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Äspö Hard Rock Laboratory

Preliminary study for developing a practical, stepwise field methodology for determining the acceptable proximity of canisters to fracture zones in consideration of future earthquakes

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Preface

This preliminary study was prepared to discuss and develop a practical, stepwise field methodology for determining the acceptable proximity of canisters to fracture zones from the perspective of secondary slippage along fractures due to future earthquakes.

Göran Bäckblom (Conrox) has acted as project manager and the lead author of this report. The expertise of several individuals was utilized. Paul La Pointe (Golder Associates, Seattle) conducted a study to find possible surrogate parameters for fracture size as this parameter is difficult to measure, yet crucial to decide whether a deposition hole is acceptable or not. He also contributed to information concerning key parameters for slip determination. Eva-Lena Tullborg investigated issues related to describing how the host rock is geochemically altered within and outside of the transition zone and finding evidences for new fracturing based on geology and geochemistry. Liisa Wikström (Posiva) reviewed the applicability of surrogate parameters for the Olkiluoto site, Roy Stanfors (RS Consult) for the Oskarshamn site and Jan Hermanson (Golder Associates, Stockholm) for the Oskarshamn and Forsmark sites. We have also received contributions from Harald Hökmark (Clay Technology), Rolf Christiansson, Raymond Munier and Jan-Olof Selroos (all at SKB) and Anders Winberg (Conterra). The wealth of information generously provided by Mark Petersen US Geol Survey in Denver US and by Bill Bryant at California Geological Survey is particularly acknowledged.

The project started in April 2004. Two review seminars were held in May and in August 2004. Additional reviews were conducted during September and October, before the report was finalised.

The authors jointly acknowledge the active and creative participation of the participants.

Täby in November 2004

Göran Bäckblom

Göran Bäckblom
Project leader

Abstract

This report presents the results of a preliminary study to determine the acceptable proximity of canisters to fracture zones from the perspective of secondary slippage along fractures due to future earthquakes. We aim for a practical, stepwise field methodology that is applicable both during preliminary site investigations and also during later phases of repository construction. However we find several conceptual uncertainties and data uncertainties that are difficult to minimise. Several key areas of investigations were carried out:

- Consistency of terminology and changes needed to capture key fracture parameters in databases, along with a detailed evaluation of what can and cannot be measured by various approaches during successive phases of site investigation;
- Use of indirect methods to identify fractures that might slip unacceptably during future earthquakes;
- The possibility of using geochemical observations and measurements to delineate fracture zones and recently-created (post-glacial) fractures from much older ones;
- Suggestions for field methodology and further field and development work.

More work is needed to clarify terminology. The division of rock into “zones” and “fractures” are too simplified a classification for some applications. There are geological linear elements to consider in between these two extremes. We need to improve nomenclature and databases for “fracture swarms” or “fracture clusters” where several short fractures are in close spatial proximity and jointly form – element by element – large, connected fracture structures. Such clusters are likely to be avoided for a deposition hole. The concept of the “deformation zone” needs additional clarifications. The total width of the “deformation zone” is the sum of the “core” of the zone and a “transition zone”, where the definition of “transition zone” should be developed further; from earthquake point of view it is the potential for new fracturing and implications for safety that is of importance.

It is beneficial if terminology used by SKB in Sweden and Posiva in Finland is harmonized to the extent possible, as this terminology currently differs, and is reflected in the parameters measured and archived in the data bases.

Models for possible earthquake damage of the engineered barriers (slip of > 0.1 m over the canister) are based on three fundamental parameters, the stress drop at the earthquake fault, the distance from the primary earthquake fault and the fracture size of the target fracture. In general the models show that the slip over a fracture decreases with decreasing fracture size and increasing distance from the primary fault. The models infer that fractures < 100 m of radii are of less importance for potentially damaging canisters that are very close (say at a distance of 100 m) to the primary earthquake fault. The validity of these models is however difficult to prove for target fractures close to the primary fault as many non-linear effects may appear in reality. For this reason it is

suggested that deposition holes intersected by large fractures (classified as radii, say > 100 m) are avoided for deposition, independent of the distance from the potential primary slip fault.

However, the probability that an individual large fracture length can be mapped deterministically among boreholes or drifts is likely to be very low. Nor is it feasible with current technology to directly measure the size of a fracture at a specific canister position. The difficulties in determining the size of a specific fracture led to the preliminary exploration of some alternative strategies. The main alternative evaluated in this preliminary study is to classify fracture sizes (large/small) rather than to deterministically decide fracture size and to use surrogate variables for this classification.

The outcrop data sets at Simpevarp, Forsmark and Olkiluoto have been examined using contingency tables (2- and n-way contingency) and neural networks. There are strikingly very few large fractures in the datasets and this has hampered the evaluation of surrogate parameters that correlate to fracture size or finding additional qualifiers for large fractures; the largest Forsmark fracture in the database is 17.5 m, in Simpevarp 11.5 m and in Olkiluoto 10 m in comparison to the larger fractures > 100 m radii that would be of importance with respect to earthquake impact assessment. For this preliminary study, fractures > 5 m in trace length were classified as “large” fractures.

Preliminary analyses show that the Simpevarp data are remarkably consistent with the results for the Forsmark data and the Olkiluoto data, given some of the limitations in the data from this Finnish site, with similar associations of large fractures with grain size, rock type, colour, surface morphology, termination style, aperture and crossing of lithologic boundaries. This suggests that the factors that lead to the formation of larger fractures are similar at all three sites, and that the surrogate variables measured capture some of these factors in a consistent way. Even when the analyses remove variables that cannot easily be measured in boreholes or core, such as termination style and crossing of lithology boundaries, useful predictions of fracture size were still possible. The fact that the use of surrogate variables appears useful when only borehole data are available suggests that the methodology can be applied during any phase of repository characterization and construction, and the models can be updated as more or different types of data become available.

Assessment of fracture mineralogy was used to study the issues of “new” fracturing and delineation of the transition zone.

- ”New” fracturing has not been possible to demonstrate, but this may partly be due to lack of suitable methods;
- “Old” origins can be assumed for most of the fractures as they host hydrothermal mineral that can not have been precipitated during the Tertiary or Quaternary;
- Reactivation is common as demonstrated by mineralogical studies on thin sections where several generations of fracture minerals is apparent in one single fracture;

- There are methods to use for age determination of hydrothermal minerals. However, there is a great problem to separate between different generations since they may be intimately inter-grown;

- Dating of "young" minerals by the ^{14}C and U-Th methods involves difficulties due to the lack of closed systems.

Conclusions about the delineation of the transition zone based on studies in the Oskarshamn area:

- The transition zone is to varying degrees characterised by a higher amount of micro-fractures than in the fresh rock as well as chloritisation of biotite and alteration of plagioclase to albite, epidote and sericite but also red-staining caused by oxidation of magnetite to hematite.

- Red-staining is easy to recognize but does not always correspond to alteration of other minerals. This means that the transition zone can be much wider than the red-stained section of the rock.

- Higher porosity and lower density (than the fresh rock) characterise usually the transition zone. The chemical characterisation of the transition zone can be difficult since the mineral alteration does not necessarily affect the whole rock chemistry.

- From this follows that mineralogy is a better tool to recognise the transition zone than geochemistry.

SKB has by previous work assessed that the concept of respect distance as a geometrical measure is less useful for issues related to thermal, chemical and transport of solutes processes, but has kept the concept for the purpose of earthquake. This study suggests that the respect distance as a geometrical measure for the earthquake issues is not very useful, as large fractures should be avoided independent of the geometrical distance from a zone to the deposition position. With respect to earthquake influence it is sufficient that an area extending 10 km from the site is mapped with respect to long fracture zones (> 30 km). If *no* faults with rupture lengths greater than 30 km are found within 10 km of the site, there is exceedingly little risk of secondary movement more than 0.1 m on faults or joints intersecting deposition holes–"the respect distance" is effectively 0 m!

Contact with researchers who investigate earthquake faulting in South Africa due to mining has been made. These projects are relevant and it is suggested SKB and Posiva become more actively involved within the next few years when the RSA project has reached the most interesting stages. Relevant research is also conducted through Pacific Earthquake Engineering Research Centre (PEER) where data on surface ruptures is utilised to evaluate mapping accuracy, displacements along and perpendicular to the main fault and it is recommended this research is followed closely.

We have also contacted repository implementers to assess interest in a possible workshop on respect distance. There has been minimal response, as the topic appears to have been framed too narrowly. A broader workshop - layout adaptation of the repository to the site-specific conditions at hand - would possibly be of more widespread interest. SKB and Posiva have jointly decided to discuss the matter of respect distance and organise a workshop in the spring of 2005.

The preliminary studies suggest some additional work:

- Current work on outcrop mapping at the sites should be planned and executed so the large fractures (> 20 m radii) are captured in the data base;
- Methods for fracture size determination/classification is high priority and further studies for finding surrogate data for size is appropriate;
- Methodology to geologically define the transition zone and to evaluate the rock in the transition zone with respect to site requirements and site preferences should be further developed;
- Present site requirements and site preferences should be revisited to detail necessary and sufficient conditions for canister positioning. Such work can be conducted as part of the work to detail the design requirements that should be established in close co-operation with safety assessors;
- It would be beneficial to further develop terminology and if possible, harmonise the nomenclature used by SKB in Sweden and Posiva in Finland.

Sammanfattning

Denna rapport sammanfattar resultat från en preliminär studie. Studien behandlar metod för att bestämma hur nära kapslar kan placeras sprickzoner med hänsyn till förskjutningar orsakade av ett framtida jordskalv. Vi söker en praktisk, stegvis metod som kan användas både under platsundersökningarna men också under senare genomförandeskeden. Studien påvisar ett flertal begreppsmässiga osäkerheter och dataosäkerheter som är svåra att minimera. Ett flertal väsentliga undersökningar genomfördes i den preliminära studien:

- Värdering av terminologi och nödvändiga förändringar för att fånga väsentliga sprickparametrar i databaser, tillsammans med en detaljerad utvärdering vad som kan mätas och vad som inte kan mätas på olika sätt vid undersökningar under olika skeden;
- Användning av indirekta metoder för att identifiera sprickor som skulle kunna förskjutas oacceptabelt mycket vid ett framtida jordskalv;
- Möjligheten av att använda geokemiska observationer och mätningar för att avgränsa sprickzoner och skilja nya (post-glaciala) sprickor från mycket äldre sprickor;
- Förslag till fältmetodik och ytterligare fält- och utvecklingsarbeten.

Mer arbete behövs för att förtydliga terminologi. Indelning av berg i ”zoner” och ”sprickor” är en alltför förenklad indelning för ett antal tillämpningar. Det finns typer av geologiska linjära element som ligger mellan de två extremerna. Vi behöver förbättra nomenklatur och databaser med hänsyn till ”spricksvärmar” och ”sprickkluster”, där flera korta sprickor är närliggande i rummet och tillsammans – element för element – bildar en större, sammanhängande sprickstruktur. Man kan anta att sådana kluster undviks där kapslar placeras. Begreppet “deformationszon” behöver ytterligare förtydligas. Zonens totala bredd är summan av ”kärnan” och en omgivande ”omvandlingszon”, där begreppet ”omvandlingszon” behöver utvecklas; från jordskalvsynpunkt är det möjligheten till ny sprickbildning och konsekvenser för säkerhet som är av vikt.

Det vore värdefullt om terminologi mellan SKB i Sverige och Posiva i Finland, så långt som möjligt harmoniseras; terminologin skiljer sig för närvarande, vilket återspeglar sig i vilka parametrar som mäts och lagras i databaser.

Modeller för skada på ingenjörsbarriärerna orsakade av jordskalv (förskjutning > 0.1 m över kapseln) innehåller tre fundamentala parametrar, spänningsfallet vid jordskalvet, avståndet från den primära jordskalvförkastningen och sprickstorleken. Modellerna visar i allmänhet att förskjutningen över en spricka avtar med minskande sprickstorlek och med ökande avstånd från den primära förkastningen. Tolkningen av modellresultaten är att sprickor med en radie < 100 m är av mindre vikt för potentiella skador på kapslar som är mycket nära den primära jordskalvsförkastningen (säg avståndet 100 m). Giltigheten för modellerna är emellertid svåra att visa för sprickor nära det primära skalvet, då många icke-linjära effekter kan uppträda i verkligheten.

Av detta skäl föreslås att deponeringshål undviks, där långa sprickor skär hålet, säg radie > 100 m, oavsett avståndet från deponeringshålet till en framtida, möjligt aktiverad förkastning.

Sannolikheten att en enskild spricka som är stor kan karteras deterministiskt över borrhål eller tunnlar är emellertid väldigt låg. Det är inte heller – med nuvarande tekniker – möjligt att direkt mäta storleken av en spricka vid en specifik deponeringsposition. Svårigheten att bestämma en sprickas storlek, har lett till att man här preliminärt prövat alternativa tillvägagångssätt. Huvudalternativet som studerats i denna preliminära studie är att klassificera sprickstorlek (stor/liten) hellre än att deterministiskt bestämma sprickstorlek och att använda alternativa, indirekta substitutsvariabler (*surrogate variables)* för klassifikationen.

Data från berghällskarteringar vid Simpevarp, Forsmark och Olkiluoto har analyserats med korstabeller (*contingency tables*) (Tvåvägs- och n-vägs), samt med neurala nätverk. Det finns ovanligt få stora sprickor i databasen, och detta har hindrat prövningen av indirekta variabler som korrelerar till sprickstorlek och metoder att hitta substitutsvariabler för stora sprickor; den största sprickan i databasen för Forsmark är 17.5 m, för Simpevarp 11.5 m och för Olkiluoto 10 m i relation till den sprickstorlek med radie > 100 m som skulle vara av betydelse med hänsyn till jordskalvseffekter. För den preliminära studien här, klassificeras sprickor > 5 m spricklängd (*trace length*) som ”stor” spricka.

Preliminära analyser visar att data från Simpevarp är utomordentligt lika data från Forsmark och Olkiluoto, med reservation för vissa begränsningar i data från den finska platsen; stora sprickor har liknande kopplingar till kornstorlek, bergartstyp, färg, ytmorfologi, sprickans avslutsstil, vidd och korsning över litologiska gränser. Detta antyder att det är liknande faktorer som leder till stora sprickor vid alla de tre platserna och att mätta substitutsvariabler konsekvent fångar dessa faktorer. Även om man i analysen avlägsnar variabler som inte är lätta att mäta i borrhål eller i kärnor, som avbrottsstil och sprickors korsning med bergartsgränser, var det möjligt att göra användbara förutsägelser av sprickstorlek. Det faktum att användning av substitutsvariabler syns vara möjlig enbart med borrhålsdata som grund, antyder att metodiken är användbar för karakterisering under alla skeden i genomförandet av förvaret och att modellerna kan uppdateras när mer eller flera typer av data är tillgängliga.

Sprickmineralogi användes för att utvärdera frågor om ny sprickbildning och avgränsning av en omvandlingszon.

- “Ny” sprickbildning har inte varit möjligt att påvisa, men detta kan till viss del bero på att lämpliga metoder saknas;
- “Gammalt” ursprung kan antas för den största andelen sprickor, eftersom de härbärgar hydrotermala mineral som inte kan ha fällts ut under tertiär- eller kvartärtiden;
- Reaktivering är vanlig, vilket påvisas i mineralogiska studier av tunnslip, där ett flertal generationer av sprickmineral är tydligt framträdande i en enskild spricka;

- Det finns metoder att datera hydrotermala mineral. Det är emellertid ett stort problem att separera olika generationer, eftersom de kan vara intimt sammanväxta;
- Datering av “unga” mineral med ^{14}C and U-Th metoder innebär svårigheter, i avsaknad av slutna system.

Slutsatser om avgränsning av omvandlingszon baseras på studier i Oskarhamnsområdet:

- Omvandlingszon är i varierande grad karakteriserad av högre andel mikrosprickor än i det friska berget, liksom kloritomvandling av biotit och omvandling av plagioklas till albit, epidot och sericit, men också rödfärgning orsakad av magnetitens oxidation till hematit.
- Rödfärgning är enkel att se, men hänger inte alltid ihop med omvandling av andra mineral. Detta innebär att omvandlingszon kan vara bredare är de rödfärgade partierna;
- Omvandlingszon karakteriseras vanligen av högre porositet och lägre densitet än i det friska berget. Kemisk beskrivning av omvandlingszon kan vara komplicerad, eftersom mineralomvandlingen inte nödvändigtvis påverkar all kemi i berget
- Från denna slutsats följer att mineralogi är en bättre metod att identifiera omvandlingszon än geokemi.

SKB har i tidigare arbeten framfört att begreppet respektavstånd, som ett geometrisk mått, är mindre användbart för frågor som relateras till termomekanik, kemi och transport av lösta ämnen, men har behållit begreppet med hänsyn till jordskalvsfrågor.

Denna studie föreslår att respektavstånd - som ett geometriskt mått - med hänsyn till jordskalv, inte är så användbart, eftersom stora sprickor ska undvikas oberoende av det geometriska avståndet från en zon till en deponeringsposition. Med hänsyn till influens från jordskalv, är det tillräckligt att ett område som sträcker sig 10 km från förvarsområdet karteras med avseende på stora sprickzoner (> 30 km). Om *inga* förkastningar med längder över 30 km påträffas inom 10 km från platsen, är det en mycket liten risk att sekundära förskjutningar mer än 0.1 m inträffar på förkastningar eller längs sprickor som skär deponeringshål - respektavståndet blir då 0!

Kontakt har etablerats med forskare i Sydafrika, som studerar jordskalvförskjutningar orsakade av gruvverksamhet. Projekten är relevanta och det föreslås att SKB och Posiva blir mer aktivt engagerade inom några år när projekten nått de mest intressanta etapperna. Relevant forskning genomförs också genom Pacific Earthquake Engineering Research Centre (PEER) i USA, där data om jordskalvsprickor i markytan används för att utvärdera karteringsnoggrannhet, förskjutningar längs med och tvärs huvudförkastningen; det föreslås att forskningen följs noggrant.

Vi har också kontaktat andra avfallsorganisationer, för att utröna intresset att ordna en workshop om respektavstånd. Responsen var minimal, eftersom det är möjligt att temat är för smalt. En bredare frågeställning - layoutanpassning av förvaret till platsspecifika förhållanden – skulle troligen få en bredare uppslutning. SKB och Posiva har beslutat att genomföra en workshop om respektavstånd under våren år 2005.

På basis av dessa preliminära studier föreslås:

- Nuvarande arbete för att kartera berghällar, ska planeras och utföras så att stora sprickor (> 20 m radie) fångas i databasen;
- Metoder för att bestämma/klassificera sprickstorlek är av hög prioritet och det är lämpligt med ytterligare studier för att finna substitutsdata för sprickstorlek;
- Metodik för att geologiskt definiera omvandlingszonen och att utvärdera berget i omvandlingszonen med hänsyn till krav och önskemål på platsen behöver vidareutvecklas;
- Nuvarande krav och önskemål på platsen bör återigen studeras för att detaljera nödvändiga och tillräckliga villkor för att välja deponeringspositioner. Sådant arbete kan genomföras som en del av arbetet att detaljera konstruktions-förutsättningarna, som ska ske i nära samarbete med dem som arbetar med säkerhetsredovisningarna;
- Det vore värdefullt att vidareutveckla terminologin och om möjligt harmonisera begreppen som används av SKB i Sverige och Posiva i Finland.

Contents

1 Introduction

This report focuses on" respect distances" a concept here loosely defined as *"the minimum distance from a deposition hole containing a spent nuclear fuel canister, to a fracture zone that may reactivate at future earthquakes and compromise safety"*.

The report is based on a preliminary study with the objectives to *"Develop and present a stepwise methodology for deciding the proximity of canisters to fracture zones in consideration of future earthquakes"* to derive methodologies that are feasible at prospective repository sites in Oskarshamn, Forsmark in Sweden and Olkiluoto in Finland.

Objectives that further develop the site investigation and engineering protocols are also part of this study, and include:

- Development of a methodology to position and accept deposition holes;
- Determination of guidelines for layouting the repository within the practical limitations imposed by logistics, necessary space requirements and need for flexibility as excavation proceeds; and
- Improvement of data collection procedures so that all necessary data for site characterization and engineering design are collected.

Based on previous studies /Bäckblom, Munier, Hökmark, 2004/ we decided that this preliminary study would focus on fracture size and the development of secondary fracturing adjacent to re-activating faults as the significant issues. We also recognized that definitions and nomenclature concerning respect distance and fracture zones would benefit from additional clarification.

In the current project, spanning the time period from March to August 2004, scope of work was divided into the following work packages:

- WP#1 Presentation of initial working hypotheses.
- WP#2 Initial studies investigating possible methods for data collection and evaluation
- WP#3 Preliminary application of methodology to Forsmark, Oskarshamn (Sweden) and Olkiluoto (Finland) sites, in order to gain confidence in the methodology and to suggest directions for improvement;
- WP#4 Possible participation in R&D-project "Drilling Active Faults in South Africa Mines";
- WP#5 Definitions and nomenclature;

- WP#6 Evaluating opportunities for an International Workshop on ”Respect Distance”;
- WP#7 Preparation of final report and proposals for studies to enhance repository siting and design; and
- WP#8 Project Management.

This report summarizes the findings from this preliminary study, beginning with an overview of the concept respect distance, and progressing through investigations designed to extend and adapt the concept to practical engineering design.

2 Evolution of the concept of respect distance

The connotation of "respect distance" derives from the first feasibility study for the KBS-3 concept. The study concluded that: "*The repository will be designed so that deposition holes will be located at a distance of at least 100 m from the nearest known zones with appreciably elevated water flows or where the rock is so crushed and weakened that the possibility of rock movements cannot be excluded.*" /SKBF/KBS, 1983, page 4:19, op. cit./. SKB has since included this concept for repository design and safety analyses like in SKB 91 /SKB, 1992/ and SR 97 /SKB, 1999a, SKB 1999b/.

SKB 91 made an initial evaluation of the importance of site properties on the overall safety of an earlier site investigation at Finnsjön. One set of calculations investigated how respect distances from the edge of the repository to nearby water conducting fracture zones impacted safety. This particular study concluded that variations of respect distances marginally effected overall safety.

The safety analysis SR 97 also used the concept of respect distances for the repository layout, but the actual distance was not a single number, but related to the importance of the fracture zone /SKB, 1999b. Section 5.2.3/. "Discontinuities" were classified as /Almén et al, 1996/:

- D1 - Discontinuity of importance for position of repository (large-scale mechanical or hydraulic boundaries) – respect distance needed to repository;
- D2 – Discontinuity of significance for the main layout of the repository - not to cross an deposition area;
- D3 – Discontinuity of significance for layout of deposition tunnels and position of deposition holes – respect distance needed to deposition hole;
- D4 – Discontinuity that does not affect repository layout;

and respect distance was defined as *"the distance from an interpreted discontinuity needed to comply with the requirements on long term safety for a deposition position"*/SKB, 1999b, op. cit. page 75 in the Swedish edition/. The work of Munier et al, 1997/ did, however, not elaborate on how the different aspects of respect distance should be computed and these were subjectively assigned values of 100 m (D1 - regional deformation zones) and 50 m (D2 - local deformation zones) where regional and local deformation zones are defined by its length and width (see also Table 4-2).

The SR 97 safety analysis included an "earthquake scenario" that assumed that secondary fracture slip exceeding 0.1 m would lead to canister failure /SKB, 1999a op. cit. page 174 in the Swedish edition /. Secondary slip on a fracture intersecting a canister deposition hole was hypothesized to occur when an earthquake occurred on a fault apart from the repository. Published studies suggest that such an earthquake might cause slippage on existing faults kilometres or tens of kilometres from the primary fault, /Petersen et al, 2004/. Compilation of similar studies and those of tectonics and seismology pertinent to Sweden were applied to assess the impact of future earthquake effects on the hypothetical repository layouts /La Pointe et al, 1997/, including the seismicity associated with the retreat of continental glaciation and extensive ice sheet unloading. The work showed that the most important parameters to calculate slip of fractures in the repository are the earthquake magnitude, the distance from the primary fracture zone (where the earthquake occurs) to the target fracture and finally the size of the fracture. The static calculations in a generic example conservatively assuming no friction in the fractures showed that slip is less than 0.1 m if magnitude is less than 7.5 and distance to the primary fault from the edge of the repository is more than 100 m. With compensation for friction in the fractures, the study suggested that no canister damages would occur for any earthquake if respect distance is > 100 m to fracture zones up to 100 km in length /SKB, 1999a op. cit. Section 11.5, page 416 in the Swedish edition/

SKB has quite recently compiled general design requirements for the repository /SKB, 2002a/ where it is stated that "respect distances shall be established successively through rock mechanics analyses and based on available information of the host rock properties" /op. cit. page 148/. The publication /op. cit. p. 174/ assumes 100 m preliminary respect distance to "regional fracture zones" (length of zones > 10 km, width of zones > 100 m) , 50 m to "local major fracture zones" (length 1-10 km, width 5-100 m) and that the deposition hole is minimum 3 m from " local minor fracture zones (length 100 m – 1km, width 0.1 -5m) in line what was used for the engineering for the SR 97 study.

Based on the general notion from the KBS-3 feasibility study where respect distances were based on distance to hydraulically conductive discontinuities we may also define "hydraulic respect distances". However this distance is not a physical distance but a distance needed to achieve a transport resistance (F[1]) for most of the flow paths being greater than 10^4 year/m. This "hydraulic respect distance" is a preference rather than a requirement /SKB, 2002a, op. cit. page 147/. The measure 10^4 year/m is likely achieved if canister positions are located some distance away from important hydraulic conductors like major fracture zones, as the zones are not assumed to add significantly to the transport resistance. In difference to SKB, Posiva is planning to account for a hydraulic respect distance and not use the concept of transport resistance for the layout of the repository.

This report primarily focuses on respect distance from an earthquake perspective, although respect distances may also be evaluated from a thermal, hydrological or chemical perspective. This study uses the concept of fracture zones in Munier et al, 2003 as point of departure where the core of the fracture zones are surrounded by transition zones ("process zones") where the width of the transition zones are proportional to the length of the fracture zone.

Thus, although the concept of respect distance was originally devised for ensuring adequate transport retardation, it is currently applied in the context of a minimum distance to a zone to ascertain that the canisters are not impaired due to future earthquakes.

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[1] F is defined as $F = a \cdot L/q$; a = flow-wetted surface per volume or rock, L = length of transport pathway, q = groundwater flux

3 Conceptual framework and background

The layout of the deep repository for the Swedish spent nuclear fuel /SKB, 2002b/ should utilise the inherent geological and hydrological properties of the site to adequately ensure future safety of the repository.

It is possible to distinguish between rock volumes or domains of the site that are suitable for deposition of the spent fuel and other domains that would not be suitable for deposition. The requirements and preferences for domains suitable for various repository components are summarized in /SKB, 2001/ with details in /Andersson et al, 2000/. These include the following requirements:

- The rock in the repository's deposition zone may not have any ore potential, i.e. may not contain such valuable minerals that it might justify mining at hundreds of metres' depth.

- Regional plastic shear zones shall be avoided if it cannot be demonstrated that the properties of the zone do not deviate from those of the rest of the rock. There may, however, be so-called "tectonic lenses" near regional plastic shear zones where the bedrock is homogeneous and relatively unaffected.

- It must be possible to position the repository with respect to the fracture zones on the site. Deposition tunnels and deposition holes for canisters may not pass through or be positioned too close to major regional and major local fracture zones. Deposition holes may not intersect identified local minor fracture zones.

- The rock's strength, fracture geometry and initial stresses may not be such that large stability problems may arise around tunnels or deposition holes within the deposition area. This is checked by means of a mechanical analysis, where the input values comprise the geometry of the tunnels, the strength and deformation properties of the intact rock, the geometry of the fracture system and the initial rock stresses.

- The groundwater at repository level may not contain dissolved oxygen. Absence of oxygen is indicated by a negative Eh, occurrence of Fe^{2+}, or occurrence of sulphide.

- The total salinity (TDS = Total Dissolved Solids) in the groundwater must be less than 100 g/l at repository level.

There are also preferences in addition to these requirements.

SKB is currently preparing detailed design premise requirements for the rock facility. The layout-step named "Layout D1" in the draft document states the following procedures should be followed with regards to respect distances:

- Map deformation zones and delineate a zone surrounding them using preliminary respect distances. Preliminary respect distances are decided as a fraction of the trace length i.e. 1 % of the trace length measured from the centre of core of the deformation zone.
- No fracture with a size characterized by an effective radius greater than100 m is allowed to intersect a deposition hole.
- Minimum distance between the periphery of the canister hole and large fractures and fracture zones are:
    - 2 m for $100 \text{ m} < R \leq 200 \text{ m}$
    - 0.01R for $R > 200$ m.

The design premises were published (/SKB, 2004a/) during the review of this report. In the report, it is stated that *"the minimum permissible distance between a deposition hole and stochastically determined fractures or fracture zones with a radius of R>100 m may, however, be changed in later design steps. The identification of such structures will be based on site-specific geological markers."* It is thus anticipated that these SKB internal design requirements will be updated periodically.

4 Terminology

As described in the Chapter 2, the concept of respect distance has been in a state of flux, which has resulted in evolving terminology. The current objective to codify the concept of respect distance for repository design and site evaluation requires that a consistent and useful series of terms are developed and used across all programmatic areas to avoid internal and external confusion. Table 4-1 shows some current terminology and definitions in use at SKB.

