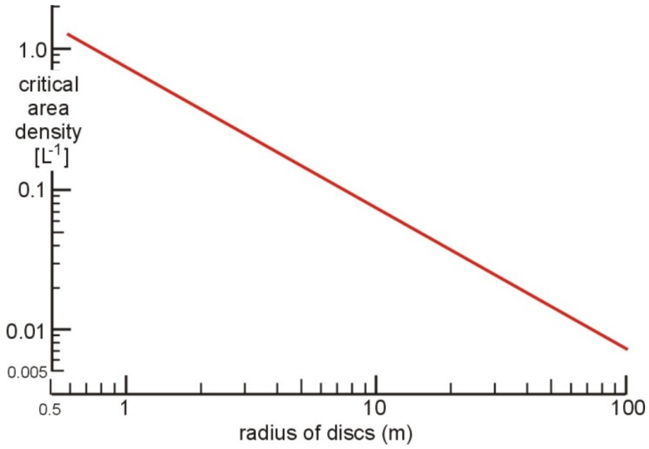


Figure 2. The effect of flow-feature size on the value of critical area density for networks of same-size discs.

Obviously a network of same-size objects is unlikely in reality, but adding large discs within a mixture has the ability to reduce the ultimate critical area density. Both the Swedish and Finnish safety cases (SKB 2010; Hartley et al. 2012) use a truncated power law to describe the distribution of fracture sizes to be found in the background fractured crystalline rock. Use of the power law envisages large numbers of very small fractures and a diminishingly small number of very large fractures so these are excluded by truncating the distribution at a minimum (r_{min}) and maximum (r_{max}) fracture size. The ratio of large to small fractures is controlled by the so-called 'shape' parameter (k_r) (It has nothing to do with the shape of the fractures.). The pdf of the truncated power law distribution is expressed by Follin et al. (2014) as:

$$\int(r) = \frac{k_r r_0^{k_r}}{r^{k_r+1}}$$

It can be seen in Figure 3 that as k_r decreases the distribution widens and for every small fracture, the probability of a large fracture in the distribution increases. Hence, low value 'shape' factors have a greater ability to lower the ultimate simulated value of critical area density than higher value shape factors. Most safety case models seem to use values around 3. It can be concluded that the choice of 'shape' factor has a very significant impact on network behaviour.

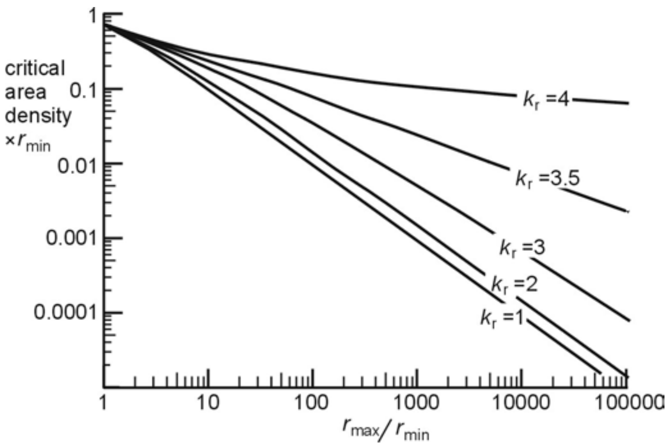


Figure 3. The impact of truncated power law parameters on the value of critical area density of a network of discs

5.2.4. The effect of network configuration on the value of critical area density

All of the results and the general formulae shown above are based on the flow-features/fractures being randomly orientated and randomly located. In contrast, fractures in nature are organised in sets usually as a result of the tectonic history of the host rock. Since Hydro-DFN models are essentially thinned structural models much effort is focussed on deriving a highly detailed structural model by mapping outcrops and logging core from fully cored boreholes. We have investigated the impact of fracture configuration by comparing the critical density of random networks with that of the same fractures organised in 3 equal orthogonal directions (Figure 4). It can be seen that the effect of orthogonal organisation is negligible increasing critical area density by between 5 and 10%.

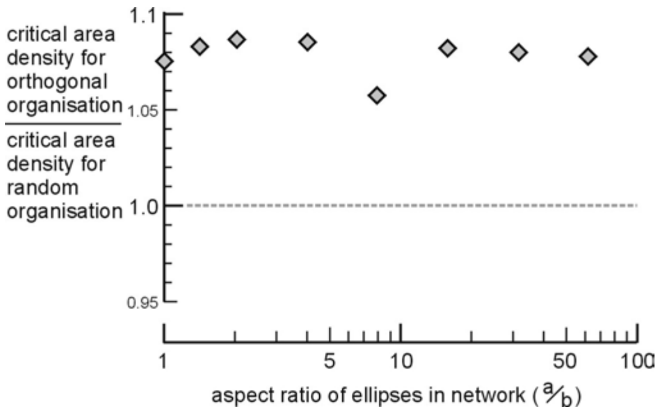


Figure 4. The effect of orthogonal organisation of flow-features compared to random organisation.

5.2.5. Summary of the impact of the underlying choices on the eventual Hydro-DFN

There are three (geometry-based) descriptors that can affect the density at which a DFN can first percolate. They are flow-feature size, flow-feature shape and network organisation. Of the three, only flow-feature size and shape have any significant impact. DFN modellers within the Swedish and Finnish repository programmes have chosen to forego the use of flow-feature shape thus limiting themselves to varying flow-feature size when trying to match measured field values of flow-feature density. They base their rejection of the influence of flow-feature shape on the paper by de Dreuzy et al. (2000) which was questioned by Black et al. (2007). Hartley and Roberts (2013) endorsed the work of de Dreuzy et al. (2000). The conclusions of de Dreuzy et al. (2000) concerning the lack of impact of flow-feature shape have since been shown to be incorrect (Barker in press). Details are given in Appendix B.

Since the structural interpretation that underpins the current DFN models suggests a power law size distribution, varying the power law index is the mechanism that increases or decreases the average size of the fractures in the models. This though, introduces a fresh problem of large numbers of small fractures. Both the Swedish and Finnish models employ a 'size-transmissivity' relationship whereby individual fracture transmissivity is proportional to fracture size. This has the effect of rendering the smaller fractures so poorly transmissive that they fall beneath the lower measurement limit of the field measurement method (see Appendix C). Thus the DFN model can have a higher area density than that measured in the field since only the more transmissive are then sufficiently transmissive to be observed. Obviously, since the transmissivity of flow-features is measured where they are intersected by boreholes, the (hydraulic) extent of a flow feature can only be estimated when pressure responses are observed in nearby boreholes. This is virtually impossible in background fractures as an element in site investigation. Only the most transmissive zones allow what is termed 'cross-hole' testing and is anyway complicated by the presence of channels on the fracture surfaces. Hence, the size-transmissivity relationship applied to background fractures at Forsmark and Olkiluoto is based on an interpretation of evidence derived from the TRUE Block Scale experiment at Äspö (Dershowitz et al. 2003). The evidence is flimsy (see Appendix C for background), the methodology is suspect and I don't believe it is good enough to warrant inclusion in a safety case..

The overall effect of the power law size distribution and the application of the size-transmissivity relationship is to create fracture network models that are dominated by large disc-like fractures that appear to match the occurrence of borehole-intersected flow-features measured by the Posiva Flow Log.

This conclusion is supported by statements of DFN modellers themselves:

> *"It is apparent… that the simulated system of connected open fractures is clustered around large fractures when using a power-law size distribution."* (Hartley and Roberts 2012)

> *"…..the size distribution can always be adjusted to reduce connectivity to the required level. However, in doing so it can produce connected networks that display characteristics inconsistent with other sorts of information."* (Hartley and Roberts 2012)*:*

> *"The size‑transmissivity model parameters shown in Table 5 were adjusted ….until a reasonable match to the four calibration targets was achieved."* (Follin et al. 2014)

5.3. Measurements and simulations

In the above sub-section, I have tried to describe in general terms how the DFN approach has been applied to the Forsmark site and what are the important concepts in determining the nature of the resulting models. In accord with the view of Neuman (2005) concerning representations of groundwater in fractured rocks, I believe the modelling should be based on hydrogeological rather than structural measurements. I have therefore compiled a brief summary of field and laboratory-based measurements of flow-features in fractured crystalline rocks. This is followed by a summary of some relevant DFN models.

5.3.1. Field measurements of flow-feature area density

The area density of flow-features is measured in boreholes using either short interval packer tests or the PFL method. Generally, the packer test method yields higher values (Figure 5) and underground tests allow lower measurement limits because they have much larger potential hydraulic gradients. The increase in measured density as the lower measurement limit of the test method decreases is apparent. Figure 5 also shows two important aspects. Firstly, the density of open fractures derived from core logging is no guide to the density of flow-features. Secondly, area density of flow-features in repository associated investigations varies over a comparatively limited range of no more than 1½ orders of magnitude. It should also be noted that the measured value of area density of flow-features for Forsmark is one of the two lowest to date.

5.3.2. Measurements of flow feature size

Measurements of flow-feature dimensions are few and far between. Of in-situ measurements, perhaps the best known are those based on tracer experiments by the group from KTH (Abelin et al. 1991; Abelin et al. 1994). All were based in the Stripa URL and were performed in the 'background' fractured rock adjacent to the underground openings. Despite problems with recovery of the tracers, they developed an image of flow within channels based on a braided concept of quite narrow width meandering around the areas of a fracture surface that are inevitably in contact (Figure 6a and b). Their concept of solute transport within a channel system was summarised by Neretnieks (2006) who advocated a channel width of 0.2 m. The concept and its approximate dimensions were roughly endorsed in experiments by Watanabe et al. (2009) (Figure 6c).

