Working Report 2011-38

Understanding Brittle Deformation at the Olkiluoto Site

Literature Supplement 2010: an Update of Posiva Working Report 2006-25

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July 2011

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ABSTRACT

Posiva Working Report 2006-25 arose from the belief that geological modelling at Olkiluoto, Finland, where an underground repository for spent nuclear fuel is at present under construction, could be significantly improved by an increased understanding of the phenomena being modelled, in conjunction with the more sophisticated data acquisition and processing methods which are now being introduced. Since the geological model is the necessary basis for the rock engineering and hydrological models, which in turn provide the foundation for identifying suitable rock volumes underground and for demonstrating long-term safety, its scientific basis is of critical importance. As a contribution to improving this scientific basis, the literature on brittle deformation in the Earth's crust was reviewed up to and including year 2005. The result was a compilation of scientific articles, reports and books on some of the key topics of significance for an improved understanding of brittle deformation of hard, crystalline rocks, particularly heterogeneous migmatitic and metamorphic rocks like those that make up the Olkiluoto bedrock. The present report is a supplement to WR 2006-25, covering the 5-year period 2006-2010, with some key earlier references and an Annotated Bibliography.

The present report is subdivided into five chapters, listing recent literature on (1) background subjects and basic principles, (2) the fabric of Olkiluoto-type intact rock (gneisses, migmatites, fault rocks), (3) formation and characteristics of brittle deformation features (fracture mechanics, brittle microtectonics), (4) fracture data acquisition and processing (statistical characterisation and modelling of fracture systems), and (5) the characterisation of brittle deformation zones (for deterministic and dynamic modelling), corresponding to the first five chapters of the earlier report. The chapters are subdivided into a number of sections, and each Section into a number of topics. In contrast to WR 2006-25, the citations are given in full under each topic and listed chronologically. The systematic arrangement and numbering of the chapters (e.g. Chapter 5: Brittle Deformation Zones), sections (e.g. Section 5.2: Fault Zone Characterisation) and topics (e.g.Topic 5.2.3: Fault Slip Analysis) is such that the Table of Contents can be used to focus quickly on the theme of interest without the necessity of looking through the whole report. In the Annotated Bibliography, each citation is listed once, according to normal bibliographic rules, whereas in the main text it may appear at several places, under different topics. An electronic copy of the report is available in Posiva's website (www.posiva.fi) to enable the easy preparation of reference lists on any topic.

Keywords: Scientific literature, bibliography, brittle deformation, crystalline rocks, Olkiluoto site, Finland, structural geology, fracture systems, fracture zones, fault zones.

OLKILUODON ALUEEN KALLIOPERÄN HAURAS DEFORMAATIO

KIRJALLISUUSSELVITYS PAIKKATUTKIMUSTA JA GEOLOGISTA MALLINNUSTA VARTEN, TÄYDENNYS RAPORTTIIN 2006-25

TIIVISTELMÄ

Olkiluodon kallioperään ollaan tällä hetkellä rakentamassa maanalaista tutkimustilaa käytetyn ydinpolttoaineen loppusijoitusta silmällä pitäen. Geologinen malli on tärkeä lähtökohta kalliomekaanisille ja hydrologisille malleille, jotka puolestaan luovat pohjan loppusijoitustiloille sopivien kalliotilavuuksien tunnistamiselle sekä vaikuttavat pitkäaikaisturvallisuuteen liittyvien analyysien tekoon; näin ollen geologisella mallilla on oltava vankka tieteellinen pohja. Posivan työraportti 2006-25 kehittyi ajatuksesta, että kehittämällä mallinnettavien ilmiöiden taustan perusteellista ymmärtämistä yhdessä kehittyneiden tiedonhankinta- sekä käsittelymenetelmien kanssa olisi myös mahdollista parantaa Olkiluodon geologiseen malliin liittyvää tieteellisyyttä. Sen vuoksi tässä raportissa on pyritty antamaan kattava selvitys hauraaseen deformaatioon liittyvän kirjallisuuden nykytilanteesta ja tärkeimmät kirjallisuuslähteet on valittu ja järjestelty nimenomaan Olkiluodon geologiaa ajatellen. Tuloksena on selvitys tärkeimmistä tieteellisistä artikkeleista, raporteista ja kirjoista, jotka liittyvät Olkiluodolle tyypillisten kiteisten kivien hauraaseen deformaation. Tämä raportti täydentää työraporttia 2006-25 viiden vuoden jakson 2006-2010 osalta.

Raportti on jaettu kuuteen lukuun, jotka kattavat seuraavat aihealueet: (1) taustat ja perusteet, (2) gneissien, migmatiittien ja siirroskivien rakenne, (3) hauraiden deformaatiopiirteiden muodostuminen ja luonne, (4) rakoaineiston hankinta ja käsittely rakosysteemien tilastollista mallinnusta varten, (5) hauraiden deformaatiovyöhykkeiden karakterisointi determinististä mallinnusta varten. Raportin luvut on jaettu kappaleisiin ja jokainen kappale edelleen eri aihepiireihin. Vastoin työraporttia 2006-25 viittaukset on kirjattu kokonaisuudessaan ja kronologisesti jokaisen kappaleen yhteyteen. Kappaleiden systemaattinen numerointi on tehty siten, että sisällysluetteloa voidaan käyttää eri teemojen nopeaan tarkasteluun ilman koko raportin läpikäyntiä. Kirjallisuusluettelossa jokainen viittaus on esitetty normaalien bibliografisten sääntöjen mukaisesti vain kerran. Päätekstissä yksittäinen viite saattaa sen sijaan esiintyä useammin kuin kerran, eri aihepiireihin liittyen. Raportti on saatavilla sähköisessä muodossa Posivan nettisivuilla (www.posiva.fi), jotta lukijan olisi helppo koota oma kirjallisuusluettelonsa mistä tahansa raportin aihepiiristä.

Asiasanat: Tieteellinen kirjallisuus, bibliografia, hauras deformaatio, kiteinen kivi, Olkiluoto, Suomi, rakennegeologia, rakosysteemit, rakovyöhykkeet, siirrosvyöhykkeet.

PREFACE

In 2006, a Posiva Working Report was published entitled "Understanding Brittle Deformation at the Olkiluoto Site. Literature Compilation for Site Characterization and Geological Modelling" (Working Report 2006-05 - Milnes 2006a). It arose from the belief that geological modelling at the Olkiluoto site could be significantly improved by an increased *understanding* of the phenomena being modelled, in conjunction with the more sophisticated data acquisition and processing methods which were then being introduced (e.g. Milnes et al. 2007). Since the geological model is the necessary basis for dynamic rock engineering and hydrological models, which in turn provide the foundation for identifying suitable rock volumes underground and for demonstrating long-term safety, its scientific basis is of critical importance. Hence, as a contribution to improving this scientific basis, the literature on brittle deformation in the Earth's crust was reviewed, and key references chosen and arranged, with the particular geology of the Olkiluoto site in mind. The result was a compilation of scientific articles, reports and books on some of the key topics which are of significance for an improved understanding of brittle deformation of hard, crystalline rocks, such as those typical for Olkiluoto. The scientific and technical literature on this subject is, of course, immense, and cannot be digested by a single person, let alone be presented in its entirety in a single report. The literature collected in that report was above all a personal selection by the author, based on material acquired during a long teaching and consulting career, and “looked through”, if not always studied in detail, during frequent browsing sessions in physical and virtual libraries. The aim of the report was not to give a rigorous and complete overview, but rather to provide pointers towards some key sources of information. It was hoped, thereby, that the interested reader would be guided towards a convenient "entry into the literature", from where he himself or she herself could start a more detailed search. For that reason, an important criterion for including a particular reference was a judgement of scientific quality and ease of access. In the case of scientific papers, this meant taking references mainly from international, peer-reviewed journals, wherever possible. The reference lists in the most recent of such papers give the reader immediate access to a more expert assessment of the most important literature on that particular topic, with a more complete coverage. Although published in hard copy, Working Report 2006-25 was accompanied by an electronic copy in Word on a CD, to make it easy for users of the report to create their own literature list on any topic. In addition, a collection of some 300 partial or complete paper copies of scientific papers cited in the Working Report was deposited in the Posiva office for consultation. Many of those papers were published before electronic distribution was possible, and they are therefore not easily available.

The present report is basically an update and a partial revision of Working Report 2006-25. The structure of the report is similar: the main Chapters are the same and the subdivision into Sections and Subsections (here called "Topics") is retained, with some minor revision. The literature reviewed, however, has been much more restricted, being confined to the technical reports which have been published between 2000 and 2010 by Posiva and SKB. Although the word "update" implies that only reports appearing since the end of 2005 (the "data freeze" for WR 2006-25) are included in the present report, I have also included key documents from the earlier report whenever I felt that it helped the reader to obtain an overview of the topic, without necessarily consulting the original. Nevertheless, the focus is on post-2005 geoscientific research, covering a

period which has been exceptional, both for Posiva and SKB. At Posiva, a major research effort has been underway with the driving of the ONKALO access tunnel and shafts, accompanied by an increased above-ground research activity, whilst in Sweden major characterisation and modelling efforts were focussed on the detailed investigation sites at Forsmark (c. 200 km from Olkiluoto) and Laxemar. During this period I have been involved in review work for both companies and have had the opportunity to follow this unique process at close hand. Nevertheless, the present compilation is only the tip of the iceberg - from the two SKB investigation sites, about 1200 technical reports have been published between 2002 and 2009, and in the same period about 500 Posiva Working Reports have appeared. Even confining myself to the most geological of the geoscience output, I cannot claim to have more than a superficial view of the whole documentation. My sifting has been focussed on identifying anything of relevance to understanding brittle deformation at Olkiluoto and the results are presented here in a form which I hope will be of practical use in coming characterisation and modelling efforts.