Table 4-1. Current Terminology for Zones

Concept	Definition	Reference
Composite zone	Deformation zone which show evidence of both brittle and ductile deformation.	Munier et al 2003
Deformation zone	An essentially 2-dimensional structure (a sub-planar structure with a small thickness relative to its lateral extent) in which deformation has been concentrated (or is being concentrated, in the case of active faults). The volume of the brittle deformation zone consists of two main elements, the core and the surrounding transition zone.	Munier et al 2003, see also Figure 4-1.
Fracture zone	A brittle deformation zone or the brittle part of a composite deformation zone.	Munier et al 2003
Transition zone	The rock volume influenced by the presence of the core of the deformation zone	This project

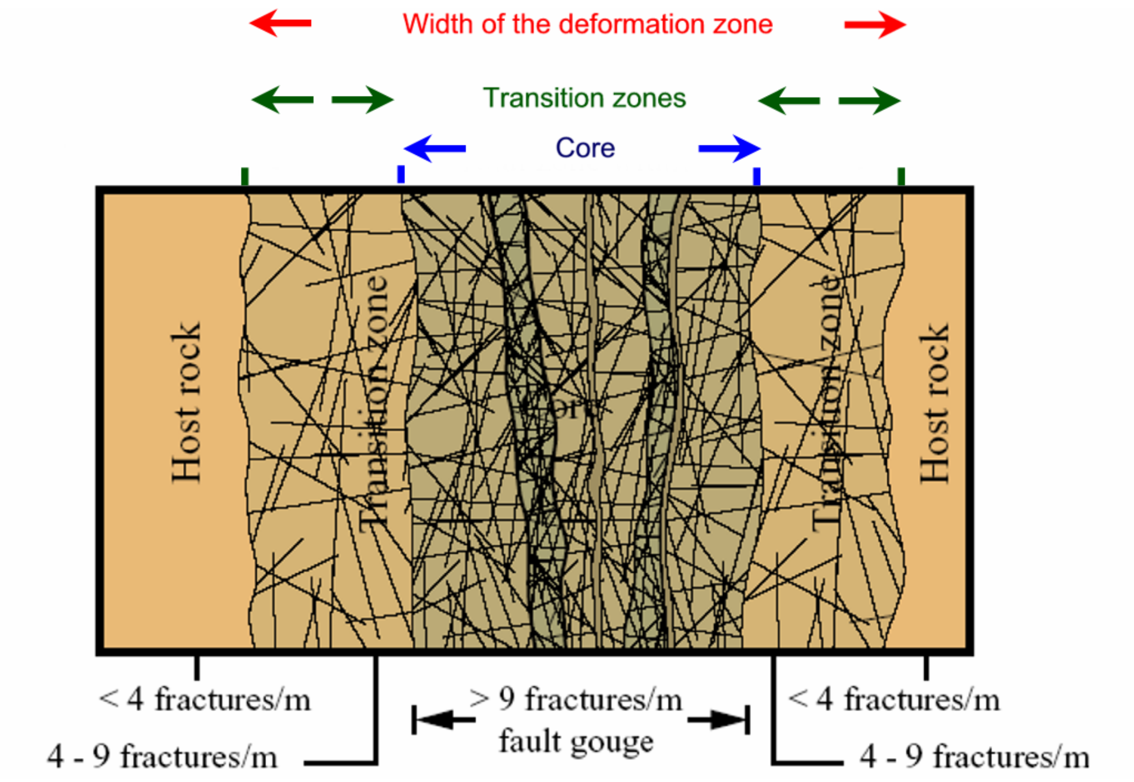

Figure 4-1. *Schematic illustration for showing the structure of a brittle deformation zone. Revised from /Munier et al, 2003/.*

The good definition of “transition zone” is still lacking, but should reflect a zone with higher probability for new fracturing in connection with earthquakes. The definitions of brittle deformation zones (fracture zones) are also related to width and length rather than transmissivity, Table 4-2, so that additional work would be needed to relate them to the F-factor (Table 8-2).

Table 4-2. Classification of brittle deformation zone in terms of approximate length and width. Revised from Andersson et al, 2000

Concept	Length	Width
Regional fracture zones	> 10 km	> 100 m
Local major fracture zones	1 km - 10 km	5 m - 100 m
Local minor fracture zones	100 m - 1 km	0.1 - 5 m
Fractures	< 100 m	< 0.1 m

We may also classify reliability of observations (Certain, Probable, Possible) in accordance with Table 4-3 in a similar way as used in the Äspö Hard Rock Laboratory.

Table 4-3. Classification of reliability of “geological signatures” for observations at surface and in sub-surface. Simplified after /Bäckblom, 1989/.

Reliability	Observations
Possible	Lineament at surface and or geophysical anomalies (magnetic, electric) in boreholes
Probable	Increased fracture intensity at an outcrop interpolated with sections of increased fracture intensity in at least one borehole (or tunnel) or geophysical anomaly or other feature interpolated with sections of increased fracture intensity in at least one borehole (tunnel).
Certain	Probable signature at the surface with observed direction of dip at surface and or unique feature in at least two boreholes (tunnels).

The matter of terminology is important and some revised terminology[2] is suggested later in this report.

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[2] It would be useful if SKB and Posiva to the extent possible harmonise terminology.

5 Possible characterisation steps and required data

This study calls for the development of a stepwise methodology for determining respect distance. Preliminary distances are decided prior to repository construction for use in the design of the preliminary layout, and subsequently finalized during the repository construction phase prior to canister emplacement.

5.1 A structure for models

The data assembled in the different phases of reconnaissance, characterization and construction are used both to produce models of the bedrock for the purpose of detailed layout and long term safety analyses, and also to guide excavation and to plan rock sealing and rock support.

The generic elements of the models are described in Olsson et al, 1994, and summarized in Table 5-1. The basic concepts during the site characterization are not likely to change, but the additional new data will become available during the project. For the purpose of site characterization, the modelling of reactivation during earthquakes depends more on the fracture network geometry or boundary conditions rather than the fracture properties. The models (example for one approach described in Table 5-2) are based on present concepts and simplifications and changes in data collection would be corollary to changes in the conceptual approach. The present study assumes that the key parameters are:

- stress drop;
- distance from the primary fault to the target fracture, and;
- the size of the target fracture.

<table>
<tr><td colspan="2">Table 5-1. Condensed description of models /Olsson et al, 1994/</td></tr>
<tr><td colspan="2">MODEL NAME</td></tr>
<tr><td colspan="2">Model scope or purpose
Specification of the intended use of the model
Process description
Specification of the process accounted for in the model,
Definition of constitutive equations</td></tr>
<tr><td>CONCEPTS</td><td>DATA</td></tr>
<tr><td colspan="2">Geometrical framework and parameters</td></tr>
<tr><td>Dimensionality and/or symmetry of model. Specification of what the geometrical (structural) units of the model are and the associated geomterical parameters (the ones fixed implicitly in the model and the variable parameters).</td><td>Specification of the size of the modelled volume. Specification of the source of data for geometrical parameters (or geometrical structure). Specification of the size of the geometrical units and resolution.</td></tr>
<tr><td colspan="2">Material properties</td></tr>
<tr><td>Specification of the material parameters contained in the model (it should be possible to derive them from the process and the geometrical units).</td><td>Specification of the source of data for material parameters (could often be the output from some other model). Specification of the value of material parameters.</td></tr>
<tr><td colspan="2">Spatial assignment method</td></tr>
<tr><td>Specification of the principles for the way in which material (and if applicable geometrical) parameters are assigned throughout the modelled volume.</td><td>Specification ot the source of data for model, material and geometrical parameters. Specification of the results of the spatial assignment.</td></tr>
<tr><td colspan="2">Boundary conditions</td></tr>
<tr><td>Specifications of (type of) boundary conditions for the modelled volume.</td><td>Specification of the source of data on boundary and initital conditions. Specification of the boundary and initial conditions.</td></tr>
<tr><td colspan="2">Numerical or mathematical tool</td></tr>
<tr><td colspan="2">Computer code used</td></tr>
<tr><td colspan="2">Output parameters</td></tr>
<tr><td colspan="2">Specification of parameters and possibly derived parameters of interest</td></tr>
</table>

Table 5-2. Simplified description of models for reactivation. Example POLY3D. /Based on Bäckblom et al, 2004/

DISPLACEMENT OVER DEPOSITION HOLE DUE TO FUTURE EARTHQUAKES

Model scope or purpose

Calculation of target fracture displacements as a function of magnitude and distance to the primary fault

Process description

Displacements and stresses at a target fracture as function of imposed slip at a primary fault (static calculations).

Linear elastic materials (Hooke's law) with fracture inclusions to simulate the target fractures

CONCEPTS	DATA
Geometrical framework and parameters	
Fracture distribution (number, orientation and sizes) within a semi-finite halfspace. Distance from primary fault to target fractures	See step 1-6 in Table 5-3
Material properties	
Young's modulus, Poisson ratio, No friction in target fractures.	Friction-less target fractures.
Spatial assignment method	
Fracture are stocastically (POLY3D) generated in the model according to set specifications.	See step 1-6
Boundary conditions	
The box is free from stresses, but a slip is assigned at the at the primary fault. (POLY3D).	
Numerical or mathematical tool	
POLY3D	
Output parameters	
Displacements	

5.2 Definition of time steps

Table 5-3 defines six steps or phases of repository siting, design and construction that correspond to new data becoming available for updating the quantification of respect distances:

Table 5-3. Definition of phases of repository siting and construction

Step #	Name of step	Typical data and methods available	Typical evaluations of possible relevance for respect distances
1	Initial site investigations	General geological mapping, topographical and geophysical lineaments: Data from a few boreholes from the surface. Outcrop mapping.	Lineaments, single hole definition of major fracture zones, typical rock mass properties (fracturing, mineralogy, fracture minerals) in a broad stochastic sense
2	Complete site investigations	Detailed outcrop mapping. Detailing of models for the target areas. Data from several cored boreholes from the surface	Existence of major and most minor fracture zones and their characteristics. Some zones with a deterministic dip and dip direction. Several cored boreholes. A few cross-hole tests.
3	Construction of access (ramp, shafts) and central area	Monitoring of boreholes. Tunnel mapping. Underground boreholes Supplementary investigations from surface	Confirmation of layout of ramp, shafts and central area. Incresased understanding of fracture clusters and their properties. Crosshole tests.
4	Construction of pilot-transport and main tunnels.	Monitoring of boreholes. Tunnel mapping. Underground boreholes. Supplementary investigations of deposition area 1 by core drilling at suitable locations	Delineation of the deposition area. Location and preliminary decision on length of the deposition tunnels
5	Construction of deposition tunnels for the deposition area	See step 1 Investigations to decide position for deposition holes (coring, testing).	Definite location for depositon tunnels and preliminary locations for deposition holes.
6	Construction of deposition holes.	Production data from drilling the hole, mapping.	Definite acceptance or avoidance of deposition hole before deposition starts.

5.3 Key parameters for slip determination

We now analyse methods for measuring or quantifying the key parameters stress drop, distance from primary fault to target fracture and fracture zone size and fracture size and at what stage the parameters may be established.

Stress drop

The maximum possible earthquake magnitude is closely related to fracture zone size. Such relations between zone or fault length are commonly used to assign maximum possible earthquakes to mapped fault traces for earthquake risk calculations. Only major fracture zones can accommodate sufficient energy to produce major earthquakes.

Major subvertical and gently dipping subhorizontal fracture zones that cut the surface are easily traced from the lineaments. However some authors think that stress drop is largely independent of size and magnitudes but takes on values that are typical of the geological setting /Scholz, 1990/. For instance, typical inter-plate earthquakes have stress drops of around 3 MPa, while intra-plate earthquakes have stress drops on the order of 15 MPa.

It is likely that stress drops and magnitudes are estimated during Step 1 or Step 2 in Table 5-3 assuming close correlation of lineaments to the real deformation zones and that the interpreted trace lengths are closely related to the potential rupture length. Horizontal zones would probably not be as important as subvertical zones for stress drop determinations in Sweden, as current tectonics and potential future glaciation/de-glaciation mechanisms favour primary fault reactivation on the vertical or sub-vertical faults.

Current seismicity in Sweden appears to be largely associated with strike-slip movements on near-vertical faults (Tíren and others, 1987). Slunga (1991) interprets these as being due to tectonic plate movements related to the North Atlantic Ridge. Others, for example, Muir-Wood (1993) present evidence for glacial rebound.

Regardless of the causes for present-day earthquakes, post-glacial earthquake occurring several thousand years ago in Sweden would have involved reverse-slip on high-angle faults, leading to the formation of the large scarps in Sweden that have been interpreted by some researchers as post-glacial faulting events associated with large earthquakes. Modeling by Stephansson and others (1978) suggests that future earthquakes would occur due to re-adjustments of existing crustal blocks in response to plate or isostatic movements, rather than from the creation of new, large-scale faults. Large-scale thrust-faulting is not known to occur at present or during possible post-glacial events in the past, and so it is unlikely that existing horizontal fractures will be the sites for future post-glacial earthquakes. However, horizontal fractures may be significant from the standpoint of flow and transport, and cannot be ignored solely due to their possible lesser importance for future post-glacial earthquake risk.

Distance from primary fault to target fracture

Only primary faults > 3 km can slip by more than 0.1 m due to reasons of energy (see compilation of empirical data in La Pointe et al, 1997) so no respect distance would actually be needed for these local major zones. With 3 km length (assume width 10-50 m) we can not take for granted that all these zones are detected during Step 1 and Step 2. Zones with width < 5 m are definitely not easy to detect at Step 1 and Step 2. However for the issue of reactivation it is likely that the distance from the primary faults to the target fractures (canister positions) more or less would be based on the investigations in Step 1 and Step 2. However we also have to assume that we locate additional zones during Step 4. We have to assume that primary faults also may be sub-horizontal.

It is possible to estimate how far away from a proposed repository that site investigations need to be carried out in order to identify faults greater than 3 km that could create problems. Coppersmith and Youngs, 2000 summarized field evidence for the amount of secondary fault slippage as a function of slip on a primary fault from large earthquakes in the Basin and Range Province of the western United States. They found that the relation between the ratio of primary to secondary slip as a function of distance between the primary fault and a secondary fault could be well characterized by a Gamma distribution. Whether this model would hold for Swedish seismicity is unknown, but assuming that it does makes it possible to estimate minimum areas of investigation required to identify and characterize primary faults. If a threshold for secondary slip is established, such as 0.1 m, then this model indicates the amount of primary slip as a function of distance that would be required to produce the threshold slip. Wells and Coppersmith, 1994 have also published tables that show statistically significant relations between a fault's surface rupture trace length, moment magnitude and maximum slip. This second table makes it possible to relate the primary slip to surface trace length and magnitude. Combining these two tables, establishes the minimum distance of investigation required for characterizing primary faults. With the assumption of a maximum possible future earthquake, the table also makes it possible to establish maximum distances of investigation. Maximum distances for magnitudes 7.0, 7.5, 8.0, 8.5 and 9.0 are shown, Table 5-4.

Table 5-4. Maximum distance of concern estimated from field earthquake data. SS = strike slip; R = reverse slip; N = normal slip; All = average for all slip types.

Earthquake Magnitude				Predicted Max Displacements (m)				Predicted Trace Length (km)			
SS	R	N	A	SS	R	N	A	SS	R	N	A
7	7	7	7	1.51	1.55	2.14	1.91	42.7	35.5	30.9	40.7
7.5	7.5	7.5	7.5	4.95	2.16	5.96	4.90	100.0	73.3	55.0	90.2
8	8	8	8	16.22	3.02	16.60	12.59	234.4	151.4	97.7	199.5
8.5	8.5	8.5	8.5	53.09	4.22	46.24	32.36	549.5	312.6	173.8	441.6
9	9	9	9	173.78	5.89	128.82	83.18	1288.2	645.7	309.0	977.2

Ratio of Secondary to Primary Slip for 0.1 m Threshold				Maximum Distance of Concern (km)			
SS	R	N	A	SS	R	N	A
0.066069	0.064565	0.046774	0.052481	4.8	4.9	5.3	5.2
0.020184	0.046238	0.016788	0.020417	6.5	5.3	6.7	6.4
0.006166	0.033113	0.006026	0.007943	8.0	5.8	8.0	7.6
0.001884	0.023714	0.002163	0.003090	9.4	6.2	9.2	8.8
0.000575	0.016982	0.000776	0.001202	10.8	6.7	10.4	9.9

This table is calculated by using the regression equations that relate earthquake magnitude to maximum primary displacement and surface rupture length published by Wells and Coppersmith, 1994, as a function of slip type. For example, a strike slip earthquake of magnitude 7.5 would have a maximum primary slip of 4.95 m and a surface rupture length (fault trace) of 100 km. The lower part of the table is calculated from Coppersmith and Youngs, 2000. The ratio is calculated by dividing the threshold secondary slip, 0.1 m, by the predicted maximum primary slip, for example, 0.1/4.95 = 0.046. Using the Gamma distribution published by Coppersmith and Youngs, 2000 that relates the ratio of secondary to primary slip as a function of distance would yield the maximum distance of concern. The table shows that even for a magnitude 9.0 earthquake, the maximum distance of investigation is not likely to be greater than about 10 km. If all large faults (those with rupture lengths greater than 30 km) have been detected within 10 km of the repository, then the site is adequately characterized, according to these relations, for the purposes of secondary slip due to earthquakes.

An interesting corollary is that if *no* faults with rupture lengths greater than 30 km are found within 10 km of the site, there is exceedingly little risk of secondary movement on faults or joints intersecting canister holes, and the respect distance is effectively 0.0!

Fracture zone sizes

Trace lengths of fracture zones during Step 1 and Step 2 are based on interpretation of topographical and geophysical lineaments. For Step 2 and any later steps, drilling and testing of and between boreholes can confirm the existence, location and extent of fracture zones.

Borehole testing techniques fall into two groups. The first group only measures data at the actual borehole or its immediate vicinity, such as would be gathered using standard geophysical logging tools. The second group provides data in a much larger volume around the hole, as for example, borehole radar. For the first group of data fracture zone size is based on the assumption of continuity between boreholes for data signatures that are reasonably similar from one borehole to the next. In the case of borehole radar, the geometry of a reflector can be interpreted for distances of 0-150 m depending on bedrock conditions and radar frequency used in the measurements. The detection reliability is influenced by the orientation of the feature; features parallel to the borehole are easier to detect than features oriented perpendicular to the borehole.

Crosshole tests or denser drilling is needed to confirm fracture zone size. Vertical Seismic Profiling (VSP), tomography and hydraulic interference tests with tracers are standard methods to evidence the geometry of fracture zones. For horizontal and sub-horizontal seismic refraction or seismic reflection could be useful methods.

Fracture sizes

Methods for fracture size determination are less obvious compared to size determination of fracture zones whereas the latter can be treated as individual elements, while fractures within a fracture group would have less information or signature to distinguish one individual fracture from the next.

In Step 1 and Step 2, fracture trace lengths are collected from outcrops with the notion that the trace length is the minimum fracture size. As mainly long fractures (> 100 m in length) are of interest, outcrops or trenches should be wide enough to cover these sizes, Figure 5-1. A limitation of outcrop data is that sub-horizontal fractures are under-represented in the statistics. Another limitation is also the potential difference between fracturing at the surface and fractures at the repository depth due to surficial weathering or stress-relief.

Figure 5-1. *Photo from trenching at Drill Site 4 at Forsmark for the purpose of mapping*

For Steps 3 to Step 6, tunnel mapping is performed. However the relation between trace length in the mapping and true fracture size requires assumptions and would still remain uncertain, Figure 5-2.

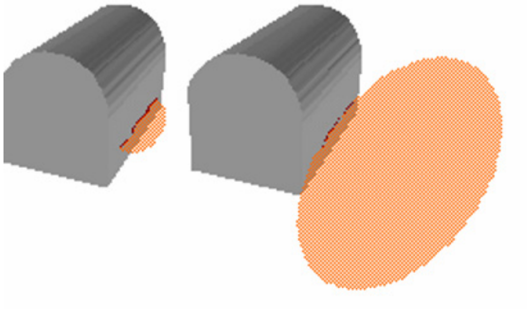


Figure 5-2. *Two similar trace lengths from tunnel mapping can represent a large span of fracture sizes. /From Hagros et al, 2003/*

Mapping of fractures is conducted within a fixed database framework where, for example, trace length, orientation, undulation and roughness, fracture mineralogy and presence of water are recorded. It is easy to intuitively decide that the number of short fractures outnumber the long fractures. The fracture and fracture zone size distribution in different scales has been investigated at e.g. at Forsmark and at Äspö and the results normalised to the investigation area, Figure 5-3.

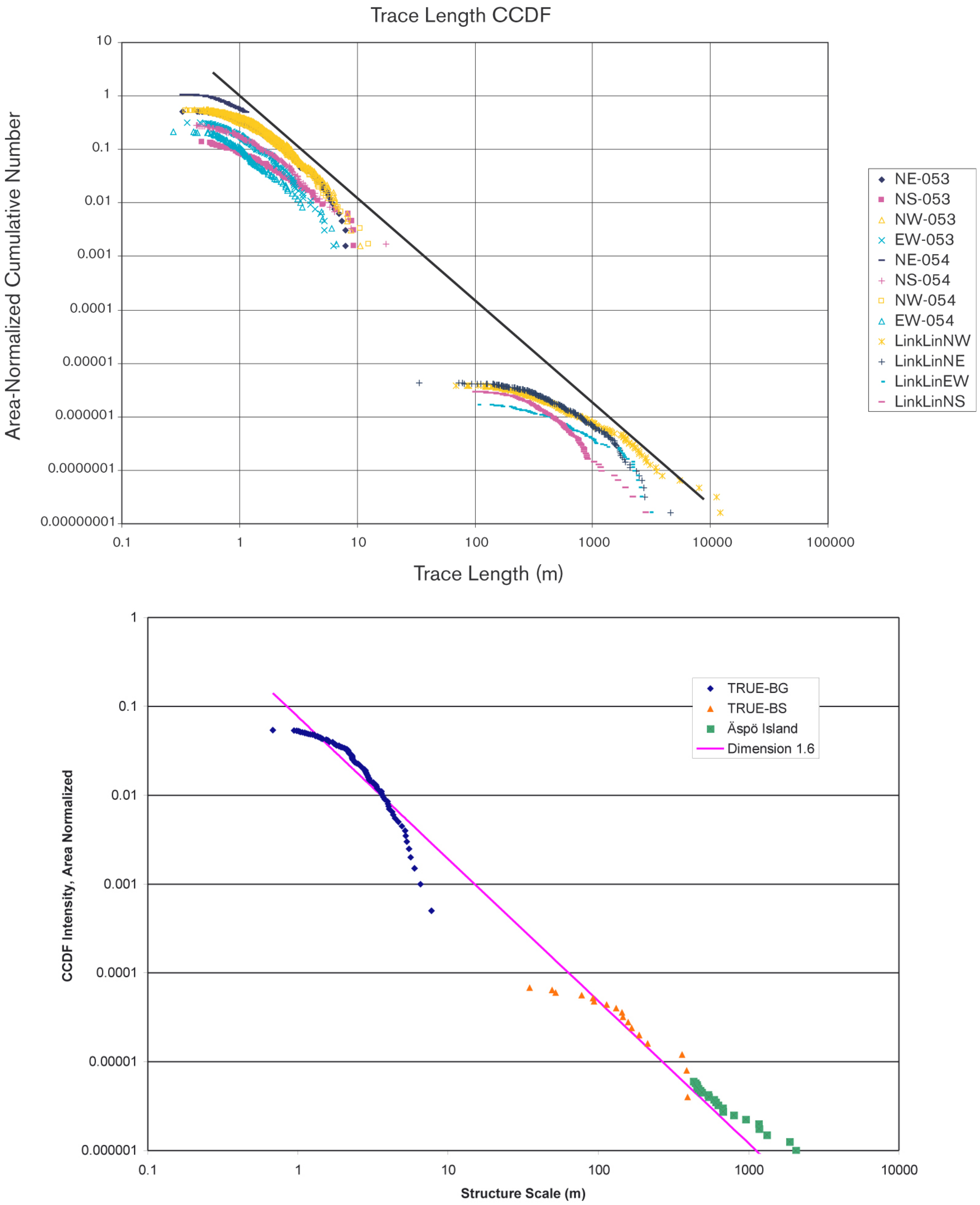


Figure 5-3. *Complementary Cumulative Density Function (CCDF) of the trace lengths Top: Four sub-vertical fracture groups at drill sites 2 and 3 at Forsmark. The plot is area normalized /SKB, 2004b/. Bottom: Results from the Äspö TRUE Block Scale site and the ÄSPÖ HRL compile as part of Task 6C of the Äspö Task Force. The data reasonably follow a straight line with the fractal dimension of 1.6 /Dershowits et al 2003, Fig A-1/.*

Relations between fracture (and structure) size and other parameters have been investigated in the Tracer Retention Understanding Experiment in Block Scale, where it is evident some sort of relation exist between fracture size and transmissivity, Figure 5-4; at any given scale there is no clear correlation between size and transmissivity but over all scales a pattern is shown where in general longer features are more transmissive than short features.

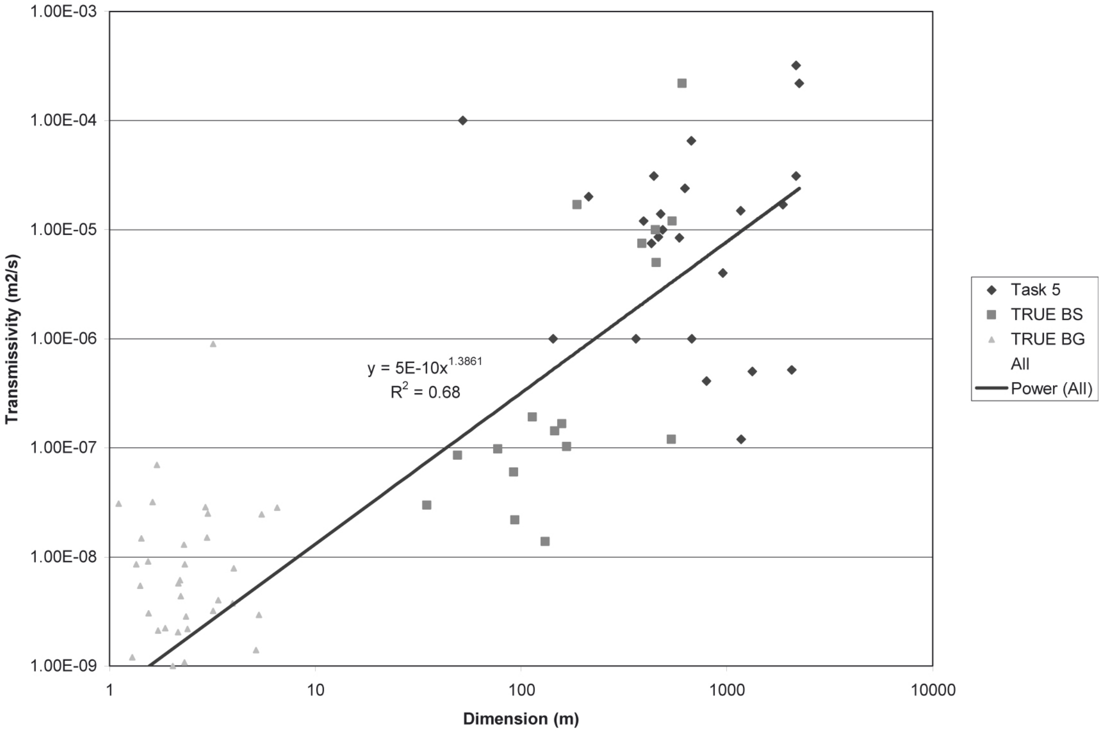


Figure 5-4. *Relationship between structure size and transmissivity /Dershowits et al, 2003, Fig A-6/.*

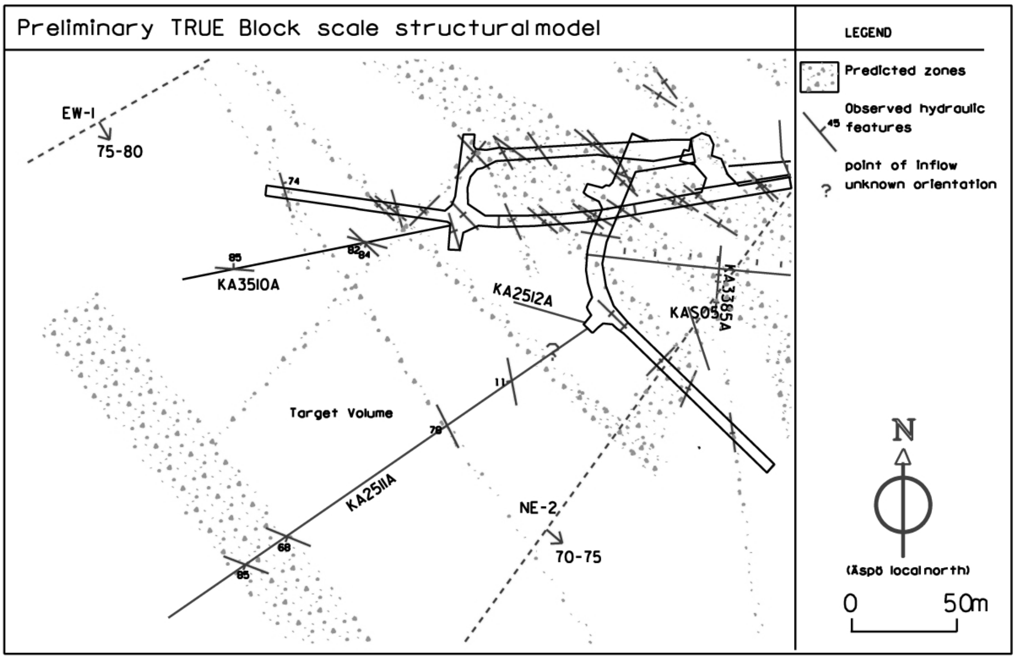
5.4 Deterministic versus stochastic determination of fracture size

From the previous discussions it is evident that it is possible to create a fracture size distribution in a stochastic sense that would be useful in spite of bias and uncertainty. It is also intuitively assumed that continued investigations can reduce the amount of uncertainty in estimating fracture sizes. For development of the field methodology it is essential to decide what level of uncertainty is tolerable, assuming the level is possible to quantify and compare to an acceptance level. The Tracer Retention Understanding Experiment (TRUE) at the Äspö Hard Rock Laboratory provides insight into this question.

An example of how the description of the fracture network evolves with time is shown in Figure 5-5. The top of the figures shows the deterministic model before and after extensive characterisation at the experimental TRUE-site. Three things are evident; the number of structures increases before and after the investigations and most of the long features are defined not by one but by several penetrating boreholes and most of the structures are more or less perpendicular to the borehole direction, probably because the core drilling was planned in such a way, but bias can not be excluded. The data in general corroborate conductive structures in NW- direction, parallel with the major horizontal stress direction.

Now, what level of determinism may be developed first at the level of repository area, then for a deposition tunnel and then at the deposition hole?