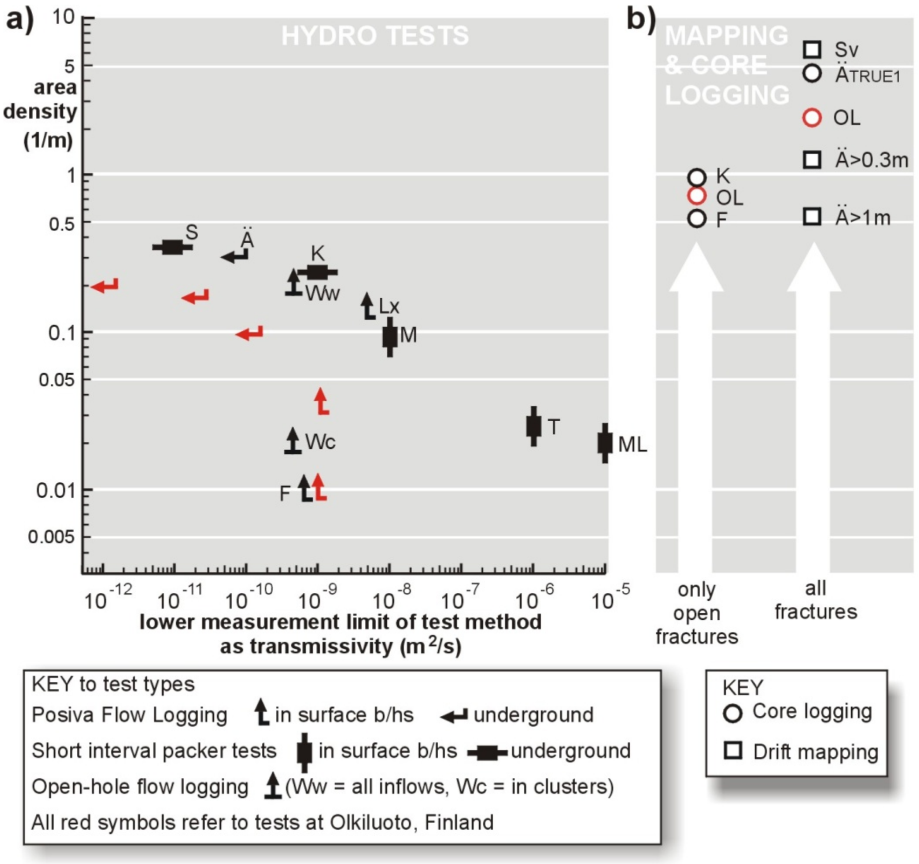


Figure 5 Values of area density derived from investigations in fractured crystalline rock at depth (100 to 500 m), a) hydro tests b) mapping and core logging. Origins of data are abbreviated; thus, 'K' = Kamaishi [*Sawada et al.,* 2000], 'Lx' = Laxemar [Follin et al. 2006], 'M' = Mórágy Granite [*Benedek and Dankó*, 2009], 'T' = Turkey Creek and 'ML' = Mirror Lake [*Wellman et al.,* 2009], 'OL' and red PFL results are from Olkiluoto, Finland [*Hartley et al.,* 2012], 'F' = Forsmark [*Follin et al.,* 2014], 'S' = SCV boreholes [*Holmes,* 1989], 'Ä' = TRUE block expt. [*Andersson et al.,* 2002], 'OL' = underground pilot holes at Olkiluoto [*Hartley et al.,* 2012], 'Sv' = Ventilation test at Stripa [*Rouleau and Gale,* 1985], '$Ä_{TRUE1}$' = TRUE single fracture expt., 'Ä>0.3m' and 'Ä>1m' = fracture mapping near TRUE1 [*Bossart et al.,* 2001], 'Ww' and 'Wc' = Sellafield, United Kingdom (Degnan et al. 2003)

There are no direct in-situ measurements of flow-feature length (assuming that the aforementioned measures are of width) but Black et al. (2017) propose that channels in background fractured crystalline rock at Stripa were often in the order of many metres between flow junctions. This was based on the evidence of tracer dispersion in the 3D Migration Test (Abelin et al. 1991) and the ability of a lattice network model to reproduce the hydraulic skin effect seen in the 'Macropermeability' Test of Wilson et al. (1981).

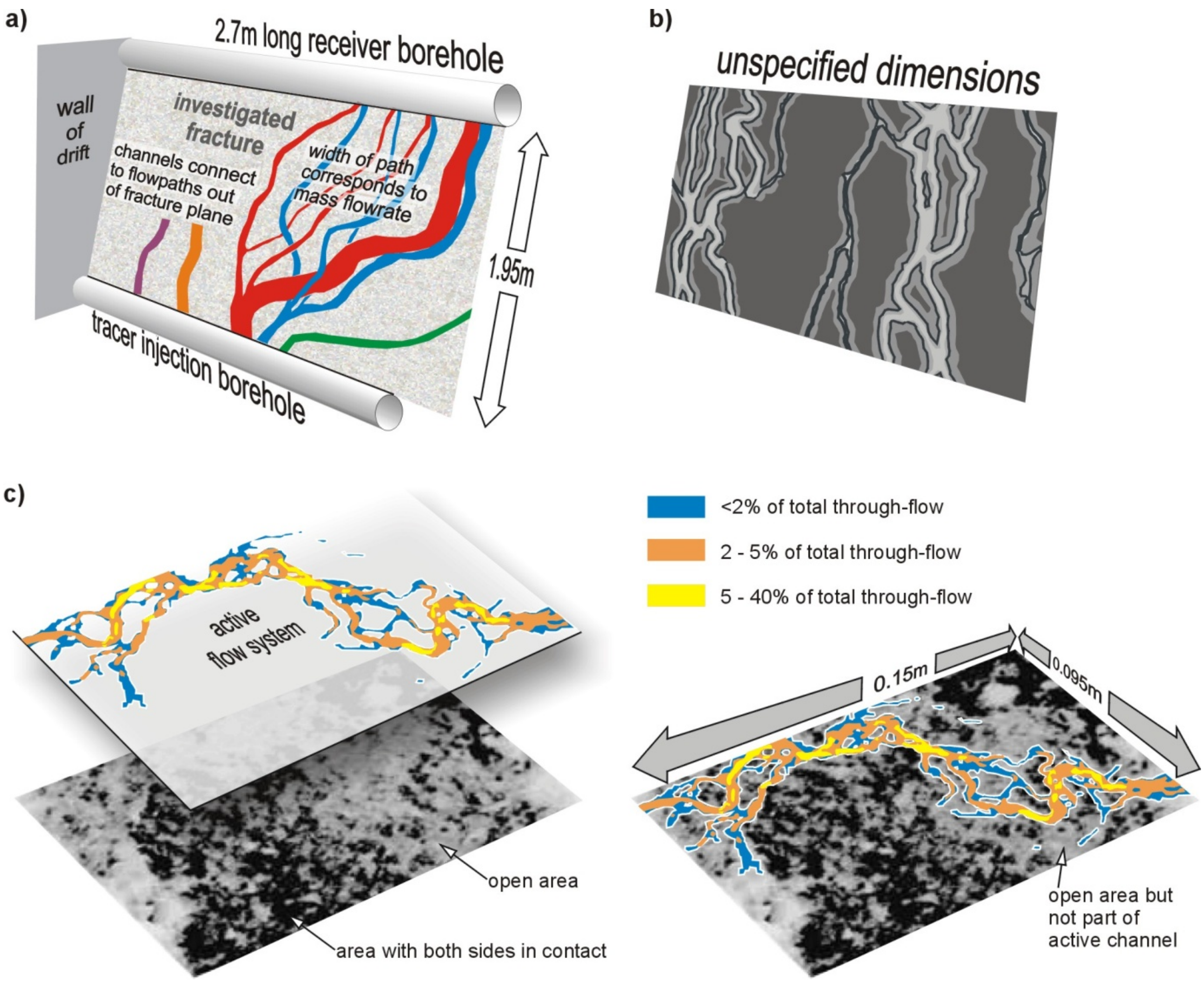


Figure 6. Flow experiments on single fractures: a) Pathways of tracers envisaged by Abelin et al. (1994); b) Channel organisation envisaged as an artist's impression by Abelin et al. (1994); c) The configuration of the channel of active flow in a laboratory sample of granite and its relationship to the fracture surface (from Watanabe et al. (2009) Fig. 10).

5.3.3. DFN simulations

There have been two general types of DFN simulations performed in connection with nuclear repositories; large scale simulations suitable for repository safety cases and smaller scale simulations associated with underground experiments.

The DFN simulation of Forsmark was typical of more recent DFN methodology. The region modelled was a cuboid, 400 x 400 m square plan by 1 km deep (Figure A1f) and according to Follin (2008) the region was simulated ten times. In Figure C4, Follin (2008) provides a pdf of the fracture sizes that provided the connected network. It is clear how it is dominated by extremely large fractures some of which penetrate from boundary to boundary of the simulated volume (Figure 7).

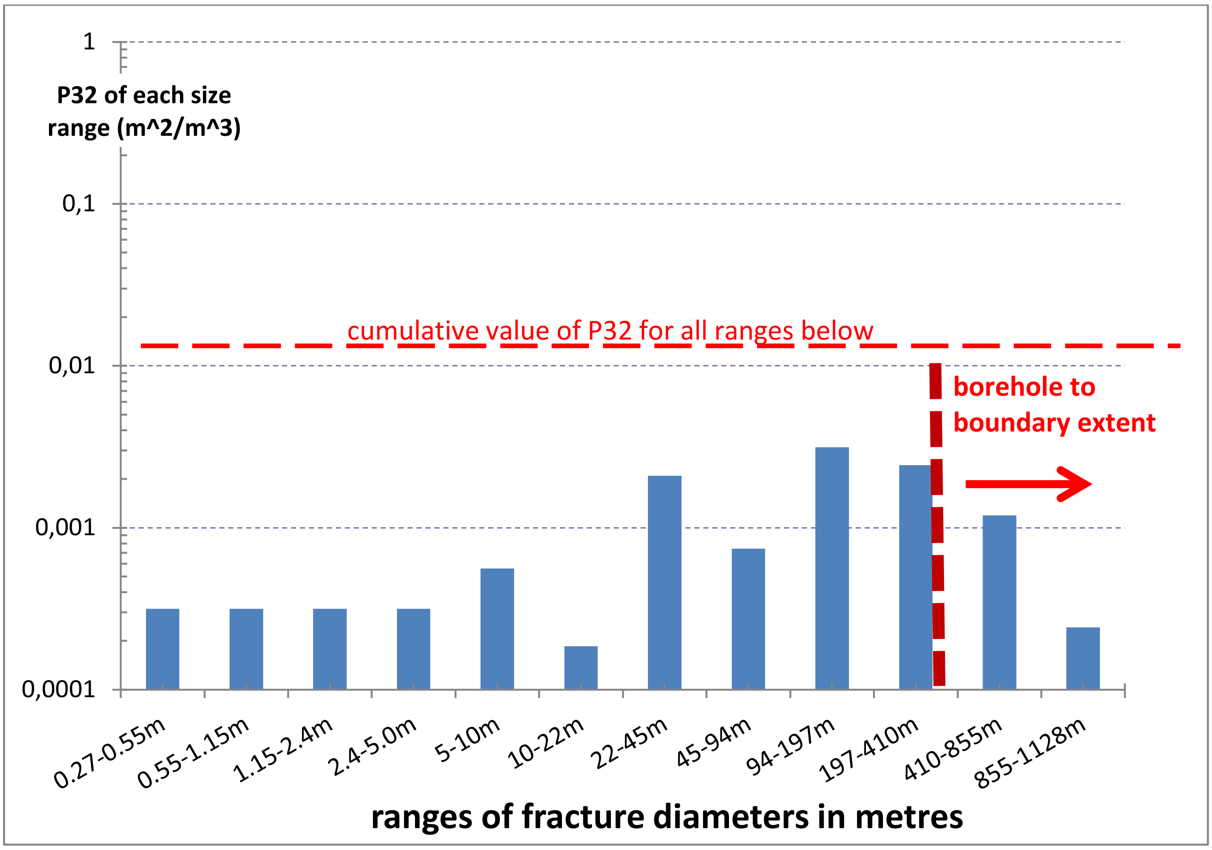


Figure 7. Re-interpretation of Figure C-4 in the form of a histogram of ranges of diameter.