The present report has two main parts. The first part consists of the Chapters and Sections listed in the List of Contents. Under each section are arranged the works falling in that category, cited in full (in contrast to WR 2006-25). The references are arranged in each list chronologically, with the most recent publications last. In many cases, the title of the report indicates why it is included in each particular list. In many other cases, this will not be clear from the title, and for more information the reader must consult the Annotated Bibliography, which is the second main part of the report. All books and major reports are cited there (arranged alphabtically, according to normal bibliographic rules), together with a list of contents, from which the Chapter in the book/report can be identified which contains the relevant material. These annotations, i.e. notes on the content of each document giving more details than the title itself, in the Bibliography are a new feature of this report (not to be found in WR 2006-25), in an attempt to make it more informative and useful.

The work of compiling this background material in a usable form has been performed under contract to Posiva Oy. The contact persons in Posiva have been Liisa Wikström (now at SKB), Jussi Mattila (now at the Geological Survey of Finland) and Ismo Aaltonen (Posiva), and I would like to thank them for their interest in the project and for many discussions along the way.

Figure 1. *Understanding brittle deformation at the Olkiluoto site. Consultants J. Hudson, S. Paulamäki and A.G. Milnes studying jopinting in shore outcrops on an island near the Olkiluoto power stations (Photo: L. Wikström).*

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Figure 2. *A section of the ONKALO access tunnel at Olkiluoto showing the extreme lithological heterogeneity which is characteristic of many parts of the Olkiluoto bedrock(Photo: Posiva).*

1 ROCK DEFORMATION: BASIC PRINCIPLES

The documents in Chapter 1 serve as a general background for this compilation of key literature on brittle deformation in the Earth's crust, particularly in relation to the Olkilluoto site and the needs of the deep disposal project for spent nuclear fuel in Finland. The documents are collected into two groups, which together provide introductory material to the most basic features of natural rock deformation. The first group (Section 1.1) is a list of basic textbooks, essentially those which I have found most useful for university courses in structural geology and tectonics, and/or most useful in connection with the application of structural principles to practical geological problems. As in the rest of this report, the selection leans towards the "geological approach", i.e. the references emphasize basic geological and tectonic principles, and the present-day understanding of the modes of formation of deformation structures and structural associations. However, some works which take a more "practical approach" are included, including some general references relevant to nuclear waste disposal in all its aspects. The second group (Section 1.2) is more "scientific" in content: together with the material presented in Working Report 2006-25, it focusses on the basic concepts of "brittle", "semi-brittle" and "ductile" rock deformation under conditions pertaining in the Earth's crust from the results of experimental rock deformation under high PT conditions, and on the construction of rheological profiles through the crust. The latter are important as a starting point for understanding the regional tectonic framework of Olkiluoto, including the important topic of glacio-tectonics, and also as background for the Sibson/Scholz fault zone model, which is the basis for the classification of deformation zones used at the Olkiluoto site (Chapter 5).

Figure 3. *Surface outcrops of a large, well exposed fault zone cutting migmatitic bedrock similar to Olkiluoto at Golta, west coast of Norway. The zone is being studied by a group of Posiva geologists on a field workshop in April 2006 (Photo: A.G. Milnes).*

1.1 General and Background Sources

1.1.1 Structural Geology
1.1.2 Brittle Deformation and Rock Mechanics
1.1.3 Nuclear Waste Disposal

Selected geoscience textbooks (Topics 1.1.1 and 1.1.2)

Turner, F.J., Weiss, L.E., 1963. **Structural Analysis of Metamorphic Tectonites**. McGraw-Hill (New York, etc.).

Ramsay, J.G., 1967. **Folding and Fracturing of Rocks**. McGraw-Hill (New York, etc.).

Fry, N., 1984. **The Field Description of Metamorphic Rocks**. Geological Society of London Handbook, Open University Press (Milton Keynes).

McClay, K.R., 1987. **The Mapping of Geological Structures.** Geological Society of London Handbook, Open University Press (Milton Keynes).

Atkinson, B.K., ed., 1987. **Fracture Mechanics of Rock**. Academic Press (London, etc.).

Passchier, C.W., Myers, J.S., Kröner, A., 1990. **Field Geology of High-Grade Gneiss Terrains**. Springer-Verlag (Berlin, etc.).

Engelder, T., 1993. **Stress Regimes in the Lithosphere**. Princeton University Press (Princeton, N.J.).

Hancock, P.L., ed., 1994. **Continental Deformation**. Pergamon Press (Oxford, etc.).

Priest, S.D., 1993. **Discontinuity Analysis for Rock Engineering**. Chapman & Hall (London, etc.).

Davis, G.H., Reynolds, S.J., 1996. **Structural Geology of Rocks and Regions. 2nd Edition**. John Wiley & Sons (New York, etc.).

NRC/CFCFF 1996. Rock **Fractures and Fluid Flow. Contemporary Understanding and Applications**. Report of the Committee on Fracture Characterization annd Fluid Flow, National Research Council, National Academy Press (Washington D.C.).

Hudson, J.A., Harrison, J.P., 1997. **Engineering Rock Mechanics. Part I: An Introduction to the Principles**. Pergamon (Amsterdam, etc.).

Scholz, C.H., 2002. **The Mechanics of Earthquakes and Faulting, 2nd Edition**. Cambridge University Press (Cambridge, U.K.).

Le Maitre, R.W., ed., 2004. **Igneous Rocks. A Classification and Glossary of Terms. 2nd Edition**. IUGS/Cambridge University Press (Cambridge, UK).

Lehtinen, M., Nurmi, P.A., Rämö, O.T., eds., 2005. **Precambrian Geology of Finland. Key to the Evolution of the Fennoscandian Shield**. Elsevier (Amsterdam, etc.).

Pollard, D.D., Fletcher, R., 2005. **Fundamentals of Structural Geology**. Cambridge University Press (Cambridge, UK).

Fettes, D., Desmons, J., eds., 2007. **Metamorphic Rocks. A Classification and Glossary of Terms**. IUGS/Cambridge University Press (Cambridge, UK).

Fossen, H., 2010. **Structural Geology**. Cambridge University Press (Cambridge, UK).

Sources related to Nuclear Waste Disposal (Topic 1.1.3)

Miller, W., Alexander, R., Chapman, N., McKinley, I., Smellie, J., 2000. **Geological Disposal of Radioactive Wastes and Natural Analogues**. Pergamon (Amsterdam, etc.).

Milnes, A.G., 2002. **Swedish deep repository siting programme. Guide to documentation of 25 years of geoscientific research (1976-2000)**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-02-18.

Milnes, A.G., 2006a. **Understanding brittle deformation at the Olkiluoto site. Literature compilation for site characterization and geological modelling**. Posiva Oy, Working Report 2006-25.

Milnes, A.G., 2006b. **Brittle Deformation of Hard Rock**. Posiva Oy, CompactDisc containing a complete set of PowerPoint presentations given in Posiva in-house course at Olkiluoto, 20-21 September, 2006

Posiva Oy, 2006. **Expected evolution of a spent nuclear fuel repository at Olkiluoto.** Posiva Oy, report POSIVA 2006-05.

Milnes, A.G., Stephens, M.B., Wahlgren, C.-H., Wikström, L., 2008. **Geoscience and high-level nuclear waste disposal: the Nordic scene**. Episodes, 31, 168-175.

Posiva Oy, 2008.. **Safety Case Plan 2008**. Posiva Oy, report POSIVA 2008-05.

Posiva 2009. **Olkiluoto Site Description 2008**. Posiva Oy, report POSIVA 2009-01.

SKB 2008b. **Site description of Forsmark at completion of the site investigation phase. SDM-Site Forsmark**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-08-05.

Ch. 1: introduction, background, project methodology, objectives, strategy

Ch. 2: investigations, available data and other prerequisites for modelling
Ch.11: summary present site understanding, incl. rock domains, brittle deformation, rock stress, bedrock hydraulic properties, and "overall confidence"
Ch.12: conclusions - fulfillment of objectives, remaining issues, implications for underground construction

SKB 2009. **Site description of Laxemar at completion of the site investigation phase. SDM-Site Laxemar**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-09-01.
Ch. 1: introduction, background, project methodology, objectives, strategy
Ch. 2: investigations, available data and other prerequisites for modelling
Ch.11: summary present site understanding, incl. rock domains, brittle deformation, rock stress, bedrock hydraulic properties, and "overall confidence"
Ch.12: conclusions - fulfillment of objectives, remaining issues, implications for underground construction

Figure 4. *Close-up of the ca. 0.5 m thick core of the fault zone shown on page 9. In the core, semi-brittle fault rocks have been overprinted by later brittle fracturing (Photo: A.G. Milnes).*

1.2 Deformation of Intact Rock under Crustal Conditions

1.2.1 High PT Experimental Rock Deformation - Basic Results
1.2.2 Rheological Profiles of the Lithosphere, and the Sibson-Scholz Fault Zone Model

For explanatory texts to these topics, see Section 1.2 in Posiva Working Report 2006-25 (Milnes 2006a).

Experimental Rock Deformation (Topic 1.2.1)

Jaeger, J.C., 1962. **Elasticity, Fracture and Flow, with Engineering and Geological Applications. 2nd Edition**. John Wiley & Sons (New York).

Turner, F.J., Weiss, L.E., 1963. **Structural Analysis of Metamorphic Tectonites**. McGraw-Hill (New York, etc.).

Ramsay, J.G., 1967. **Folding and Fracturing of Rocks**. McGraw-Hill (New York, etc.).

Paterson, M.S., 1978. **Experimental Rock Deformation - the Brittle Field**. Springer-Verlag (Berlin, etc.).

Evans, B., Frederich, J.T., Wong, T.-F., 1990. **The brittle-ductile transition in rocks: recent experimental and theoretical progress.** American Geophysical Union, Geophysical Monograph 56, 1-20.

Twiss, R.J., Moores, E.M., 1992. **Structural Geology**. W.H. Freeman & Co. (New York).