Top:



Bottom:

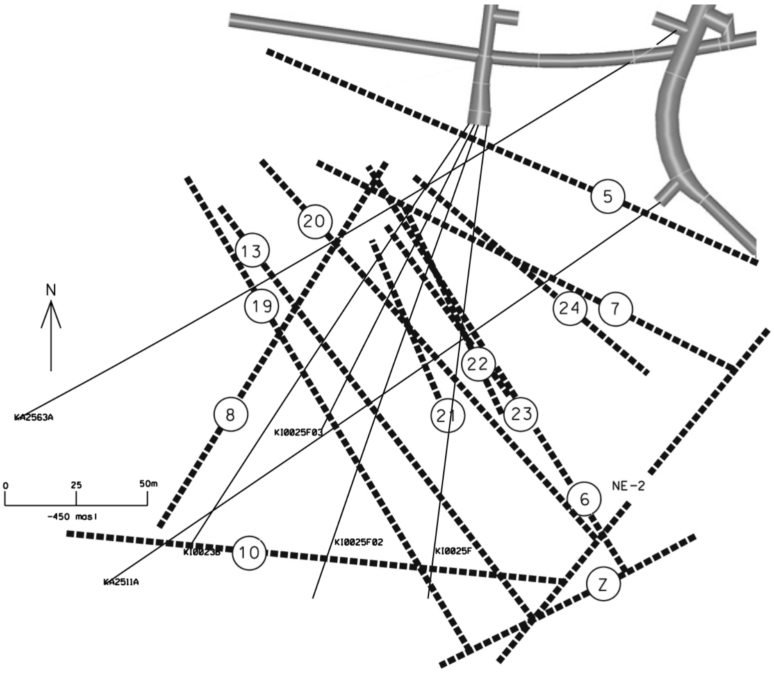


Figure 5-5. *Top: Primary deterministic hydrostructural model in the vicinity of the planned TRUE Block Scale site /Winberg, et al, 2001/. Bottom: Final hydrostructural model of the Äspö TRUE Block Scale site /Winberg et al, 2002/.*

5.5 Deterministic determination of fracture size in the scale of the repository area – geometrical considerations

Figure 5-6 shows the main tunnel that is constructed in Step 4 (Table 5-3). It is assumed that the main tunnel is excavated more or less perpendicular to the future deposition tunnels and that the main tunnel is excavated along one side of the intended repository area. Prior to excavation of the deposition tunnels that may be open for about 5 years detailed investigations of the repository area will commence. It is likely that core drilling takes place along every deposition tunnel, starting with general definition drilling and later with infill drilling to decide the extent of the deposition tunnels and to refine the previous picture of the site.

The preliminary nomenclature ("Certain", "Probable" and "Possible") in Table 4-3 is applied with the assumption that two observations of a feature/fracture really are observations of the same discontinuity. For the sake of the discussion and simplicity, we here assume that **at least need two visual observations separated at a distance of 100 m are required to classify a fracture size as diameter > 100 m and that we really can establish a "geological signature" for a fracture/discontinuity of such length.**

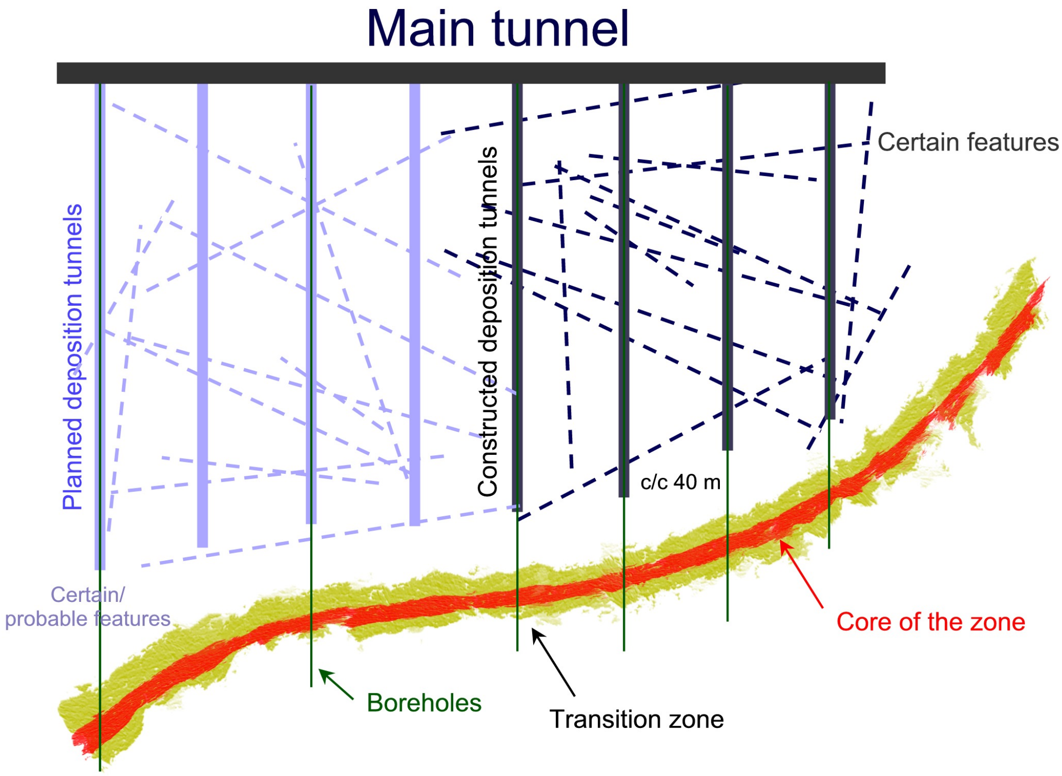


__Figure 5-6.__ Sketch of a generic repository layout with generic site conditions

The deterministic knowledge of the site is not assumed to be at a higher level than at the start of the TRUE Block Scale test before construction of the main tunnel (Figure 5-5 top). Now assuming that only fractures with diameter > 100 m are of interest and that several boreholes are drilled or tunnels with c/c 40 m – 50 m are excavated, then in theory, ideally they could be connected by mapping in the adjacent holes/tunnels all features that are aligned at arcsin (40/100), i.e. around 25º from the direction of the investigation hole/cored hole, assuming vertical fractures, see Figure 5-7.

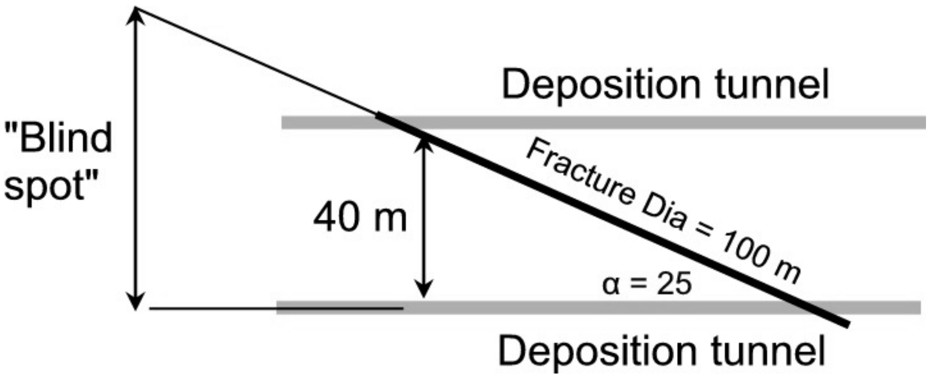


Figure 5-7. *Fractures at diameter = 100 m is only observable for α > 25º when deposition tunnels are separated by a distance of 40 m.*

For features more or less parallel to the tunnel direction, the interpretation of fracture size can only be indirect for diameter < 100 m. In the real case we also map the main tunnel and tunnels on the opposite site of the main tunnel to interpret the fracture network in repository area scale.

The mapping and single hole and cross-hole investigation in the cored holes can delineate features like minor fracture zones in the deposition area if they carry a specific signature. However it would be unlikely if fractures in one hole could be traced to the next parallel hole some 40 m away.

After the definition drilling (maybe at a distance of c/c 160 m) the preliminary layout of the repository area will be more or less fixed and after infill drillings at each preliminary location of the deposition tunnels are completed, the extent of the repository area is more or less fixed.

5.6 Deterministic determination of fracture size in the scale of the deposition tunnel and deposition hole – geometrical considerations

We now apply a similar approach for the deposition tunnel and deposition holes, Figure 5-8. The deposition tunnel is 200 – 400 m in length and has a height of about 5 m; the deposition holes c/c 6 m are 8 m deep. In an analogous manner, features with dip direction parallel to the tunnels are identified, and the length of fractures having a diameter > 100 m for fractures dipping arcsin (18/100) = 10º is determined by observation in both deposition tunnels and deposition holes, or arcsin (8/100) = 5º for deposition holes only.

Figure 5-9 summarizes this reasoning:

- An appropriate fracture/tunnel relative orientation is key for intersecting large fractures;
- Each fracture must have a unique and measurable signature to make correlation possible;
- Long fractures (Diameter > 100m) perpendicular to deposition tunnels are more reliably detected than those that are sub-parallel;
- Due to the abundance of vertical deposition holes, the extent of horizontal fractures probably will have less uncertainty than vertical fractures;
- If long, vertical fractures are delineated in the deposition tunnel, the likelihood for long fractures to compromise depositions holes can be reduced or eliminated by local adjustment of the precise location of the deposition hole to avoid them. This option is not viable for sub-horizontal fractures that may cut the deposition holes as the depth of the holes is more or less fixed.

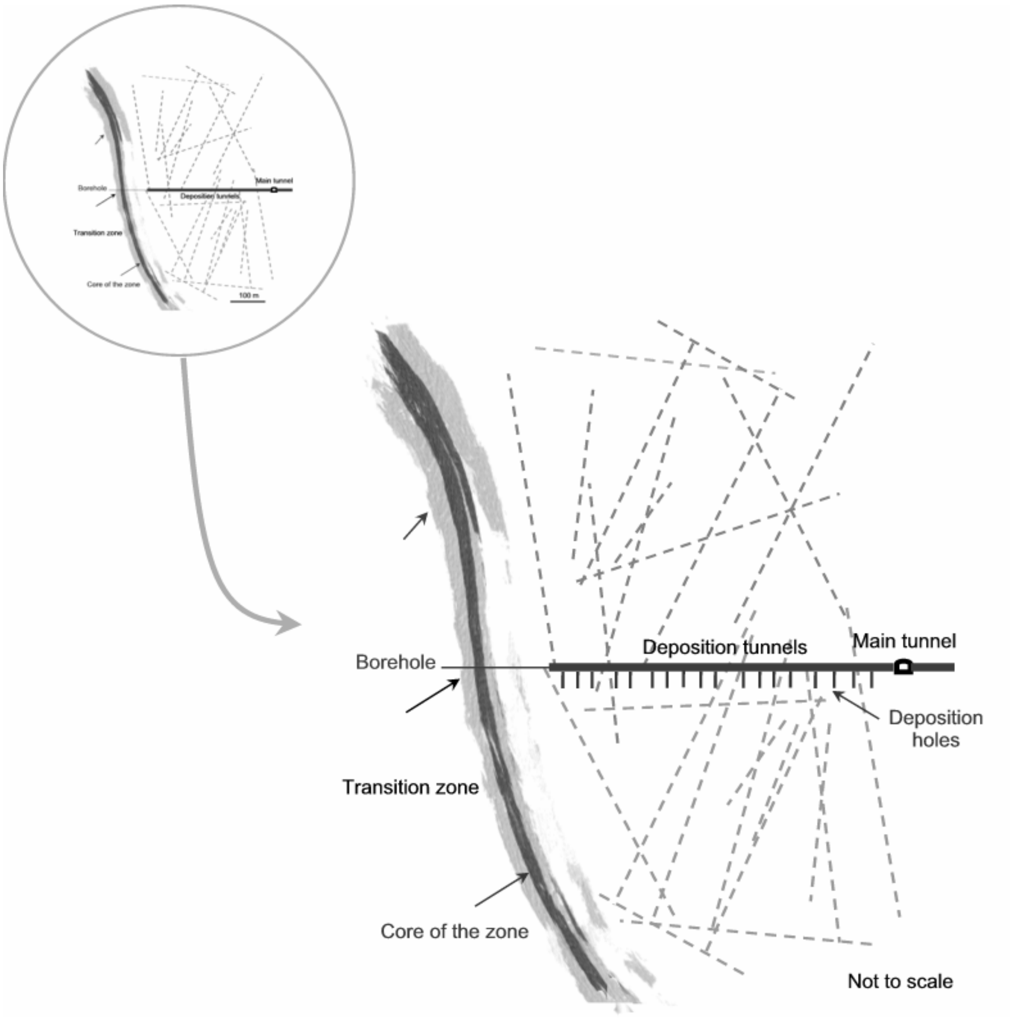


Figure 5-8. Sketch of the situation around the deposition holes

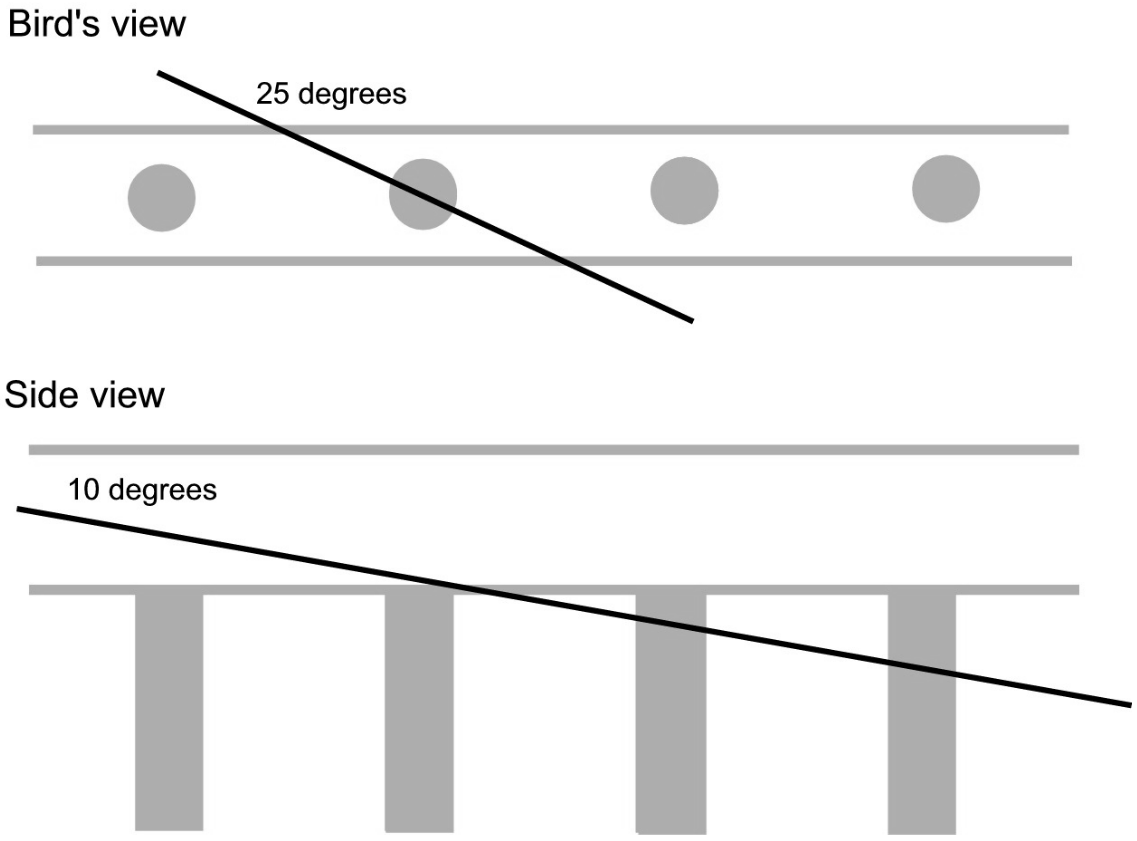


Figure 5-9. *Sketch for illustrating influence of fracture orientation on observability.*

However, the location of the fracture relative to repository boundaries also plays a role. In the situation where a fracture is centred well within the repository block, the fracture could be detected in several locations and delineated with minimal uncertainty, Figure 5-10. But fractures centred outside the repository block are not as well delineated, Figure 5-11. Assume that two fractures are detected in the deposition holes closest to the primary fault. In this case it is not possible to resolve whether the fracture sizes are R = 10 m or R = 50 m, so that there are no geometrical means to observe the fracture size for those fractures that are most interesting to study. Thus: **Fracture size estimation (by observations in tunnels and deposition holes) are less precise, the closer you are to the boundary of the repository area.**

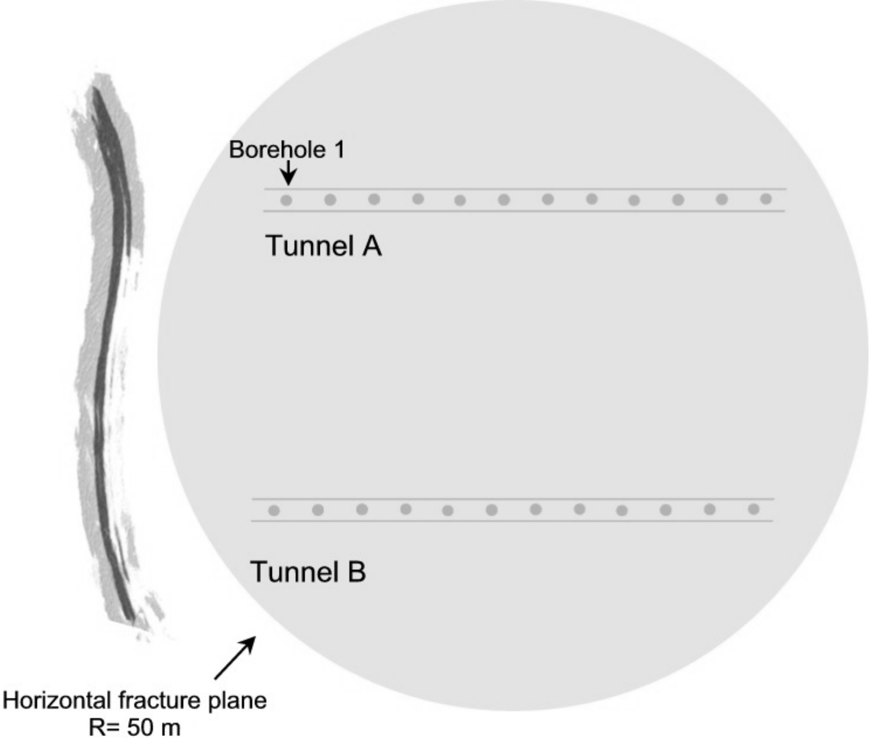


Figure 5-10. *Ideal situation for fracture size determination; horizontal fracture that cut several deposition holes and would be observable in all these.*

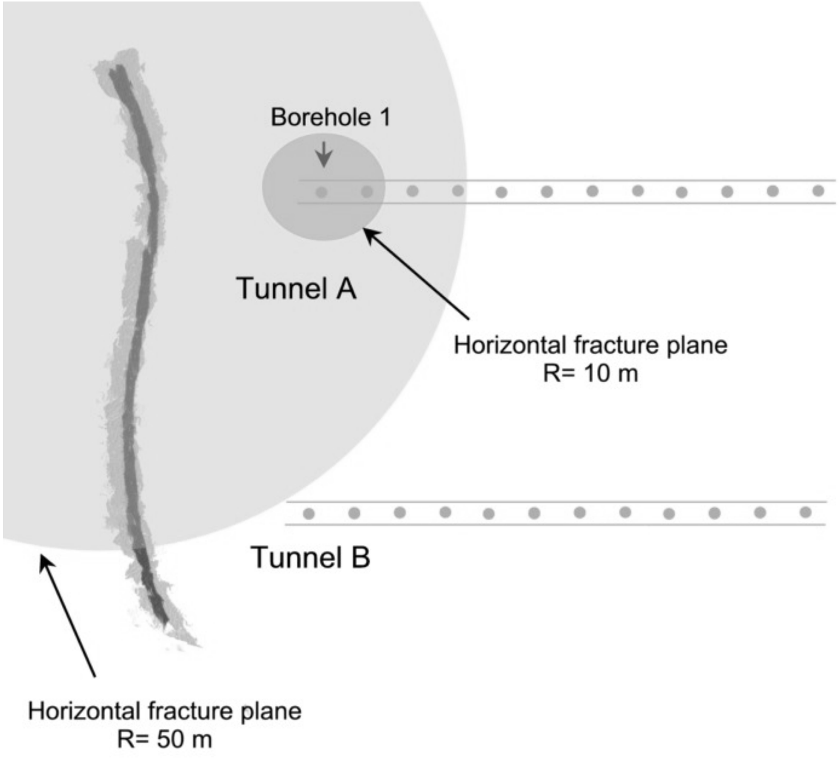


Figure 5-11. *Typical situation for fracture size determination assuming horizontal fractures that cut several deposition holes and would be observable in all these. For the deposition holes close to the repository area, we would have no means to decide whether observations are for an R= 10 m of for an R = 50 m fracture.*

5.7 Determination of unique signatures of fractures and their determination in boreholes

The previous sections lead to the conclusion that fracture mapping in tunnels and in deposition holes has limited value for determination of large fracture sizes and especially for the deposition holes close to the repository boundaries, even if under the unrealistic assumption that every individual fracture has a unique signature. In reality, it is very difficult to determine that a fracture observed at one location is the same fracture observed at another distant location.

For fracture zones, the geometrical extent might be delineated by geophysical or hydrogeological means or even by geological mapping as the zones often carry some sort of signature, like fracture mineralogy, and general character that corroborate the interpolation from one location to the next location. A similar situation would not be likely to occur in general for individual fractures, as the fracture properties do not contrast sufficiently with the rock mass. For example, an individual fracture would not change seismic velocity enough to produce a distinct cross-hole anomaly compared to the general variability in the rock mass seismic properties. A similar lack of contrast pertains to other geophysical and geohydrological cross-hole methods as well.

What may come out of the mapping and boreholes studies would not likely be the individual properties of an individual fracture, but rather the stochastic properties (orientation, roughness, aperture, planarity, morphology, mineralogy etc.) for a group of fractures.

6 Alternative approach to fracture size determination

6.1 Method description

As it is problematic to directly measure fracture size in deposition holes, it is worthwhile to consider other possible alternatives to decide whether an observed fracture disqualifies a canister position. A potentially useful alternative investigated in this preliminary study is to use surrogate variables to classify individual fractures as above or below a specified size threshold.

A surrogate variable is a variable that is related, in some degree, to the variable of interest. There are many observable and measurable parameters of a fracture that may relate to a fracture's size. These include aperture, transmissivity, weathering, mineral infillings, planarity, roughness, orientation and morphology. Used together, these surrogate variables may make it possible to classify whether a specific fracture is above or below a size threshold.

The disqualification of a canister position based on fracture size does not require an *estimate* of the fracture size, but rather a *classification* as to whether the fracture is above or below a specified size threshold. Classification is an easier mathematical task, since it is dichotomous, than estimation, which has a continuum of possible outcomes. Estimation of fracture size requires more information content than classification, and so is likely to prove less useful than classification.

The basis for the use of surrogate variables is that large fractures may have particular geometric properties, such as being planar rather than curved, or occurring in a particular orientation; be associated with rock that has favourable mechanical properties for the development of large fractures; or have distinguishing secondary features, such as characteristic mineral infillings that occur only when the fracture is part of a regional flow network, and hence likely to be larger than those that are not part of the regional flow network. In a mathematical framework,

$$FractureSize = f(x_i)$$

where x_i are one or more geometrical, mechanical or secondary parameters. The mathematical form of $f(x_i)$ could be quite complex in the sense that it may be a non-linear function of the predictor (independent) variables whose mathematical form is not known, and also in the sense that the independent variables may be correlated to some extent with one another. The simplest form of the functional relation would be a multivariate linear expression of the form:

$$FractureSize = a_0 + a_1 V_1 + a_2 V_2 + ... + a_n V_n$$

in which the independent variables, V_i, are not correlated. It is unlikely that this simple mathematical model will adequately describe a useful predictive relation.

Moreover, the variables that can be mapped are not *continuous* variables over a defined or known range; rock type is an example of a variable that is not a continuous variable, but rather a *categorical* of *nominal* variable. A third type of variable consists of *ordinal* variables, in which the categories have relative ranking based on magnitude. Roughness categories are an example of ordinal variables.

The fact that most of the potentially useful variables are not continuous means that techniques based only on continuous variables, such as multivariate regression, cannot incorporate a large portion of the mappable data, which is of the ordinal and nominal type. Moreover, the continuous variables that can be measured, such as orientation and aperture, generally appear to have low correlation with fracture size. Other variables, such as transmissivity, are restricted largely to boreholes, and it might prove prohibitively expensive to carry out on a large scale. Thus, the methods that could prove most useful in terms of using all of the data captured in outcrop and potentially measurable at various stages of the site investigations and construction cannot rely upon continuous variables alone, and must be able to incorporate all three data types.

There are several possible mathematical ways to develop mathematical classification schemes for categorizing data: Probabilistic Neural Nets (PNN); Linear Discriminant Analysis; Contingency Table Analysis (CTA).

Linear discriminant analysis assumes that data is continuous, uncorrelated and requires that the classification function be a first order polynomial of the independent variables. This is not appropriate for the surrogate data. Both neural nets and contingency table analysis can accommodate all three types of data, handle correlations, and do not place the same limitations on functional form that LDA imposes.

Thus, two alternative and complementary mathematical techniques were applied at each site, 2-way and n-way contingency table analyses, and Probabilistic Neural Nets.

To make a preliminary evaluation of this approach, data sets from recent outcrop studies at Simpevarp, Forsmark and Olkiluoto have been used to try out a variety of different mathematical approaches to see if a robust classification can be achieved. In all of these methods, it is also possible to quantify the uncertainty associated with the classification, so this uncertainty can be quantified and propagated into the safety calculations.

6.1.1 Contingency Tables

Contingency tables quantify the strength of associations between classes of data. Each class has subclasses or states. The following hypothetical example explains how contingency tables can be used to identify and quantify associations between fracture size and other measurable variables. For the purposes of illustration, fractures have been divided into greater than 20 m and less than 20 m. Two independent variables, “A” and “B” having subclasses or states a_1, a_2 and a_3, and b_1 and b_2, respectively, have been tabulated from 50 measurements as shown in Table 6-1:

Table 6-1. Hypothetical contingency table example results

Fracture Size Class	**a_1**	**a_2**	**a_3**	**Subtotal**
<= 20 m	25	12	3	40
> 20 m	1	1	8	10
Subtotal	26	13	11	50
Fracture Size Class	**b_1**	**b_2**	**Subtotal**	
<= 20 m	7	33	40	
> 20 m	3	7	10	
Subtotal	10	40	50	

This table first can be used to determine if either variable might be a useful predictor of fracture size. Consider Variable A. Overall, there are 26 traces that have state a_1, 13 that have state a_2, and 11 that have state a_3. There are 40 fractures out of 50 (80 %) that belong to the <= 20 m class, and 10 out of 50 (20 %) that belong to the > 20 m class. If the state of variable A made no difference, then the ratios of 26:13:11 determined for the entire population, in which state plays no role, should be approximately the same in each size class. In other words, the number of measurements expected for the <= 20 m class would be 20.8:10.4:8.8, and 5.2:2.6:2.2 for the > 20 m class. Statistically significant departures from these expected values indicate that a particular independent variable state is associated with a dependent variable state or class. In the hypothetical example above, state a_3 is clearly associated with fracture whose trace lengths are greater than 20 m.

On the other hand, variable B appears to have little association with fracture size. Theoretically, the expected numbers for b_1 and b_2 would be 8 and 32 for the <= 20 m class, and 2 and 8 for the > 20 m class, which is not statistically significantly different than the observations of 7 and 33, and 3 and 7.

This type of preliminary analysis identifies which variables and which subclasses (or states) may be associated with long or short fractures. The next step is to quantify this relation and use it to calculate the probability that a fracture having certain observed states belongs to the > 20 m or <= 20 m class.

The probability that a variable has a value of *n*, given that the expected number of observations is *m*, and the degrees of freedom *d*, can be quantified using the chi-square distribution. If variables A and B both relate to fracture size, and A and B are independent, then the joint probability for belonging, say, to the > 20 m fracture class is simply the product of the individual state probabilities. For example, the probability of a fracture belonging to the > 20 m class given that it has states a_2 and b_1 is:

$$\Pr(>20 \mid a_2 \cap b_1) = \Pr(>20 \cap a_2 \cap b_1) / \Pr(a_2 \cap b_1)$$

Although somewhat laborious to calculate when the number of independent variables becomes large, it is possible to quantify the probability that it belongs to the > 20 m class given that any combination of independent variables is true or false.

This type of analysis is useful for categorizing fractures for the purposes of safety analysis, as the goal is to determine whether a particular fracture belongs to a class that could be large enough to have unacceptable secondary slips during an earthquake or not. It is not necessary to actually predict the fracture size, but only to categorize it properly based upon a threshold.

SPSS for Windows™ Release 11.0.0 was used to compute the contingency tables and their statistical significance. The statistical results underlying the contingency table analyses for the three sites are contained in electronic appendices due to the sheer volume of the results. There are several measures of the statistical significance of the results that are reported.

A drawback of using existing outcrop data for these preliminary studies is that the largest fractures mapped are not very large. For example, the largest trace length measured in Forsmark is less than 12 m in length, which is likely to be well below the threshold size for secondary slip. This suggests that any additional work should be designed to measure fractures of larger size, in the range of tens if not hundreds of meters.

Nonetheless, the studies on the existing outcrop data do show that the use of surrogate variables may provide a viable means for categorizing fractures into length classes.

6.1.2 Neural Nets

Neural nets are also well-suited to the mathematical requirements of the mixed data types, nonlinear functional relationships, and possible correlation among the independent variables expected for this type of data. There are three broad types of neural nets in terms of their mathematical function: predictive nets that calculate a continuous variable; classifier nets that categorize data into two or more categories; and unsupervised nets that look for natural groupings in the data. The classifier nets are analogous in function to classical linear discriminant analysis, while the unsupervised nets are analogous to nearest neighbour cluster analysis techniques. A common predictive net is the Back Propagation Neural net, abbreviated BPNN, of which there are many subtypes. A particularly powerful classifier net is the Probabilistic Neural Net (PNN). Because it is much easier to classify dependent variables, such as fracture size, than to predict the actual size, PNN's are evaluated in this preliminary study.