At the smaller scale, the DFN model of the Äspö TRUE Block Scale experiment was a cube with an edge of 200 m. It was dominated by the specified '100 m scale' fractures plus the 'synthetic 100 m scale' fractures (see Figure 5.2 of Dershowitz et al. 2003). The latest experiment-scale models are of responses to PFL measurements in boreholes coincident with excavation at Olkiluoto and includes background fractures with a mean 'size' of 31 m (radius or diameter is unspecified) (Sawada et al. 2015). One of the models by Sawada et al. 2015 again uses a 200 m cube with a narrow size distribution and attempts to reproduce inflow variation by simulating flow within a 20 x 20 m rough fracture that produces channelling.

In general, DFN simulations to date have tended to incorporate large diameter fractures which by virtue of matching simulated system area density to measured area density must be 'open' throughout.

5.4. Understanding variations in head

As already stated in 5.1, the SKB approach to demonstrating that their modelling is credible, and that they understand the groundwater system due to contain their repository, is to simulate the long term evolution of the water chemistry and the frequency of flow features in boreholes. The SKB approach ignores the local variations in head caused by underground openings and prefers to simulate the large scale. At Äspö for example, the response to the excavation, dominated at large scale by the regional features of Rhén et al. (1997), was modelled by a number of groups. In contrast, the TRUE Block Scale volume was simulated using model boundaries located away from the underground opening and only used head responses in the context of borehole to borehole tests within a 200 m cube.

The re-interpretation of head responses at Stripa by Black et al. (2017) shows that it is possible to understand and reproduce near-excavation head responses using a relatively simple two-parameter lattice model based on a 'long channel concept'.

The intended repository host rock should have very low bulk hydraulic conductivity and relic heads from glacial events thousands of years ago can be retained within the background rock. The idea was demonstrated by Black and Barker (2016) for the English Lake District which saw the ice recede thousands of years before that of Forsmark and therefore should be less likely to retain measurable head effects.

In 2012, I reviewed the hydrogeological aspects of the Forsmark site investigation and noticed that the borehole testing had recorded heads but they hadn't been interpreted as a group. Since the boreholes are isolated, only vertical gradients are interpretable so I adjusted them for water density to convert them to environmental head to reveal vertical gradients. In an effort to get some general relationships from the data, I decided to form the results sets into groups: downward flowing , neutral and upward flowing. I include an example of downward flowing heads as seen in Forsmark boreholes 10A and 6C (Figure 8). Further examples are shown in Appendix C. I am not offering an interpretation but they certainly offer many questions and it seems quite probable that improved understanding of previous glacial cover would ensue.

5.5. Summary of concerns

I have three basic concerns though they are all linked to a greater or lesser extent to a central problem, the current incarnation of DFN models. The second concern is about the lack of attempted head interpretation and the third is about increasing complexity.

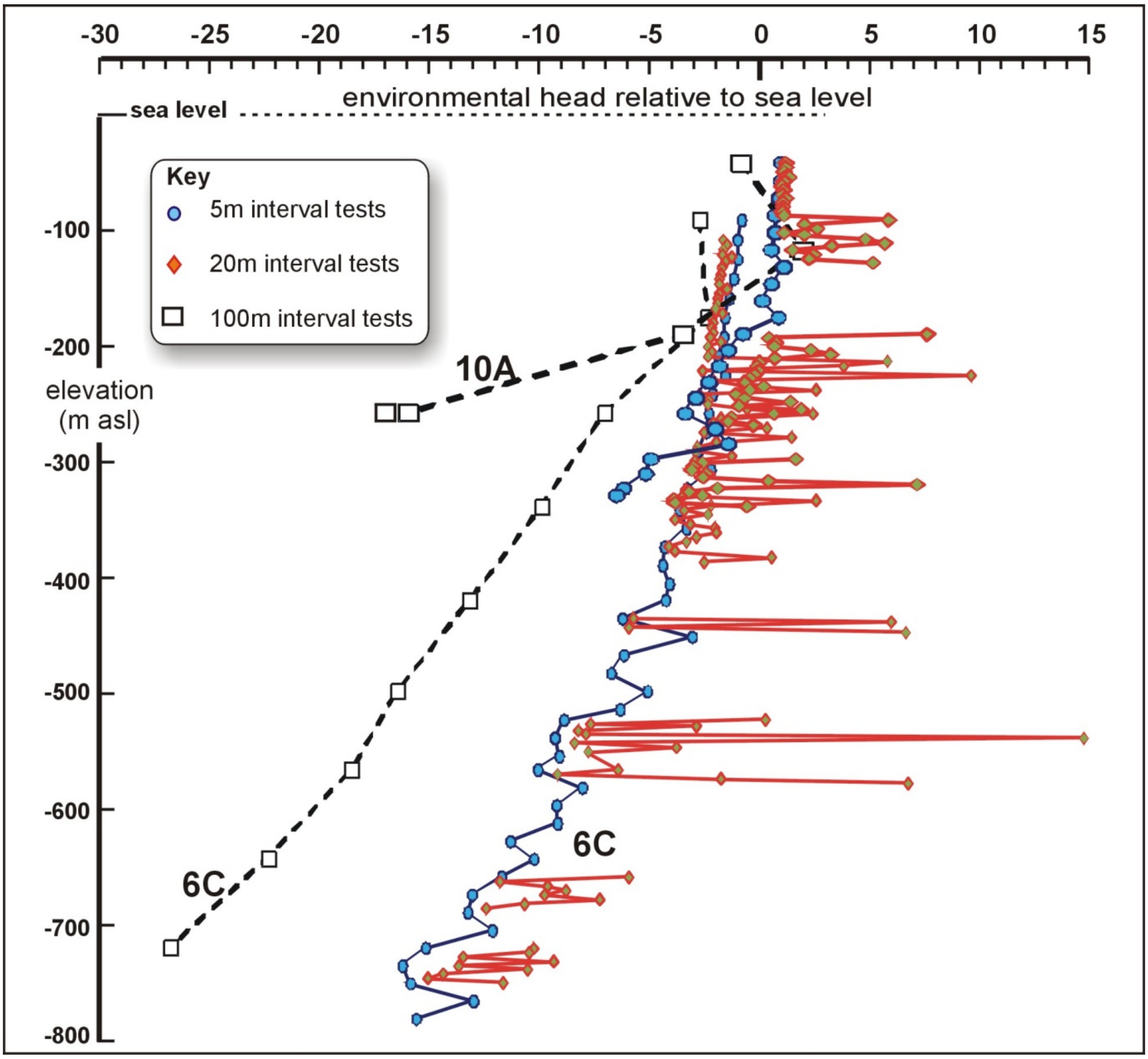


Figure 8 PSS head results from KFM10A and KFM 6C indicating downward flowing groundwater.

5.5.1. Current DFN models

The current DFN models have two significantly limiting underlying concepts. They assume that all flow features are equidimensional and that every fracture to fracture intersection is a potential flow junction. These become a problem because all repository investigations are yielding low values of area density and, out of all possible shapes of flow feature, equidimensional ones require the highest values of area density for a network to percolate. The impact of the assumption is readily demonstrated with reference to the area density derived for the proposed repository zone at

Forsmark (Figure 9). As can be seen, if all the equidimensional flow features are the same size, they require to be 40 m in diameter. This somewhat explains the distribution of sizes used in the Forsmark safety case (Figure 7). A 40 m diameter equidimensional flow-feature, open over its entire surface is implausible.

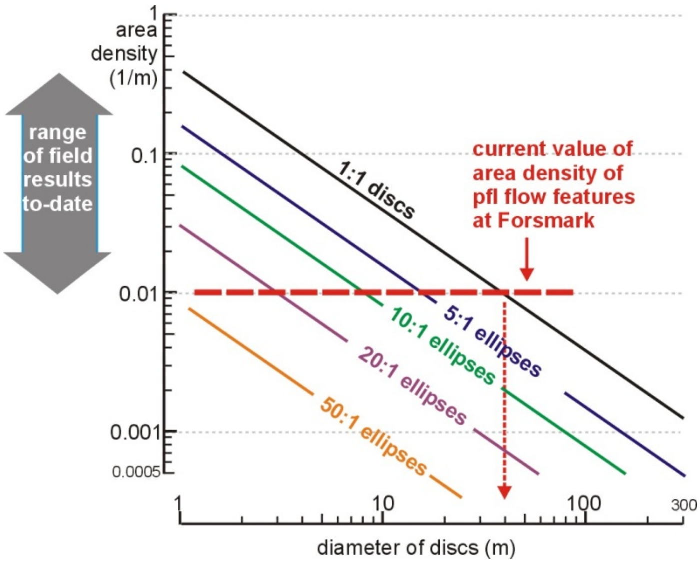


Figure 9. Size and shape combinations required of same size networks of flow features of the indicated shapes in order to just percolate.

A second aspect of the equidimensional assumption is that where channel models are based on structural interpretation, itself based on the equidimensional assumption, the derived density of intersections is too high. Any resultant channel model will be too dense and will not replicate the behaviours noted by Black et al. (2017).

The other aspect of current DFN models which causes me concern is the use of the size-transmissivity relationship which appears to be based on the most flimsy of evidence.

5.5.2. Interpretation of head

The reason this is linked to the problem of DFN modelling is not immediately obvious. However, because of the equidimensional assumption, the models require large flow features to reach the low values of area density measured in the field. These in turn, require large simulation volumes in order to include enough fractures to include enough large sizes within the power law size distribution (de Dreuzy et al. 2003). Hence they tend to be unsuitable for small-scale problems such as in the vicinity of an excavation.