Engelder, T., 1993. **Stress Regimes in the Lithosphere**. Princeton University Press (Princeton, N.J.).

Lockner, D.A., 1995. **Rock failure**. In: Rock Physics and Phase Relations. A Handbook of Physical Constants. American Geophysical Union (Washington DC), Reference Shelf 3, 127-147.

Snoke, A.W., Tullis, J., Todd, V.R., 1998. **Fault-related Rocks. A Photographic Atlas**. Princeton University Press (Princeton, NJ).

Rheological Profiles of the Lithosphere, and the Sibson-Scholz Fault Zone Model (Topic 1.2.2)

Ranalli, G., 1995. **Rheology of the Earth. 2nd Edition**. Chapman & Hall (London, etc.).

Gratier, J.P., Renard, F., Labaume, P., 1999. **How pressure solution creep and fracturing process interact in the upper crust to make it behave in both a brittle and viscous manner**. Journal of Structural Geology, 21, 1189-1197.

Imber, J., Holdsworth, R.E., Butler, C.A., Strachan, R.A., 2001. **A reappraisal of the Sibson-Scholz fault zone model: the nature of the frictional to viscous ("brittle-ductile") transition along a long-lived, crustal-scale fault, Outer Hebrides, Scotland**. Tectonics, 20, 601-624.

Scholz, C.H., 2002. **The Mechanics of Earthquakes and Faulting, 2nd Edition**. Cambridge University Press (Cambridge, U.K.).

Braathen, A., Osmundsen, P.T., Gabrielsen, R.H., 2004. **Dynamic development of fault rocks in a crustal scale detachment: an example from western Norway**. Tectonics, 23, TC4010, doi:10.1029/2003TC001558.

Moisio, K., Kaikkonen, P., 2004. **The present day rheology, stress field and deformation along the DSS profile FENNIA in the central Fennoscandian Shield**. Journal of Geodynamics, 38, 161-184.

Fossen, H., 2010. **Structural Geology**. Cambridge University Press (Cambridge, UK).

2 FABRIC OF INTACT ROCK

A unique feature of the bedrock at Olkiluoto in the context of nuclear waste disposal is the small-scale heterogeneity and anisotropy of the intact rock, which together form the intact rock "fabric". Heterogeneity refers to compositional variations, which are present on all scales, particularly the rapid alternation of mafic and felsic rock types, within the migmatites themselves and between the migmatites and the intruding veins and dykes. Anisotropy refers to the preferred oientation of minerals grains and aggregates which is a typical feature of many of the rock types encountered at Olkiluoto. In comparison, at other crystalline rock sites which are under consideration as deep repository locations, world wide, the intact rock is relatively homogeneous and isotropic (e.g. Simpevarp), although anisotropy may be significant in places (e.g. Forsmark). As a result of the strong rock fabric at Olkiluoto, numerous problems arise for which there is little or no international experience within the nuclear industry. This is particularly true in the context of understanding the brittle deformation of this heterogeneous and anisotropic bedrock at a later stage in its history, and the consequences it has for repository design, groundwater flow, in situ stress estimation, and many other aspects related to construction and long-term safety. Hence, a prerequisite for analysing the brittle structures at Olkiluoto is a detailed knowledge of the fabric of the intact rock, something which has less significance in most other sites. In Chapter 2, some basic literature is given on the techniques and results of analysing rock fabrics which have resulted form ductile deformation and partial melting in the Earth's crust. The analysis of ductile deformation features is treated in many textbooks since Ramsay's classical work in the late 1950s (cf. Ramsay 1967), as presented in Section 2.1. These general works form a background for focussing on two topics which are particularly relevant at Olkiluoto, the development of foliation and lineation (planar and linear fabrics, respectively), and the structure of ductile shear zones. A list of works describing the geophysical and rock mechanics significance of rock anisotropy is added here, because of its particular importance for Olkiluoto. The main emphasis of Section 2.2, in contrast, is on partial melting and its role in the formation and deformation of migmatites, and the development of syntectonic and post-tectonic vein and dyke systems. The formation of fault rocks under ductile and semi-brittle conditions (mylonites and cataclasites) is the subject of the Section 2.3. Since fault rocks are cohesive, they form intact rock with particular properties, even though occurring within deformation zones. In the final section (Section 2.4), the focus is on the significance of the intact rock fabric for practical problems in rock engineering and geophysics.

2.1 Tectonites and Tectonic Fabric Analysis

2.1.1 Foliation and Lineation
2.1.2 Structural Relations in Ductile Shear Zones
2.1.3 Rock Anisotropy in Engineering and Geophysics

For explanatory texts to these topics, see Section 2.1 in Posiva Working Report 2006-25 (Milnes 2006a).

Tectonic Fabric Analysis in General (including Topics 2.1.1 and 2.1.2)

Turner, F.J., Weiss, L.E., 1963. **Structural Analysis of Metamorphic Tectonites**. McGraw-Hill (New York, etc.).

Ramsay, J.G., 1967. **Folding and Fracturing of Rocks**. McGraw-Hill (New York, etc.).

Hobbs, B.E, Means, W.D., Williams, P.F., 1976. **An Outline of Structural Geology**. Wiley (New York, etc.).

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McClay, K.R., 1987. **The Mapping of Geological Structures.** Geological Society of London Handbook, Open University Press (Milton Keynes).

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Passchier, C.W., Trouw, R.A.J., 1996. **Microtectonics**. Springer (Berlin).

Davis, G.H., Reynolds, S.J., 1996. **Structural Geology of Rocks and Regions. 2nd Edition**. John Wiley & Sons (New York, etc.). ***Ch. 8: Cleavage, Foliation and Lineation***

Holness, M.B., ed., 1997. **Deformation-enhanced Fluid Transport in the Earth's Crust and Mantle**. Chapman & Hall (London, etc.).

Snoke, A.W., Tullis, J., Todd, V.R., 1998. **Fault-related Rocks. A Photographic Atlas**. Princeton University Press (Princeton, NJ).

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Paulamäki, S., 2007. **Geological mapping of the region surrounding the Olkiluoto site**. Posiva Oy, Working Report 2007-30.

Väisänen, M., Skyttä, P., 2007. **Late Svekofennian shear zones in southwestern Finland**. GFF, 129, 55-64.

Wahlgren, C.-H., Curtis, P., Hermanson, J., Forssberg, O., Öhman, J., Fox, A., LaPointe, P., Drake, H., Triumf, C.-A., Mattsson, H., Thunehed, H., Juhlin, C., 2008. **Geology Laxemar. Site descriptive modelling, SDM-Site Laxemar**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-54.

Fossen, H., 2010. **Structural Geology**. Cambridge University Press (Cambridge, UK).

Rock Anisotropy in Engineering and Geophysics (Topic 2.1.3 - in WR 2006-25 see Topics 2.4.1-2.4.4)

Hudson, J.A., Harrison, J.P., 1997. **Engineering Rock Mechanics. Part I: An Introduction to the Principles**. Pergamon (Amsterdam, etc.).

Ramsay, J.G., Lisle, R., 2001. **The Techniques of Modern Structural Geology. Volume 3: Applications of Continuum Mechanics to Structural Geology**. Academic Press (London, etc.).

Nasseri, M.H.B., Rao, K.S., Ramamurthy, T., 2003. **Anisotropic strength and deformational behaviour of Himalayan schists**. International Journal of Rock Mechanics and Mining Sciences, 40, 3-23.

Rudzki, M.P., 2003. **On the propagation of an elastic surface wave in a transversely isotropic medium**. Journal of Applied Geophysics, 54, 185-190. (In Special Issue "Advances in seismic anisotropy")

Tonon, F., Amadei, B., 2003. **Stresses in anisotropic rock masses: an engineering perspective building on geological knowledge**. International Journal of Rock Mechanics and Mining Science, 40, 1099-1120.

Hakala, M., Kuula, H., Hudson, J., 2005. **Strength and strain anisotropy of Olkiluoto mica gneiss**. Posiva Oy, Working Report 2005-61.

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Figure 5. *Small-scale joint clusters cross-cutting sheared, well foliated migmatites in shore outcrops on an island adjacent to the Olkiluoto peninsula (Photo 2006-14.4A from the Appendix "Outcrop Photographs" in Lindberg 2007, scale bar 15 cm).*

2.2 Migmatites and Magmatites

2.2.1 Migmatisation and Magmatism
2.2.2 Migmatite Types and Structures
2.2.3 Veins and Dykes (Post-Migmatitic Minor Intrusions and Mineral Veins)

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Figure 6. *A mafic dyke cross-cutting poorly foliated migmatitic rocks on glacially striated shore outcrops near Olkiluoto (Photo 2006-63.2A from the Appendix "Outcrop Photographs" in Lindberg 2007, scale bar 15 cm).*

2.3 Fault Rocks (Rocks Formed in Ductile and Semi-Brittle Deformation Zones)

2.3.1 Terminology, Classification, Genesis
2.3.2 Mylonites and Related Rocks
2.3.3 Cataclasites and Related Rocks
2.3.4 Pseudotachylite

For explanatory texts to these topics, see Section 2.3 in Posiva Working Report 2006-25 (Milnes 2006a).