In a PNN, continuous independent variables are used without transformation for input. For ordinal variables, positive integers are assigned to each class representing their rank. for example, if there were three roughness classes, smooth, medium rough and very rough, then "smooth' would be given the value of 1, "medium rough" would be given the value 2, and "very rough" would be given the value of 3. For nominal or class variables, each state would become a separate variable. If there were five rock types, then each rock type would become a new variable, and the value of 1 or 0 assigned to it representing whether the fracture was situated in that rock type or not. There are additional renormalizations and non-linear transformations of the variables within the PNN as well, but these are not part of the data preparation step. The reference /Ward Systems Group, 1996/ provides an excellent overview of PNN's, BPNN's and the operational steps in training and applying these nets to different types of problems.

NeuroShell 2® Release 3.0 was used to develop the Probabilistic Neural Nets.

6.1.3 Explanation of variable codings

For reasons of compactness, the tables and figures that describe the results of the contingency table and neural net analyses use variable acronyms that are tied to the SKB database codes, but not readily interpretable without explanation. The correspondence between the variable names and what the variables mean is given in Table 6-2.

Table 6-2. Explanation of variable codings

Variable	Variable Explanation	Code	Acronym	Subclass Description
TERMA	Termination of "A" fracture end	o	TA_o	ending on fracture outside of outcrop
		p	TA_p	ending of fracture (blind)
		t	TA_t	termination against another
		y	TA_y	fractures divides into Y
		x	TA_x	fracture termination against lithologic boundary
TERMB	Same as TERMA, but for other fracture end		TB_*	
RELATION	Describes relation between fracture and lithologic boundaries	a	RR_a	fracture does not cross boundary
		b	RR_b	fracture crosses boundary
		c	RR_c	fracture crosses several boundaries
		d	RR_d	fracture is in boundary
APERTURE	openess of fracture	c	Ap_c	open
		o	Ap_o	sealed
FORM	fracture surface morphology	p	Form_p	stepped, jmps up to 1 m
		t	Form_t	undulating
		u	Form_u	planar
SURFACE		h	S_h	slickensided
		p	S_p	planar
		r	S_r	rough
ALTERATION		s	S_s	smooth
		0	AL_0	rock is not altered
		1	AL_1	rock has alteration, but not red
		2	AL_2	rock is altered, but not disintegrated
		r	AL_r	reddish alteration halo
		rr	AL_rr	dark reddish alteration halo
LITH	host rock lithology	1058	L1058	Granite
		1061	L1061	Pegmatite
		1098	L1098	Pegmatitic Granite
		2017	L2017	Amphibolite
		101054	L101054	Tonalite to granodiorite, metamorphic

Variable	Variable Explanation	Code	Acronym	Subclass Description
		101056	L101056	Granodiorite, metamorphic
		101057	L101057	Granite to granodiorite, metamorphic, medium-grained
		101058	L101058	Granite, metamorphic, aplitic
		101061	L101061	Pegmatite, pegmatitic granite
		102017	L102017	Amphibolite
		103076	L103076	Felsic to intermediate volcanic rock, metamorphic
		111058	L111058	Granite, fine- to medium-grained
GRAINSIZE	host rock grain size	2	GS_2	Fine-grained (<1 mm)
		3	GS_3	fine-medium
		4	GS_4	Coarse-grained (> 5 mm)
		9	GS_9	Medium-grained (1-5 mm)
		98	GS_98	metamorphic
COLOR	host rock color	2	Col_2	red
		4	Col_4	grey
		6	Col_6	dark-grey
		8	Col_8	grey
		9	Col_9	black
		10	Col_10	red
		11	Col_11	light red
		13	Col_13	black
		18	Col_18	red-grey
		19	Col_19	grey-red
		82	Col_82	greyish red
		200	Col_200	dark
		205	Col_205	dark green

6.2 Analyses of data for Forsmark

The Forsmark data derives from outcrop studies from five outcrops: AFM000053, AFM000054, AFM001097, AFM001098 and AFM100201. The variables measured for which there was sufficient amount of data were lithology, structure, grain size, colour, trace length, fracture strike, fracture dip, termination on the “A” end, termination on the “B” end, rock relation, aperture, form and surface roughness. There were 5,899 traces with sufficient data for the independent and dependent variables. The trace length threshold was set at 5.0 m. This value was selected as it was about the largest threshold that could be used for the outcrop data in which the largest trace was only 17.5 m in length. The 5.0 m value represented approximately the 98.2 percentile of the data. Fractures with mapped trace lengths > 5.0 m are termed the “large” fractures, and the remainder as “small”.

The output for the calculations is contained in electronic form in the attached electronic files, as the output is quite lengthy. All files generated will be compiled on a CD and provided to SKB as a project deliverable.

6.2.1 Contingency Table Analyses

Considering first the 2-way contingency table results for each independent variable paired with the trace length, it was possible to identify certain associations that had a higher (or lower) than average probability for being associated with large fractures.

Table 6-3. 2-way contingency table for trace length vs. termination style

Crosstab

			TERMA						
				o	p	t	x	y	Total
GROUP	0	Count	3	181	2995	2454	54	106	5793
		Expected Count	3.9	196.4	2982.4	2452.1	54.0	104.1	5793.0
		% within GROUP	.1%	3.1%	51.7%	42.4%	.9%	1.8%	100.0%
		% within TERMA	75.0%	90.5%	98.6%	98.3%	98.2%	100.0%	98.2%
		% of Total	.1%	3.1%	50.8%	41.6%	.9%	1.8%	98.2%
	1	Count	1	19	42	43	1	0	106
		Expected Count	.1	3.6	54.6	44.9	1.0	1.9	106.0
		% within GROUP	.9%	17.9%	39.6%	40.6%	.9%	.0%	100.0%
		% within TERMA	25.0%	9.5%	1.4%	1.7%	1.8%	.0%	1.8%
		% of Total	.0%	.3%	.7%	.7%	.0%	.0%	1.8%
Total		Count	4	200	3037	2497	55	106	5899
		Expected Count	4.0	200.0	3037.0	2497.0	55.0	106.0	5899.0
		% within GROUP	.1%	3.4%	51.5%	42.3%	.9%	1.8%	100.0%
		% within TERMA	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	.1%	3.4%	51.5%	42.3%	.9%	1.8%	100.0%

Crosstab

			TERMB						
				o	p	t	x	y	Total
GROUP	0	Count	4	142	2912	2559	50	126	5793
		Expected Count	3.9	155.2	2903.9	2555.2	51.1	123.7	5793.0
		% within GROUP	.1%	2.5%	50.3%	44.2%	.9%	2.2%	100.0%
		% within TERMB	100.0%	89.9%	98.5%	98.3%	96.2%	100.0%	98.2%
		% of Total	.1%	2.4%	49.4%	43.4%	.8%	2.1%	98.2%
	1	Count	0	16	45	43	2	0	106
		Expected Count	.1	2.8	53.1	46.8	.9	2.3	106.0
		% within GROUP	.0%	15.1%	42.5%	40.6%	1.9%	.0%	100.0%
		% within TERMB	.0%	10.1%	1.5%	1.7%	3.8%	.0%	1.8%
		% of Total	.0%	.3%	.8%	.7%	.0%	.0%	1.8%
Total		Count	4	158	2957	2602	52	126	5899
		Expected Count	4.0	158.0	2957.0	2602.0	52.0	126.0	5899.0
		% within GROUP	.1%	2.7%	50.1%	44.1%	.9%	2.1%	100.0%
		% within TERMB	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	.1%	2.7%	50.1%	44.1%	.9%	2.1%	100.0%

The above two tables describe the associations between termination style and fracture size class. Group 1 indicates large fractures. It is clear that termination style “o”, (ending outside of outcrop) is positively associated with large fractures, and negatively associated with “p” terminations (blind ending). This is not particularly surprising, as large fractures should have a higher probability of ending outside the mapped area, and a much lower probability of ending blindly inside the mapped area.

Table 6-4. 2-way contingency analysis for fracture size. vs. relation with lithologic boundary

Crosstab

			RELATION					Total
				a	b	c	d	
GROUP	0	Count	3	4255	515	968	52	5793
		Expected Count	2.9	4222.7	511.6	998.7	57.0	5793.0
		% within GROUP	.1%	73.5%	8.9%	16.7%	.9%	100.0%
		% within RELATION	100.0%	99.0%	98.8%	95.2%	89.7%	98.2%
		% of Total	.1%	72.1%	8.7%	16.4%	.9%	98.2%
	1	Count	0	45	6	49	6	106
		Expected Count	.1	77.3	9.4	18.3	1.0	106.0
		% within GROUP	.0%	42.5%	5.7%	46.2%	5.7%	100.0%
		% within RELATION	.0%	1.0%	1.2%	4.8%	10.3%	1.8%
		% of Total	.0%	.8%	.1%	.8%	.1%	1.8%
Total		Count	3	4300	521	1017	58	5899
		Expected Count	3.0	4300.0	521.0	1017.0	58.0	5899.0
		% within GROUP	.1%	72.9%	8.8%	17.2%	1.0%	100.0%
		% within RELATION	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	.1%	72.9%	8.8%	17.2%	1.0%	100.0%

Table 6-4 shows the relation between the fracture trace and lithologic boundaries.

There is a strong positive association between boundary class "c" and large fractures. A "c" class means that the fracture crosses several boundaries. Likewise, large fractures are negatively associated with class "a", which is for fractures that do not cross any boundary, and to a lesser extent with "b", representing the class where fractures cross only one boundary. This too, makes sense, as large fractures have a much higher probability of crossing multiple boundaries and not being confined between boundaries.

Table 6-5. 2-way contingency analysis for fracture size vs. aperture

Crosstab

			APERTURE				Total
				0	c	o	
GROUP	0	Count	4	1	4495	1293	5793
		Expected Count	3.9	1.0	4494.8	1293.3	5793.0
		% within GROUP	.1%	.0%	77.6%	22.3%	100.0%
		% within APERTURE	100.0%	100.0%	98.2%	98.2%	98.2%
		% of Total	.1%	.0%	76.2%	21.9%	98.2%
	1	Count	0	0	82	24	106
		Expected Count	.1	.0	82.2	23.7	106.0
		% within GROUP	.0%	.0%	77.4%	22.6%	100.0%
		% within APERTURE	.0%	.0%	1.8%	1.8%	1.8%
		% of Total	.0%	.0%	1.4%	.4%	1.8%
Total		Count	4	1	4577	1317	5899
		Expected Count	4.0	1.0	4577.0	1317.0	5899.0
		% within GROUP	.1%	.0%	77.6%	22.3%	100.0%
		% within APERTURE	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	.1%	.0%	77.6%	22.3%	100.0%

Interestingly, there is no association between aperture and fracture size (Table 6-5).

Table 6-6. 2-way contingency table for fracture size vs. fracture form.

Crosstab

			FORM				
				p	t	u	Total
GROUP	0	Count	3	2473	780	2537	5793
		Expected Count	2.9	2463.9	783.7	2542.5	5793.0
		% within GROUP	.1%	42.7%	13.5%	43.8%	100.0%
		% within FORM	100.0%	98.6%	97.7%	98.0%	98.2%
		% of Total	.1%	41.9%	13.2%	43.0%	98.2%
	1	Count	0	36	18	52	106
		Expected Count	.1	45.1	14.3	46.5	106.0
		% within GROUP	.0%	34.0%	17.0%	49.1%	100.0%
		% within FORM	.0%	1.4%	2.3%	2.0%	1.8%
		% of Total	.0%	.6%	.3%	.9%	1.8%
Total		Count	3	2509	798	2589	5899
		Expected Count	3.0	2509.0	798.0	2589.0	5899.0
		% within GROUP	.1%	42.5%	13.5%	43.9%	100.0%
		% within FORM	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	.1%	42.5%	13.5%	43.9%	100.0%

Table 6-6 shows the relation between fracture form (stepped, undulating or planar) and size. Large fractures show a negative association with "p" (planar), and a moderate positive association with "t" (stepped) and "u" (undulating). It may be that stepped fractures are either portions of faults, rather than joints, or possibly a series of smaller *en echelon* joints that have been sheared and developed into a single fracture through re-activation, although these speculations would require revisiting the outcrops to establish whether there might be other explanations as well.

Table 6-7. 2-way contingency analyses of fracture size vs. fracture roughness.

Crosstab

			SURFACE			
				r	s	Total
GROUP	0	Count	7	4937	849	5793
		Expected Count	6.9	4934.7	851.4	5793.0
		% within GROUP	.1%	85.2%	14.7%	100.0%
		% within SURFACE	100.0%	98.2%	97.9%	98.2%
		% of Total	.1%	83.7%	14.4%	98.2%
	1	Count	0	88	18	106
		Expected Count	.1	90.3	15.6	106.0
		% within GROUP	.0%	83.0%	17.0%	100.0%
		% within SURFACE	.0%	1.8%	2.1%	1.8%
		% of Total	.0%	1.5%	.3%	1.8%
Total		Count	7	5025	867	5899
		Expected Count	7.0	5025.0	867.0	5899.0
		% within GROUP	.1%	85.2%	14.7%	100.0%
		% within SURFACE	100.0%	100.0%	100.0%	100.0%
		% of Total	.1%	85.2%	14.7%	100.0%

The table showing the association between roughness and size (Table 6-7) suggests a moderately positive association between size and smoothness, but it is not statistically significant.

Table 6-8. 2-way contingency analysis of fracture size. vs. alteration degree.

Crosstab

			ALTERATI						Total
				0	1	2	r	rr	
GROUP	0	Count	39	4337	288	7	1068	54	5793
		Expected Count	40.3	4331.7	287.7	6.9	1069.4	57.0	5793.0
		% within GROUP	.7%	74.9%	5.0%	.1%	18.4%	.9%	100.0%
		% within ALTERATI	95.1%	98.3%	98.3%	100.0%	98.1%	93.1%	98.2%
		% of Total	.7%	73.5%	4.9%	.1%	18.1%	.9%	98.2%
	1	Count	2	74	5	0	21	4	106
		Expected Count	.7	79.3	5.3	.1	19.6	1.0	106.0
		% within GROUP	1.9%	69.8%	4.7%	.0%	19.8%	3.8%	100.0%
		% within ALTERATI	4.9%	1.7%	1.7%	.0%	1.9%	6.9%	1.8%
		% of Total	.0%	1.3%	.1%	.0%	.4%	.1%	1.8%
Total		Count	41	4411	293	7	1089	58	5899
		Expected Count	41.0	4411.0	293.0	7.0	1089.0	58.0	5899.0
		% within GROUP	.7%	74.8%	5.0%	.1%	18.5%	1.0%	100.0%
		% within ALTERATI	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	.7%	74.8%	5.0%	.1%	18.5%	1.0%	100.0%

The analyses for alteration degree (Table 6-8) suggest that larger fractures have a higher degree of alteration than smaller fractures. Large fractures have lower than expected numbers in class “0”, about the expected values in “1” and “2”, and higher than expected values in classes “r” and “rr”.

The following lithology classes (Table 6-9) are positively associated with large fractures: 1058 (granite), 1098 (pegmatitic granite), 103076 (Felsic to intermediate volcanic rock, metamorphic). Others are negatively associated: 101054 (Tonalite to granodiorite, metamorphic), 101057 (Granite to granodiorite, metamorphic, medium-grain), 101058 (Granite, metamorphic, aplitic), and possibly 111058 (Granite, fine- to medium-grained). It may be that the coarser-grained igneous and felsic volcanic rocks are better suited mechanically to the development of large fractures than are the more mafic and finer-grained felsic rocks.

Table 6-10 shows the associations between fracture size and the structure in the rock. There is a positive association between large fractures and structure class 45 (columnar) and a negative association with class 20 and 53 (banded).

Table 6-11 shows that there is a relation between grain size and fracture size. Classes 9 (medium) and 4 (coarse) are positively associated, while classes 2 (fine) and 3 (medium) are negatively associated. This may be related to the associations of the lithology classes, in that the granite and pegmatites are more coarsely grained than the lithologies that had smaller grain sizes.

Colour (Table 6-12) also shows associations with fracture size. In this case, colour may be highly correlated with rock type, as large fractures are negatively associated with colours 11 (light red) and 18 (red-grey), and positively associated with 19 (grey-red).

All results are contained in file Fors_2_way.pdf, including the tests for statistical significance.

In summary, the 2-way tables show that many of the surrogate variables have some degree of positive or negative association with fracture size, even though the threshold to distinguish “large” from “small” fractures is 5 m. The differences should be more pronounced for a larger threshold, so this initial investigation at Forsmark suggests that the use of surrogate variables may prove useful.

Table 6-9. 2-way contingency analyses of fracture size vs. lithology.

Crosstab

			LITH												
			1058.00	1061.00	1098.00	2017.00	101054.00	101056.00	101057.00	101058.00	101061.00	102017.00	103076.00	111058.00	Total
GROUP	0	Count	1468	6	645	29	413	89	1162	1028	117	13	725	98	5793
		Expected Count	1497.6	5.9	649.1	28.5	410.5	88.4	1144.1	1011.5	114.9	12.8	732.6	97.2	5793.0
		% within GROUP	25.3%	.1%	11.1%	.5%	7.1%	1.5%	20.1%	17.7%	2.0%	.2%	12.5%	1.7%	100.0%
		% within LITH	96.3%	100.0%	97.6%	100.0%	98.8%	98.9%	99.7%	99.8%	100.0%	100.0%	97.2%	99.0%	98.2%
		% of Total	24.9%	.1%	10.9%	.5%	7.0%	1.5%	19.7%	17.4%	2.0%	.2%	12.3%	1.7%	98.2%
	1	Count	57	0	16	0	5	1	3	2	0	0	21	1	106
		Expected Count	27.4	.1	11.9	.5	7.5	1.6	20.9	18.5	2.1	.2	13.4	1.8	106.0
		% within GROUP	53.8%	.0%	15.1%	.0%	4.7%	.9%	2.8%	1.9%	.0%	.0%	19.8%	.9%	100.0%
		% within LITH	3.7%	.0%	2.4%	.0%	1.2%	1.1%	.3%	.2%	.0%	.0%	2.8%	1.0%	1.8%
		% of Total	1.0%	.0%	.3%	.0%	.1%	.0%	.1%	.0%	.0%	.0%	.4%	.0%	1.8%
Total		Count	1525	6	661	29	418	90	1165	1030	117	13	746	99	5899
		Expected Count	1525.0	6.0	661.0	29.0	418.0	90.0	1165.0	1030.0	117.0	13.0	746.0	99.0	5899.0
		% within GROUP	25.9%	.1%	11.2%	.5%	7.1%	1.5%	19.7%	17.5%	2.0%	.2%	12.6%	1.7%	100.0%
		% within LITH	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	25.9%	.1%	11.2%	.5%	7.1%	1.5%	19.7%	17.5%	2.0%	.2%	12.6%	1.7%	100.0%

Table 6-10. 2-way contingency analyses of fracture size vs. structure.

Crosstab

			STRUCTUR				Total
			20.0	45.0	53.0	98.0	
GROUP	0	Count	788	2345	1744	818	5695
		Expected Count	779.5	2361.1	1734.7	819.7	5695.0
		% within GROUP	13.8%	41.2%	30.6%	14.4%	100.0%
		% within STRUCTUR	99.2%	97.5%	98.7%	98.0%	98.2%
		% of Total	13.6%	40.4%	30.1%	14.1%	98.2%
	1	Count	6	60	23	17	106
		Expected Count	14.5	43.9	32.3	15.3	106.0
		% within GROUP	5.7%	56.6%	21.7%	16.0%	100.0%
		% within STRUCTUR	.8%	2.5%	1.3%	2.0%	1.8%
		% of Total	.1%	1.0%	.4%	.3%	1.8%
Total		Count	794	2405	1767	835	5801
		Expected Count	794.0	2405.0	1767.0	835.0	5801.0
		% within GROUP	13.7%	41.5%	30.5%	14.4%	100.0%
		% within STRUCTUR	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	13.7%	41.5%	30.5%	14.4%	100.0%

Table 6-11. 2-way contingency analyses for fracture size vs. grain size.

Crosstab

			GRAINSIZ				Total
			2	3	4	9	
GROUP	0	Count	1920	89	768	3016	5793
		Expected Count	1909.1	88.4	769.9	3025.6	5793.0
		% within GROUP	33.1%	1.5%	13.3%	52.1%	100.0%
		% within GRAINSIZ	98.8%	98.9%	98.0%	97.9%	98.2%
		% of Total	32.5%	1.5%	13.0%	51.1%	98.2%
	1	Count	24	1	16	65	106
		Expected Count	34.9	1.6	14.1	55.4	106.0
		% within GROUP	22.6%	.9%	15.1%	61.3%	100.0%
		% within GRAINSIZ	1.2%	1.1%	2.0%	2.1%	1.8%
		% of Total	.4%	.0%	.3%	1.1%	1.8%
Total		Count	1944	90	784	3081	5899
		Expected Count	1944.0	90.0	784.0	3081.0	5899.0
		% within GROUP	33.0%	1.5%	13.3%	52.2%	100.0%
		% within GRAINSIZ	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	33.0%	1.5%	13.3%	52.2%	100.0%

Table 6-12. 2-way contingency analyses of fracture size vs. rock colour.

Crosstab

			COLOR						Total
			4.0	6.0	11.0	13.0	18.0	19.0	
GROUP	0	Count	89	441	1796	13	1291	2163	5793
		Expected Count	88.4	438.0	1781.4	12.8	1271.7	2200.7	5793.0
		% within GROUP	1.5%	7.6%	31.0%	.2%	22.3%	37.3%	100.0%
		% within COLOR	98.9%	98.9%	99.0%	100.0%	99.7%	96.5%	98.2%
		% of Total	1.5%	7.5%	30.4%	.2%	21.9%	36.7%	98.2%
	1	Count	1	5	18	0	4	78	106
		Expected Count	1.6	8.0	32.6	.2	23.3	40.3	106.0
		% within GROUP	.9%	4.7%	17.0%	.0%	3.8%	73.6%	100.0%
		% within COLOR	1.1%	1.1%	1.0%	.0%	.3%	3.5%	1.8%
		% of Total	.0%	.1%	.3%	.0%	.1%	1.3%	1.8%
Total		Count	90	446	1814	13	1295	2241	5899
		Expected Count	90.0	446.0	1814.0	13.0	1295.0	2241.0	5899.0
		% within GROUP	1.5%	7.6%	30.8%	.2%	22.0%	38.0%	100.0%
		% within COLOR	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	1.5%	7.6%	30.8%	.2%	22.0%	38.0%	100.0%

n-way contingency

n-way contingency tables combine can be used to examine the simultaneous associations of n-1 independent variables with a dependent variable, in this case, fracture size. The results of the n-way contingency analyses for all the variables presented in the 2-way analyses in the preceding section are contained in electronic form in file Fors_n_way.pdf.

The results are an illustration of what could be done to obtain the probabilities needed for an actual analysis that would make it possible to predict the probability of a fracture with observed mappable characteristics being above or below a chosen threshold size.

For example, the 2-way tables suggested that particular values of grain size, colour, form, surface, alteration and lithology had positive associations with size. What would the probability be if all of these positive associations occurred simultaneously? The n-way table can be used to calculate this probability. For example, a fracture might have the following mapped variable values:

- grain size = 9
- form = t
- lithology = 1058

These independent variables could all be measured from core or in outcrop at an early stage of site characterization.

Evaluation of the data shows that in the Forsmark data set, less than 2 % of all fractures are large. A random guessing model, in which a fracture is randomly assigned to the large or small category according to its proportion in the data, would not correctly assign any fractures to the large class. All large fractures would be missed, although some small fractures would be incorrectly assigned to the large category. The contingency table above would correctly assign over 22 % of the large fractures to their correct class.

6.2.2 Probabilistic Neural Nets

The Forsmark data set only contained 106 fractures with mapped traces greater than 5.0 m out of several thousand mapped traces. The net was calibrated by combining these 106 traces with the data from the 106 smallest traces, and then randomly separating the 212 traces into two data sets each having an equal number of large and small traces. The reason for using the smallest traces was to accentuate the possible differences between small and large traces. The resulting trained net was then applied to the remaining trace data, all of which was in the small class.

In a PNN, the importance of a variable for classification is related to the value of its *smoothing factor*, which can vary from 0.0 to 3.0. A high value indicates importance, while a low value indicates unimportance. Since there is a certain amount of stochasticity in PNN training, variables that are highly correlated can actually substitute for one another. For example, if variables C and D are highly correlated and both highly correlate with the dependent variable, it is likely that one independent variable will have a high smoothing factor while the other has a low factor. Whether this factor is C or D depends upon the random number seed used to start the calibration process.

Table 6-13. Smoothing factors for PNN calibration for Forsmark fracture data.

Input name	Individual smoothing factor
L101058	2.93
L101054	2.61
L1061	2.51
Surface_s	2.40
L111058	2.29
L2017	2.18
L101061	1.91
Surface_r	1.74
Gsize_9	1.55
L101056	1.32
L102017	0.85
L1058	0.76
Gsize_3	0.53
L1098	0.13
Ap_c	0.04
Form_p	0.02
Gsize_4	0.01
Form_u	0.01
Form_t	0.00
Gsize_2	0.00
Ap_o	0.00
L101057	0.00
L103076	0.00

Table 6-13 shows the smoothing factors for the calibration. The factors are always positive, regardless of whether they have a negative or positive influence on the classification. Lithologies 101058 and 1010054 have the strongest influence on classification. From the 2-way contingency tables, it can be assumed that the association is negative. Surface roughness is also important, as is the grain size class 9 (medium). These results conform to what was found in the 2-way contingency analyses in terms of which variables were important.

Results for the training and testing sets show excellent agreement with the classification of large and small (Table 6-14). The training set has a classification success rate of greater than 94 % accuracy; the test set has a success rate of greater than 98 %. When the threshold of 0.7 is applied to the remainder, or production set, all of which are small fractures, the calibrated net correctly classifies as small 5,607 out of 5,686, or 98.6 % of the fractures. This result suggests that surrogate variables may prove useful.

It should be noted that not all measured variables were used in this net. Only variables such as rock type, grain size, surface morphology and aperture, which can be measured in borehole data, were used. This was done to test whether the neural net approach could be useful during preliminary stages of investigation, where only borehole data may be available. Variables like termination style, although measurable in outcrop, are not possible to measure in borehole data. The fact that the net does an excellent job of classifying large and small fractures even with this reduced set of variables suggests that the approach could be valuable even in early stages of site characterization prior to excavation.

The neural net applied to the Simpevarp data set uses all of the variables, as an alternative to the reduced set for Forsmark, allowing for comparison.

Table 6-14. PNN results for classification of training and testing sets for Forsmark fracture data.

Network type	**PNN, genetic adaptive**	
Input file name	C:\...\SKBRES~1\FORSMARK\FORS_PNN.TRN	
Patterns processed	106	
Patterns classified correctly	101	
Patterns classified incorrectly	5	
Smoothing factor	0.9961177	
Categories	C1	C2
Actual winners	53	53
Classified winners	54	52
Actual losers	53	53
Classified losers	52	54
True positives	51	50
False positives	3	2
True negatives	50	51
False negatives	2	3
True postiive proportion	0.9623	0.9434
False positive proportion	0.0566	0.0377
Network type	**PNN, genetic adaptive**	
Input file name	C:\...\SKBRES~1\FORSMARK\FORS_PNN.TST	
Patterns processed	106	
Patterns classified correctly	101	
Patterns classified incorrectly	5	
Smoothing factor	0.9961177	
Categories	C1	C2
Actual winners	53	53
Classified winners	54	52
Actual losers	53	53
Classified losers	52	54
True positives	53	52
False positives	1	0
True negatives	52	53
False negatives	0	1
True postiive proportion	1	0.9811
False positive proportion	0.0189	0

6.3 Analyses of data for Simpevarp

The Oskarshamn (Simpevarp) data derives from outcrop studies at four locations, ASM000025, ASM000026, ASM000205 and ASM00206. The variables measured for which there was sufficient amount of data were lithology, structure, grain size, colour, trace length, fracture strike, fracture dip, termination on the "A" end, termination on the "B" end, rock relation, aperture, form and surface roughness. There were 3,908 traces with sufficient data for the independent and dependent variables. The trace length threshold was set at 5.0 m. This value was selected as it was about the largest threshold that could be used for the outcrop data in which the largest trace was only 11.4 m in length. The 5.0 m value represented approximately the 99.4 percentile of the data. Fractures with mapped trace lengths > 5.0 m are termed the "large" fractures, and the remainder as "small".

6.3.1 Contingency Table Analyses

Table 6-15 shows the association between lithology and fracture size. Lithology 501044 (Granite to quartz monzodiorite, generally porphyritic) dominates the large size fractures. This association between a more coarsely grained granitic igneous rock and large fractures is similar to what was found in the Forsmark data.

Table 6-15. 2-way contingency analyses of fracture size vs. lithology.

Crosstab

			LITHOLOG					
			501030	501036	501044	501061	511058	Total
SIZE	0	Count	1274	800	1661	23	124	3882
		Expected Count	1266.2	796.1	1673.7	22.9	123.2	3882.0
		% within SIZE	32.8%	20.6%	42.8%	.6%	3.2%	100.0%
		% within LITHOLOG	100.0%	99.9%	98.6%	100.0%	100.0%	99.4%
		% of Total	32.6%	20.5%	42.5%	.6%	3.2%	99.4%
	1	Count	0	1	23	0	0	24
		Expected Count	7.8	4.9	10.3	.1	.8	24.0
		% within SIZE	.0%	4.2%	95.8%	.0%	.0%	100.0%
		% within LITHOLOG	.0%	.1%	1.4%	.0%	.0%	.6%
		% of Total	.0%	.0%	.6%	.0%	.0%	.6%
Total		Count	1274	801	1684	23	124	3906
		Expected Count	1274.0	801.0	1684.0	23.0	124.0	3906.0
		% within SIZE	32.6%	20.5%	43.1%	.6%	3.2%	100.0%
		% within LITHOLOG	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	32.6%	20.5%	43.1%	.6%	3.2%	100.0%

Grain size associations are shown in Table 6-16. As was the case for the Forsmark data, large fractures are preferentially associated with grain size class 9 (medium grained), perhaps reflecting the close tie between lithology and grain size.

Rock colour (Table 6-17) also shows analogous associations to the Forsmark data. This table shows that large fractures preferentially belong to colour classes 18 (red-grey) and 19 (grey-red), again probably reflecting the association between granitic rocks and their reddish grey coloration.