So, there is little history of interpretation of head variation either around underground openings or of the larger regional scale natural variations caused by previous history such as glaciations and sea level changes. The interpretation of previous ice sheet effects in the groundwater beneath the English Lake District by Black and Barker (2016) concluded that bulk modulus was a key factor in deriving an explanation of what might have happened. I assume that some field measurements could be included within the set of proposals for glacial research.

5.5.3. Complexity and demonstrability

Most of the items in the hydrogeology sections of the 2016 RD&D programme envisage including more processes and complexity within a central DFN based flow structure. Given my views on the existing DFN modelling, it is hardly surprising that I'm not sure that this is a way forward to reducing uncertainty in the ultimate safety case, which is a stated objective in Section 5.8. Furthermore, I wonder if the ultimate comprehensive model, with all its process parameters picked from probability distributions, can be run sufficiently often to be statistically credible. And could one link outcome to input choice?

The title of the report SKB TR-16-15 includes "Research, Development and Demonstration". I question whether some of the intended increased complexity can be demonstrated.

6. Recommendations

These recommendations are proposed within the context of the start of underground construction and the development of practical strategies to identify safe locations for deposition holes. This will place emphasis on the ability to conceptualise and simulate at small scales and inform decision making quickly. I recommend that:

1. Alternative conceptual models based around channels are developed. These would be independent of the structural interpretation and modelling of the fracture systems required by rock mechanics and construction engineering. They would be based on actual measurements of hydrogeological phenomena. The 'long channel' concept of Black et al. (2017) is an example.
2. SKB should develop experience in understanding head variations in the near field. Progress in understanding the Excavation Damaged Zone and its limited extent (Ericsson et al. 2015) in conjunction with a conceptual model appropriate to the smaller scale should enable progress. In addition, SKB should either explain or interpret the natural head variations seen in the Forsmark site investigation boreholes.

3. There should be a thorough attempt to establish the size-transmissivity relationship. If it cannot be established it should not be used in future.

I have only read a relatively small portion of SKB's 2016 RD&D programme but I felt that there was very little in the way of specific objectives for the various items of research and development so that progress could be measured. Also there was no mention of 'demonstration'.

The question of alternative conceptual models to that of the current DFN approach has been raised before but without progress. It may be that SKB fear that a channel concept would result in a poorer safety case. In contrast, I believe that the network of flowing groundwater would be more dispersed and there would be less likelihood of the deleterious effect of a rapid route to the biosphere via one of the large features inherent in the current DFN simulations.

Appendix A Equidimensional elements in DFN models

DFN models first started appearing in the mid 1980s when early versions of the FracMan™ and ConnectFlow™ (NAPSAC) suites of models were applied at Stripa. The FracMan™ code assumed that all stochastically generated fractures were equidimensional polygons whilst NAPSAC used squares and 'low aspect ratio rectangles' (i.e. <2:1). A disc-based code based in France and LBL, USA was developed for a short period at the end of the 1980s. The two codes, FracMan and ConnectFlow have been in the forefront of DFN modelling since and have continued to use equidimensional elements right up to the present (Figure A1).

I note that the new, seemingly most advanced DFN model suite (DFNWorks), originating fron the Los Alamos Laboratory uses equidimensional polygons as its basic element (Hyman et al. 2015).

The six images of Figure A1 are of different scales: b), c) and d) are all supposedly of 'background' fractures which are what could be expected to form the 'nearfield' of a repository. Images a), c) and f) show realisations used in the current Swedish and Finnish Safety Cases. They are taken from:

Dershowitz W, Winberg A, Hermanson J, Byegård J, Tullborg E-L, Andersson P, Mazurek M, 2003. Äspö Hard Rock Laboratory. Äspö Task Force on modelling of groundwater flow and transport of solutes. Task 6c. A semi-synthetic model of block scale conductive structures at the Äspö HRL. SKB IPR-03-13, Svensk Kärnbränslehantering AB.

Follin, S, Hartley L, Rhén I, Jackson P, Joyce S, Roberts D, Swift B (2014) A methodology to constrain the parameters of a hydrogeological discrete fracture network model for sparsely fractured crystalline rock, exemplified by data from the proposed high-level nuclear waste repository at Forsmark, Sweden. Hydrogeology Journal, 22: pp. 313-331, DOI 10.1007/s10040-013-1080-2

Hartley, L., P. Appleyard, S. Baxter, J. Hoek, D. Roberts and D. Swan. 2012. Development of a Hydrogeological Discrete Fracture Network Model for the Olkiluoto Site descriptive Model 2011. Working Report of Posiva OY. Helsinki, Finland, No. 2012-32

Hyman, JD, Kara, S, Makedonska, N, Gable, CW, Painter, SL and HS Viswanathan. 2015. DFNWORKS: A discrete fracture network framework for modeling subsurface flow and transport. Computers and Geosciences 84: 10-19.

Jackson, C.P. and S.P. Watson 1997 NIREX 97: An assessment of the post-closure performance of a deep waste repository at Sellafield , Volume 2: hydrogeological conceptual model development -

effective parameters and calibration. Science Report of UK Nirex Ltd. S/97/012, 328pp

Sawada A, Saegusa H, Takeuchi S and WS Dershowitz. 2015 Äspö Task Force on modelling of groundwater flow and transport of solutes Task 7 – Groundwater flow and transport modelling of fracture system at regional,block, and single-fracture scale, Olkiluoto. SKB report P-13-46

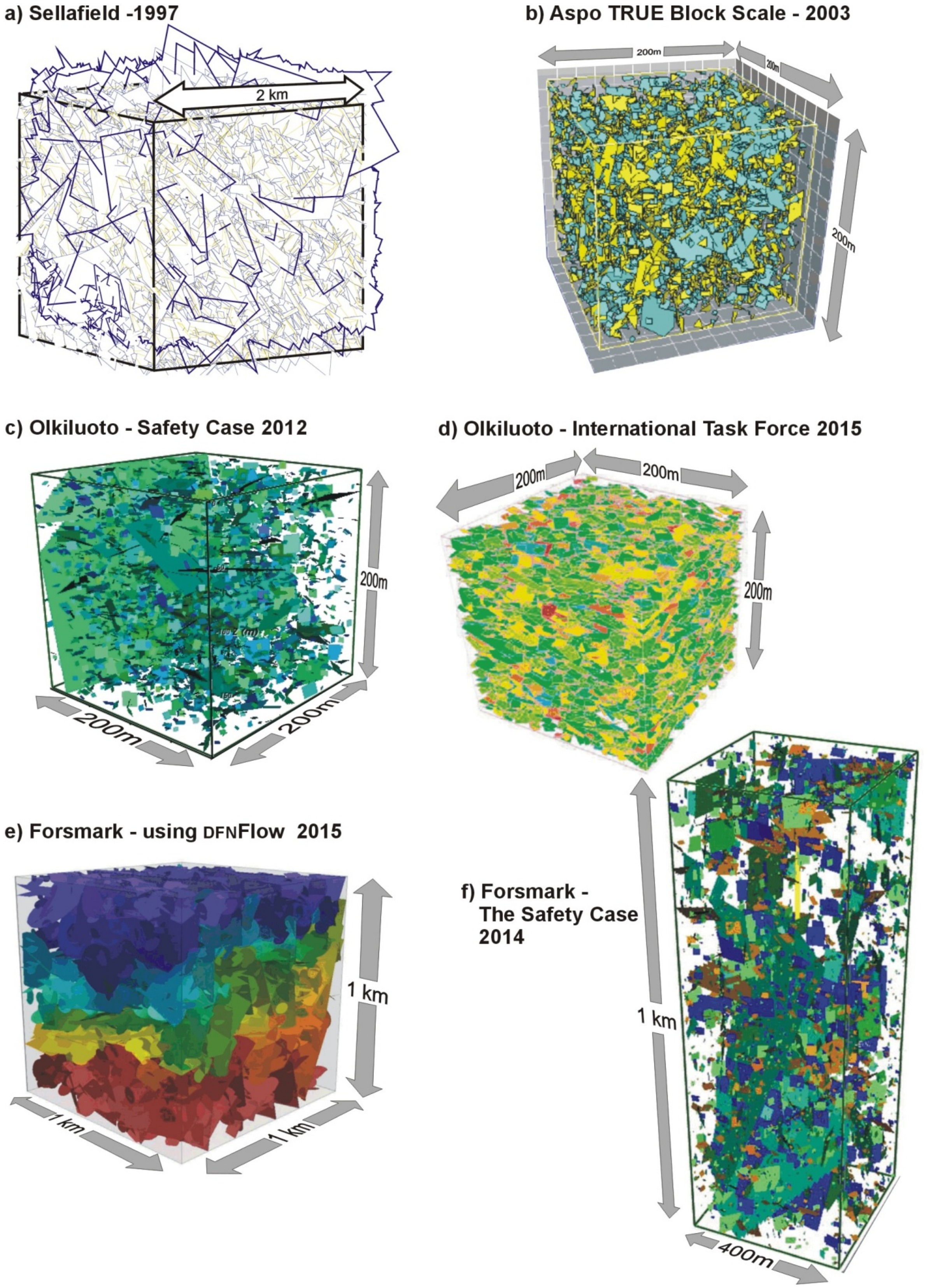


Figure A1. Examples of the use of equidimensional elements in DFN models: a)from Jackson and Watson (1997); b) from Dershowitz et al.(2003); c) from Hartley et al (2012); d) from Sawada et al. (2015); e) from Hyman et al. (2015) and f) from Follin et al. (2014)

Appendix B. Conversion of 'percolation parameter' of de Dreuzy et al. (2000)

Numerical box model experiments involving networks of same-size discs evolving into ellipses have been reported by de Dreuzy et al. (2000), Yi and Tawerghi (2009) and Barker (in press) (Figure B1a). The results show two significant aspects. The first is the impact of different definitions of critical density giving rise to a wide variation in the value for discs on the Y-axis. The second is the value of maximum critical density which occurs at an aspect ratio of one (i.e. discs) in the cases of Yi and Tawerghi (2009) and Barker (in press) but at a value around five for de Dreuzy et al. (2000). Furthermore, the critical density results of de Dreuzy et al. (2000) show negligible tendency to decrease with increasing aspect ratio unlike the other two investigations. The apparent inconsistency can be resolved by re-plotting the ellipse results relative to a dimensionless critical density (Fig. B1b).