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2.4 Characterisation of Intact Rock at Olkiluoto

2.4.1 Petrology and Rock Alteration
2.4.2 Rock Mechanics Properties
2.4.3 Thermal properties

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Figure 7. *Poorly foliated migmatitic rocks showing early veins (ptygmatically folded) and later neosome segregations (unfolded) on glacially striated shore outcrops near Olkiluoto (Photo 2006-107A from the Appendix "Outcrop Photographs" in Lindberg 2007, scale bar 15 cm).*

3 BRITTLE DEFORMATION IN EXPERIMENT AND NATURE

The papers cited in this Chapter refer to the general process of brittle deformation, mainly based on the results of laboratory experiments (Section 3.1) and observations made on structures and structural associations formed by the brittle deformation of rocks in Nature (Section 3.2). The first theme is often referred to as *fracture mechanics* and is empirical/mechanical in nature. The second theme is descriptive/geological in essence, and has been referred to as *brittle microtectonics*. From this point on, we focus on situations corresponding to the upper part of the Sibson-Scholz fault zone model (Topic 1.2.2), the part dominated by *cataclasis*, which is the general name for all deformation mechanisms related to mechanical breakage and frictional slip (cf. Section 2.3). Cataclasis leads to a wide spectrum of geological structures, on many different scales, from microcracks to crustal faults, and is almost always accompanied by fluid migration, creating complicated interrelationships between fracturing, alteration and mineral growth. Aspects of cataclasis which lead to the formation of incoherent fault products, such as fault gouge and fault breccia, are particularly important for understanding fault and fracture zone properties, and are included in this Chapter as a separate group (Section 3.3). Incoherent fault products are often grouped together with mylonites and cataclasites as "fault rocks", in spite of the fact that they would not normally be classified as "rocks" due to their incohesive nature (cf. Section 2.3). As for intact rock (Chapter 2), this Chapter ends with a listing of works in which the general aspect of fracturing at Olkiluoto are described, phenomenologically, including reports in which the overall mechanical properties of fractured rock are modelled or estimated (Section 3.4).

Figure 8. *Moderately foliated tonalitic migmatites with streaked-out and in places isoclinally folded neosome segregations, cut through by large joints and a pegmatite vein. Glacially striated shore outcrop near Olkiluoto (Photo 2006-125B from the Appendix "Outcrop Photographs" in Lindberg 2007, scale bar 15 cm).*

3.1 Fracture Mechanics

3.1.1 Opening Crack Propagation (Rupture Mode I)
3.1.2 Shear Rupture (Rupture Modes II and III)
3.1.3 Frictional Slip

For explanatory texts to these topics, see Section 3.1 in Posiva Working Report 2006-25 (Milnes 2006a).

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3.2 Brittle Microtectonics

3.2.1 Terminology, Types of Tectonic Fractures
3.2.2 Extension Joints
3.2.3 "Shear Joints"
3.2.4 Single-Plane Faults and Related Features
3.2.5 Fracture Chronology, Fracture Mineralization, Wall-Rock Alteration, etc.

For explanatory texts to these inter-related topics, see Section 3.2 in Posiva Working Report 2006-25 (Milnes 2006a).

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SKB 2009. **Site description of Laxemar at completion of the site investigation phase. SDM-Site Laxemar**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-09-01.

Tammisto, E., Palmén, J., Ahokas, H., 2009. **Database for hydraulically conductive fractures**. Posiva Oy, Working Report 2009-30.

Palmén, J., Tammisto, E., Ahokas, H., 2010. **Database for hydraulically conductive fractures - update 2009**. Posiva Oy, Working Report 2010-13.

Kuva, J., Voutilainen, M., Timonen, J., Aaltonen, I., 2010. **Tomographic imaging of 12 fracture samples selected from Olkiluoto deep drillholes**. Posiva Oy, Working Report WR 2010-38.

Figure 9. *Migmatitic bedrock intersected by three sets of joints on a shore outcrop near Olkiluoto (Photo 2006-126.2A from the Appendix "Outcrop Photographs" in Lindberg 2007, scale bar 15 cm).*

3.3 Incohesive Fault Products

3.3.1 Fault gouge and fault breccia
3.3.2 Clay and clay smearing

For explanatory texts to these Topics, see Section 3.3 in Posiva Working Report 2006-25 (Milnes 2006a).

Chester, F.M., Logan, J.M., 1986. **Implications for mechanical properties of brittle faults from observations of the Punchbowl Fault Zone, California**. Pure and Applied Geophysics, 124, 79-106.

Chester, F.M., Logan, J.M., 1987. **Composite planar fabric of gouge from the Punchbowl Fault, California**. Journal of Structural Geology, 9, 6211-634.

Snoke, A.W., Tullis, J., Todd, V.R., 1998. **Fault-related Rocks. A Photographic Atlas**. Princeton University Press (Princeton, NJ).

Fukuchi, T., 2001. **Assessment of fault activity by ESR dating of fault gouge; an example of the 500m core samples drilled into the Nojima earthquake fault in Japan**. Quaternary Science Reviews, 20, 1005-1008.

Habimana, J., Labiouse, V., Descoeudres, F., 2002. **Geomechanical characterisation of cataclastic rocks: experience from the Cleuson-Dixence project**. International Journal of Rock Mechanics and Mining Sciences, 39, 677-693.

Braathen, A., Osmundsen, P.T., Gabrielsen, R.H., 2004. **Dynamic development of fault rocks in a crustal scale detachment: an example from western Norway**. Tectonics, 23, TC4010, doi:10.1029/2003TC001558.

Zwingmann, H., Offler, R., Wilson, T., Cox, S.F., 2004. **K-Ar dating of fault gouge in the northern Sydney Basin, NSW, Australia - implications for the breakup of Gondwana**. Journal of Structural Geology, 26, 2285-2295.

Gehör, S., 2007. **Mineralogical characterization of gouge fillings in ONKALO facility at Olkiluoto**. Posiva Oy, Working Report WR 2007-33.

Mänttäri, I., Mattila, J., Zwingmann, H., Todd, A.J., 2007. **Illite K-Ar dating of fault breccia samples from ONKALO underground research facility, Olkiluoto, Eurajoki, SW Finland**. Posiva Oy, Working Report 2007-67.

Kuva, J., Voutilainen, M., Timonen, J., Aaltonen, I., 2010. **Tomographic imaging of 12 fracture samples selected from Olkiluoto deep drillholes**. Posiva Oy, Working Report WR 2010-38.

Figure 10. *Fault gouge and incohesive fault breccia in the core of as small fault in migmatitic bedrock, Flatanger, west coast of Norway (Photo: A.G. Milnes).*

3.4 Characterisation of Fracturing at Olkiluoto

3.4.1 Fracturing in Intact Rock (outside Brittle Deformation Zones)
3.4.2 Fracturing in and around Brittle Deformation Zones
3.4.3 Bulk Properties of Fractured Rock (Rock Mechanics and Thermal Properties)

Geological Relationships observed in Outcrops, Trenches and Tunnels (Topics 3.4.1 and 3.4.2)

Talikka, M., 2005. **Geological mapping of the Olkiluoto 3 construction site**. Posiva Oy, Working Report 2005-32.

Engström, J., 2006. **Geological mapping of investigation trench OL-TK8 at the Olkiluoto study site, Eurajoki, SW Finland**. Posiva Oy, Working Report 2005-44.

Nordbäck, N., Talikka, M., 2006. **Geological mapping of investigation trench TK9 at the Olkiluoto study site, Eurajoki, SW Finland**. Posiva Oy, Working Report 2006-51.

Mattila, J., Aaltonen, I., Kemppainen, K., Talikka, M., 2007. **Geological mapping of the investigation trench OL-TK11, the Storage Hall area**. Posiva Oy, Working Report 2007-27.

Nordbäck, N., Engström, J., 2006. **Geological mapping of investigation trench OL-TK12 at the Olkiluoto study site, Eurajoki, SW Finland**. Posiva Oy, Working Report 2006-104.

Nordbäck, N., 2007. **Geological mapping of investigation trench OL-TK14 at the Olkiluoto study site, Eurajoki, SW Finland**. Posiva Oy, Working Report 2006-51.

Lindberg, A., 2007. **Search for glacio-isostatic faults in the vicinity of Olkiluoto**. Posiva Oy, Working Report 2007-05.

Vaarma, M., Vuokko, J., 2009. **Geological mapping of investigation trench OL-TK15 and OL-OK16 at the Olkiluoto study site, Eurajoki, SW Finland**. Posiva Oy, Working Report 2009-52.

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Lahti, M., Ahokas, T., Nordbäck, N., Paananen, M., Paulamäki, S., Vaittinen, T., 2009. **The ONKALO Area model, version 1.1**. Posiva Oy, Working Report WR 2009-113.

Lindberg, A., 2010. **Geological mapping of investigation trench OL-TK17 at the Olkiluoto Study Site, Eurajoki, SW Finland**. Posiva Oy, Working Report WR 2010-01.

Nordbäck, N., Engström, J., 2010. **Outcome of the geological mapping of the ONKALO underground research facility access tunnel, chainage 990-1980**. Posiva Oy, Working Report WR 2010-41.

Nordbäck, N., 2010. **Outcome of the geological mapping of the ONKALO underground research facility access tunnel, chainage 1980-3116**. Posiva Oy, Working Report WR 2010-42.

Bulk Properties of Fractured Rock (Topic 3.4.3)

Remes, H., Kuula, H., Somervuori, P.,, Hakala, M., 2009. **ONKALO rock mechanics model (RMM), version 1.0**. Posiva Oy, Working Report 2009-55.

Hudson, J.A., Johansson, E., 2006. **Summary of rock mechanics work completed for Posiva before 2005**. Posiva Oy, report POSIVA 2006-04.

Summaries, Compilations, Syntheses, Analogous Data from Sweden

Hudson, J.A., Cosgrove, J.W., 2006. **Geological history and its impact on the rock mechanics properties of the Olkiluoto site**. Posiva Oy, Working Report 2006-14.

Kuusisto, S., Lehtokangas, M., 2007. **Selected visualizations and summaries of the contents of the fracture database, deformation zone intersection data, and deviation survey measurements regarding boreholes OL-KR1 - OL-KR33B**. Posiva Oy, Working Report WR 2007-07.

Milnes, A.G., Wikström, L., Aaltonen, I., Front, K., Gehör, S., Kemppainen, K., Kärki, A., Mattila, J., Paananen, M., Paulamäki, S., 2007. **Geological data acquisition for site characterisation at Olkiluoto: framework for the phase of underground investigations**. Posiva Oy, Working Report 2007-32.