Table 6-16. 2-way contingency analyses of fracture size vs. grain size.

Crosstab

			GRAINSIZ				Total
			2	3	4	9	
SIZE	0	Count	1279	120	23	2460	3882
		Expected Count	1271.1	119.3	22.9	2468.7	3882.0
		% within SIZE	32.9%	3.1%	.6%	63.4%	100.0%
		% within GRAINSIZ	100.0%	100.0%	100.0%	99.0%	99.4%
		% of Total	32.7%	3.1%	.6%	63.0%	99.4%
	1	Count	0	0	0	24	24
		Expected Count	7.9	.7	.1	15.3	24.0
		% within SIZE	.0%	.0%	.0%	100.0%	100.0%
		% within GRAINSIZ	.0%	.0%	.0%	1.0%	.6%
		% of Total	.0%	.0%	.0%	.6%	.6%
Total		Count	1279	120	23	2484	3906
		Expected Count	1279.0	120.0	23.0	2484.0	3906.0
		% within SIZE	32.7%	3.1%	.6%	63.6%	100.0%
		% within GRAINSIZ	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	32.7%	3.1%	.6%	63.6%	100.0%

Table 6-17. 2-way contingency analyses of fracture size vs. colour.

Crosstab

			COLOR							Total
			3	4	6	10	11	18	19	
SIZE	0	Count	2	799	1274	125	21	860	801	3882
		Expected Count	2.0	795.1	1266.2	124.2	20.9	867.6	806.0	3882.0
		% within SIZE	.1%	20.6%	32.8%	3.2%	.5%	22.2%	20.6%	100.0%
		% within COLOR	100.0%	99.9%	100.0%	100.0%	100.0%	98.5%	98.8%	99.4%
		% of Total	.1%	20.5%	32.6%	3.2%	.5%	22.0%	20.5%	99.4%
	1	Count	0	1	0	0	0	13	10	24
		Expected Count	.0	4.9	7.8	.8	.1	5.4	5.0	24.0
		% within SIZE	.0%	4.2%	.0%	.0%	.0%	54.2%	41.7%	100.0%
		% within COLOR	.0%	.1%	.0%	.0%	.0%	1.5%	1.2%	.6%
		% of Total	.0%	.0%	.0%	.0%	.0%	.3%	.3%	.6%
Total		Count	2	800	1274	125	21	873	811	3906
		Expected Count	2.0	800.0	1274.0	125.0	21.0	873.0	811.0	3906.0
		% within SIZE	.1%	20.5%	32.6%	3.2%	.5%	22.4%	20.8%	100.0%
		% within COLOR	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	.1%	20.5%	32.6%	3.2%	.5%	22.4%	20.8%	100.0%

Table 6-18. 2-way contingency analyses of fracture size vs. termination style.

Crosstab

			TERMA						
			X	o	p	t	x	y	Total
SIZE	0	Count	2	127	957	2496	131	169	3882
		Expected Count	2.0	127.2	952.1	2499.5	132.2	169.0	3882.0
		% within SIZE	.1%	3.3%	24.7%	64.3%	3.4%	4.4%	100.0%
		% within TERMA	100.0%	99.2%	99.9%	99.2%	98.5%	99.4%	99.4%
		% of Total	.1%	3.3%	24.5%	63.9%	3.4%	4.3%	99.4%
	1	Count	0	1	1	19	2	1	24
		Expected Count	.0	.8	5.9	15.5	.8	1.0	24.0
		% within SIZE	.0%	4.2%	4.2%	79.2%	8.3%	4.2%	100.0%
		% within TERMA	.0%	.8%	.1%	.8%	1.5%	.6%	.6%
		% of Total	.0%	.0%	.0%	.5%	.1%	.0%	.6%
Total		Count	2	128	958	2515	133	170	3906
		Expected Count	2.0	128.0	958.0	2515.0	133.0	170.0	3906.0
		% within SIZE	.1%	3.3%	24.5%	64.4%	3.4%	4.4%	100.0%
		% within TERMA	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	.1%	3.3%	24.5%	64.4%	3.4%	4.4%	100.0%

Crosstab

			TERMB						
			X	o	p	t	x	y	Total
SIZE	0	Count	3	105	923	2522	133	196	3882
		Expected Count	3.0	105.3	920.3	2526.4	132.2	194.8	3882.0
		% within SIZE	.1%	2.7%	23.8%	65.0%	3.4%	5.0%	100.0%
		% within TERMB	100.0%	99.1%	99.7%	99.2%	100.0%	100.0%	99.4%
		% of Total	.1%	2.7%	23.6%	64.6%	3.4%	5.0%	99.4%
	1	Count	0	1	3	20	0	0	24
		Expected Count	.0	.7	5.7	15.6	.8	1.2	24.0
		% within SIZE	.0%	4.2%	12.5%	83.3%	.0%	.0%	100.0%
		% within TERMB	.0%	.9%	.3%	.8%	.0%	.0%	.6%
		% of Total	.0%	.0%	.1%	.5%	.0%	.0%	.6%
Total		Count	3	106	926	2542	133	196	3906
		Expected Count	3.0	106.0	926.0	2542.0	133.0	196.0	3906.0
		% within SIZE	.1%	2.7%	23.7%	65.1%	3.4%	5.0%	100.0%
		% within TERMB	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	.1%	2.7%	23.7%	65.1%	3.4%	5.0%	100.0%

Fracture termination styles (Table 6-18) show a somewhat different set of associations than the Forsmark data. This table shows that large fractures tend to have a slightly positive association with the “o” (termination outside of mapped area) class and a negative association with the “p” class of termination (blind), as did the Forsmark data. However, large fractures also show a positive association with “t” terminations, which was not seen in the Forsmark data.

As was also the case for the Forsmark data, large fractures seem preferentially associated (Table 6-19) with rock relation class “c” (crossing several boundaries), and negatively associated with class “a” (crossing only one boundary).

Table 6-19. 2-way contingency analyses of fracture size vs. rock relation.

Crosstab

			ROCKRELA				Total
			a	b	c	d	
SIZE	0	Count	3530	87	197	68	3882
		Expected Count	3527.2	86.5	200.8	67.6	3882.0
		% within SIZE	90.9%	2.2%	5.1%	1.8%	100.0%
		% within ROCKRELA	99.5%	100.0%	97.5%	100.0%	99.4%
		% of Total	90.4%	2.2%	5.0%	1.7%	99.4%
	1	Count	19	0	5	0	24
		Expected Count	21.8	.5	1.2	.4	24.0
		% within SIZE	79.2%	.0%	20.8%	.0%	100.0%
		% within ROCKRELA	.5%	.0%	2.5%	.0%	.6%
		% of Total	.5%	.0%	.1%	.0%	.6%
Total		Count	3549	87	202	68	3906
		Expected Count	3549.0	87.0	202.0	68.0	3906.0
		% within SIZE	90.9%	2.2%	5.2%	1.7%	100.0%
		% within ROCKRELA	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	90.9%	2.2%	5.2%	1.7%	100.0%

Table 6-20 shows that large fractures are positively associated with open fractures, rather than sealed, as was the case for the Forsmark data, although the associations were much weaker than in the Simpevarp data.

One of the differences between the results for the Forsmark and Simpevarp data sets is shown in the associations with fracture surface morphology (Table 6-21). In the Forsmark data, class “t” (stepped) was positively associated with large fractures. This is not the case for the Simpevarp data, where there is a negative association. Like the Forsmark data, there is a negative association between “p” (planar) and large fractures. In the Simpevarp data, however, the strongest positive association is between class “u:” (undulating) and large fractures. Although stepped fractures were more positively associated in the Forsmark data, and both were negatively associated with planar fractures, the consistent association seems to be that non-planar fractures, whether they be stepped or undulating, are more likely to be large than planar ones.

There are no significant associations between fracture size and surface roughness (Table 6-22).

Table 6-20. 2-way contingency analyses of fracture size vs. aperture.

Crosstab

			APERTURE		Total
			c	o	
SIZE	0	Count	3283	599	3882
		Expected Count	3274.8	607.2	3882.0
		% within SIZE	84.6%	15.4%	100.0%
		% within APERTURE	99.6%	98.0%	99.4%
		% of Total	84.1%	15.3%	99.4%
	1	Count	12	12	24
		Expected Count	20.2	3.8	24.0
		% within SIZE	50.0%	50.0%	100.0%
		% within APERTURE	.4%	2.0%	.6%
		% of Total	.3%	.3%	.6%
Total		Count	3295	611	3906
		Expected Count	3295.0	611.0	3906.0
		% within SIZE	84.4%	15.6%	100.0%
		% within APERTURE	100.0%	100.0%	100.0%
		% of Total	84.4%	15.6%	100.0%

Table 6-21. 2-way contingency analyses of fracture size vs. form.

			FORM			Total
			p	t	u	
BIG	0	Count	2045	598	1240	3883
		Expected Count	2042.9	595.5	1244.6	3883.0
		% within BIG	52.7%	15.4%	31.9%	100.0%
		% within FORM	99.5%	99.8%	99.0%	99.4%
		% of Total	52.4%	15.3%	31.7%	99.4%
	1	Count	10	1	12	23
		Expected Count	12.1	3.5	7.4	23.0
		% within BIG	43.5%	4.3%	52.2%	100.0%
		% within FORM	.5%	.2%	1.0%	.6%
		% of Total	.3%	.0%	.3%	.6%
Total		Count	2055	599	1252	3906
		Expected Count	2055.0	599.0	1252.0	3906.0
		% within BIG	52.6%	15.3%	32.1%	100.0%
		% within FORM	100.0%	100.0%	100.0%	100.0%
		% of Total	52.6%	15.3%	32.1%	100.0%

Table 6-22. 2-way contingency analyses of fracture size vs. surface type.

			SURFACE			
				r	s	Total
BIG	0	Count	21	3821	41	3883
		Expected Count	20.9	3821.4	40.8	3883.0
		% within BIG	.5%	98.4%	1.1%	100.0%
		% within SURFACE	100.0%	99.4%	100.0%	99.4%
		% of Total	.5%	97.8%	1.0%	99.4%
	1	Count	0	23	0	23
		Expected Count	.1	22.6	.2	23.0
		% within BIG	.0%	100.0%	.0%	100.0%
		% within SURFACE	.0%	.6%	.0%	.6%
		% of Total	.0%	.6%	.0%	.6%
Total		Count	21	3844	41	3906
		Expected Count	21.0	3844.0	41.0	3906.0
		% within BIG	.5%	98.4%	1.0%	100.0%
		% within SURFACE	100.0%	100.0%	100.0%	100.0%
		% of Total	.5%	98.4%	1.0%	100.0%

Overall, the results for the Simpevarp data are remarkably consistent with the results for the Forsmark data, showing similar associations with grain size, rock type, colour, surface morphology, termination style, aperture and crossing of lithologic boundaries. This suggests that the factors that lead to the formation of larger fractures is similar at both sites, and that the surrogate variables measured capture some of these factors in a consistent way.

All results are contained in file Oskar_2_way.pdf, including the tests for statistical significance.

Results for the n-way contingency analyses are contained in Oskar_n_way.pdf. As an example, consider a fracture having the following characteristics:

- grain size = 9 (medium grained)
- form = u (undulating)
- lithology = 501044 ((Granite to quartz monzodiorite, generally porphyritic)
- surface = r (rough)

About 17 % of all fractures in the database have these four characteristics. They also make up about 17 % of all the small fractures, but over 46 % of all large fractures. This suggests that fractures with these characteristics are about 2 to 3 times more likely to be longer than 5 m than not. This result is not as successful as for the Forsmark data, possibly due to the much smaller number of measurements and the more uniform lithology in the Simpevarp data.

6.3.2 Probabilistic Neural nets

The Simpevarp data set only contains 24 fractures with mapped traces greater than or equal to 5.0 m out of several thousand mapped traces. The net was calibrated by combining these 24 traces with the data from the 24 smallest traces, and then randomly separating the 48 traces into two data sets each having an equal number of large and small traces. The reason for using the smallest traces was to accentuate the possible differences between small and large traces. The resulting trained net was then applied to the remaining trace data, all of which was in the small class. The smoothing factors are shown in Table 6-23.

Table 6-23. Smoothing factors for PNN analysis of Simpevarp fracture data.

Input name	Individual smoothing factor
TA_p	3.00
RR_c	2.98
TA_o	2.84
RR_b	2.71
Form_u	2.64
Ap_o	2.53
GS_9	2.44
L_501036	2.41
S_p	2.38
L_501044	2.31
Col_3	2.26
L_511058	2.22
S_s	2.21
GS_3	1.87
TA_x	1.40
TB_p	1.29
TB_y	1.28
Form_p	1.12
Col_4	1.02
Col_11	0.92
Ap_c	0.62
GS_4	0.59
Form_t	0.52
Col_19	0.49
TB_x	0.47
Col_10	0.47
TA_y	0.42
RR_a	0.40
GS_2	0.38
Form_o	0.35
TB_o	0.35
L_501030	0.29
S_r	0.25
L_501061	0.16
TA_t	0.11
Col_18	0.11
TB_t	0.11

This table shows what variables the PNN found useful for classifying the fracture data.

The next table (Table 6-24) shows how well the PNN performed in classifying the training, testing and validation data sets. The classification success is quite good using the threshold of 0.5. When this threshold is optimized, using a value of 0.90 (or 0.10, depending on whether the threshold is used for identifying large or small fractures, respectively) for classifying a fracture as large, the success rises from 72.3 % to 85.0 %.

Table 6-24. Classification success statistics for PNN for Simpevarp fracture data.

Network type:	**PNN, genetic adaptive**	
Input file name:	C:\PROJECTS\SKBRES~1\SIMPEV~1\SIMP_PNN.TRN	
Patterns processed:	24	
Patterns classified correctly:	23	
Patterns classified	1	
Smoothing factor:	0.813647	
Categories:	C1	C2
Actual winners:	12	12
Classified winners:	11	13
Actual losers:	12	12
Classified losers:	13	11
True positives:	11	12
False positives:	0	1
True negatives:	12	11
False negatives:	1	0
True positive proportion:	0.9167	1
False positive proportion:	0	0.0833
Network type:	**PNN, genetic adaptive**	
Input file name:	C:\PROJECTS\SKBRES~1\SIMPEV~1\SIMP_PNN.TST	
Patterns processed:	24	
Patterns classified correctly:	24	
Patterns classified	0	
Smoothing factor:	0.813647	
Categories:	C1	C2
Actual winners:	12	12
Classified winners:	12	12
Actual losers:	12	12
Classified losers:	12	12
True positives:	12	12
False positives:	0	0
True negatives:	12	12
False negatives:	0	0
True positive proportion:	1	1
False positive proportion:	0	0
Network type:	**PNN, genetic adaptive**	
Input file name:	C:\PROJECTS\SKBRES~1\SIMPEV~1\SIMP_PNN.PRO	
Patterns processed:	3860	
Patterns classified correctly:	2791	
Patterns classified	1069	
Smoothing factor:	0.813647	
Categories:	C1	C2
Actual winners:	3860	0
Classified winners:	2791	1069
Actual losers:	0	3860
Classified losers:	1069	2791
True positives:	2791	0
False positives:	0	1069
True negatives:	0	2791
False negatives:	1069	0
True positive proportion:	0.7231	
False positive proportion:		0.2769

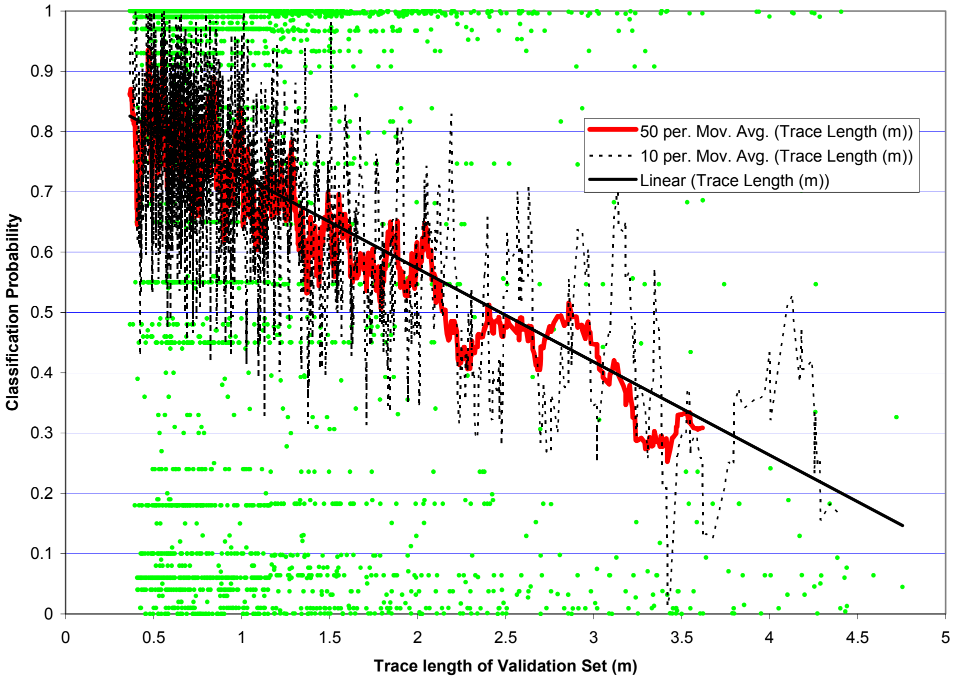


***Figure 6-1.** Classification probability as a function of trace length for Simpevarp validation test set.*

Another way to assess the performance of the net is shown in Figure 6-1, where trace length is plotted against the PNN's classification probability. They raw predictions are exceedingly noisy, but when a 50-point moving average is applied to the data, the trend line, shown in the graph, shows that the PNN is very good at classifying small fractures but becomes less effective as fracture trace lengths approach 5.0 m. Note that all of the smoothed trend line is above the threshold of 0.10 used for distinguishing small fractures, even though about 15 % of the unsmoothed data fell below that threshold. The least-squares fit to the data (black straight line) takes on the probability value of approximately 0.10 when trace length approaches 5.0 m, which indicates that a threshold value of 0.10 is optimal for discriminating small from large fractures in this data set.

Overall, the predictive capability of the PNN is quite good, even for this very low threshold of 5.0 m.

6.4 Analyses of data for Olkiluoto

The Olkiluoto data derives from trench studies at two locations: OL-TK1 and OL-TK2. The variables measured for which there was sufficient amount of data were dip direction, dip, rock type, trace length, ending, form, quality and aperture. There were 778 traces with sufficient data for the independent and dependent variables. The trace length threshold was set at 5.0 m. This value was selected as it was about the largest threshold that could be used for the outcrop data in which the largest trace was only 10 m in length. The 5.0 m value represented approximately the 96.1 percentile of the data. Fractures with mapped trace lengths > 5.0 m are termed the "large" fractures, and the remainder as "small".

6.4.1 Contingency Table Analyses

The format and sampling protocols differ for the data from Olkiluoto. At Olkiluoto, fracture traces have been exposed through shallow trenching, leading to long (200 – 300 m), relatively narrow (2 – 5m) strips rather than the more square outcrops in the previous two Swedish sites. The narrowness of the strip means that the trace length that can be measured is very much more effected by censoring than in the previous analyses. It also introduces a possible bias in the data in that only fractures that tend to be subparallel in strike with the trench strike will have sufficient trace length exposed to be classified as “large”, or greater than 5 m. Based on the preliminary studies here, orientation does not seem to be as strongly associated with large fractures as do other variables, so it may be that this bias is not too important in the current investigations. However, it does suggest that future data collected to study the effectiveness of surrogate variables would be better gathered in ways that do not severely censor the trace lengths.

In addition, the classification of surrogate fracture properties in the Finnish data differs in some ways from the Swedish data. For example, the Swedish data classifies a fracture as either “Open” or “Sealed”; in the Finnish data, fractures can be classified as “Open”, “Tight” or “Filled”. The Swedish classification allows for a “Stepped” fracture surface, but the Finnish data does not contain this class. There is also a much greater abundance of metamorphic rock types in the Finnish data.

As a result, the inclusion of the Finnish data provides an interesting cross-validation of the conclusions drawn for the Swedish data. The fact that the classifications differ somewhat makes it possible to qualitatively evaluate whether the associations are sensitive to the exact classifications used, or whether the same general tendencies are present, even though the classification differs. In the Swedish data, medium- to coarse-grained granitic rock was positively associated with longer fractures, as were open fractures.

The first 2-way contingency table is for rock type (Table 6-25):

Table 6-25. 2-way contingency table analyses of fracture size vs. lithology.

Crosstab

			ROCKTYPE							
			GB	GR	KGN	MGN	PG	SGN	TON	Total
SIZECL	l	Count	0	3	0	10	2	6	10	31
		Expected Count	.0	5.1	.8	11.3	.5	8.6	4.7	31.0
		% within SIZECL	.0%	9.7%	.0%	32.3%	6.5%	19.4%	32.3%	100.0%
		% within ROCKTYPE	.0%	2.3%	.0%	3.5%	15.4%	2.8%	8.5%	4.0%
		% of Total	.0%	.4%	.0%	1.3%	.3%	.8%	1.3%	4.0%
	s	Count	1	126	19	273	11	210	107	747
		Expected Count	1.0	123.9	18.2	271.7	12.5	207.4	112.3	747.0
		% within SIZECL	.1%	16.9%	2.5%	36.5%	1.5%	28.1%	14.3%	100.0%
		% within ROCKTYPE	100.0%	97.7%	100.0%	96.5%	84.6%	97.2%	91.5%	96.0%
		% of Total	.1%	16.2%	2.4%	35.1%	1.4%	27.0%	13.8%	96.0%
Total		Count	1	129	19	283	13	216	117	778
		Expected Count	1.0	129.0	19.0	283.0	13.0	216.0	117.0	778.0
		% within SIZECL	.1%	16.6%	2.4%	36.4%	1.7%	27.8%	15.0%	100.0%
		% within ROCKTYPE	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	.1%	16.6%	2.4%	36.4%	1.7%	27.8%	15.0%	100.0%

This table shows that large fractures have a positive association with rock types PG (pegmatite) and TON (tonalite or quartz diorite), and a negative association with SGN (vein gneiss). Although there is a slight negative association with GR (granite) as well, this association is statistically insignificant due to the very small number of data points.

The mica migmatites (KGN and MGN) show no association with fracture size. With the exception of the results for the granite class, which are probably not statistically significant, it seems the tendency is for large fractures to be preferentially associated with intermediate to acidic, unmetamorphosed igneous rocks, while smaller fracture are associated with metamorphosed rocks.

Table 6-26 shows the results for fracture size and fracture termination. There is a positive association of large fractures with “P” (both ends covered) terminations, and a negative association with “N” (both ends visible). This is not surprising, given the strong censoring effects on trace length for the trench data.

Table 6-26. 2-way contingency analyses of fracture size vs. fracture termination style

Crosstab

			ENDING				Total
				N	O	P	
SIZECL	l	Count	1	5	13	12	31
		Expected Count	.1	11.8	12.4	6.7	31.0
		% within SIZECL	3.2%	16.1%	41.9%	38.7%	100.0%
		% within ENDING	50.0%	1.7%	4.2%	7.1%	4.0%
		% of Total	.1%	.6%	1.7%	1.5%	4.0%
	s	Count	1	291	299	156	747
		Expected Count	1.9	284.2	299.6	161.3	747.0
		% within SIZECL	.1%	39.0%	40.0%	20.9%	100.0%
		% within ENDING	50.0%	98.3%	95.8%	92.9%	96.0%
		% of Total	.1%	37.4%	38.4%	20.1%	96.0%
Total		Count	2	296	312	168	778
		Expected Count	2.0	296.0	312.0	168.0	778.0
		% within SIZECL	.3%	38.0%	40.1%	21.6%	100.0%
		% within ENDING	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	.3%	38.0%	40.1%	21.6%	100.0%

The effects of trench orientation bias on trace length are evident in Figure 6-2. The figure shows a cross-plot of dip direction and trace length (dots) for trench TK-2, as well as a sine wave fitted through non-linear least squares to the data. The fitted sine wave has a maximum amplitude for fracture strikes at 105° (and 285°), which implies that the long dimension of the trench is also trending in this direction. In fact, trench TK-2 has two distinct trends: about east-west and another segment that trends about 110°, which is highly consistent with this result.

Table 6-27 shows the associations between fracture length and fracture surface morphology. Morphologies “S” (planar) and “K” (curved) have negative associations, while “M” (winding, equivalent to undulating in Swedish data?) has a positive association with large fractures. These results are similar to the Swedish data, where both sites had a negative association with planarity and a positive association with undulating fractures. Curved fractures do not appear as a distinct class in the Swedish data, so direct comparison is not possible.

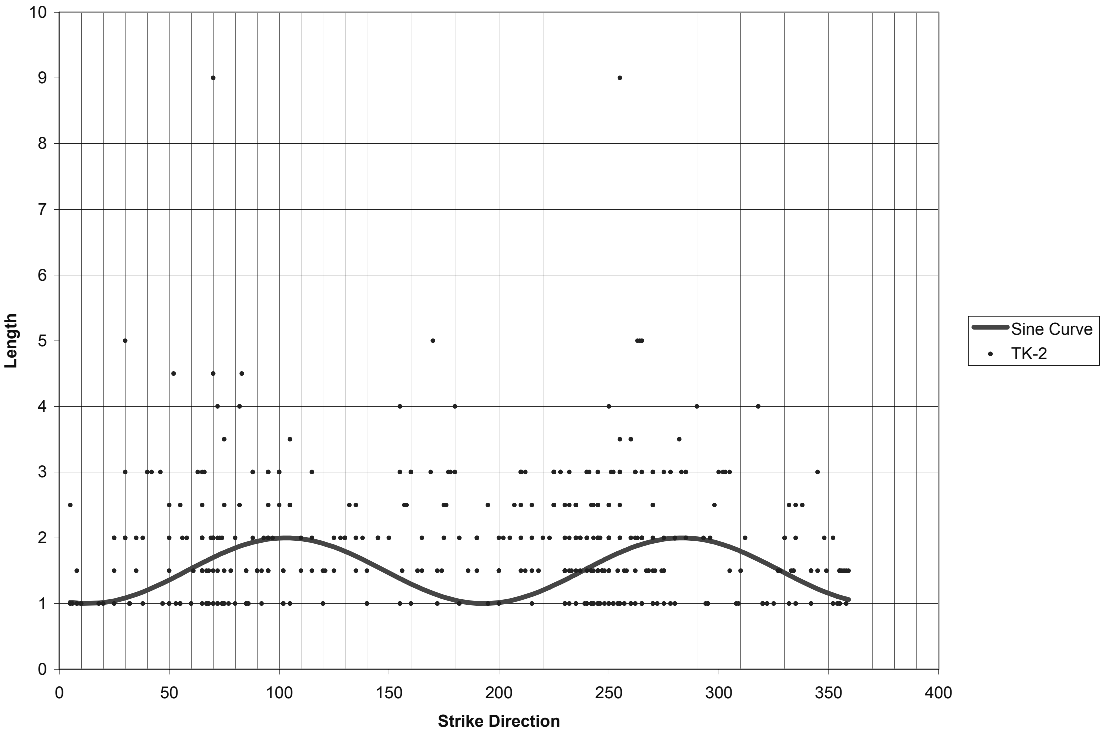


Figure 6-2. Impact of trench orientation on observed fracture trace length.

Table 6-27. 2-way contingency analyses of fracture size vs. surface morphology.

Crosstab

			FORM				
				K	M	S	Total
SIZECL	l	Count	2	2	19	8	31
		Expected Count	.4	4.3	15.2	11.1	31.0
		% within SIZECL	6.5%	6.5%	61.3%	25.8%	100.0%
		% within FORM	18.2%	1.9%	5.0%	2.9%	4.0%
		% of Total	.3%	.3%	2.4%	1.0%	4.0%
	s	Count	9	105	363	270	747
		Expected Count	10.6	102.7	366.8	266.9	747.0
		% within SIZECL	1.2%	14.1%	48.6%	36.1%	100.0%
		% within FORM	81.8%	98.1%	95.0%	97.1%	96.0%
		% of Total	1.2%	13.5%	46.7%	34.7%	96.0%
Total		Count	11	107	382	278	778
		Expected Count	11.0	107.0	382.0	278.0	778.0
		% within SIZECL	1.4%	13.8%	49.1%	35.7%	100.0%
		% within FORM	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	1.4%	13.8%	49.1%	35.7%	100.0%

Table 6-28. 2-way contingency analyses for facture size vs. aperture/filling

Crosstab

			QUALITY					
				AV	TA	TI	TŽ	Total
SIZECL	l	Count	3	16	0	12	0	31
		Expected Count	.7	15.9	.2	13.9	.3	31.0
		% within SIZECL	9.7%	51.6%	.0%	38.7%	.0%	100.0%
		% within QUALITY	16.7%	4.0%	.0%	3.4%	.0%	4.0%
		% of Total	.4%	2.1%	.0%	1.5%	.0%	4.0%
	s	Count	15	383	5	336	8	747
		Expected Count	17.3	383.1	4.8	334.1	7.7	747.0
		% within SIZECL	2.0%	51.3%	.7%	45.0%	1.1%	100.0%
		% within QUALITY	83.3%	96.0%	100.0%	96.6%	100.0%	96.0%
		% of Total	1.9%	49.2%	.6%	43.2%	1.0%	96.0%
Total		Count	18	399	5	348	8	778
		Expected Count	18.0	399.0	5.0	348.0	8.0	778.0
		% within SIZECL	2.3%	51.3%	.6%	44.7%	1.0%	100.0%
		% within QUALITY	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
		% of Total	2.3%	51.3%	.6%	44.7%	1.0%	100.0%

Table 6-28 shows the associations between fracture aperture/filling and fracture trace length. This table shows only very weak associations. There are slight negative associations with class TI (tight), TA (filled) and TŽ.

There is another interesting association that was not explicitly tested in the 2-way or n-way contingency tables: the possible association of dip with length. (Figure 6-3 is a cross-plot of dip vs. length. This figure makes it very clear that a necessary condition (though not sufficient) for a fracture being classified as large is that its dip is greater than 47 degrees. When a new variable related to dip was created in the Olkiluoto data set, with classes “V” (fractures with dip greater than 47 degrees) and “H” (fractures with dips less than or equal to 47 degrees), the following 2-way table resulted (Table 6-29)

This table indicates that 93.5 % of all large fractures have dips greater than 47°. While this is not a sufficient condition, as many small fractures also have dips greater than 47°, it is almost a necessary condition.