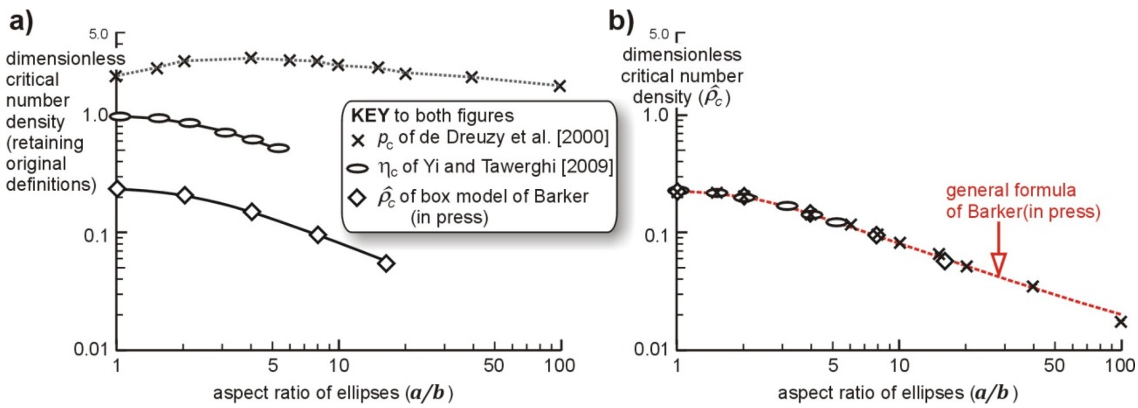


Fig. B1. Values of critical density for networks of same-size ellipses from Monte Carlo simulations: a) densities used by authors; b) densities converted to $n_c\,(a\,b)^{3/2}$, where n_c is critical number density [L^{-3}], with line representing the formula given in Eq. 3.

Barker (in press) considers a fracture model in the form of a mixture of elliptical plates of zero thickness, each of area A and perimeter P at number density, n (centres per unit volume). Consider the dimensionless density defined by:

$$\rho = \langle A^k P^{3-2k} \rangle n \qquad \text{(B1)}$$

where the angular bracket $\langle\ \rangle$ represents averaging over all fractures. Through Monte Carlo simulations it is found that by choosing $k = 0.774$ at the percolation threshold density, n_c, this dimensionless density is always close to a single value:

$$\rho_c = 8.2 \pm 0.2 \tag{B2}$$

for aspect ratios up to 16. The same result was found to apply to any mixture of convex plate shapes and sizes provided that for each plate A and P are replaced by the area and perimeter of an ellipse with the same aspect ratio and product AP. Many previously published percolation thresholds, when converted to the same dimensionless density (Eq. B1), were found to lie within the range given in Eq. (B2)

De Dreuzy et al. (2000) define their percolation parameter as

$$p = \pi^2 N \langle e \rangle \frac{\langle l^3 \rangle}{L^3} \tag{B3}$$

Where *'L'* is the system size and *'N'* is the number of ellipses in system, *'l'* the semi-major axis of an ellipse (here termed *'a'*) and *'e'* (eccentricity) is *'b/a'* where *'b'* is the semi minor ellipse axis.

So for a single size and shape of ellipse their '*p*' becomes,

$$p = \pi^2 N \left(\frac{b}{a}\right) \frac{a^3}{L^3} = \pi^2 \frac{N}{L^3} ba^2 = \pi^2 n\, ba^2 \tag{B4}$$

Where *n* is number density (units of L^{-3}). Using a dimensionless number density, d_n, ($= (ab)^{3/2} n$), this reduces to:

$$d_n = \frac{p}{\pi^2 \sqrt{a/b}} \tag{B5}$$

Dividing the results of de Dreuzy et al. (2000) by $\pi^2 \sqrt{a/b}$ produces the result shown in Fig. B1b.

Appendix C. The size-transmissivity relationship

Although it might seem intuitive that more extensive fractures should be more transmissive than smaller ones, why should this be the case? The transmissiveness of a fracture should be some function of fracture roughness, rock strength and stress, none of which are likely to be correlated with extensiveness. Despite these philosophical shortcomings, the concept is embedded in both the Swedish and Finnish safety cases via their respective DFN models (SKB TR-10-52 Section 6.6.10 and Hartley et al. 2013 Posiva Working Report 2012-42, Appendix D).

I am not aware of any experiment designed to evaluate or demonstrate such a relationship and neither of the two safety case reports (i.e TR-10-52 and Posiva WR 2012-42) provides any justifying publication. However, Frampton and Cvetkovich (2010) provide three references in support of a size-transmissivity relationship. The first, Walmann et al. (1996), concerns some laboratory tests using clay. The second, Neuman (2008) is about the development of a theory of scaling seemingly supported by measurements in an unconsolidated aquifer. The last refers to a relationship developed by Dershowitz et al. (2003) for the TRUE Block Scale Project at Äspö. Along with David Hodgkinson, I reviewed the report on behalf of the international task force and we concluded (Black and Hodgkinson 2005),

> *"The model is built with the assumption of scale-related characteristics applying to some major characteristics namely transmissivity and microstructural model. …these relationships are not necessarily correct and should not be used in other contexts without further justification."*

The reasoning behind the size-transmissivity relationship is summarised in Figure 4-1 of Dershowitz et al. (2003) and replotted here with additions as Figure C1 and bears closer inspection.

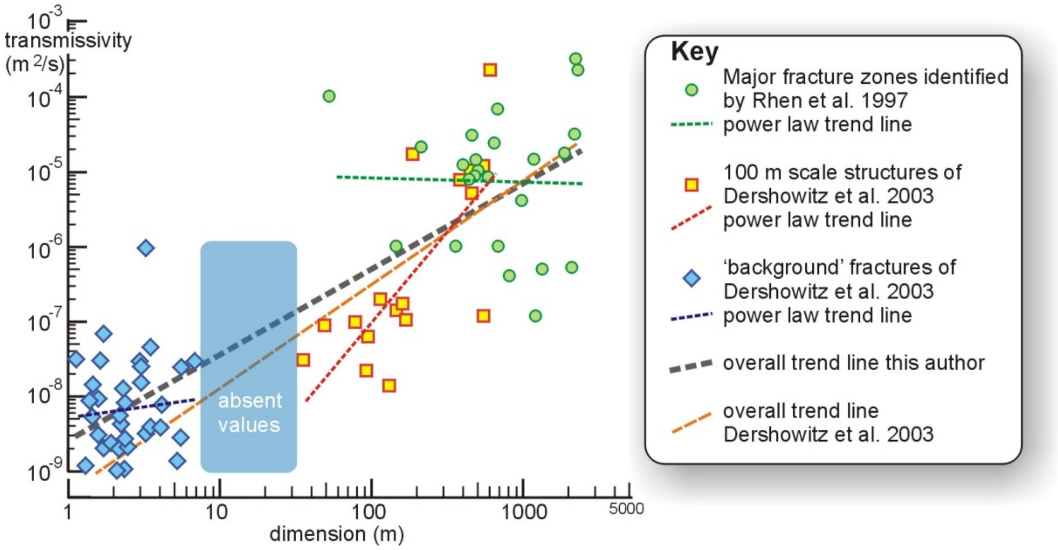


Fig. C1.The correlation between fracture size and transmissivity suggested by Dershowitz et al. 2003

The figure contains three groups of values of significantly different origin representing different scales. The largest fractures are major fracture zones identified during the site investigation for the Äspö Hardrock Research Laboratory (HRL) and subsequently tested to derive appropriate values of transmissivity (usually a mean of varying values). The so-called '100 m scale' structures were found in the rock volume used by the TRUE- Block Scale tracer experiments and were partly identified on the basis of their raised hydraulic properties. The 'background' fractures are apparently the set of hydraulic test results within the tracer test volume that are not assigned to any of the '100 m scale' features. Since there is no information on the actual size of fractures yielding the individual test results, they are simply assigned an arbitrary size taken from a log-normal size distribution.

There are many problems with this approach as represented in Figure 4-1 of Dershowitz et al. (2003). The first group are almost trivial but tend to obscure understanding:

- The x-axis is labelled dimension. Are the major fracture zones actually trace length or the largest dimension as defined in Appendix A2 of Rhén et al. (1997)? How are the limits of the '100 m scale' fractures determined? Surely transmissivity is not constant over the whole surface of such features! The text indicates that the 'background' fractures are defined in terms of their radius (since they are equidimensional). Is that consistent with the other two groups in the diagram?
- In Section 4.3, Dershowitz et al. (2003) state that the background fractures are based on the statistics of Table 3-1 which have a log normal distribution of 'size equivalent radius' with a mean of 6 m and a standard deviation(SD) of 3 m. This is not what is plotted in Figure 4-1 which looks more like the mean of 2 m and SD of 1 m mentioned in the text on page 48. Further confusion is created by the references in Tables 3.1 and 3.2 not matching those recorded in the list of references.
- The overall trendline shown in Figure 4-1 does not match the trendline I derived and does not look likely to be correct for the overall dataset shown.

The second group of problems is more serious. Firstly, what sort of a power law distribution of fracture sizes has no fractures in the range 7 m to 36 m? It is also clear that by changing the mean and SD of the background fracture sizes a wide range of size-transmissivity relationships could be derived. Overall it seems that a very unlikely fracture system is envisaged by the authors. The last and most serious problem is the issue of selectivity. By selecting the mid-size fractures partly on the basis of their enhanced transmissivity compared to the test results of all fractures, the authors have effectively presumed a size-transmissivity relationship in the first instance. It is of note that the major fracture zones were selected on the basis of their size and apparent geological importance before they were hydraulically tested and show no size-transmissivity correlation at all.

Probably unaware of the flimsy justification for a size-transmissivity relationship, the concept was embedded in the documentation for the Forsmark safety case (SKB 2010). So, the bedrock was divided into 'Hydraulic Conductor Domains' (HCD), essentially the specifically identified major fracture zones, and the so-called 'Hydraulic Rock Domains' (HRD), basically the rest of the fractured crystalline rock. The HRDs are effectively the rock immediately surrounding the disposed waste and are treated stochastically as a 3D network of equi-dimensional fractures whose sizes are taken from a truncated power law distribution. These stochastically generated fractures are then assigned a value of transmissivity either taken at random from a distribution about a mean (Figure C2a) or according to their size (Figure C2 a and b). The 'Data Report' of SKB (TR-10-52) recommended the use of the semi-correlated relationship.