Glamheden, R., Fredriksson, A., Röshoff, K., Karlsson, J., Hakami, H., Christiansson, R., 2007. **Rock mechanics Forsmark. Site descriptive modelling Forsmark stage 2.2**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-07-31.

Glamheden, R., Lanaro, F., Karlsson, J., Lindberg, U., Wrafter, J., Hakami, H., Johansson, M., 2008. **Rock mechanics Forsmark. Modelling stage 2.3. Complementary analysis and verification of the rock mechanics model**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-66.

Hakami, E., Frederiksson, A., Lanaro, F., Wrafter, J., 2008. **Rock mechanics Laxemar. Site descriptive modelling, SDM-Site Laxemar**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-57.

Mattila, J., 2009. **Constraints on the fault and fracture evolution at the Olkiluoto region**. Posiva Oy, Working Report WR 2009-130.

Tammisto, E., Palmén, J., Ahokas, H., 2009. **Database for hydraulically conductive fractures**. Posiva Oy, Working Report 2009-30.

Palmén, J., Tammisto, E., Ahokas, H., 2010. **Database for hydraulically conductive fractures - update 2009**. Posiva Oy, Working Report 2010-13.

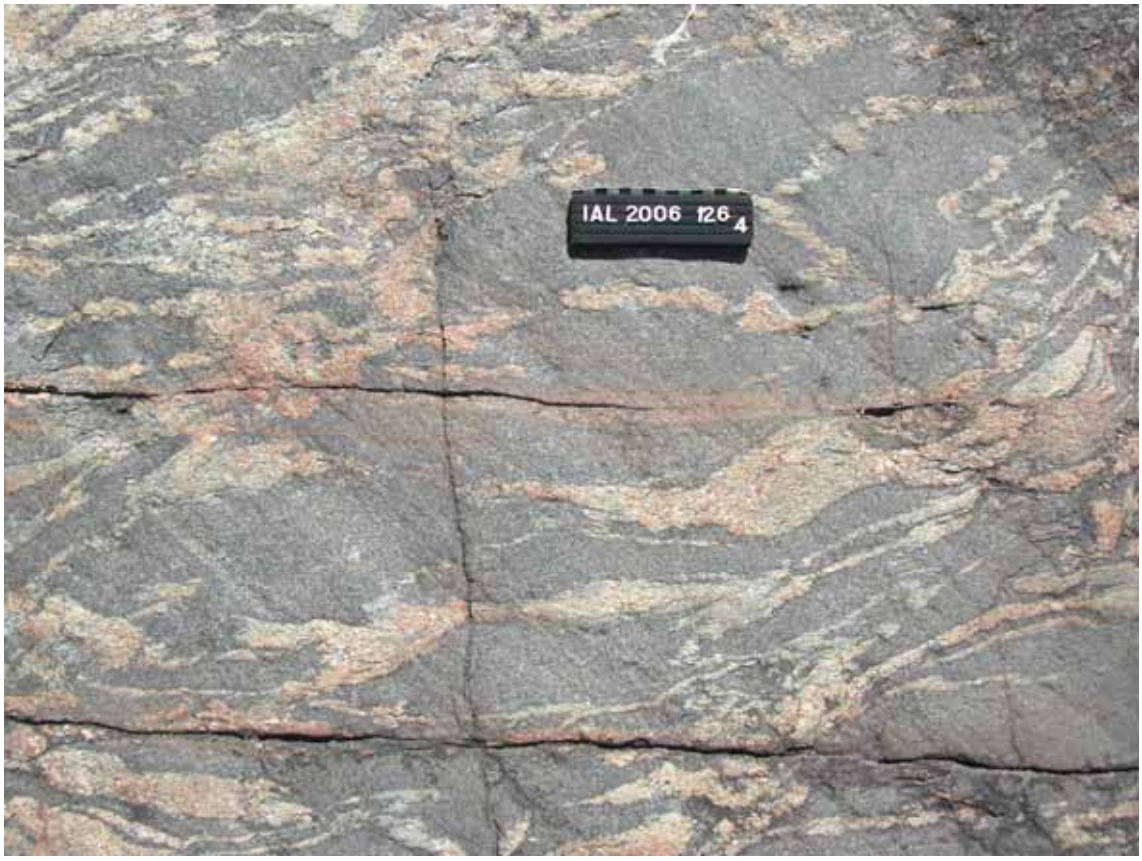

Figure 11. *Migmatitic bedrock intersected by two sets of joints of different ages: the "E-W" joints show mineralization and wall-rock alteration, which is cut through by the younger, "N-S", unmineralized joints. Glacially striated shore outcrop near Olkiluoto (Photo 2006-126.4B from the Appendix "Outcrop Photographs" in Lindberg 2007, scale bar 15 cm).*

4 FRACTURE DATA ACQUISITION AND PROCESSING

The literature cited in Chapter 3 was mainly concerned with the geological description of small-scale brittle structures and structural associations, and their interpretation in terms of mode of formation under crustal conditions. The emphasis was on "understanding", which is a prerequisite for meaningful structural modelling. However, structural modelling also requires "quantification", i.e. the systematic acquisition of numerical data, followed by suitable statistical processing, to provide the necessary input parameters for the computations. This is the subject of Chapter 4. Here I choose to simplify the discussion by referring to the objects of investigation as "fractures" (strictly speaking, "tectonic fractures", see discussion in Milnes 2006a,b). I assume that each individual fracture measured has been described and classified individually, and that, where appropriate, the statistical procedures can be applied separately to all fractures of a particular type or group (joints, faults, veins, discontinuities, water-conducting features, etc.). All fractures and fracture systems, of whatever type, have certain geometrical elements in common (orientation, size, frequency, etc.), and a selection from the extensive literature on these parameters is given in Section 4.1. Also, the first step in the processing of orientation and frequency data are included here, since the results of such processing have been used for defining *fracture domains*, an important concept which has been developed in Sweden and Finland since the publication of Working Report 2006-25.

In Section 4.2, the references focus on *how* the measurements are made, i.e. fracture data acquisition in practice. There are two main types of data collection which, in different situations, are being carried out at Olkiluoto: linear sampling (e.g. core and borehole logging, scanline logging) and areal sampling (e.g. fracture mapping on outcrops, in trenches and along tunnel walls). With regard to the logging of oriented core to produce a systematically acquired fracture data set, two situations must be distinguished: *preliminary logging*, as carried out at the drillsite immediaely after the core is drawn (used for rock engineering purposes), and *detailed logging*, as carried out in the core archive, side-by-side with borehole-wall imagery and geophysical logs acquired in the borehole (used for statistical anaylsis and modelling of fracture systems). Both these are carried out both at the SKB investigation sites and at Olkiluoto, but unfortunately the detailed logging at Olkiluoto has not yet been properly documented.

Section 4.3 lists reports in which different types of fracture system characterisation, and subsequent analysis and modelling, are documented. There are three main areas of application, each using different methodology - (1) in support of deterministic geological modelling (identification and characterisation of deformation zones), (2) in support of underground construction and host rock suitability assessment (e.g Q-system), and (3) as input for Discrete Fracture Network modelling (as a basis for dynamic modelling of groundwater flow and seismic risk studies).

4.1 Fracture Parameters

4.1.1 Fracture Orientation, Definition of Fracture Sets
4.1.2 Degree of Fracturing (Fr. Frequency, Density, Intensity), Definition of Fracture Domains
4.1.3 Fracture Size and Size Distribution in Fracture Sets
4.1.4 Spatial Distribution of Fractures, Connectivity

For explanatory texts to these topics, see Section Posiva Working Report 2006-25 (Milnes 2006a). Topics 4.1.3 and 4.1.4 are addressed in more detail under Topic 4.3.3 in the present report.

Fracture parameters - works containing overviews

Priest, S.D., 1993. **Discontinuity Analysis for Rock Engineering**. Chapman & Hall (London, etc.).

Holmén, J.G., Outters, N., 2002. **Theoretical study of rock mass investigation efficiency**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-02-21.

Lisle, R.J., Leyshon, P.R., 2004. **Stereographic Projection Techniques for Geologists and Civil Engineers. 2nd Edition**. Cambridge University Press (Cambridge, UK).

Munier, R., 2004. **Statistical analysis of fracture data, adapted for modelling Discrete Fracture Networks - version 2**. Swedish Nuclear Fuel and Waste Management Company (SKB), report SKB R-04-66.

Milnes, A.G., Wikström, L., Aaltonen, I., Front, K., Gehör, S., Kemppainen, K., Kärki, A., Mattila, J., Paananen, M., Paulamäki, S., 2007. **Geological data acquisition for site characterisation at Olkiluoto: framework for the phase of underground investigations**. Posiva Oy, Working Report 2007-32.

Fox, A., LaPointe, P., Hermanson, J., Öhman, J., 2007. **Statistical geological discrete fracture model. Forsmark modelling stage 2.2**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-07-46.

Buoro, A., Dahlbo, K., Wiren, L., Holmén, J., Hermanson, J., Fox, A., 2009. **Geological discrete-fracture network model (version 1) for the Olkiluoto site, Finland**. Posiva Oy, Working Report WR 2009-77.

Definition of Fracture Domains based on Fracture Orientation/Intensity Statistics (Topics 4.1.2 and 4.1.3)

Fox, A., LaPointe, P., Hermanson, J., Öhman, J., 2007. **Statistical geological discrete fracture model. Forsmark modelling stage 2.2**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-07-46.

Olofsson, I., Simeonov, A., Stigsson, M., Stephens, M.B., Follin, S., Nilsson, A.-C., Röshoff, K., Lindberg, U., Lanaro, F., Fredriksson, A., Persson, L., 2007. **Site descriptive modelling, Forsmark stage 2.2. A fracture domain concept as a basis for the statistical modelling of fractures and minor deformation zones, and interdisciplinary coordination**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-07-15.

LaPointe, P., Fox, A., Hermanson, J., Öhman, J., 2008. **Geological discrete fracture network model for the Laxemar site. Site descriptive modelling, SDM-Site Laxemar**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-55.