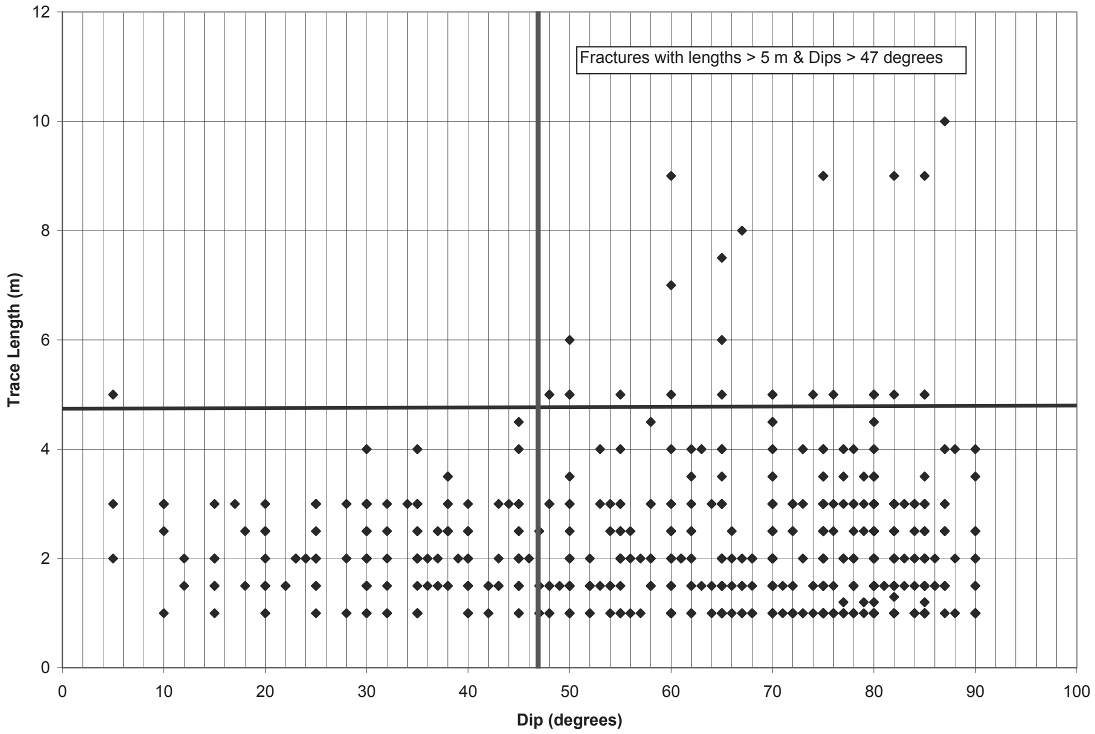


Figure 6-3. *Plot of Fracture Dip vs. Fracture Trace Length. Red line indicates division between fractures dipping less than 47 degrees and those dipping greater than 47 degrees. Blue line indicates division between fractures with trace lengths less than 5 m and those with lengths greater than 5 m.*

All results are contained in file Olk_2_way.pdf, including the tests for statistical significance.

Results for the n-way contingency analyses are contained in Olk_n_way.pdf. As an example, consider a fracture having the following characteristics that would seem to differentiate larger fractures from smaller based on the 2-way tables:

- Rock type: TON or PG (tonalite or pegmatite)
- Termination Style: P (both ends covered)
- Morphology: M (winding fracture)

Table 6-29. 2-way contingency analyses of fracture length vs. dip class.

Crosstab

			DIPCLASS		
			H	V	Total
SIZECL	l	Count	2	29	31
		Expected Count	6.6	24.4	31.0
		% within SIZECL	6.5%	93.5%	100.0%
		% within DIPCLASS	1.2%	4.7%	4.0%
		% of Total	.3%	3.7%	4.0%
	s	Count	164	583	747
		Expected Count	159.4	587.6	747.0
		% within SIZECL	22.0%	78.0%	100.0%
		% within DIPCLASS	98.8%	95.3%	96.0%
		% of Total	21.1%	74.9%	96.0%
Total		Count	166	612	778
		Expected Count	166.0	612.0	778.0
		% within SIZECL	21.3%	78.7%	100.0%
		% within DIPCLASS	100.0%	100.0%	100.0%
		% of Total	21.3%	78.7%	100.0%

Large fractures account for about 3.7 % of all trench fracture data from TK-1 and TK-2. If the characteristics had no association with fracture size, then the percentage of large fractures having these three characteristics should be in the same ratio of 0.037:0.963. In other words, the small fractures to large fracture ratio should be about 26.

In reality the percentage of large fractures to all fractures sharing the three characteristics listed above is about 37.5 %, slightly more than ten times the amount expected in these characteristics were not associated with size.

6.4.2 Probabilistic Neural Nets

The smoothing factors (Table 6-30) show a close correspondence to the results from the contingency table analyses in terms of which variables have strong associations with fracture length. The variables with the highest smoothing factors are “P” terminations, Rock types granite, tonalite and pegmatite, the dip class (greater or less than 47°), curved fracture surface morphology, and aperture/filling class TA (filled).

Table 6-31 shows how well the PNN was able to classify the Olkiluoto fracture data. The calibration of the training and test sets was generally very good, although it was not perfect. There were no false positive for the C1 variable (which corresponds to large fractures), which implies that no small fractures were mistakenly classified as large. However, there were 3 large fractures that were misclassified as small. The testing set, on the other hand, had three false positives and no false negatives, implying that three small fractures were misclassified as large ones. The production set, which consists of only small fractures, as a consequence can only have false positives. The false positive rate was about 45 %, which is not very useful.

A possible explanation for the decreased lack of classification success may be due to differences between the Finnish and Swedish data sets. A comparison of Figure 6-3 to Figure 6-1 shows that the PNN for Simpevarp evidently had surrogate variables that were more powerful in predicting large vs. small fractures. This difference is expressed by the range of classification probability at Simpevarp, which ranges from over 0.90 down to 0.1 for lengths from 0.0 to 5.0 m, while the same size range only spans classification probabilities from 0.6 to 0.2. It is possible that part of the explanation for the lower success in the PNN for Olkiluoto is that:

1. trace lengths are binned to half-meter classes (1.0m, 1.5 m, 2.0 m etc.), rather than recorded as their actual lengths;
2. there are fewer variables available for the Olkiluoto data (for example, alteration degree and surface roughness data were not available);
3. the amount of data is less;
4. there may be significant biases related to trench orientation because of the narrowness of the trench exposure.

Table 6-30. Smoothing factors for PNN calibration for Olkiluoto facture data.

Input name	Individual smoothing factor	Variable Description
Term_P	2.99	Both ends of the fracture are covered by soil, etc.
R_GR	2.96	Granite host rock
R_TON	1.54	Tonalite host rock
Dip Class	1.52	Dip either ≥ 47° or < 47°
Morph_K	1.46	Curved fracture
Qual_TA	1.36	Filled fracture
R_PG	0.91	Pegmatite host rock
Morph_M	0.75	Winding (“undulating”) fracture
Term_N	0.38	Both ends visible
Qual_AV	0.19	Open fracture
Qual_TI	0.11	Tight fracture
Qual_Other	0.05	Other type of fracture filling
R_MKGN	0.01	Mica migmatite host rock
Term_O	0.00	One end covered
Morph_S	0.00	Planar fracture
R_SGN	0.00	Vein gneiss

In general, however, the results for Olkiluoto are consistent in several ways with the Swedish data. These include:

1. Associations of large fractures with medium to coarse-grained quartz-bearing igneous rocks, undulating surfaces, and openness/lack of mineral filling; and
2. Negative associations with planar fractures, mineral fillings, and non-medium to coarse grained igneous rocks, though in the Olkiluoto case these are not volcanics or mafic intrusives, but metamorphic rocks of various types.

The association with steeper dips seen in the Olkiluoto data was not apparent in the Swedish data for reasons not clear. The association may have to do with the fact that steeper fractures are more likely to propagate and "grow" longer due to horizontal compressive plate movements such as have existed in Fennoscandia over hundreds of millions of years. This tectonic situation suggests that the maximum in situ stress is horizontal, and at least in the near surface, the minimum principal stress is vertical. This promotes strike-slip movement on vertical faults, re-activation of appropriately oriented reverse faults, and propagation of subvertical joints. Instrumental earthquake records for Fennoscandia suggest that current earthquakes are either strike-slip or reverse fault slip, which is consistent with more steeply-dipping faults being re-activated.

The apparent association between dip and fracture length shows a second side to the use of surrogate variables. In the Swedish examples, the focus was on identifying large fractures, in other words, looking for sets of "sufficient" conditions. The 47° dip threshold, however, shows how a surrogate variable can be used with high probability to rule out that a particular fracture is likely to be large. This suggests that with a more comprehensive series of data sets overcoming some of the size limitations previously described, it would be possible to classify fractures into one of three groups: definitely small; definitely large; and a third group with quantified uncertainty, rather than just the two groups, "definitely large" and "not large".

The preliminary results for Olkiluoto suggest that future efforts to use surrogate variables to predict size should not rely on trench data, due to its severe censoring effects and orientation bias. It is also recommended that additional fracture parameters be measured, such as alteration type, alteration degree, surface roughness and whatever else can be consistently measured. Moreover, it is also recommended that all categories have no blanks. For example, it is not possible to determine if a blank in the mineral filling column means that there was no filling, the filling was not recorded, or the filling did not fit in an existing category. There should never be any blank fields in data tables used for surrogate variable studies, because of the potential for confusing "not present" with "not measured".

6.5 Validation of surrogate variable approaches

In this preliminary assessment, the usefulness of surrogate variables was assessed by using neural nets and contingency tables to predict whether fracture traces were above or below a length threshold. Another way to build confidence is to compare the percentage of fractures that the PNN or contingency tables predict to be large, with the percentage above the same threshold that could be predicted from fracture size scaling studies. For example, /La Pointe and Hermanson, 2002/ conducted trace length and fracture intensity analyses for four Finnish sites. The equations that describe how many fractures there are greater than or equal to a given size as a function of area can be easily extended to how many fractures greater than or equal to a threshold size would be in a specified rock volume. For boreholes in a particular orientation, it is possible to calculate how many above and below the threshold would be intersected, leading to a proportion of intersected fractures above the threshold. If the neural net were applied to these same boreholes, it would also be possible to calculate the proportion predicted by the PNN to be above the selected size threshold. If these two independently-derived proportions are relatively similar, then confidence in the predictions of the PNN (or contingency tables) is increased, and constitutes a form of cross-validation useful for repository license application.

Table 6-31. PNN results for classification of training and testing sets for Olkiluoto fracture data.

Network type:	**PNN, genetic adaptive**	
Input file name:	OLK_PNN.TRN	
Patterns processed:	30	
Patterns classified correctly:	27	
Patterns classified incorrectly:	3	
Smoothing factor:	1	
Categories:	C1	C2
Actual winners:	15	15
Classified winners:	12	18
Actual losers:	15	15
Classified losers:	18	12
True positives:	12	15
False positives:	0	3
True negatives:	15	12
False negatives:	3	0
True positive proportion:	0.8	1
False positive proportion:	0	0.2
Network type:	**PNN, genetic adaptive**	
Input file name:	OLK_PNN.TST	
Patterns processed:	30	
Patterns classified correctly:	27	
Patterns classified incorrectly:	3	
Smoothing factor:	1	
Categories:	C1	C2
Actual winners:	14	16
Classified winners:	17	13
Actual losers:	16	14
Classified losers:	13	17
True positives:	14	13
False positives:	3	0
True negatives:	13	14
False negatives:	0	3
True positive proportion:	1	0.8125
False positive proportion:	0.1875	0
Network type:	**PNN, genetic adaptive**	
Input file name:	OLK_PNN.PRO	
Patterns processed:	718	
Patterns classified correctly:	325	
Patterns classified incorrectly:	393	
Smoothing factor:	1	
Categories:	C1	C2
Actual winners:	0	718
Classified winners:	393	325

Network type:	**PNN, genetic adaptive**	
Actual losers:	718	0
Classified losers:	325	393
True positives:	0	325
False positives:	393	0
True negatives:	325	0
False negatives:	0	393
True positive proportion:		0.4526
False positive proportion:	0.5474	

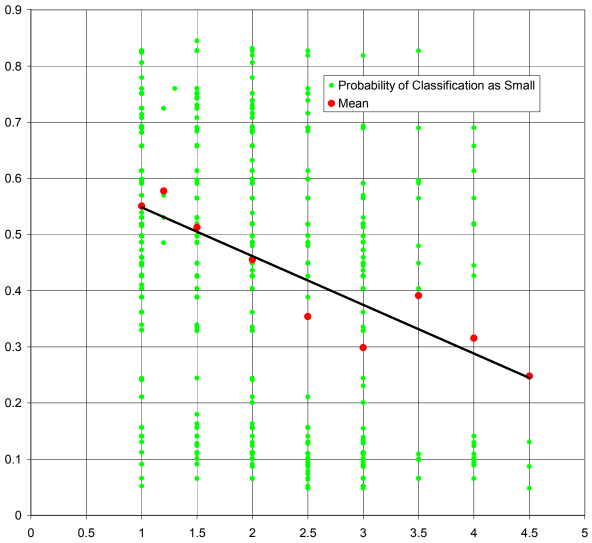


***Figure 6-4.** Classification probability as a function of trace length for Olkiluoto validation test set.*

6.6 Conclusions regarding the use of surrogate variables

The results for the Forsmark, Simpevarp and Olkiluoto sites indicate that the use of surrogate variables could prove useful in identifying fractures likely to be larger than a certain threshold value from those that are below. However, the work is only preliminary, and has the following limitations:

1. The threshold used to distinguish large from small fractures was chosen to be 5.0 m, which is much smaller than the actual threshold that would be used for identifying fractures on which secondary slip during an earthquake could compromise the safety of a canister. The 5.0 m threshold was selected because the outcrop data available contained no fractures longer than 20 m, and very few fractures greater than 5.0 m. The fact that the approaches were still able to classify large and small fractures with reasonable accuracy suggests that a larger threshold would only improve the classification success.

2. Some of the variables that can be measured in outcrops cannot be measured in boreholes, although they can be measured in underground openings. These variables include such features as termination style and whether the fracture crosses multiple lithologic boundaries, which cannot be measured in a borehole or from core very easily. However, some of the analyses used only variables that could be measured in boreholes, and still showed successful classification of large and small fractures, so that it appears that it would still be possible to identify, with some error, large fracture from small even in borehole data at an early stage. In particular, it might prove useful to map the density of predicted large fractures from multiple boreholes during early site reconnaissance to assess whether there were particular regions in the rock volume that have a higher probability of large fractures, perhaps leading to a re-design of the layout.

3. For future work, this study should be extended to data sets where considerably longer fracture traces have been measured. It is not necessary to systematically map all fractures in a larger area, but rather to incorporate new fracture data at each site specifically targeting fractures that are tens of meters or hundreds of meters in extent. In this regards, trench data or other methods of mapping fractures that heavily censor fracture lengths are not desirable. It is not necessary that every fracture be measured; it is more important to gather a sample that

    - obtains data over a large range of fracture sizes, including those above and below the specified size threshold;

    - obtains data in all of the major rock types expected to be present, and within each lithology, covers a range in variation of other parameters that appear to be important at each site.

4. Validation of the methods should be attempted using the procedure described in Section 6.5, to further assess whether the use of surrogate variables appears as potentially useful as it does in these preliminary investigations.

7 Methods for detection of "new" fracturing and delineation of the transition zone

7.1 Introduction

In order to estimate the risk of creating new fractures by earthquakes during the post-closure phase of a geological repository, it is important to review the formation of such fractures during the Quaternary history of the potential repository sites at Forsmark and Oskarshamn. If "new" fracturing can be documented the extent and orientation of these fractures provide important information to the understanding of the site.

The methods available for dating of faults and fractures are reviewed and problems involved in age-determination of fractures are discussed in Tullborg et al., 2001 with the most relevant information extracted here:

New fracturing or faulting is difficult to prove due to the shortcomings in methods for dating these types of fractures. The methods are few and the uncertainties involved are usually considerable. There are two different approaches:

1. constraining of fault movements; and
2. radiometric dating of minerals precipitated in the fractures.

Fault movements can be constrained by

a. determining when movements likely occurred along the fault planes e.g. displacement of dated sequences of sediments (cf. e.g. Lagerbäck 1979;1990);

b. identifying differences in uplift curves revealed by fission track (e.g. Hansen 1995) or U-Th-He-datings (on-going pilot study by P. Söderlund carried out on drill-cores from Äspö) on both sides of a fault. The shortcoming with the first approach is that this method can only be used in places where the geological setting provides stratified sediments on top of the bedrock surface, and the shortcomings with the second approach is that drill-cores on both sides of the fault is needed and the vertical component of the faulting must amount to several hundred meters in order to be detectable.

Reactivation of fractures is documented in different scales. In outcrops reactivation is demonstrated as e.g. brittle structures (open fractures) following older, semi ductile structures and in micro scale reactivation of sealed fractures can bee seen as new fractures dividing individual mineral grains. Two examples of textures are given in Figure 7-1 and Figure 7-2 showing the contrast between a successive growth of minerals filling a fracture and a reactivated sealed fracture where the new fracture split the previous sealing.

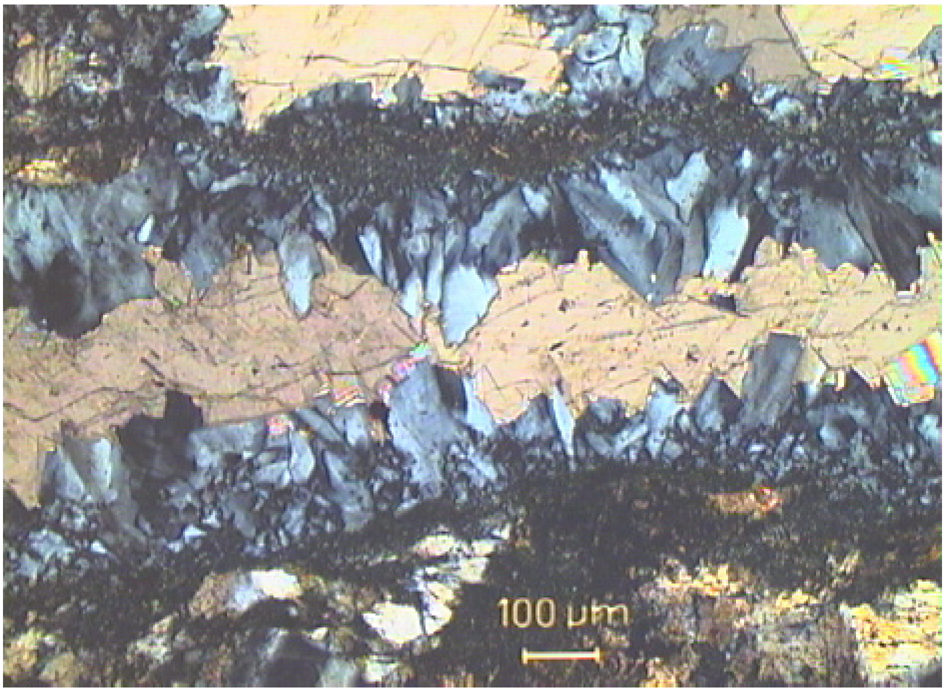


Figure 7-1. *Fracture coated by adularia is later sealed by calcite. Photomicrograph from thin-section KSH01: 287 m (Drake and Tullborg, 2004 (in press).*

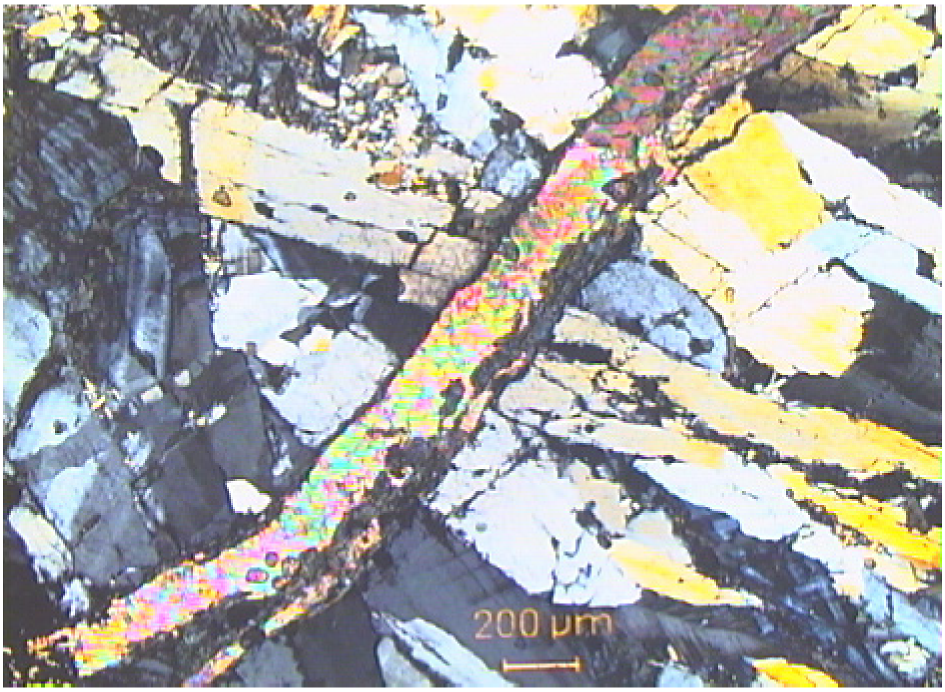


Figure 7-2. *Idiomorphic prehnite (Pr) is cut distinctly by fracture subsequently sealed by calcite (Cal), KSH01:208 m (Drake and Tullborg, 2004 in press)*

Radiometric dating of minerals precipitated in the fractures can be useful, but for dating of Quaternary mineralizations there are only few methods available such as ^{14}C -dating e.g. tested on Klipperås samples (Possnert and Tullborg 1989) and U-Th -dating. There are two serious problems with the radiometric dating of late fracture minerals:

1. The precipitation rate of minerals is generally slow and the fractures have been open with groundwater circulation during a considerable time span, which leads to continuous redistribution of radioisotopes; and.

2. the minerals precipitated can be so much younger than the formation of the fracture itself that the age information easily can be misinterpreted.

It is therefore important that the fractures used for radiometric dating are thoroughly investigated to uncover the presence of dissolution textures (older minerals may have been dissolved) and that the wall rock is studied in order to reveal alteration caused by hydrothermal fluids, which indicates that the fracture is originally significantly older.

Under development are methods that include the use of biomarkers (products from plants) which can be incorporated in calcites. These biomarkers are strong indications of Quaternary origins and can thus serve as dating methods. The problem still remains that this does not date the fracture, only the filling.

The Fennoscandian shield has been formed and reworked during a very long time period, from ~2500 Ma to ~950 Ma. However, temperatures above 100°C have not occurred since the Tertiary and for most places since the Cretaceous. Hydrothermal minerals in fractures have therefore not precipitated in the fractures during the latest 100 Ma to 50 Ma. The investigations carried out at different sites however, show that:

- the majority of fractures have coatings or wall rock alteration, which are hydrothermal in origin;

- subsequent reactivation is very common. (Tullborg and Larson 1982, 1983, Larson and Tullborg 1984, Tullborg 1986; Stanfors et al1999).

As a starting point for new site investigations there are a number of questions that needs to be considered and hopefully answered for each site. These are:

- Can ”new” fracturing be demonstrated?

- Can ”old” origins be proven for all or most of the fractures?

- Is reactivation the common case?

- Which methods can be used, and what material is available at the specific site for age determinations?

- Can mineralogy help to de lineate the transition zone between the fractures and the “good rock”

7.2 Analyses of data for Östahammar (Forsmark)

Fracture mineralogy has been studied and is reported from the first three deep cored drill-holes at Forsmark (Sandström et al., 2004). The most common fracture minerals in the area are quartz, K-feldspar (adularia), chlorite, laumontite, calcite, prehnite, epidote, pyrite, analcime and apophyllite. Among the clay minerals the most common is corrensite, which is mixed layer clay with alternating layers of chlorite and smectite or vermiculite. Other clay minerals, less common in the samples here studied, are illite, smectite and mixed-layer illite/smectite. It is probable that the amount of clay minerals is underestimated since they have been washed out by flushing of drill-water or by other unwanted disturbances during the drilling procedure.

Examination of the drill cores indicates 6 different generations of fracture mineralizations. In decreasing age, these are; 1) quartz-epidote, 2) prehnite, 3) laumontite-calcite-adularia-chlorite/corrensite 4) idiomorphic quartz-adularia-albite-analcime, 5) calcite and pyrite 6) calcite-clay minerals. Asphaltite has been identified and belongs probably to Generation 6 or possibly to Generation 5. The present understanding is that that Generation 1 is clearly separated in time from Generations 2 and 3. The latter generations are probably one prolonged and intense period of hydrothermal alteration with creation of new fractures in the area. Subsequently Generation 4 and 5 have precipitated, probably as a result of a significantly later period of hydrothermal circulation grading into low temperature conditions (<100° C). It is probable that all these events are older than 600 Ma. However, precipitation of minerals in Generation 6 may have occurred from the Proterozoic through the Quaternary, and it is possible that the continuation of the fracture mineral studies will produce a subdivision of the mineralizations that have taken place during this long time period.

The wall rock alteration is most intense around the epidote, prehnite and laumontite bearing fractures. The dominant alteration is saussuritization of the plagioclase, chloritization of the biotite and seritization of the K-feldspar. The altered wall rock is red-coloured due to micro-grains of hematite, mainly in the plagioclase. Especially the laumontite sealed fractures occur in swarms usually with one or two water conducting fractures in a network of sealed fractures. The delineation of the transition zone around these fracture swarms is not possible distinguish without more detailed studies.

In the upper 100 meters of the bedrock, horizontal to sub-horizontal hydraulically conductive fractures/fracture zones are present. These are often filled with clay minerals, altered rock fragments and calcite. The ages of this material is unknown but the history of these zones seems to be complex. Unfortunately much of the material from these zones is severely disturbed but some samples have been possible to collect and studies are ongoing.

At the location for the deep drill hole KFM05A a potentially postglacial horizontal fracturing/movement filled with loose sediments was found, Figure 7-3. The infillings have been identified and documented (Albrecht et al., 2004) and several dm long drill cores were drilled from the surface through vertical fractures and also through the main horizontal fracture. The results are summarised below.

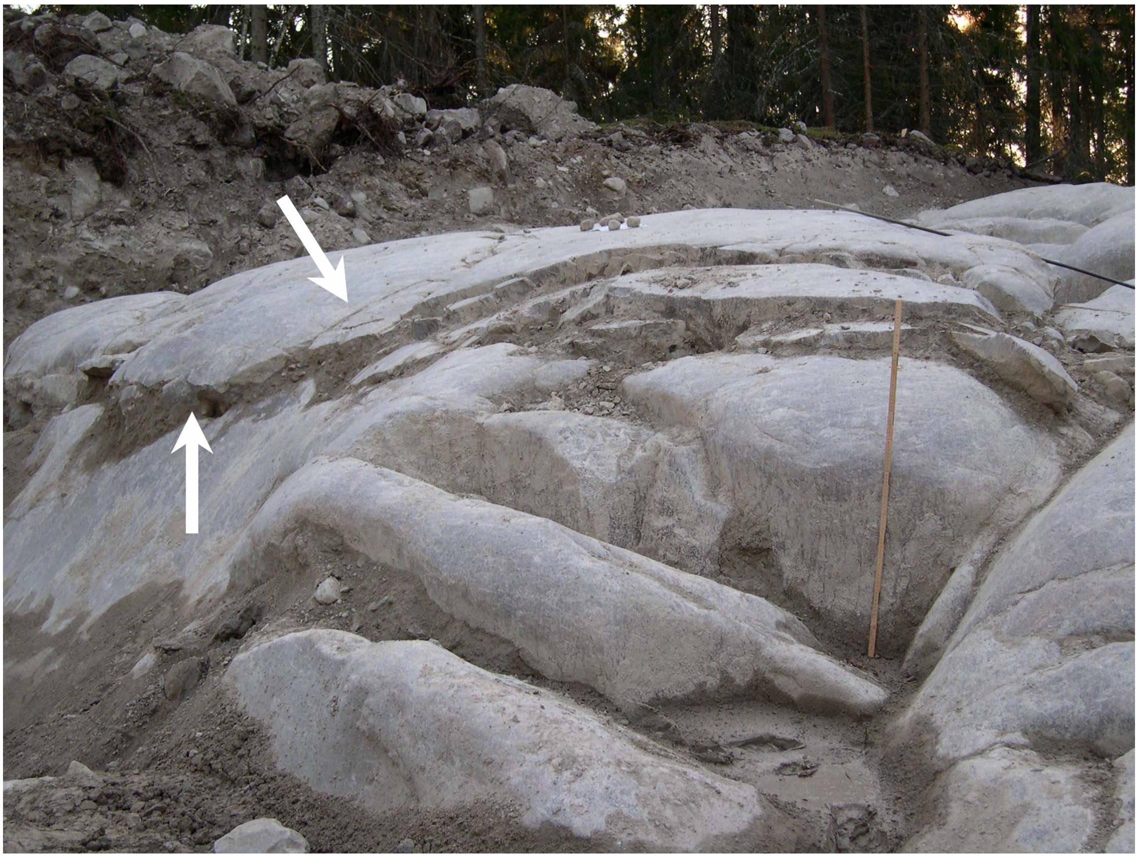


Figure 7-3. *Sediment filled horizontal fracture at drill site 5 in Forsmark (Albrecht et al., in press). Lower arrow shows the horizontal fracture. Upper arrow shows the small vertical fractures that have indications of displacements in the order of some cm.*

The results from the study show that the horizontal fracture is filled with glacial sediments (till). There is no significant weathering on the bedrock fracture surfaces studied in the small drill-cores. Two samples from the horizontal fracture surfaces show occurrence of idiomorphic quartz grown on the surfaces. This is typical for many fractures in the Forsmark area. Calcite has been sampled from the vertical fracture coating in drill core 4. Stable isotope values are in accordance with a recent precipitates (post-glacial) means that the horizontal fractures probably have older precursors although possibly weak (quartz is not expected to crystallise during ambient conditions), but some of the short vertical fractures could have been created in postglacial time.