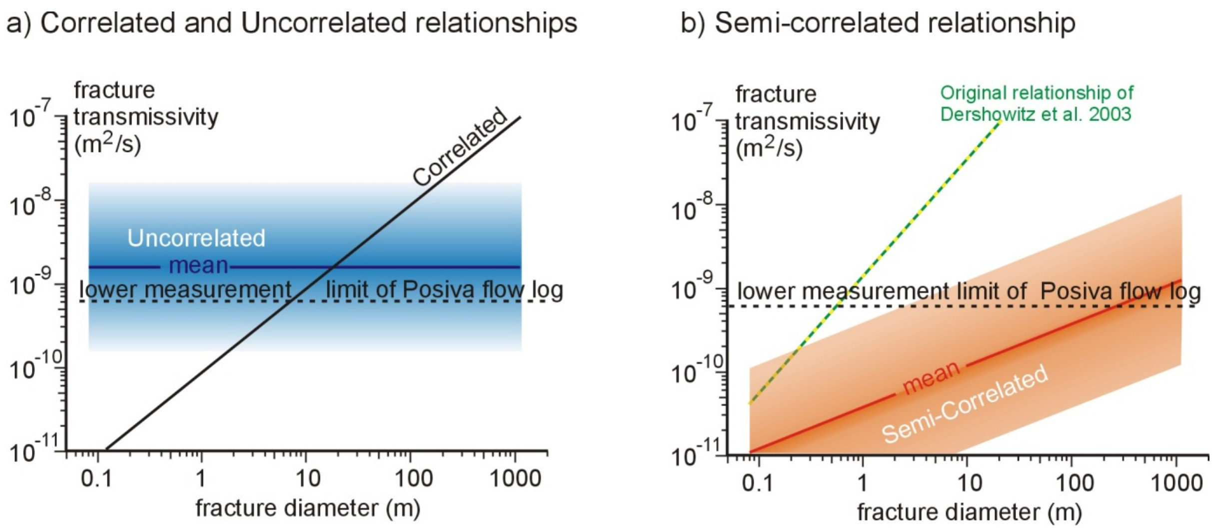


Figure C2. The size-transmissivity relationships suggested for the safety case of the proposed repository zone at Forsmark (from SKB 2010); a) the 'correlated' and 'uncorrelated' cases; b) the 'semi correlated' case. Notes. The distributions are truncated at their limits of applicability. The shaded areas represent a one standard deviation spread of possible values about the mean. The measurement limit value is derived from Follin et al. (2014). The relationships are shown on two sets of axes for clarity only.

It is readily apparent from Figure C2 that the semi-correlated transmissivity-size relationship has a powerful effect on the outcome. It can be seen that the Semi-Correlated relationship will be most effective in reducing simulated inflows to values below the threshold of the field measurements. This has the effect of hiding all fractures of less than about 2 m diameter from the possibility of being seen by the PFL measuring procedure and increasing the likelihood of the most extensive fractures forming the flow network. This view is effectively stated by Hartley and Roberts. 2012:

> *"…three different transmissivity models are considered, the ranges of transmissivities that each relationship produces are fairly similar for the fractures with radii in the range c 10 m to 100 m (see Follin et al. 2007, Rhén et al. 2008, Joyce et al. 2010). Fractures in this size range are thought to be most important in determining the connectivity characteristics of the fracture network, .."*

Appendix D Environmental heads in the KFM boreholes

The environmental heads derived from the PSS tests are very interesting. Naturally, the short-term nature of the testing is a significant effect and low transmissivity intervals don't have time to gain or regain equilibrium. A typical results set is shown in Figure D1 One of the characteristics of the results overall is that the 100m intervals average out minor head variations both because they average out variations in situ and because being longer they have a higher transmissivity than the shorter sections and therefore approach equilibrium more quickly. Essentially they regain equilibrium in the 20 minutes available. The problem of not regaining equilibrium becomes more prevalent amongst the results as interval length declines and the 'spikey' nature of the 20m and 5m results is the outcome. Overall, KFM3A & B exhibit a small upward head gradient.

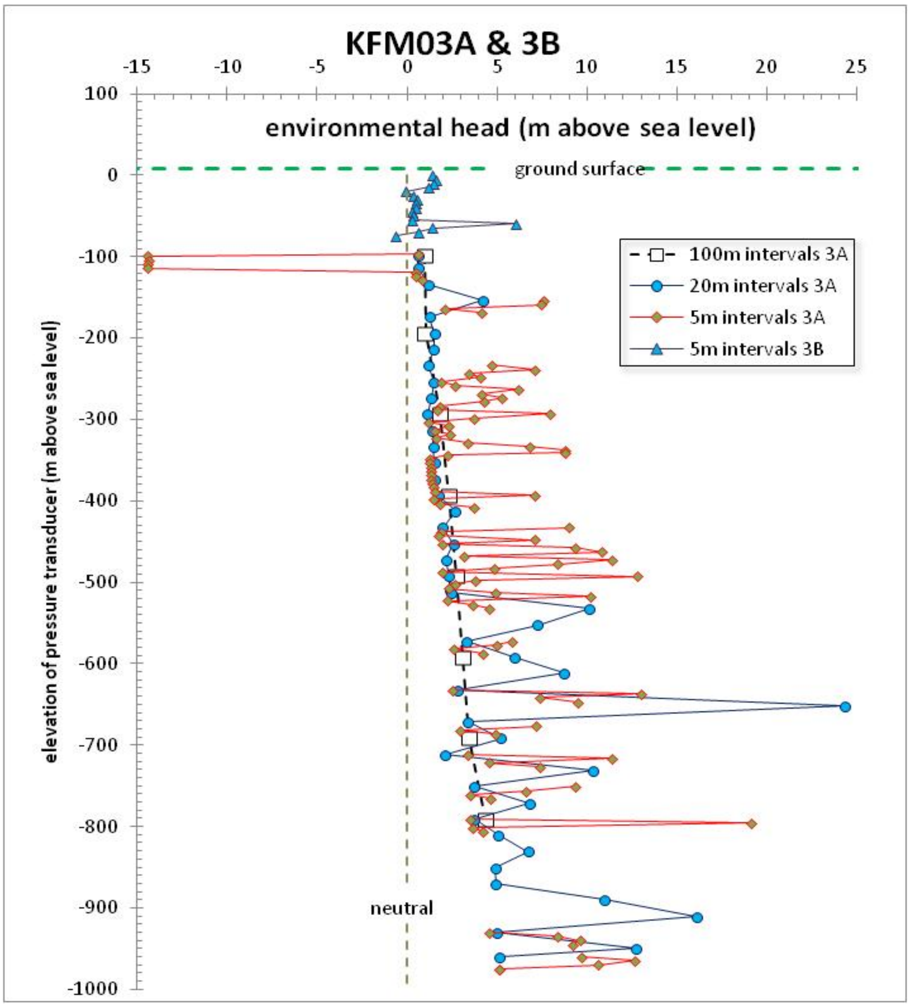


Figure D1 A typical set of PSS head results

Several points should be borne in mind:

- the density correction at 1000m depth is about 6m of water head meaning that up to 6m of head has already been subtracted from the results in Figure D1.

- The transducer is located at the top of each interval so each datapoint applies to the appropriate length of borehole beneath it. This is most marked in the 100m long intervals

The dataset has many intriguing results. For instance two thirds of the profiles feature a divergence between the 100m interval results and the shorter interval tests. One such is KFM09A. The shorter interval tests appear to indicate a small upward gradient whereas the 100m results indicate the opposite. There may well be an obvious practical explanation such as a long period of prior pumping since the 100m tests were usually performed first.

I have also added a rough average of a sample of data from the monitoring report (P-09-42). Although it represents long sections of borehole and the values are most likely 'freshwater heads', they represent downward flow to depth. Topographically driven flows would normally result in raised heads at depth in boreholes in the discharge area, i.e. near to the coast.

In an effort to get some general relationships from the data, I decided to form the results sets into groups: downward flowing , neutral and upward flowing. They are presented below as Figures D3, D4 and D5.

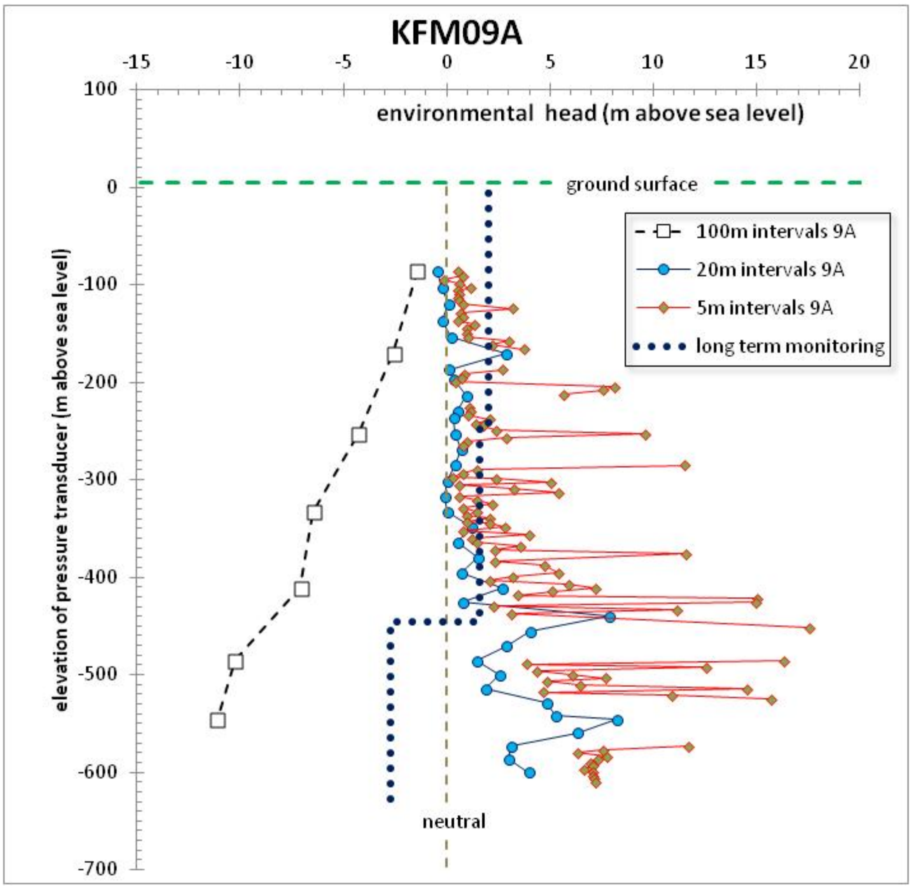


Figure D2 PSS head results from KFM09A plus some roughly averaged heads from the programme of long term monitoring