Buoro, A., Dahlbo, K., Wiren, L., Holmén, J., Hermanson, J., Fox, A., 2009. **Geological discrete-fracture network model (version 1) for the Olkiluoto site, Finland**. Posiva Oy, Working Report WR 2009-77.

4.2 Systematic Fracture Data Acquisition

4.2.1 Basic Principles of Linear and Areal Sampling
4.2.2 On-site Fracture Logging of Drillholes (--> Preliminary Fracture Data)
4.2.3 Detailed Fracture Logging of Drillholes (Core Logging combined with OPTV and Geophysical Logs, etc. --> Definitive Fracture Data)
4.2.4 Linear Sampling - Scanline Logging (Outcrops,Tunnel Walls)
4.2.5 Areal Sampling - Fracture Trace Mapping (Outcrop-Trench-Tunnel)
4.2.6 Fracture Databases (Data Storage/Retrieval, Quality Control)

For explanatory texts to these topics, see Posiva Working Report 2005-25 (Milnes 2006a).

Basics (Topic 4.2.1)

Priest, S.D., 1993. **Discontinuity Analysis for Rock Engineering**. Chapman & Hall (London, etc.).

Davis, G.H., Reynolds, S.J., 1996. **Structural Geology of Rocks and Regions. 2nd Edition**. John Wiley & Sons (New York, etc.).

NRC/CFCFF 1996. Rock **Fractures and Fluid Flow. Contemporary Understanding and Applications**. Report of the Committee on Fracture Characterization annd Fluid Flow, National Research Council, National Academy Press (Washington D.C.).

Drilling, Geophysical Logging, OPTV/BIPS Reports (Topic 4.2.2)

Olkiluoto (Examples)

Majapuro, J., 2006a. **Optical imaging of the boreholes KR37, KR37B and KR38 at Olkiluoto 2005**. Posiva Oy, Working Report 2006-17.

Majapuro, J., 2006b. **Geophysical borehole logging of the boreholes KR37, KR37B and KR38, at Olkiluoto**. Posiva Oy, Working Report 2006-30.

Öhberg, A., Heikkinen, E., Hirvonen, H., Kemppainen, K., Majapuro, J.,Niemonen, J., Pöllänen, J., Rouhiainen, P., 2006a. **Drilling and associated borehole measurements of the pilot hole ONK-PH3**. Posiva Oy, Working Report 2006-20.

Toropainen, V., 2007. **Core drilling of deep borehole OL-KR46 at Olkiluoto in Eurajoki 2007**. Posiva Oy, Working Report 2007-74.

Tarvainen, A.-M., 2007a. **Optical imaging of borehole PR10 at Olkiluoto 2006**. Posiva Oy, Working Report 2007-13.

Tarvainen, A.-M., 2007b. **Optical imaging of drillholes OL-KR40, OL-KR41, OL-KR41B, OL-KR42, OL-KR42B, OL-KR43 and OL-KR43B at Olkiluoto, 2006 and 2007**. Posiva Oy, Working Report 2007-14.

Toropainen, V., 2008a. **Core drilling of deep borehole OL-KR48 at Olkiluoto in Eurajoki 2007**. Posiva Oy, Working Report 2008-05.

Toropainen, V., 2008b. **Core drilling of deep borehole OL-KR47 at Olkiluoto in Eurajoki , 2007-2008**. Posiva Oy, Working Report 2008-13.

Tarvainen, A.-M., Heikkinen, E., 2008. **Geophysical drillhole logging and optical imaging of the drillholes.....OL-KR46.....OL-KR47....OL-KR48.....at Olkiluoto 2007 and 2008**. Posiva Working Report 2008-61.

Tiensuu, K., Heikkinen, E., Lahti, M., 2009. **Acoustic imaging of the drillholes.....OL-KR46.....at Olkiluoto 2008**. Posiva Working Report 2009-41.

Julkunen, A., Kallio, L., Kuusisto, M., 2009. **Drillhole gamma-ray spectrum logging in drillholes .... OL-KR46, OL-KR47....OL-KR48 and ground survey at Olkiluoto in Eurajoki, 2007 and 2008**. Posiva Working Report 2009-68.

Forsmark (Examples)

Claesson, L.-A., Nilsson, G., 2004. **Forsmark site investigation. Drilling of the telescopic borehole KFM05A at drilling site DS5**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-04-222.

Gustafsson, J., Gustafsson, C., 2004. **Forsmark site investigation. RAMAC and BIPS logging in borehole KFM05A**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-04-152.

Torben Nielsen, U., Ringgaard, J., 2004. **Forsmark site investigation. Geophysical borehole logging in borehole KFM05A and HFM19**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-04-153

Thunehed, H., Keisu, M., 2004. **Forsmark site investigation. Interpretation of borehole geophysical measurements in KFM05A, HFM14, HFM15 and HFM19**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-04-154.

Claesson, L.-A., Nilsson, G., 2007. **Forsmark site investigation. Drilling of the cored boreholes KFM09A and KFM09B, and overburden drilling of KFM09C at drill site DS9**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-06-169.

Nielsen, U.T., Ringgaard, J., Vangkilde-Pedersen, T., 2006. **Forsmark site investigation. Geophysical borehole logging in boreholes KFM09A, KFM07B, HFM25, HFM27 and HFM28**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-06-22.

Stephens, M.B., Fox, A., LaPointe, P., Simeonov, A., Isaksson, H., Hermanson, J., Öhman, J., 2007. **Geology Forsmark. Site descriptive modelling, Forsmark stage 2.2**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport SKB R-08-64.

Core Logging Reports and Drillhole Syntheses (Topic 4.2.3)

Olkiluoto (Examples)

None available at the time of writing.

Forsmark (Examples)

Petersson, J., Berglund, J., Wängnerud, A., Danielsson, P., Strahle, A., 2004. **Forsmark site investigation. Boremap mapping of telescopic drilled borehole KFM05A**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-04-295.

Carlsten, S., Petersson, J., Stephens, M., Thunehed, H., Gustafsson, J., 2004. **Forsmark site investigation. Geological single-hole interpretation of KFM05A, HFM14-15 and HFM19 (DS5)**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-04-296.

Carlsten, S., Döse, C., Gustafsson, J., Keisu, M., Petersson, J., Stephens, M., 2006. **Forsmark site investigation. Geological single-hole interpretation of KFM09A and KFM07B**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-06-134

Glamheden, R., Curtis, P., 2006. **Comparative evaluation of core mapping results for KFM06C and KLX07B**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-06-55.

Petersson, J., Skogsmo, G., von Dalwigk, I., Wängnerud, A., Berglund, J., 2006. **Forsmark site investigation. Boremap mapping of cored borehole KFM09A**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-06-130.

Forsmark and Laxemar - Compilation of all Single-Hole Interpretations during Site Investigations

Stephens, M.B., Fox, A., LaPointe, P., Simeonov, A., Isaksson, H., Hermanson, J., Öhman, J., 2007. **Geology Forsmark. Site descriptive modelling, Forsmark stage 2.2**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport SKB R-08-64.

Wahlgren, C.-H., Curtis, P., Hermanson, J., Forssberg, O., Öhman, J., Fox, A., LaPointe, P., Drake, H., Triumf, C.-A., Mattsson, H., Thunehed, H., Juhlin, C., 2008. **Geology Laxemar. Site descriptive modelling, SDM-Site Laxemar**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-54.

SKB 2009. **Site description of Laxemar at completion of the site investigation phase. SDM-Site Laxemar**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-09-01.

Scanline Logging (Topic 4.2.4)

La Pointe, P.R. & Hudson, J.A., 1985: **Characterization and interpretation of rock mass joint patterns**. Geol. Soc. Amer. Spec. Paper 199

Milnes, A.G., Gee, D.G., 1992. **Bedrock stability in Southeastern Sweden. Evidence from fracturing in the Ordovician limestones of Northern Öland**. Swedish Nuclear Fuel and Waste Management Company (SKB),Technical Report TR 92-23.

Bossart, B., Hermanson, J., Mazurek, M., 2001. **Äspö Hard Rock Laboratory. Analysis of fracture networks based on structural and hydrogeological observations on different scales**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR 01-21.

Mauldon, M., Dunne, W.M., Rohrbaugh, M.B., 2001. **Circular scanlines and circular windows: new tools for characterizing the geometry of fracture traces**. Journal of Structural Geology, 23, 247-258.

Fracture Trace Mapping - Examples (Topic 4.2.5)

Bossart, B., Hermanson, J., Mazurek, M., 2001. **Äspö Hard Rock Laboratory. Analysis of fracture networks based on structural and hydrogeological observations on different scales**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR 01-21.

Hermanson, J., Hansen, L., Wikholm, M., Cronquist, T., Leiner, P., Vestgård, J., Sandahl, K.-A., 2004. **Detailed fracture mapping of four outcrops at the Simpevarp peninsula and Ävrö**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project Report P-04-35.

Mattila, J., Aaltonen, I., Kemppainen, K., Talikka, M., 2007. **Geological mapping of the investigation trench OL-TK11, the Storage Hall area**. Posiva Oy, Working Report 2007-27.

Engström, J., Kemppainen, K., 2008. **Evaluation of the geological and geotechnical mapping procedures in use in the ONKALO access tunnel**. Posiva Oy, Working Report WR 2008-77.

Lindberg, A., 2010. **Geological mapping of investigation trench OL-TK17 at the Olkiluoto Study Site, Eurajoki, SW Finland**. Posiva Oy, Working Report WR 2010-01.

Stephens, M.B., Fox, A., LaPointe, P., Simeonov, A., Isaksson, H., Hermanson, J., Öhman, J., 2007. **Geology Forsmark. Site descriptive modelling, Forsmark stage 2.2**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport SKB R-08-64.