The above given fracture mineral information reviewed in the context of late earth quakes can be summarised as follows:

- Fracture have been initiated and reactivated during several events in the Proterozoic.
- Further reactivation and to lesser extent creation of fractures during the Phanerozoic have probably occurred, but as most of the fractures have hydrothermal fillings or dissolution features indicating former presence of secondary minerals the major formation of fractures must have occurred long before the Quaternary.
- Reactivation (which partly may be young) of fractures and faults especially in the upper 100 m of the bedrock is indicated.

7.3 Analyses of data for Oskarshamn (Simpevarp)

Within this area so far, fracture mineral studies have only been carried out on the first borehole at Simpevarp (Drake and Tullborg in press). However, earlier reported studies e.g. Stanfors et al., 1999 and Landström et al., 2001 from the Äspö area can also be taken into consideration.

The most common fracture minerals in the area are chlorite, calcite, epidote, quartz, low temperature K-feldspar (adularia), prehnite, laumontite, albite, fluorite, But also Ba-zeolite (harmotome), barite, pyrite, titanite, anatase/rutile, apatite, muscovite, hematite, apophyllite, REE-carbonate, amphibole, ilmenite and clay minerals, dominantly illite, mixed layer clays (illite-smectite), corrensite and to lesser degree smectite. Rarely, additional sulphides like chalcopyrite, galena and sphalerite have been found.

Several generations of mineralisation have been identified of which the first are quartz fillings, probably associated with post-magmatic circulation. Subsequent greenschist facies conditions (epidote, quartz, calcite, pyrite, muscovite and some albite and Fe-Mg chlorite with titanite) in combination with ductile deformation, resulted in the formation of epidote-mylonite. The epidote-mylonite seems to be associated with the oxidation and the formation of hematite, causing extensive red-staining of the wall-rock along the fractures. This relatively early formed mylonite has later been reactivated in association with brittle deformation conditions. The subsequent breccia sealing by prehnite-fluorite marks the ultimate ending point of the extensive red-staining of the wall-rock and also the change in conditions, from greenschist to prehnite-pumpellyite facies. Later fracture fillings consisting of calcite and Fe-Mg chlorite was followed by semi-ductile to brittle deformation, inducing dark-red coloured hematite-cataclasite formation together with adularia, Mg-chlorite and calcite. The latest hydrothermal mineralisation shows a decreasing formation temperature series as follows; Mg-chlorite, adularia, laumontite (Ca-zeolite), hematite, harmotome (Ba-zeolite), pyrite, Fe-chlorite (spherulitic), calcite + REE-carbonates and clay minerals. The appearance of zeolites infers formation conditions in the ranges of zeolite facies. These minerals might have been formed at one continuous event or at several different events with gradually lower temperatures. It is probable that these events formed at the latest during the Palaeozoic The outermost coatings along the hydraulically conductive fractures consist mainly of clay minerals of mixed layer clay type (corrensite=chlorite/smectite and illite/smectite) together with calcite and minor grains of pyrite. Low temperature calcites have been formed during various conditions and from both saline and fresh groundwaters. The stable isotope results from the fracture calcites support largely the above given sequence of events.

It has been documented by fission track analyses (Tullborg et al., 1996 and Cederbom et al., 2000) that the Äspö (Simpevarp/Laxemar) area was covered beneath a 3-4 km thick pile of Paleozoic sediments until the late Paleozoic and the sedimentary cover was probably not completely removed until the late Tertiary as the sub-Cambrian peneplane is largely preserved (Lidmar-Bergström 1996). Dating of clay minerals from fracture zones at Äspö show ages of 300 to 400 Ma (Maddock et al.,1994) indicating a formation during the period of maximum cover.

In conclusion:

- Many of the fracture at Äspö have ductile precursors
- The majority of fractures have hydrothermally altered fracture walls (cf. e.g. Andersson et al., 2002).

Reactivation is very common and the large hydraulically conductive fracture zones have probably been open and water conducting for very long times. Hydrothermal alteration of the wall rock is common and has usually resulted in saussuritisation of the plagioclase (plagioclase → albite + sericite+ epidote) and breakdown of biotite to form chlorite. The alteration is often accompanied by oxidation that has resulted in redstaining caused by micro-grains of hematite. The width of the altered zone varies from < 1 cm around small fractures up to dm to m around fracture zones. The extent of the altered zone is not always corresponding to the redstaining. The alteration zone has usually higher porosity, higher density of microfractures and higher frequency of sealed fractures. Much of the clay minerals found in these zones have been formed during temperatures above 100° C (e.g. the Redox Zone, Banwart et al., 1995). Suggested ages for the hydrothermal mineral sequences are given in Figure 7-4.

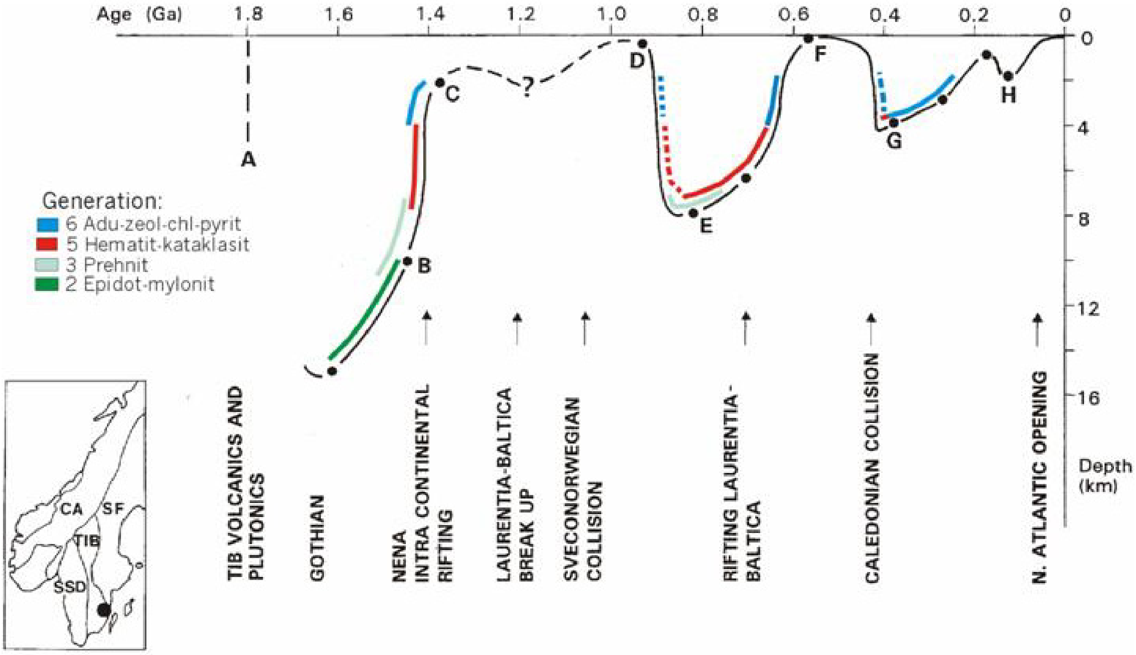


Figure 7-4. Subsidence and uplift of the present land surface in the Oskarshamn-Västervik area (Tullborg et al. 1996 and references therein). Inserted are possible fracture-filling-events for the different generations (Drake and Tullborg in press). A. Intrusion of the TIB granitoids . B. K-Ar ages of biotite in TIB granitoids. C. Intrusion of the Götemar Granite. D. Intrusions of dolerite into unconsolidated Almesåkra conglomerate. E. Titanite fission-track ages. F. Sub-Cambrian peneplain. G. Apatite fission-track ages. H. Cretaceous marine sedimentation.

Ground water circulation during the Quaternary have caused precipitation and dissolution of calcite fracture minerals along the pre-existing fractures down to depth of 500 meters and in some zones even deeper (Tullborg 2003).

Creation of new fractures during the Quaternary has not been possible to document but small scale, near surface movements (cm-dm scale) have been argued for by Mörner, 2003.

7.4 Conclusions

Revisiting the questions posed in the introduction of this chapter it can be concluded that:

- ”New” fracturing has not been possible to demonstrate, but this may partly be due to lack of suitable methods.
- “Old” origins can be assumed for most of the fractures as they host hydrothermal mineral that can not have been precipitated during the Tertiary or Quaternary
- Reactivation is common as demonstrated by mineralogical studies on thin sections where several generations of fracture minerals are apparent in one single fracture.
- There are methods to use for age determination of hydrothermal minerals. However, there is a great problem to separate between different generations since they may be intimately inter-grown.
- Dating of “young” minerals by the ^{14}C and U-Th methods involves difficulties due to the lack of closed systems.

Conclusions about the delineation of the transition zone:

- The transition zone is to varying degrees characterised by a higher amount of micro-fractures than in the fresh rock as well as chloritisation of biotite and alteration of plagioclase to albite, epidote and sericite but also red-staining caused by oxidation of magnetite to hematite.
- Red-staining is easy to recognize but does not always correspond to alteration of other minerals. This means that the transition zone can be much wider than the red-stained section of the rock.
- Higher porosity and lower density (than the fresh rock) and higher frequency of sealed fractures characterise usually the transition zone. The chemical characterisation of the transition zone can be difficult since the mineral alteration does not necessarily affect the whole rock chemistry.
- From this follows that mineralogy is a better tool to recognise the transition zone than geochemistry and that the delineation of the transition zones is site specific.

8 Suggested approach to field methodology for determination of respect distance

Application of the present site requirements and preferences (see Chapter 3) in combination with an implementation sequence (Table 5-3) illustrates how compliance may evolve with time. The results in Table 8-1 suggest **that the site investigation phase (Step 1 and Step 2) should resolve compliance for most of the requirements**. However this may be a misconception; the stated requirements are likely necessary but not sufficient for the complete repository implementation. It is important to recall that the full title of Andersson et al, 2000 is *What requirements does the KBS-3 repository make on the host rock? Geoscientific suitability indicators and* ***criteria for siting and site evaluation.*** It is likely that the requirements and preferences would be developed and refined before deposition starts.

Table 8-1. Compliance with requirements and timing

Requirement	In what step is compliance at latest verified	Comment
The rock in the repository's deposition zone may not have any ore potential, i.e. may not contain such valuable minerals that it might justify mining at hundreds of metres' depth.	Step 1 and step 2 (before construction starts)	Lithological investigations
Regional plastic shear zones shall be avoided if it cannot be demonstrated that the properties of the zone do not deviate from those of the rest of the rock. There may, however, be so-called "tectonic lenses" near regional plastic shear zones where the bedrock is homogeneous and relatively unaffected.	Step 1 and step 2 (before construction starts)	Tectonic investigations
It must be possible to position the repository with respect to the fracture zones on the site. Deposition tunnels and deposition holes for canisters may not pass through or be positioned too close to major regional and major local fracture zones. Deposition holes may not intersect identified local minor fracture zones.	Major regional (> 10 km): Step 1 and Step 2 (before construction starts). Major local: (1-10 km) Step 5 (before construction of deposition tunnels. Local minor (100 m – 1 km). Step 6 before construction of deposition holes	Tectonic investigations
The rock's strength, fracture geometry and initial stresses may not be such that large stability problems may arise around tunnels or deposition holes within the deposition area. This is checked by means of a mechanical analysis, where the input values comprise the geometry of the tunnels, the strength and deformation properties of the intact rock, the geometry of the fracture system and the initial rock stresses.	Step 1 and step 2 (before construction starts)	Rock mechanical, but is uncertain that it is viable, especially with respect to heating effects
The groundwater at repository level may not contain dissolved oxygen. Absence of oxygen is indicated by a negative Eh, occurrence of Fe (II), or occurrence of sulphide.	Step 1 and step 2 (before construction starts)	Chemical
The total salinity (TDS = Total Dissolved Solids) in the groundwater must be less than 100 g/l at repository level.	Step 1 and step 2 (before construction starts)	Chemical

It is likely that the general design requirements /SKB, 2002a/ would be a better start for development of methodology than the general site requirements, Andersson et al, 2000.

From a general perspective we here simplify the reasoning and assume that avoidance criteria only are tied to the need for long term safety and assume that avoidance of site domains due to construction issues is a matter that can be compensated for with time or money.

Now assuming we only reflect on long term safety, we describe processes that might affect the safety to understand whether decisions on respect distances to discontinuities in the general sense are beneficial. We distinguish thermal, hydrological, mechanical, chemical and biological processes, Table 8-2.

Table 8-2. Example of issues related to respect distance

Process	**Issues**	**Present status of understanding of "respect distance" in the general sense**
Thermal	Large-scale heating may generate reactivation of faults	Maximum shear displacement develops about 200 years after the waste deposition. Larger slips > 0.1 m only for fractures > 700 m in length /Hakami, Olofsson, 2002/ Thermal heating does not affect respect distance"
Hydrogeological	Future earthquakes may generate water level changes	Changes are temporary and the transients will not liquify the buffer /Bäckblom, Munier, 2002, Pusch, 2000./ Water level changes do not affect respect distance
	Re-activation of faults may cause local new fracturing close to the faults that locally may change the transmissivity	New fracturing is assumed within the transition zone that is to be avoided /Munier et al, 2003/
	Re-activation of faults may cause changes in the regional/local stress field that mat influence the local transmissivities. Open fractures may close and closed fractures may open.	The local spatial variability may change but not likely the average of the parameters. Studies show that open fractures have been open for very long time or at several different periods (cf. Stanfors et al., 1999)
	Flow resistance, F should be at least > 10^4/y for most of the canister positions	The F-value is a model parameter and no method is yet devised how F will be decided in practice. 50-100 m transport distance in ”Swedish crystalline rock” is often ”enough” to achieve F> 10^4 year/m for retention. For these reasons it is worthwhile to keep a ”hydraulic respect distance” like 50-100 m to major transmissive zones.
Mechanical	Slip of discontinuities in the deposition hole due to earthquakes that may impair the barrier function	No damaging slip with a certain distance to the faults and when large fracture sizes are avoided in the deposition hole /Bäckblom, Hökmark, Munier, 2004/
	Dynamic loading may shear the buffer	Barriers (buffer, canister) act as a rigid body / Bäckblom, Munier, 2002/
Chemical-biological	Future earthquakes may generate water level changes	Changes are temporary /Bäckblom, Munier, 2002/
	Draw-down during construction may cause upconing of brines	Changes are temporary (a few hundred eyars) and will likely be restored /Vieno et al, 2003/

Let the term “respect distance” apply for avoidance for any reasons. If this is the case, then methods need to be available that are updatable and that utilize:

- Data that can be obtained prior to repository construction for the design of the preliminary layout;
- Data that can be obtained during construction but prior to canister emplacement in order to situate or qualify a canister position as an acceptable canister deposition hole.

A mistake (deeming a position is safe when in fact it is not – type II error[3]) should also be within the tolerances of the safety case.

Table 8-2 more clearly defines the aspects of the program where “respect distance” is an issue. Thermal issues are not relevant for “respect distance”, so there is no need to devise field methodology for them. The same applies to several of the hydrogeological issues. The “F-factor-issue” is not a requirement but a preference. If the F-factor is treated as a stochastic rather than a deterministic parameter for the individual deposition holes, the F-factor determination becomes an issue for the general investigation programme rather than the field investigation methodology to decide “respect distance”.

The remaining issues for “respect distance” are tied to:

- possible creation of new fractures
- possible slip of discontinuities at the deposition holes.

The first issue requires definition of the extent of an area close to the core of the deformation zones where new fractures may develop; for the second issue, determination and identification of fractures above a critical size threshold is required.

In view of these statements it is suggested that the descriptive geological classification of “transition zone” is a geological description to reflect the area with previous influences from the fracture zone with higher possibility for new fracturing.

For the field methodology we assume:

1. First priority is to find the geometry and character of the core of deformation zones
2. Second priority is to decide the extent of the transition where rock properties may deviate from the properties of the host rock. The rock properties in the transition zone should be evaluated against the SKB requirement and preferences for the site.
3. Third priority is to avoid large fractures crossing the deposition holes as these may cause slip > 0.1 m

Within this framework, the concept of “respect distance” is not applicable. The canister position is either within the secondary fracturing zone or it is not; the canister position is either intersected by an unacceptably large fracture or it is not. A more appropriate strategy for the investigations is to avoid the core of the zone and the volumes within the transition zone that do not fulfil the site requirements and preferences. The large

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[3] Type II-error: Accepting the null-hypotheses H_0 when H_0 is false

fractures that may appear outside of the secondary fracture zones anywhere in the host rock volume are also to be avoided irrespective of the distance to the faults as present modelling of earthquake response cannot be validated for earthquakes close to the target fractures.

The field methodology for finding the geometry and character of the core of deformation zones are standard technology so this pre-study would not need to describe these methods. Field methodology to delineate the core from the transition zone and the transition zone from the host rock is not yet fully developed, but are discussed in this preliminary study. The methods to describe fracture sizes are reviewed in the preliminary study.

For the practical planning of the field methodology it is also of interest to understand the volumes of rock to be investigated within a certain time frame. An indication of how much rock volume needs to be characterized can be estimated by considering the requirements of an initial deposition area to house 200-400 canisters. This will require around 5-10 deposition tunnels with length around 300 m. Separation in distance between tunnels are on the order of 40 m; thus, the minimum space needed for investigations thus is about 400·400 m or a horizontal footprint of at least 160 000 m^2.

8.1 Delineation of transition zones

Munier et al, 2003 and by Lindqvist and Tunehed, 2003 review statistical means to delineate the transition zone using the Fracture Zone Index (FZI). FZI is a classification of the rock mass encountered in a borehole with respect to rock quality, and is carried out according to SKB method description MD 810.003. The purpose of the method is to aid in identifying potential fracture zones in a borehole as one of the components in the single hole interpretation (MD 810.003). The FZI-method uses multivariate statistics to describe and classify the rock mass into:

- Wall rock (normally fractured rock) – FZI < 0.5
- Transition zone – FZI 0.5–1.5
- Possible fracture zone – FZI > 1.5

The primary input data for the calculation consist of fracture frequency, borehole radar reflectors and geophysical borehole logging data. Of the geophysical logs, caliper, sonic and resistivity logs gives the most significant contribution. The process of converting these different data sets to a single parameter (FZI) is based on Principle Component Analysis as described in method description MD 810.003.

The left graph in shows the predicted FZI as a black line and the original classified GFZI* (= manual fracture zone classification) with red cross-hatching versus length along the borehole. The central graph shows GFZI and FZI in grey after smoothing with a 5 point median filter. The right graph shows FZI in grey as discrete classes according to the intervals: FZ I <0.5 → discrete FZI=0; 0.5 <FZI <1.25 → discrete FZI=1; FZI> 1.25 → discrete FZI = 2. Note that the border between the two highest classes was set to 1.25 in this presentation instead of 1.5 since this choice gave a slighter better agreement with the manual fracture zone classification.

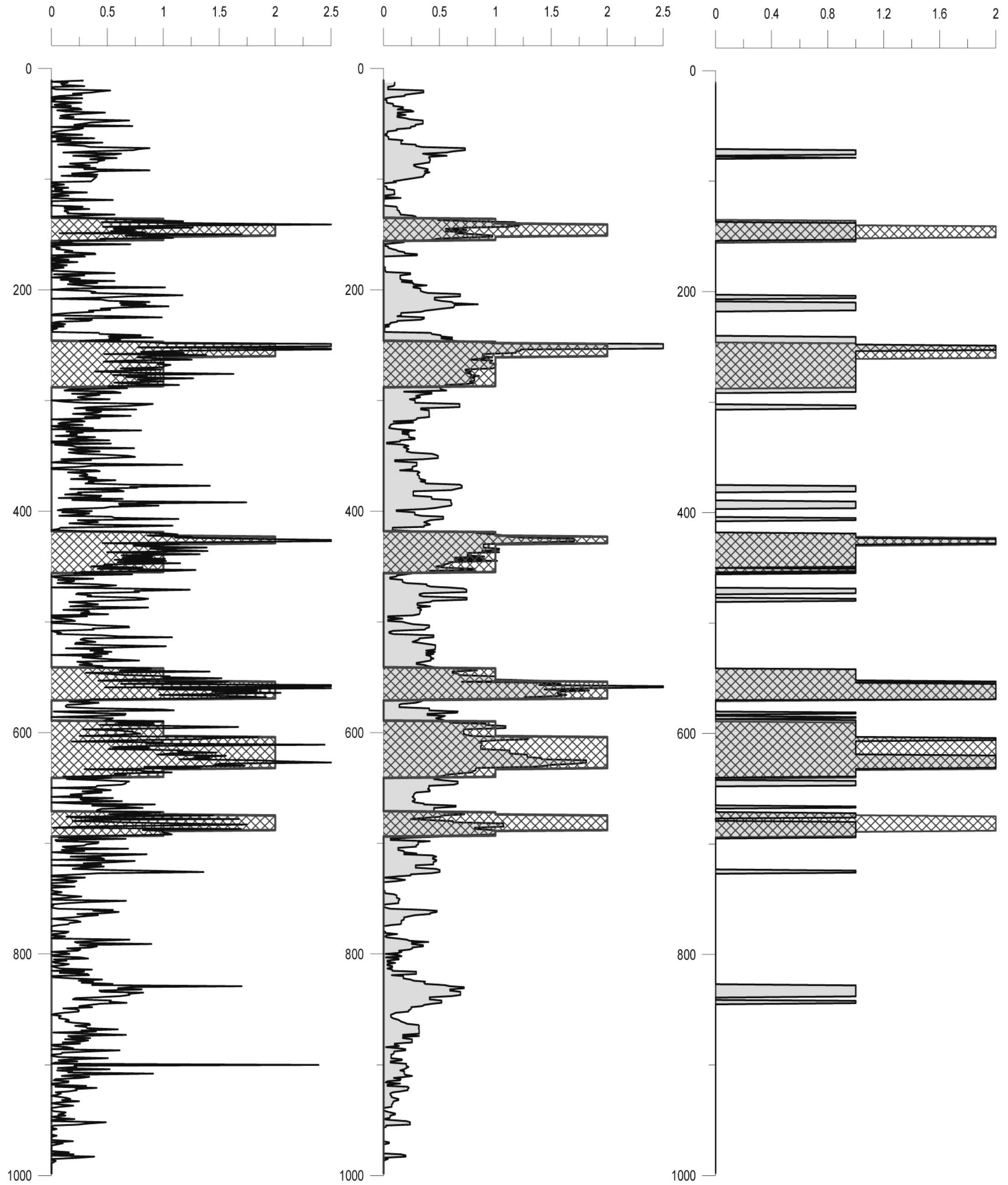

Figure 8-1. *Application of Principal Component Analysis for fracture zone classification. See text for description. /Fig 4-30 in Lindqvist, Tunehed, 2003/*

The advantages by using some sort of FZI is that it is based on data from boreholes that likely would be a prime source for data for all stages of the repository implementation. Previous work /Lindqvist and Tunehed, 2003/ however has limited value as the statistical manipulation was biased by the manual classification that was used for calibration. Definitions of FZI-classes should be supportive only, but the final classification should be based on a human judgement.

We need to further develop stringent methods to classify the boundaries of the "functional transition zone" based on the data that would be sampled from the cores or by measurements in the borehole or between boreholes.

Based on the reasoning in Chapter 7 it is argued that studies on mineralogy and fracturing would be helpful to delineate the transition zone.

8.2 Fracture size determination

Based on the reasoning in Chapter 5 and Chapter 6 it is understood that true fracture size determination underground would be purely coincidental, but that fracture classification and the use of surrogate parameters might be a possible resort for managing the earthquake issues.

The difficulties to determine fracture sizes will have implications for fracture network modelling; variables like distance between fractures and orientation of fracture are updatable as the site characterisation proceeds. The third variable needed – fracture size – will then not be an updatable parameter during the site characterisation process making the fracture network modelling less attractive and more difficult to qualify.

The F-factor is an important key parameter that captures the radionuclide transport in the rock. Of special relevance are the transmissive and/or large fractures that may connect the near-field to the fracture zones where not much retardation can be assumed. While the fracture network models might be difficult to qualify other approaches might be needed to quantify the F-factor in an iterative, updatable manner.

8.3 Qualification of methods

Methodology for estimating respect distance with respect to earthquakes as for any other issues should be:

- Reliable - results should be correct
- Robust – results should not be too sensitive with respect to minor variation in data
- Repeatable – similar results should be arrived with iterative application of methodology with same data
- Testable – the results should be possible to verify

It is evident that the methodology to decide respect distance with respect to earthquakes never can be qualified in the full sense; the results are not testable and the reliability is difficult to validate.

The quest for fracture size distribution and all other matters with respect to site characterization is carried out during the Site Investigation Phase and during preparation of the programme in progress for "Characterisation, Testing and Demonstration during Construction, Operation and Closure of the repository".

9 Search for co-operative research on respect distances

A part of this preliminary study was to search for possible co-operative research; the outcome of this activity is described below.

9.1 Participation in the South African project

The project plan identified opportunities in on-going research in South Africa. The studies "Drilling Active Faults in South African Mines" within the International Continental Scientific Drilling Program focuses on reactivation of fractures within the core and transition zones due to magnitude 3-5 earthquakes, and has been integrated with activities within NELSAM: Natural Earthquake Laboratory in South African Mines The most up-to-date information is found at the site http://earth.es.huji.ac.il/reches/DAFSAM/NELSAM_NSF_CD.pdf.

The proposed research addresses the following major topics in earthquake science. The scientific objectives of NELSAM are to contribute key data in each of these problem areas:

- Nucleation processes. Could near-field monitoring determine the scales and processes of nucleation and eventual size of the ensuing dynamic rupture? Could near-field monitoring detect additional signatures (e.g., geochemical and electromagnetic anomalies, cascading events) of the earthquake preparation processes?

- Rupture processes. What are the detailed properties, dynamics and energetics of the rupture process (velocity, geometry, crack vs. pulse mode of rupture; dynamic versus geometric sources of heterogeneity; possible opening motion)?

- Stress/Strain/Strength. What are the orientations, magnitude and heterogeneity of the stress/strain fields in the vicinity of an active fault? How do these fields change with time? With mining? With seismic and aseismic processes? Do the stress/strain fields control seismicity and what is the style of this control?

- Characterization of an active fault-zone. What are the geological, mechanical, and geochemical components of an active fault-zone (geometry, composition, rheology)? How does fault fluid and gas chemical composition vary during the earthquake cycle?

- Microbial activity in active faults. What are the effects of faulting and earthquakes on the microbiological activity in the fault-zone? Do active fault-zones host unique communities? Do seismic events increase the microbiological activity or its diversity?

The US National Science Foundation (NSF) is supporting the project for at least three years so the seismic network can be launched. The general idea is then to carefully describe some major fracture zones (including e.g. microbiology) before a magnitude 3-4 earthquake, wait for the event and then re-do the characterization. A project outline and schedule is shown in Figure 9-1 and Figure 9-2 respectively. Based on the discussions with Prof. Ze'ev Reches, it is understood that a quite open data policy would be applied and it is likely SKB/Posiva can contribute in kind to the project to test and develop field methodology. However a definite drawback is that the transition zone studies at Matjhabeng and A.R.M shaft #5 not yet published and this work can only be accessed through Prof. Reches or Dr Ori Dor, now at Univ. of Southern California. Prof. Reches has tentatively arranged for the timely reporting of the studies and SKB (Raymond Munier) has offered a small contribution to facilitate the reporting.

In summary: There is no benefit to participate now in the project, but when work has progressed both in RSA and in Sweden/Finland, there would be benefits in closer cooperation. These benefits include:

- A test of methods to delineate the fracture zone and also define the "process zone" or "transition zone" from the fracture zone to the average rock mass
- An assessment of methods to detect and measure slip in the sidewall rock so we extend a database for coupling primary fault slip to secondary slip in the rock mass
- An evaluation of methods to detect new or comparatively young fracturing in the rock mass or methods to show there are no new fracturing in the sidewall rock
- A test case for the refinement and validation of methods to deterministically estimate fracture size at a given position or estimating/classifying size by using other surrogate parameters coupled to size (like aperture, transmissivity, weathering, mineral infillings, planarity, roughness, orientation and morphology etc.)

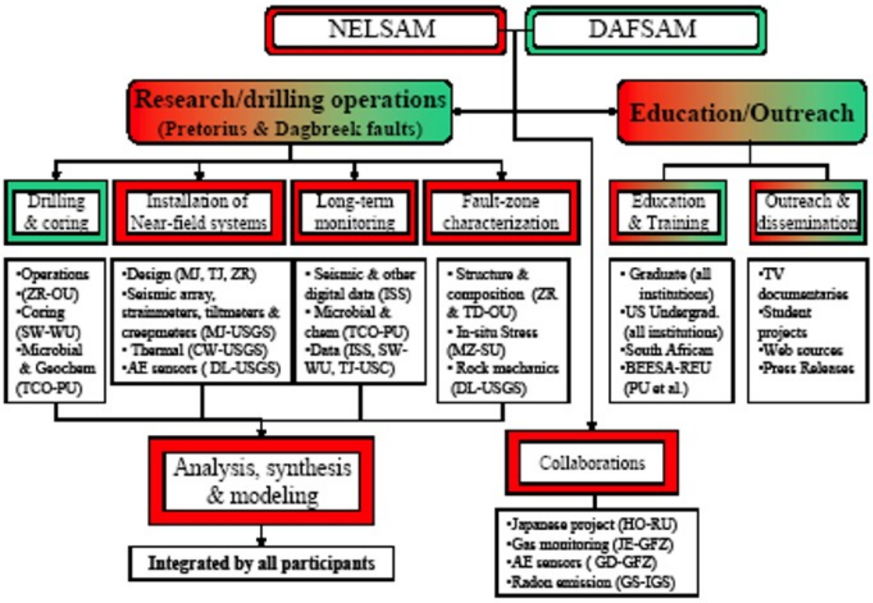

Fig. 1. Science and management teams in NELSAM (current proposal, mark in red) and DAFSAM (funded by ICDP, marked in green). Abbreviations: ZR-OU Ze'ev Reches, U of Oklahoma; SW-WU Sue Webb, Witwatersrand University; TCO-PU TC Onstott, Princeton university; MJ-USGS Malcolm Johnston, US Geological Survey; CW-USGS Collin William, US Geological Survey; DL-USGS David Lockner, US Geological Survey; TD-OU Tom Dewers, U of Oklahoma; MZ-SU Mark Zoback, Stanford University; HO-RU Hiroshi Ogasawara, Ritsumeikan University, Japan; JE-GFZ Joerg Erzinger, GeoForschungsZentrum, Germany; GD-GFZ Georg Dresen, GeoForschungsZentrum, Germany; GS-IGS Gideon Stienitz, Israel Geological Survey

Figure 9-1 *Outline of activities within the RSA-project*

A schedule is shown in Figure 9-2.