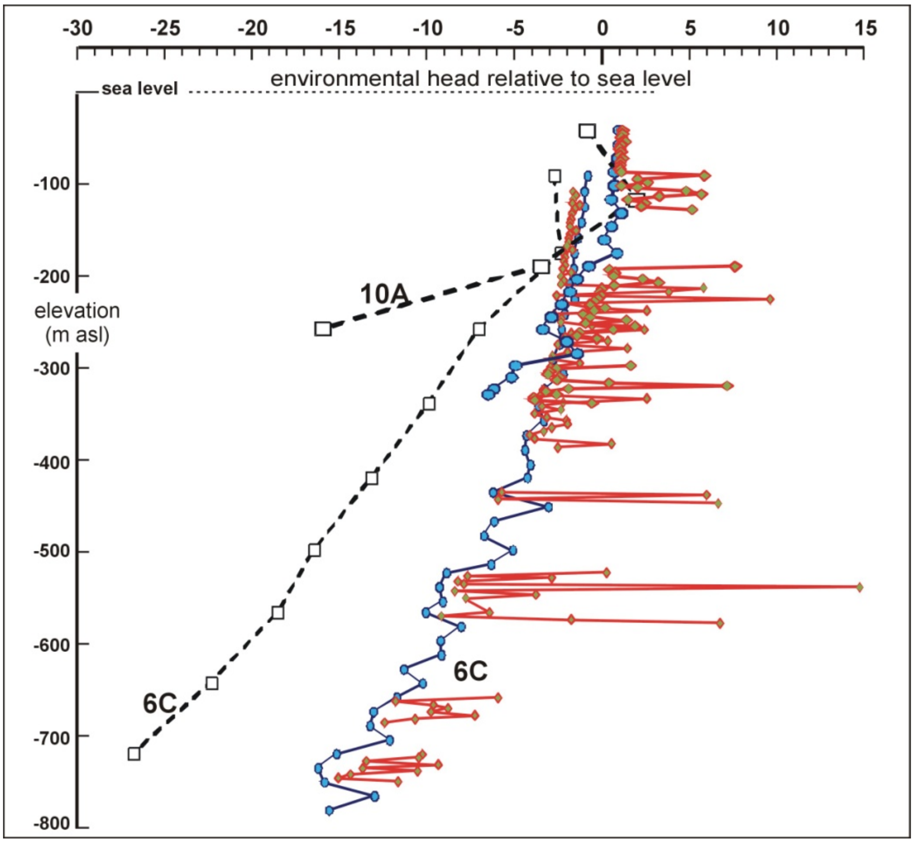


Figure D3 The ‘downward flowing’ PSS head results.

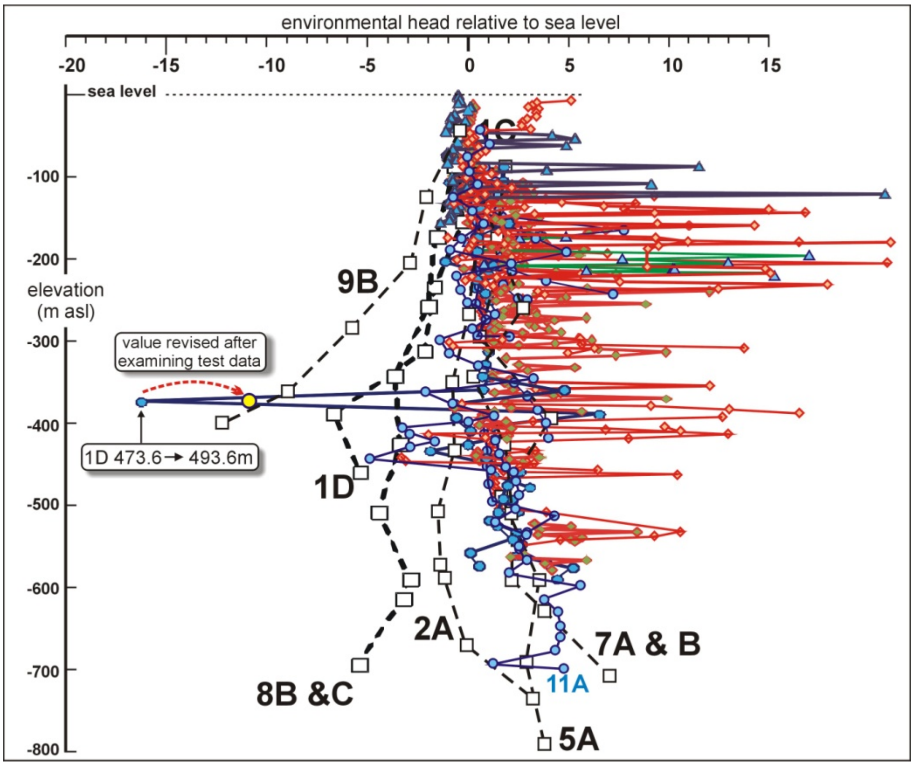


Figure D4 The ‘neutral’ PSS head results

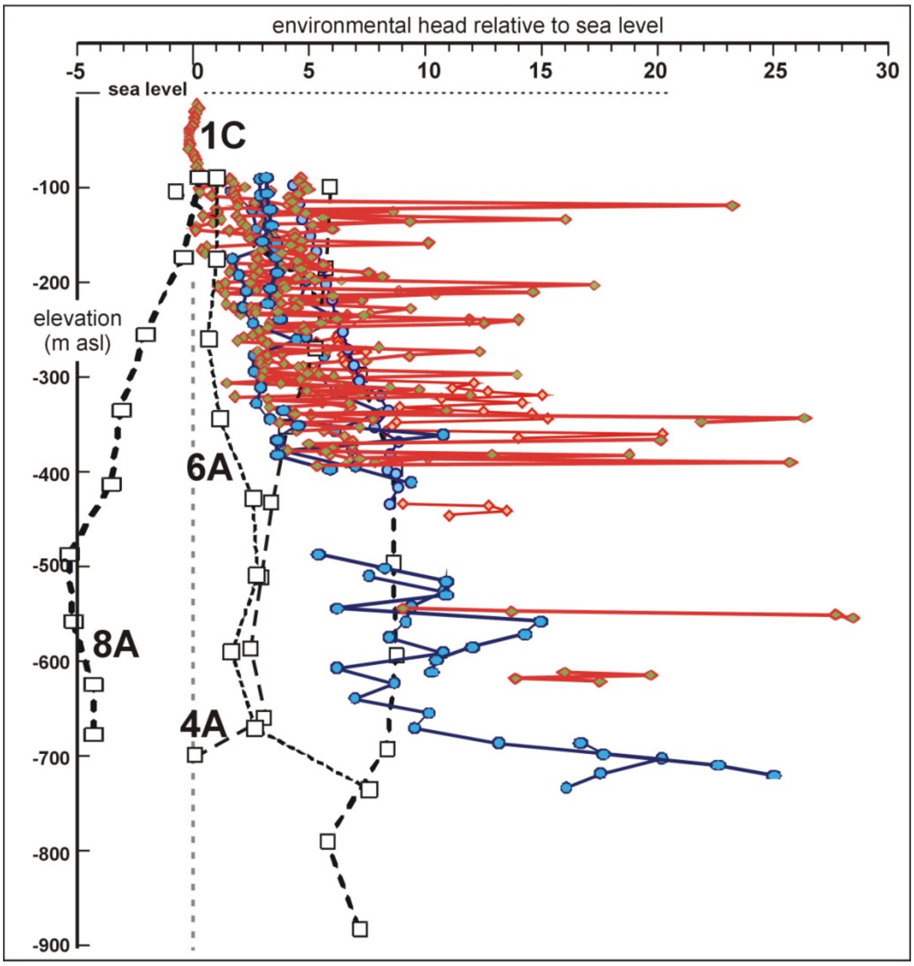


Figure D5 The 'upward flowing' PSS head results

There are many inconsistencies in these results which may well be resolved by a thorough examination of each test and the addition of knowledge derived from the long term monitoring.

Whatever the outcome, it is unlikely that the head profiles at depth are the result of the present-day topographically driven flow that dominates near the surface.

7. References

Abelin, H., Birgersson, L., Gidlund, J. and Neretnieks, I. (1991) A large-scale flow and tracer experiment in granite 1. Experimental design and flow distribution. Water Resources Research 27/12 , pp3107 – 3117.

Abelin, H., Birgersson, L., Widén, H., Ågren, T., Moreno, L, Neretnieks, I. (1994) Channeling experiments in crystalline fractured rocks. J. of Contaminant Hydrology, 15, pp. 129-158. doi: 10.1016/0169-7722(94)90022-1

Andersson, P., J. Byegård, W. Dershowitz, T. Doe, J. Hermanson, P. Meier, E-L Tullborg and A. Winberg (2002) Final report of the TRUE Block Scale project: 1. Characterisation and model development. Technical Report of Svensk Kärnbränslehantering AB (SKB), Stockholm. TR-02-13.

Barker JA. Intersection statistics and percolation criteria for fractures of mixed shapes and sizes Computers and Geosciences in press

Benedek K, Dankó G (2009) Stochastic hydrogeological modelling of fractured rocks: a generic case study in the Mórágy Granite Formation (South Hungary). Geologica Carpathica, Vol. 60/ 4, 271—281. doi: 10.2478/v10096-009-0019-y

Berkowitz B (2002) Characterizing flow and transport in fractured geological media:
A review. Advances in Water Resources 25: 861–884. Doi:10.1016/S0309-1708(02)00042-8

Black, J.H. and J.A. Barker. 2016. The puzzle of high heads beneath the West Cumbrian coast, U.K.: a possible solution. Hydrogeology Journal. 24: pp. 439 – 457.

Black, J.H. and D.P. Hodgkinson 2005 Äspö Task Force on modelling of groundwater flow and transport of solutes: Review of Task 6C. Technical Report of Swedish Nuclear Fuel and Waste Management Co. No. R-05-33, 28pp

Black, J.H., Barker, J.A. and Woodman, N.D. 2007. An investigation of 'sparse channel networks' Characteristic behaviours and their causes. Report of SKB, (Swedish Nuclear Fuel and Waste Management Co), Stockholm, Sweden. Research Report, R-07-35, 123pp.