Fracture Databases (Topic 4.2.6)

Kuusisto, S., Lehtokangas, M., 2007. **Selected visualizations and summaries of the contents of the fracture database, deformation zone intersection data, and deviation survey measurements regarding boreholes OL-KR1 - OL-KR33B**. Posiva Oy, Working Report WR 2007-07.

Munier, R., Stigsson, M., 2007. **Implementation of uncertainites in borehole geometries and geological orientation data in SICADA**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-07-19.

Tammisto, E., Palmén, J., Ahokas, H., 2009. **Database for hydraulically conductive fractures**. Posiva Oy, Working Report 2009-30.

Palmén, J., Tammisto, E., Ahokas, H., 2010. **Database for hydraulically conductive fractures - update 2009**. Posiva Oy, Working Report 2010-13.

Figure 12. *Systematic mapping of fractures, lithological contacts and foliation in the heterogeneous, migmatitic bedrock exposed in the ONKALO access tunnel, Olkiluoto. (Photo: Posiva).*

4.3 Processing and Analysis of Systematically Acquired Fracture Data

4.3.1 In Support of Deterministic Geological Modelling
4.3.2 In Support of Underground Construction and Host Rock Suitability
4.3.3 As Input for DFN Modelling

For explanatory texts to Topics 4.3.2 and 4.3.3, see Section 4.3 in Posiva Working Report 2006-25 (Milnes 2006a).

Fracture Data Processing in Support of Deterministic Geological Modelling (Topic 4.3.1)

Bossart, B., Hermanson, J., Mazurek, M., 2001. **Äspö Hard Rock Laboratory. Analysis of fracture networks based on structural and hydrogeological observations on different scales**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR 01-21.

Milnes, A.G., 2006a. **Understanding brittle deformation at the Olkiluoto site. Literature compilation for site characterization and geological modelling**. Posiva Oy, Working Report 2006-25.
The characterisation and modelling of fracture zones for deterministic modelling is based on a project-oriented combination of material from Sections 2.3 (Fault rocks), 3.2 (Brittle microtectonics), 3.3 (Incohesive fault products), 5.2 (Fault zone geometry and kinematics) and 5.3 (Fault zone architecture) - explanatory texts on all these themes are to be found in this reference.

Stephens, M.B., Fox, A., LaPointe, P., Simeonov, A., Isaksson, H., Hermanson, J., Öhman, J., 2007. **Geology Forsmark. Site descriptive modelling, Forsmark stage 2.2**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport SKB R-08-64.

Mattila, J., 2009. **Constraints on the fault and fracture evolution at the Olkiluoto region**. Posiva Oy, Working Report WR 2009-130.

Fracture Data Processing for Underground Construction and Host Rock Suitability Assessment (Topic 4.3.2)

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5 BRITTLE DEFORMATION ZONES (FRACTURE ZONES)

The emphasis in Chapter 4 was on stochastic modelling, i.e. on the collection of statistically sound fracture data sets, and the use of the latter for building fracture system models for various uses, particularly in “averagely fractured rock”. The term “averagely fractured rock” designates the rock mass in the blocks between the “fracture zones” in traditional nuclear waste terminology. "Fracture zones" are by definition large enough to be located, mapped and reconstructed at a repository site and are to be avoided when designing the deposition tunnels. Hence, the identification, characterisation and subsurface reconstruction of “fracture zones” is perhaps the most important aspect of deterministic geological modelling during site characterization. This is the main emphasis in the present Chapter, which begins with some general works leading to the fundamental classification of all types of deformation zone, as it is at present in use at Olkiluoto (Section 5.1). Most fracture zones at Olkiluoto - and for nuclear waste disposal, the most important types of fracture zones to be avoided - fall within the category *fault zone* in the classification scheme (Milnes et al. 2007), and most of this chapter concentrates on the relevant literature on this subject. In Section 5.2, the emphasis is on fault zone geometry and kinematics, i.e. on the quantitative parameters necessary for describing the 3D geometry of fault zones, and the amount and direction of movement, as well as on the “real world” spatial variations in fault zone geometry which have been studied in detail in the last decade. This is followed by a section on the geological characterization of fault zones (Section 5.3), and the properties of fault zone materials, with examples from Olkiluoto. Because of the importance of “fracture zones” (a term which is synonymous with “brittle deformation zones” in the present classification system, see Milnes et al. 2007) for site investigations in Sweden and Finland, the most recent literature from the Olkiluoto, Forsmark and Laxemar sites is reviewed in Sections 5.4 and 5.5. Section 5.4 focusses on techniques and methodologies, and the use of the data for the identification, characterisation and parameterisation of fracture zones (the "ICP step" in deterministic geological modelling, see Milnes et al. 2007). Section 5.5 concentrates on the application of this data to the development of simplified 3D models of the sites, by extrapolating and correlating between borehole, tunnel and surface intersections and by embedding the data in a 3D visualisation system (the "ECV step" in geological modelling). References to the problems which arise when applying geological models to safety-related problems (respect distance, critical structures, confidence/uncertainty estimation, etc.) are also included in this section. Finally, a section is added which lists works dealing with the dynamic aspects of fracturing and faulting, and related rock mechanics processes (Section 5.6).

5.1 Deformation Zones

5.1.1 Terminology and Classification
5.1.2 Brittle Deformation Zones (fault zones, joint zones)

For explanatory texts to these topics, see Section 5.1 in Posiva Working Report 2006-25 (Milnes 2006a).

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Figure 13. *A semi-brittle deformation zone, later affected by brittle fracturing, intersecting and fragmenting migmatitic rocks in a shore outcrop near Olkiluoto (Photo 2006-130.1B from the Appendix "Outcrop Photographs" in Lindberg 2007, scale bar 15 cm).*

5.2 Fault Zone Geometry and Kinematics

5.2.1 Fault Parameters (Slip, Displacement, Thickness)
5.2.2 Spatial Variations in Fault Geometry ("Faults in the Real World")
5.2.3 Fault Slip Analysis

For explanatory texts to these topics, see Section 5.2 in Posiva Working Report 2006-25 (Milnes 2006a).

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Kim, Y.-S., Sanderson, D.J., 2005. **The relationship between displacement and length of faults: a review**. Earth-Science Reviews, 68, 317-334.

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5.3 Fault Zone Characterization

5.3.1 Fault Zone Architecture
5.3.2 Composite Deformation Zones
5.3.3 Properties of Fault Zones and Fault Zone Materials
5.3.4 Documentation of Exposed Fault Zones at Olkiluoto (Outcrop, Trench, Tunnel)

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Figure 14. *Slickenside fracture surface in a fault zone cutting altered pegmatitic granite in shore outcrops near Olkiluoto(Photo 2006-78.5B from the Appendix "Outcrop Photographs" in Lindberg 2007, scale bar 15 cm).*

5.4 Fracture Zones in Crystalline Bedrock ("ICP"= Identification, Characterisation, Parameterisation)

5.4.1 Programmes, Strategies, Techniques, Methodologies, etc.
5.4.2 Fracture Zones at Olkiluoto (Surface and Borehole Geology+Geophysics, with Tunnel Control)
5.4.3 Fracture Zones at Forsmark and Laxemar (Surface and Borehole Geology+Geophysics, without Tunnel Control)
5.4.4 Underground Observations - ONKALO, Äspö

For pre-2006 listings, see Section 5.4 in Posiva Working Report 2006-25; for more complete coverage of SKB and Posiva fracture zone research up to year 2000, see Milnes 2002.

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5.5 Deterministic Geological Modelling of Fracture Zones in Sweden and Finland ("ECV" = Extrapolation, Correlation, Visualisation)

5.5.1 Site descriptive modelling Olkiluoto
5.5.2 Site descriptive modelling Forsmark-Laxemar
5.5.3 Respect distance, critical structures, long fractures, etc.
5.5.4 Confidence, uncertainty, reproducibility, the human factor

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Figure 16. *A very long fracture cutting through poorly foliated migmatitic gneisses on a shore outcrop near Olkiluoto (Photo 2006-63.1A from the Appendix "Outcrop Photographs" in Lindberg 2007, scale bar 15 cm). Towards the waterline the joint intersects the mafic dyke shown on page 17. Post-glacial movement on this joint of 2-4 cm (height difference of the glacially striated surface on either side) cannot be excluded (see Pere 2009, p. 3 and Fig. 3).*

5.6 Dynamic Aspects

5.6.1 Influence of Underground Construction on the Host Rock (EDZ, etc.)
5.6.2 Effect of Earthquakes on Underground Excavations
5.6.3 Reactivation of Fractures during Seismic Events
5.6.4 Glacio-Tectonics, Post-Glacial Faulting and Paleoseismicity in Fennoscandia
5.6.5 Present day Dynamics of Olkiluoto in a Regional Context (In situ Stress, etc.)