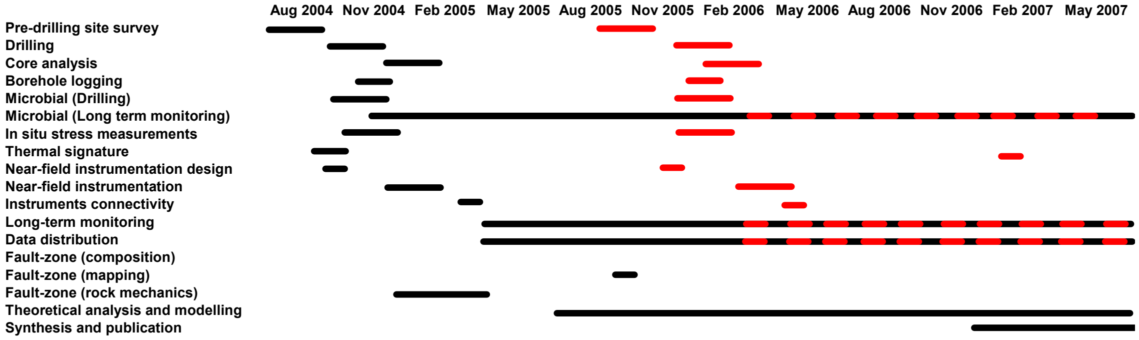

Figure 9-2. *Timetable for the NELSAM/DAFSAM project. Black bars refer to Pretorius fault operations and red bars relate to Dagbreek fault operations.*

9.2 Studies of surface ruptures and fault displacements in the US

The study by /Bäckblom et al 2004/ is mainly based on studies of underground facilities and modelling of target fracture slip. Petersen et al, 2004 presents methodology that is complementary and developed for the purpose of finding a suitable respect distance from a surface facility or lifeline to an active fault[4]. The Alquist-Priolo Earthquake Fault Zoning Act prevents construction of habitable buildings on the surface trace of an active fault (defined as having ruptured within the past 10,000 years) but it is recognized by the authors that facilities close to faults needs careful considerations. The work is an extension of previous work for the Yucca Mountain Project.

The surface rupture data sets used are shown in Figure 9-3 where the main rupture triggered movements on nearby potentially unstable faults.

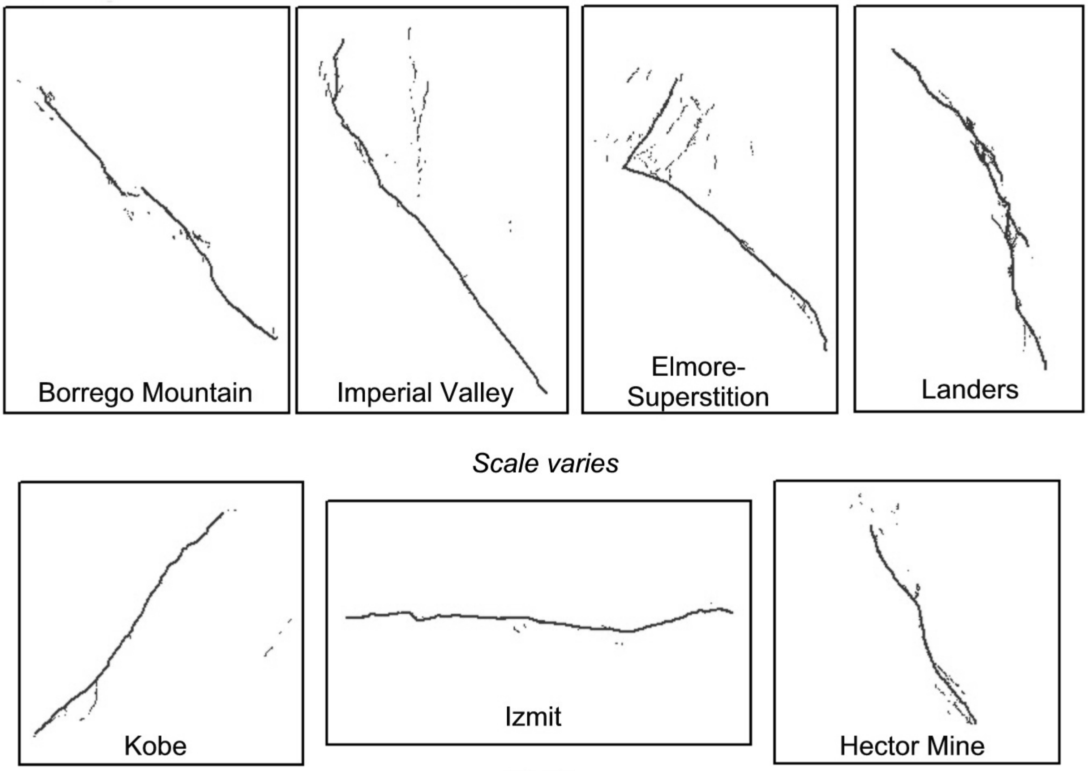

Figure 9-3. *Surface rupture traces used /Revised from Petersen et al, 2004/.*

One part of the study is mapping accuracy and the Hector Mine earthquake offset bomb craters were useful markers, Figure 9-4.

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[4] The figures in this section are from the presentation by Dr. Mark Petersen, US Geol Survey, at the 13th World Conf. in Earthquake Engineering and generously provided to the lead author of this report.

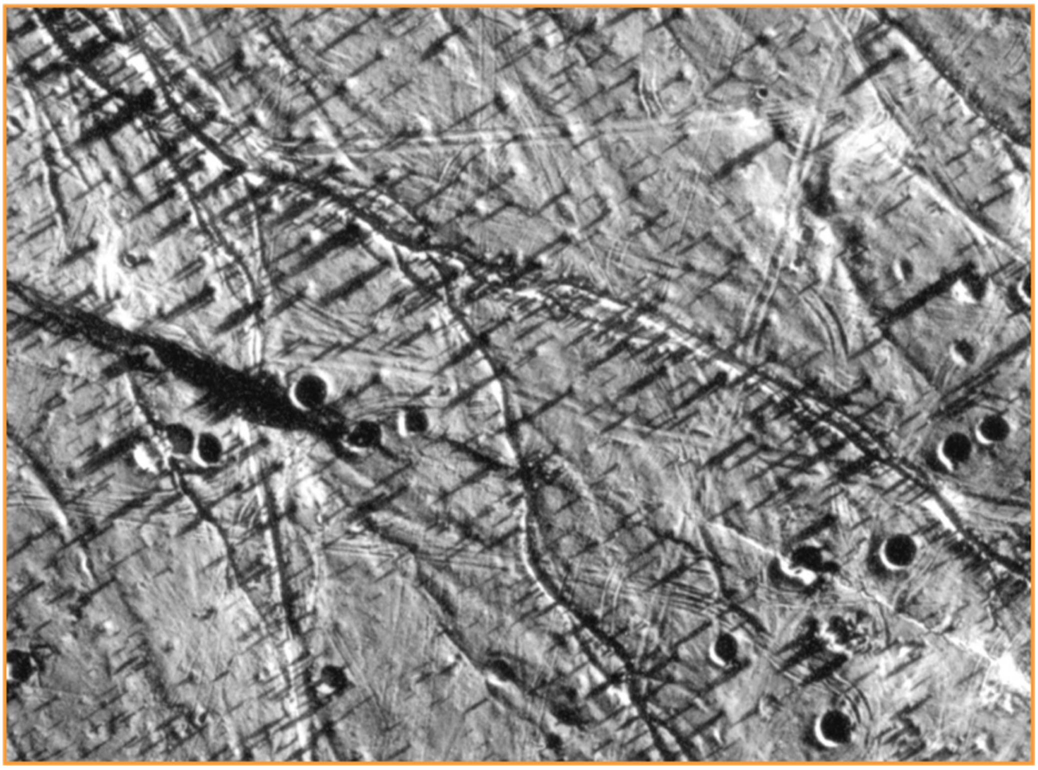


Figure 9-4. *Offset bomb craters from the Hector Mine Earthquake*

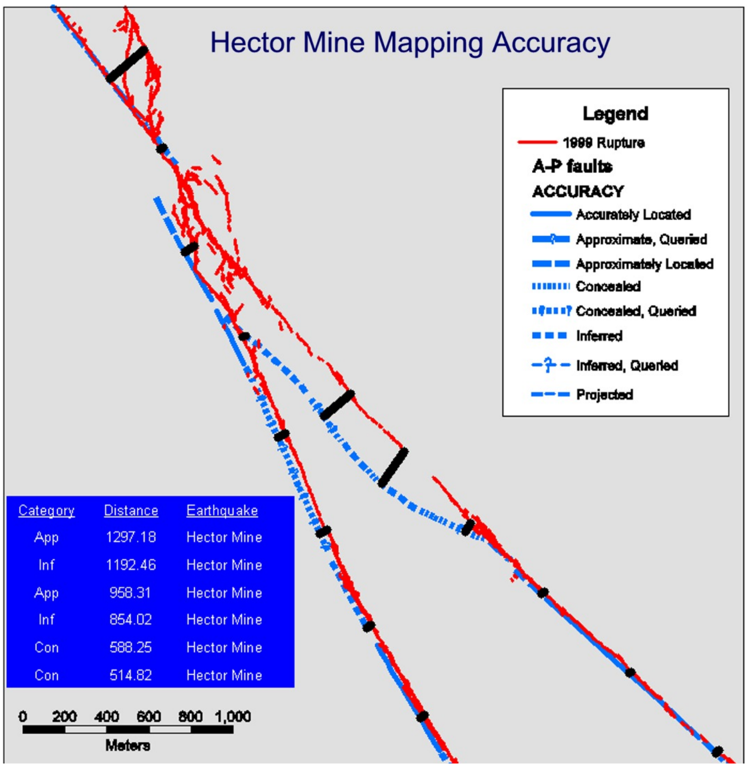
The surface rupture did not follow earlier mapped faults and the accuracy was dependent on uncertainty in the mapping, Figure 9-5.

METHODS

Use digitized A-P traces and ruptures

Digitize perpendicular distance between mapped trace and rupture trace

Line lengts represents difference between mapped trace and rupture trace, attributed accordingly to uncertainty category



Category	Distance	Earthquake
App	1297.18	Hector Mine
Inf	1192.46	Hector Mine
App	958.31	Hector Mine
Inf	854.02	Hector Mine
Con	588.25	Hector Mine
Con	514.82	Hector Mine

Figure 9-5. *Surface rupture also took place at previously unmapped/hidden faults*

Displacements in the main faults and surrounding structures were carefully analysed both along the faults as well as perpendicular to the faults. Figure 9-6 clearly corroborates that displacements are at the maximum at the centre of the fault with smaller displacements at the ends of the fault.

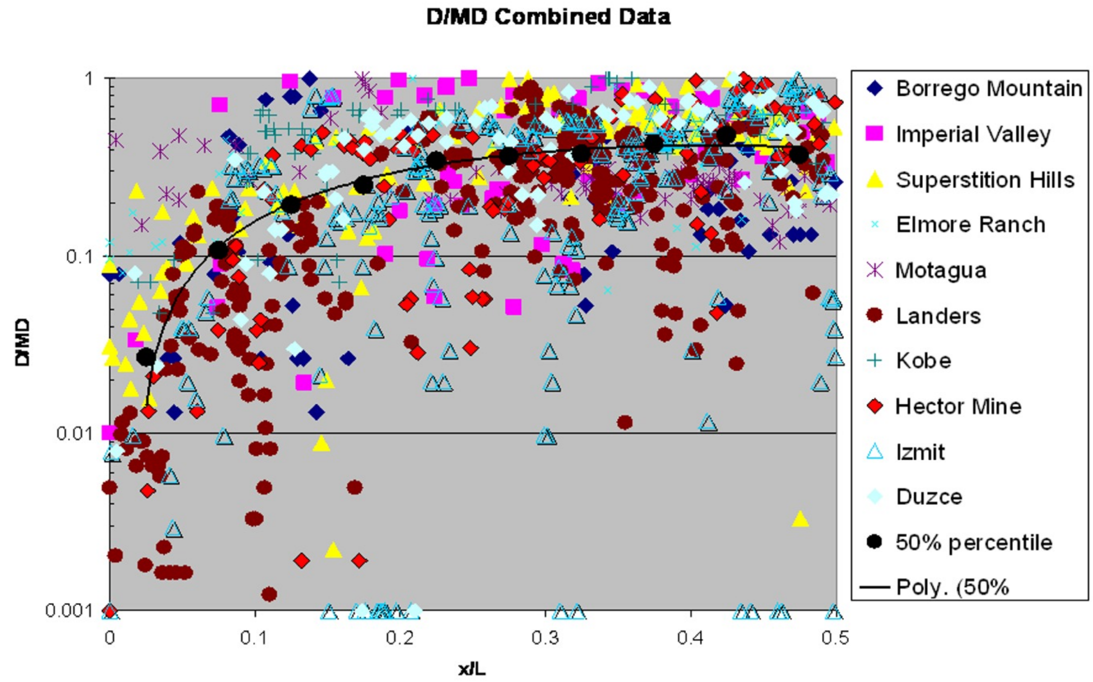


Figure 9-6. *Displacements data along the fault. The y-axis indicated the measured displacements divided by average displacements and the x-axis the distance from the end of the fault x divided by the total length of the rupture.*

Displacements at perpendicular distance from a main fault are shown in Figure 9-7 and in Figure 9-8.

With a set of probability functions, the probability for displacements at different perpendicular distances to the fault is calculated. An example is shown in Figure 9-9 where a fault has a characteristic magnitude of 7.26 and with a recurrence of 250 years. The vertical axis is the surface displacement to be exceeded with probabilities of 2 %, 5 %, and 10 % in 50 years respectively. For this illustration, the fault trace location is assumed to be well located, with a standard deviation of 10 meters.

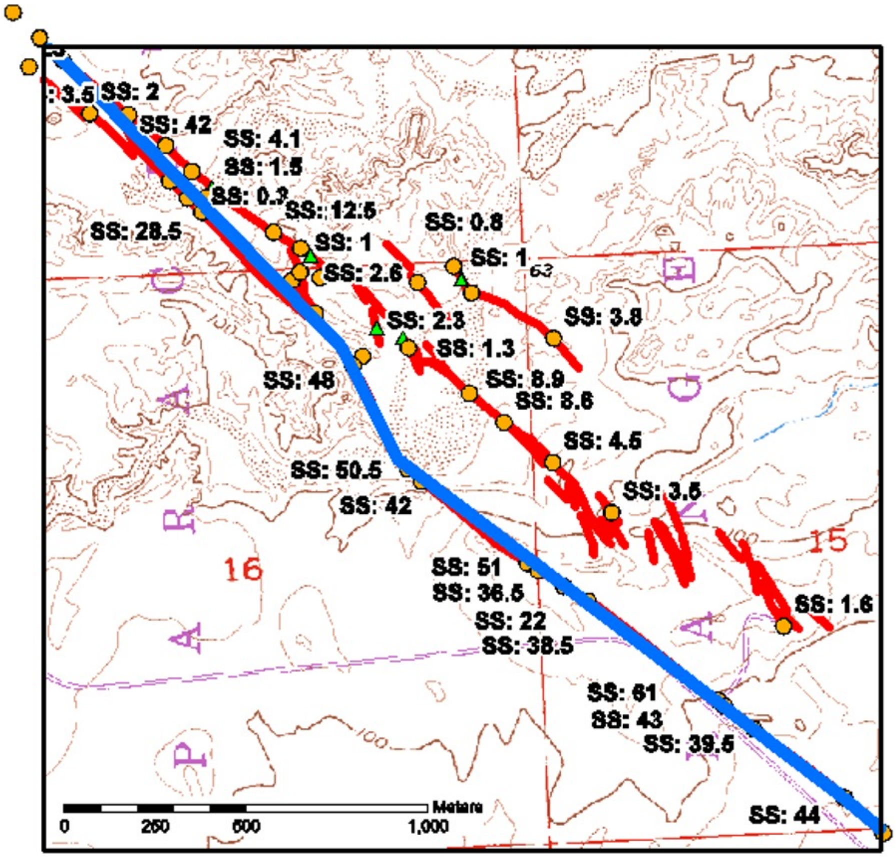


Figure 9-7. *Ruptures due to the Superstition Earthquake of 1987. Measurements in centimetres of displacements at perpendicular distance from the main fault. SS indicates Strike-Slip.*

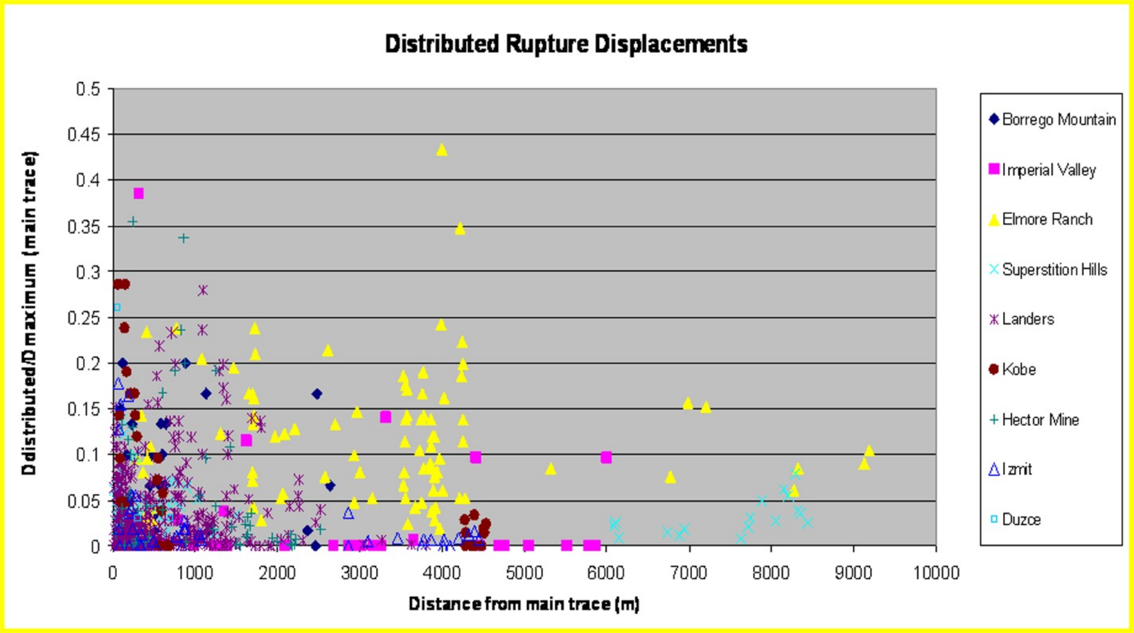


Figure 9-8. *Distributed rupture displacements as a function of the perpendicular distance to the main fault.*

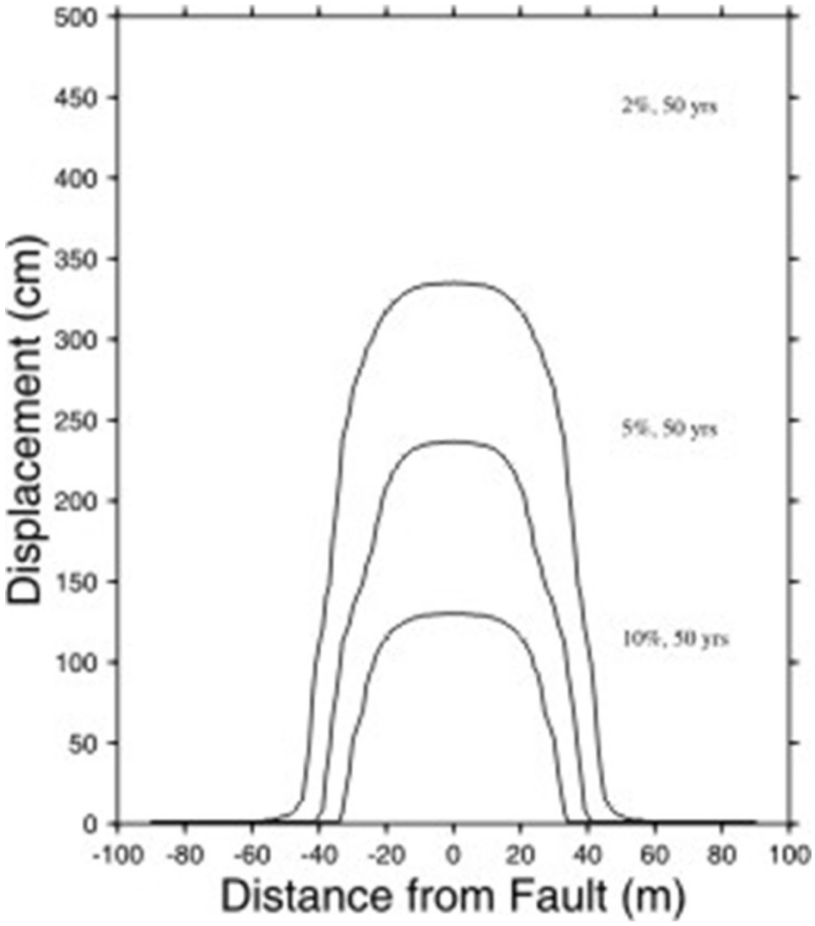


Figure 9-9. *Example of fault displacement hazard on a transect that crosses the fault.*

An interesting issue is whether the ruptures shown in Figure 9-3 are reactivation or creation of new discontinuities? The question was answered by Dr Bill Bryant at the California Geological Survey (pers.comm.)

At Landers there were a great many complex, minor ruptures, usually along stepovers that had no geomorphic evidences of prior rupture. Most of the principal stepovers, however, did have evidence of previous displacements and, in hindsight could be recognized. In one sense, many of the minor displacements at the surface appeared to be new fractures, although I would presume that at depth they probably coalesced into pre-existing fault zones. It would be difficult to preserve these minor displacements in the type of surface materials they typically developed in. For example, at the southern part of the Landers rupture (Flamingo Heights area) there was a broad zone of minor displacements that occurred in loose fluvial and eolian sands, but these offsets cannot likely be found today. However, when looking at the configuration of the Johnson Valley fault in this area, it becomes obvious that there is a slight right-releasing bend in the fault exactly where this zone of displacements occurred - even had the expected sense of displacement.

Given the tectonic framework of the Landers event within the Eastern California shear zone, one would now expect a complex rupture pattern, anticipating that a broader zone of minor rupture and diffuse fracturing would occur at and near the surface. On the other hand, large ruptures on the San Andreas fault in the Carrizo Plain, for example, demonstrate repeated rupture along the same fault for the past several thousand years.

Generally speaking, most future surface faulting will occur along previous recent surface faulting. Armed with the knowledge that minor changes in fault strike often produce a more complex surface rupture pattern, one could anticipate "new surface fractures" at the distal ends of faults, at steps and bends in faults, and near the intersection of faults.

It is recommended that SKB closely tracks the R&D also in the US to build confidence in the primary conceptual idea that reactivation is along pre-existing zones and that the permanent effects of the reactivations are localised to the rupture zone and/or nearby existing faults with very local effects on the fractures.

9.3 International workshop within the nuclear community

We have contacted repository implementers (Andra, Enresa, Nagra, NUMO, Posiva, USDOE/YMP) to assess interest in a possible workshop on respect distance. There has been minimal response, as the topic appears to have been framed too narrowly and it seems that the issue of earthquakes and layout is actively pursued by very few organizations. In consultation with SKB (Rolf Christiansson) it is suggested that a broader workshop - layout adaptation of the repository to the site-specific conditions at hand - possibly would be of more widespread interest. However it is thought that the good co-operation with NUMO, JNC and CRIEPI could be fully utilized. SKB and Posiva have jointly decided to discuss the matter of respect distance and organise a workshop in the spring of 2005.

10 Conclucion

Based on this preliminary study conducted over a couple of months, a number of conclusions have been prepared.

Estimation of fracture length by mapping

In the absence of clear geological signatures as may be evident for a fault, it is nearly impossible to map large fractures underground. The probability that the same large fractures (> 100 m radii) can be traced deterministically by investigations is likely to be very low. The parameter “fracture size” is in general not possible to measure directly at a specific canister position. What we can aim for is classification of fracture sizes by using surrogate parameters for fracture sizes.

Use of surrogate parameters for fracture size

Preliminary studies of outcrop data sets at Forsmark, Oskarshamn (Simpevarp) in Sweden and Olkiluoto in Finland clearly suggest that we can classify fracture size likely to be larger than a certain threshold from those that are below by using data that can be collected in boreholes. The study was somewhat hampered by the very few large fracture sizes in the databases and efforts should be made to really map the large fractures at the outcrops as these large fractures are important for the safety analyses.

Terminology

More work is needed to clarify terminology. The division of rock into “zones” and “fractures” are too simplified a classification for some applications. There are geological linear elements to consider in between these two extremes. We need to improve nomenclature and databases for “fracture swarms” or “fracture clusters” where several short fractures are in close spatial proximity and jointly form – element by element – large, connected fracture structures. Such clusters are likely to be avoided for a deposition hole.

The concept of the “deformation zone” needs additional clarifications. The total width of the “deformation zone” is the sum of the “core” of the zone and a “transition zone”, where the definition of “transition zone” should be developed further; from earthquake point of view it is the potential for new fracturing and implications for safety that is of importance.

It is beneficial if terminology and nomenclature used by SKB in Sweden and Posiva in Finland is harmonised to the extent possible.

Geometrical distance from a deformation zone to a deposition position for reasons of potential slip

Models for possible earthquake damage of the engineered barriers (slip of > 0.1 m over the canister) are based on three fundamental parameters, the stress drop at the earthquake fault, the distance from the primary earthquake fault and the fracture size of the target fracture. In general the models show that the slip over a fracture decreases with decreasing fracture size and increasing distance from the primary fault. The models infer that fractures < 100 m of radii are of less importance for damage even if canisters are closer than 100 m to the primary earthquake fault. The validity of the these models is however difficult to prove for target fractures close to the primary fault as many non-linear effects may appear in reality. For this reason it is suggested that deposition holes intersected by large fractures (classified as radii > 100 m) are avoided for deposition, independent of the distance from the potential primary slip fault.

Geometrical distance from a deformation zone to a deposition position for reasons of potential new fracturing

This study shows that primary faulting may create secondary faulting at several kilometres distance from the primary fault trace, but it is likely that the secondary faulting is reactivation of old zones. Previous studies also show that some new fractures may develop but only very close to a reactivated fault.

The methods to show that existing fractures are “new” are unfortunately not very reliable, but there several possible methods to date mineral fillings and thereby establish the age of the fracture. There are no evidences of new fracturing (since last glaciation) at depth at Simpevarp and Forsmark.

With the hypothesis that new fracturing due to an earthquake is taking place within the transition zone and that the transition zone presently is excluded for deposition, suggests that further studies of the transition zone are useful.

The transition zone

There is need to clarify the methodology to define the width of the transition zone and this preliminary study suggests: The transition zone is to varying degrees characterised by a higher amount of micro-fractures than in the fresh rock. Higher porosity and lower density (than the fresh rock) characterise usually the transition zone. The chemical characterisation of the transition zone can be difficult since the mineral alteration does not necessarily affect the whole rock chemistry. From this follows that mineralogy is a better tool to characterise the transition zone than geochemistry.

Usefulness of the concept of respect distance

SKB has by previous work assessed that the concept of respect distance as a geometrical measure is less useful for issues related to thermal, chemical and transport of solutes processes, but has kept it for the purpose of earthquakes. This study suggests that the respect distance as a geometrical measure for the earthquake issues is not very useful, as large fractures should be avoided independent of the geometrical distance from a zone to the deposition position.

11 Discussion

Methods for site characterization should be reliable, robust, repeatable and testable, employ parameters that are useful and feasible to measure, and are updatable during the course of the repository implementation.

Determination of "respect distance" due to transport modelling is of less interest as the key parameter not distance by itself but flow resistance in which distance is only one of the model parameters. The flow resistance modelling is likely to be stochastic where the overall behaviour of the repository is described. In the case where the site characterization provides deterministic description of the flow paths, the model (and the repository layout) may be constrained by these deterministic features.

It is possible to conceive of a "respect distance" to faults with respect to temperature effects and possible effects of changes in groundwater chemistry. Temperature effects are minor, however, and the overall groundwater chemistry should be favourable and the site and the repository safety robust for foreseen variations in the groundwater chemistry.

The quest for "respect distance" for possible future earthquakes is a matter of completeness of scenarios. We cannot exactly estimate how many strong earthquakes will occur in Fennoscandia during a future deglaciation and even less so how many of those would occur exactly at the location of the repository. However the models imply that consequences of large earthquakes would be insignificant even when using truly pessimistic assumptions. On the other hand we need to admit that fully realistic dynamical modelling is exceedingly complex, and difficult to validate. We would require a number of strong earthquakes close to a fully instrumented and described site to validate the models. However, fracture mechanics and field studies show that large fractures and fracture zones are more prone for reactivations. These need to be in the range of 2-3 km in length to displace 0.1 m. Such long fracture zones will be detected in the characterization of the site and of course avoided for deposition holes. Furthermore as the likelihood for higher transmissivity somehow is correlated to the length of fractures there are several reasons to avoid those features close to the canisters. From general point of view it is then more useful to find methods to avoid large fractures in the deposition holes than to identify how close to a fracture zone the canister can be deposited; it is anticipated that such a distance can be very small as long as the rock conditions in the deposition hole and its immediate surrounding comply with the requirements and preferences of a repository site.

The introduction of a new concept like “transition zone” might be useful from a geological perspective, but it is not to taken for granted that the functional classification of suitability should be tied to “transition zones”. The volume of transition zone of the rock should not be treated as “unsuitable for deposition”, but rather to be used as a volume where “deposition is possible” or even “probable” in the first run. Additional zone-specific studies should be employed to decide whether the volume is proven, probable, possible or not suitable for deposition.

For the layout of the repository the core of the deformation zone – the fracture zone – should be defined. The transition zone should functionally be treated as a zone of lower probability for deposition.

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