Black, J.H., N.R. Woodman and J.A. Barker. 2017 Groundwater flow into underground openings in fractured crystalline rocks: - an interpretation based on long channels. Hydrogeology J.l, 25:445 - 463

Bossart P, Hermanson J, Mazurek M. 2001 Analysis of fracture networks based on the integration of structural and hydrogeological observations at different scales. Report of Svensk Kärnbränslehantering AB (SKB), Stockholm. TR-01-21.

Davy P, Le Goc R, Darcel C, 2013. A model of fracture nucleation, growth and arrest, and consequences for fracture density and scaling. Journal of Geophysical Research: Solid Earth 118, 1393–1407.

Davy P, Le Goc R, Darcel C, Bour O, de Dreuzy J-R, Munier R, 2010. A likely universal model of fracture scaling and its consequence for crustal hydromechanics. Journal of Geophysical Research 115. doi:10.1029/2009jb007043

de Dreuzy J-R, Davy P, Bour O. 2000 Percolation parameter and percolation-threshold estimates for three-dimensional random ellipses with widely scattered distributions of eccentricity and size. J. of The American Physical Society, Physical Review E, Vol. 62/5: 5948-5952. Doi:1063-651X/2000/62(5)5948(5)

Degnan PJ, Littleboy AK, Michie UMcl, Jackson CP, Watson SP. 2003 Fracture-dominated flow in the Borrowdale Volcanic Group at Sellafield, NW England: the identification of potential flowing features, development of conceptual models and derivation of effective parameters. Geological Society, London, Special Publications 2003; v. 214; p. 197-219. doi: 10.1144/GSL.SP.2003.214.01.12

Dershowitz W, Winberg A, Hermanson J, Byegård J, Tullborg E-L, Andersson P, Mazurek M, 2003. Äspö Hard Rock Laboratory. Äspö Task Force on modelling of groundwater flow and transport of solutes. Task 6c. A semi-synthetic model of block scale conductive structures at the Äspö HRL. SKB IPR-03-13, Svensk Kärnbränslehantering AB.

Ericsson, L.O., J.Thörn, R. Christiansson, T Lehtimäki, H. Ittner, K. Hansson, C. Butron, O. Sigurdsson, and P Kinnbom. 2015 A demonstration project on controlling and verifying the excavation-damaged zone: Experience from the Äspö Hard Rock Laboratory Report of Svensk Kärnbränslehantering (SKB) AB., Stockholm SKB R-14-30.

Follin S, 2008. Bedrock hydrogeology Forsmark. Site descriptive modelling, SDM-Site Forsmark. Report of Svensk Kärnbränslehantering AB (SKB), Stockholm. R-08-95, Follin S, Levén J, Hartley L, Jackson P, Joyce S, Roberts D, Swift B, 2007. Hydrogeological characterisation and modelling of deformation zones and fracture domains, Forsmark modelling stage 2.2. SKB R-07-48, Svensk Kärnbränslehantering AB.

Follin, S, Hartley L, Rhén I, Jackson P, Joyce S, Roberts D, Swift B. 2014. A methodology to constrain the parameters of a hydrogeological discrete fracture network model for sparsely fractured crystalline rock, exemplified by data from the proposed high-level nuclear waste repository at Forsmark, Sweden. Hydrogeology Journal, 22: pp. 313-331, DOI 10.1007/s10040-013-1080-2

Follin, S., M. Stigsson,and U. Svensson 2006 Hydrogeological DFN modelling using structural and hydraulic data from KLX04 Preliminary site description Laxemar subarea – version 1.2. Report of Svensk Kärnbränslehantering (SKB) AB., Stockholm SKB R-06-24

Frampton A, Cvetkovic V 2010 Inference of field-scale fracture transmissivities in crystalline rock using flow log measurements. Water Resources Research 46, W11502, doi:10.1029/2009WR008367.

Hartley L and Roberts D, 2013. Summary of discrete fracture network modelling as applied to the hydrogeology of the Forsmark and Laxemar sites. Report of Svensk Kärnbränslehantering AB. (SKB) R-12-04,

Hartley L, Appleyard P, Baxter S, Hoek J, Roberts D, Swan D. 2012 Development of a hydrogeological discrete fracture network model for the Olkiluoto site descriptive model 2011 Vol.1. Working Report of Posiva Oy, Helsinki, Finland 2012 – 32, pp. 252.

Hartley, L., P. Appleyard, S. Baxter, J. Hoek, D. Roberts and D. Swan. 2011. Development of a Hydrogeological Discrete Fracture Network Model for the Olkiluoto Site descriptive Model 2011. Working Report of Posiva OY. Helsinki, Finland, No. 2012-32

Hökmark H, Lönnqvist M, Fälth B, 2010. THM-issues in repository rock. Thermal, mechanical, thermo-mechanical and hydro-mechanical evolution of the rock at the Forsmark and Laxemar sites. SKB TR-10-23, Svensk Kärnbränslehantering AB.

Holmes DC 1985 Site Characterization and Validation – Single Borehole Testing, Stage 1. Tech. Report No. 89 - 04, pp59. Report of the Stripa Project, managed on behalf of OECD/NEA by Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden.

Hyman, JD, Kara, S, Makedonska, N, Gable, CW, Painter, SL and HS Viswanathan. 2015. DFNWORKS: A discrete fracture network framework for modeling subsurface flow and transport. Computers and Geosciences 84: 10-19.

Joyce S, Simpson T, Hartley L, Applegate D, Hoek J, Jackson P, Roberts D, Swan D, Gylling B, Marsic N, Rhén I, 2010. Groundwater flow modelling of periods with temperate climate conditions – Laxemar. SKB R-09-24, Svensk Kärnbränslehantering AB.

Munier R, Mattila J, 2015. MEMO on Terminology. POS-021685, ver 1.0 Posiva Oy, Finland

Neretnieks, I. 2006, Channeling with diffusion into stagnant water and into a matrix in series. Water Resources Research, Vol. 42. Paper No. *W11418*, 15pp

Neuman SP 2005 Trends, prospects and challenges in quantifying flow and transport through fractured rocks. Hydrogeology J. 13:124-147. doi: 10.1007/s10040-004-0397-2

Neuman, S. P. (2008), Multiscale relationships between fracture length, aperture, density and permeability, Geophys. Res. Lett., 35, L22402, doi:10.1029/2008GL035622.

Rhén I, Forsmark T, Hartley L, Jackson P, Roberts D, Swan D, Gylling B, 2008. Hydrogeological conceptualisation and parameterisation. Site descriptive modelling, SDM-Site Laxemar. SKB R-08-78, Svensk Kärnbränslehantering AB.

Rhén I, G. Bäckbom, G. Gustafson, R. Stanfors and P. Wikberg 1997 Äspö HRL – Geoscientific evaluation 1997/2. Results from pre-investigations and detailed site characterization, Summary report. Report of Svensk Kärnbränslehantering (SKB) AB., Stockholm SKB TR-97-03

Rhén I, Thunehed H, Triumf C-A, Follin S, Hartley L, Hermansson J, Wahlgren C-H. 2007 Development of a hydrogeological model description of intrusive rock at different investigation scales: an example from south-eastern Sweden. Hydrogeology Journal 15, 47–69. doi: 10.1007/s10040-006-0124-2

Rouleau A, Gale JE 1985 Statistical characterization of the fracture system in the Stripa Granite, Sweden. Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., Vol. 22/6, pp. 353-367.

Sawada A, Saegusa H, Takeuchi S and WS Dershowitz. 2015 Äspö Task Force on modelling of groundwater flow and transport of solutes Task 7 – Groundwater flow and transport modelling of fracture system at regional,block, and single-fracture scale, Olkiluoto. Report of Svensk Kärnbränslehantering AB. (SKB) P-13-46

Sawada A, Uchida M, Shimo M, Yamamoto H, Takahara H, Doe TW 2000 Non-sorbing tracer migration experiments in fractured rock at the Kamaishi Mine, Northeast Japan. Engineering Geology, Vol. 56:1-2, 75-96. doi:10.1016/S0013-7952(99)00135-

Selroos J-O, Appleyard P, Bym T, Follin S, Hartley L, Joyce S, Munier R, 2015. The stochasticdeterministic transition in discrete fracture network models and its implementation in a safety assessment application by means of conditional simulation. Abstract H53I-02, AGU Fall meeting, 14–18 December 2015, San Francisco.

SKB 2010 Data report for the safety assessment SR-Site. Report of Svensk Kärnbränslehantering (SKB) AB., Stockholm SKB TR-10-52,

SKB 2016 RD&D Programme 2016 Programme for research, development and demonstration of methods for the management and disposal of nuclear waste. Report of Svensk Kärnbränslehantering (SKB) AB., Stockholm SKB R-12-04,

Srivastava R M, 2002. Probabilistic discrete fracture network models for the Whiteshell Research Area. Ontario Power Generation Report 06819-REP-01200-10071-R00, Ontario Power Generation, Nuclear Waste Management Division, Canada.

Srivastava, R.M. 2007 Fracture network modelling: an integrated approach for realisation of complex fracture network geometries. Proc. 2nd AMIGO workshop, 20-22 Sep., 2005, Toronto. OECD – NEA Vol 179: 77-82.

Walmann, T., A. Malthe - Sørenssen, J. Feder, T. Jøssang, P. Meakin, and H. H. Hardy (1996), Scaling relations for the lengths and widths of fractures, Phys. Rev. Lett., 77(27), 5393‑5396.

Watanabe N, Hirano N, Tsuchiya N 2009 Diversity of channeling flow in heterogeneous aperture distribution inferred from integrated experimental-numerical analysis on flow through shear fracture in granite. J. of Geophysical Res. Vol. 114, B04208, doi:10.1029/2008JB005959.

Wellman TP, Shapiro AM, Hill MC (2009) Effects of simplifying fracture network representation on inert chemical migration in fracture-controlled aquifers. Water Resources Research, Vol. 45, W01416, pp. 21. doi:10.1029/2008WR007025

Wilson, C.R., J.C.S. Long, R.M. Galbraith, K. Karasaki, H.K. Endo, A.O. DuBois, M.J. McPherson and G. Ramqvist (1981), Geohydrological data from the Macropermeability Experiment at Stripa, Sweden. Report of the Lawrence Berkeley National Laboratory, No. LBL-12520, 194 pp.

Yi Y.B. and E. Tawerghi. 2009 Geometric percolation thresholds of interpenetrating plates in three-dimensional space. Phys. Rev. E 79, 041134, 6pp. doi: 10.1103/PhysRevE.79.041134.