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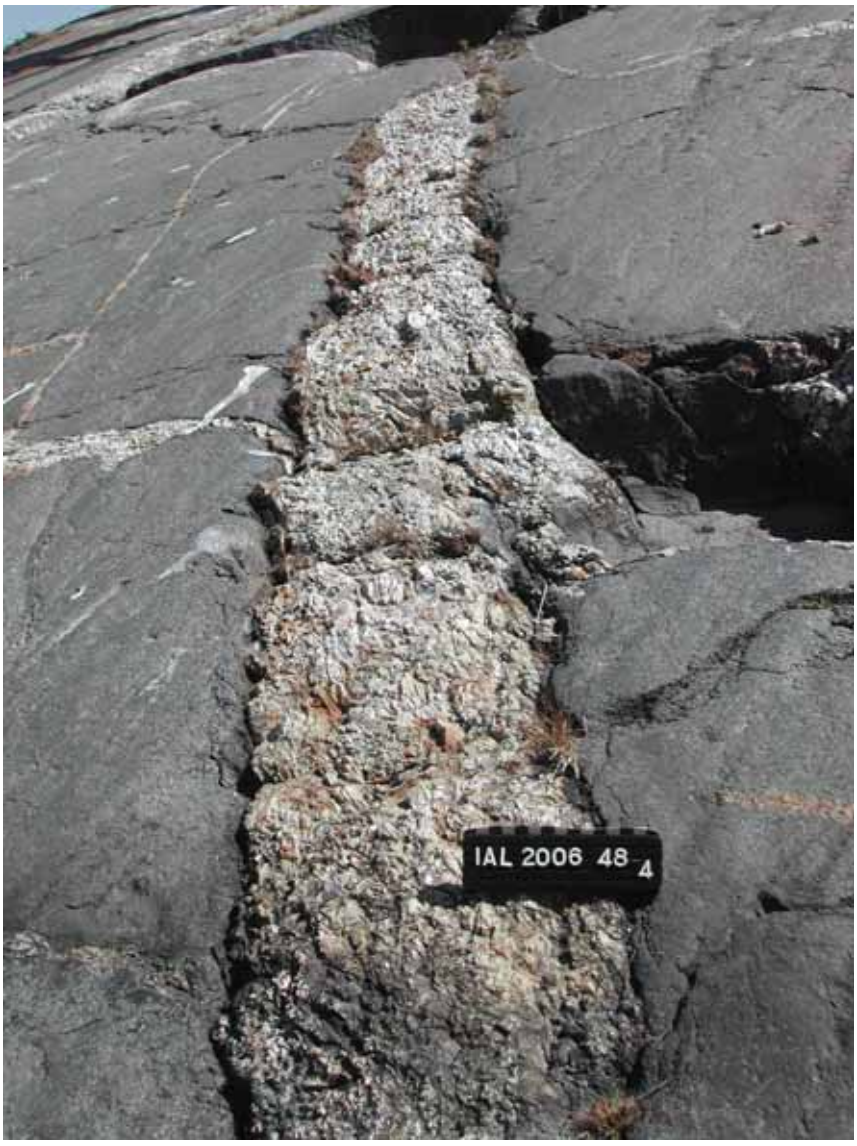

Figure 17. *Pegmatite vein cutting through mica-gneiss in a shore outcrop near Olkiluoto (Photo 2006-48.4B from the Appendix "Outcrop Photographs" in Lindberg 2007, scale bar 15 cm).*

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- geometry of the Nojima fault, Japan: damage structure inferred from borehole core permeability (Lockner et al.)
- Nojima fault: microstructures and their implications for permeability and strength (Moore, Lockner, et al.)
- non-planar faults: mechanics of slip and off-fault damage (Dieterich, Smith)

Bond, C.E., Gibbs, A.D., Shipton, Z.K., Jones, S., 2007. **What do you think this is? "Conceptual uncertainty" in geoscience interpretation**. GSA Today, 17, doi:10.1130/GSAT01711A.1
- experiment with 412 independent interpretations of the same set of seismic data from a known tectonic setting (human factor extremely important!)

Bossart, B., Hermanson, J., Mazurek, M., 2001. **Äspö Hard Rock Laboratory. Analysis of fracture networks based on structural and hydrogeological observations on different scales**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR 01-21.
- important report for methodology of structural data acquisition in tunnel (combining tunnel observations - window mapping, scanline logging - with borehole data), and subsequent processing/modelling using also hydrogeological data
- series of conceptual models at different scales (Fig. 4-1)
- series of fracture trace maps of tunnel and niche walls
- data base documented as pdf files on CD-ROM (missing from my copy)

Braathen, A., Osmundsen, P.T., Gabrielsen, R.H., 2004. **Dynamic development of fault rocks in a crustal scale detachment: an example from western Norway**. Tectonics, 23, TC4010, doi:10.1029/2003TC001558.
- distinguish primary cohesion and secondary cohesion of fault rocks - cataclasites considered to be example of primary cohesion (sec. cohesion = cemented or indurated breccia - also pseudotachylite)
- discussion of previous classificatons of "fault-related rocks"
- composite fault rock section of Nordfjord-Sogn detachment, using their new, refined terminology, based on Kvamhesten exposures
- comparison of new classification with Sibson-Scholz fault zone model, and discussion of many terms and definitions used and misused in the literature

Brown, M., 1994. **The generation, segregation, ascent and emplacement of granite magma: the migmatite-to-crustally-derived-granite connection in thickened orogens**. Earth Science Reviews, 36, 83-130.

Buoro, A., Dahlbo, K., Wiren, L., Holmén, J., Hermanson, J., Fox, A., 2009. **Geological discrete-fracture network model (version 1) for the Olkiluoto site, Finland**. Posiva Oy, Working Report WR 2009-77.

Ch. 2: DFN methodology, including discussion of fracture parameters

Ch. 3: Derivation of the Olkiluoto geological DFN, concentrating on fr. orientation and fr. intensity relationships and statistics (including the "Holmén method" of determining P32 from borehole fracture data - see Holmén and Outters 2002 - in contrast to the "Wang method" used by SKB - see LaPointe et al. 2008)

Ch. 4: Model calibration and verification

Bäckblom, G., 2008. **Excavation damage and disturbance in crystalline rock - results from experiments and analyses**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report TR-08-08.

- summarizes results from major experiments and studies in Canada, Finland, Japan, Sweden and Switzerland on spalling, excavation damage and disturbance (EDZ), particularly with regard to increased transmissivity

Bäckblom, G., Munier, R., 2002. **Effects of earthquakes on the deep repository for spent fuel in Sweden based on case studies and preliminary model results**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-02-24.

Bödvarsson, R., Lund, B., Roberts, R., Slunga, R., 2006. **Earthquake activity in Sweden. Study in connection with a proposed nuclear waste repository in Forsmark or Oskarshamn**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-06-67.

*- aim to evaluate **seismic risks on time scales of 100 years** (approx. period of instrumental observation) **and 1000 years** (but not longer, i.e. not on time scale of an Ice Age)*

- one magn. 5 earthquake per 100 years, one magn. 6 per 1000 years expected

- present state of stress (also from focal measurements and measurements in Siljan boreholes) evaluated

- analysis of GPS measurements and question of aseismic slip addressed

Carlsson, A., Christiansson, R., 2007. **Construction experiences from underground works at Oskarshamn. Compilation report**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-07-66.

- summarizes experience for power station, CLAB and Äspö construction

Ch. 2: geological, structural and engineering geological overview of Simpevarp area

Ch. 6: Äspö underground rock laboratory

Ch. 7: rock mass properties and conditions , including description of the heterogeneity of the rock mass in blocks 10x10x10 m^3

Carlsten, S., Petersson, J., Stephens, M., Thunehed, H., Gustafsson, J., 2004. **Forsmark site investigation. Geological single-hole interpretation of KFM05A, HFM14-15 and HFM19 (DS5)**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-04-296.

Carlsten, S., Döse, C., Gustafsson, J., Keisu, M., Petersson, J., Stephens, M., 2006. **Forsmark site investigation. Geological single-hole interpretation of KFM09A and KFM07B**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-06-134

- example of the final interpretation of all the data from a single drillhole, carried out by SKB for each drillhole sunk

Chester, F.M., Logan, J.M., 1986. **Implications for mechanical properties of brittle faults from observations of the Punchbowl Fault Zone, California**. Pure and Applied Geophysics, 124, 79-106.

- early description of the "zone of damaged host rock" (now known as the "damage zone", in descriptions of fault zone architecture) resulting from cataclastic and fluid-assicted processes at 2-4 km depth

- experimental data (strength, permeability) for damage zone rocks and also gouge from the fault core

- *inactive arm of **San Andreas fault**; fault gouge zone bounded by damaged wall rock zone; cataclasis assisted by fluids; expt. data from gouge rocks (e.g. permeability increases towards fault in damage zone, then drops - gouge acts as seal!)*

Chester, F.M., Logan, J.M., 1987. Composite planar fabric of gouge from the Punchbowl Fault, California. Journal of Structural Geology, 9, 6211-634.

Claesson, L.-A., Nilsson, G., 2007. **Forsmark site investigation. Drilling of the cored boreholes KFM09A and KFM09B, and overburden drilling of KFM09C at drill site DS9**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-06-169.
- *example of the preliminary on-site logging carried out at each drilling site in the SKB site investigations, before transport of the cores to the core archive for continued investigation (see Petersson et al. 2006 and Carlsten et al. 2006 for detailed geological core logging and final single-hole interpretation)*

Claesson, L.-A., Nilsson, G., 2004. **Forsmark site investigation. Drilling of the telescopic borehole KFM05A at drilling site DS5**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-04-222.

Cooke, M.L., Underwood, C.A., 2001. **Fracture termination and step-over at bedding interfaces due to frictional slip and interface opening**. Journal of Structural Geology, 23, 223-238.

Coppersmith, K.J., Youngs, R.R., Sprecher, C., 2009. **Methodology and main results of seismic source characterization for the PEGASOS Project, Switzerland**. Swiss Journal of Geosciences, 102, 91-105.
- *methodology and results of PEGASOS project (Probabilistische Erdbeben-Gefährdungs-Analyse für KKW-Stand-Orte in der Schweiz) - published previously as Nagra report (NAGRA 2004)*
- *hazard analysis for 4 Swiss nuclear power plants, following US Nuclear Regulatory guidelines with quantification of uncertainties, also conceptual (reactivation of basement faults, thin-skinned v. thick-skinned Jura tectonics)*
- *4 research teams working in parallel - comparison of results: see Figs. 13-15*

Cosgrove, J., Stanfors, R., Röshoff, K., 2006. **Geological characteristics of large fractures and minor deformation zones and strategy for their detection in a repository**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport SKB R-06-39.
- *results of the EXPECT project*

Ch. 2: The identification of deformation zones larger than r = 50 m in tunnels and deformation holes: some topics covered - 2.4 Extension and shear fractures; 2.5 Discrete and diffuse fractures and brittle deformation zones; 2.7: Spacing distribution and the evolution of fracture sets and networks; 2.9: Second-order structures linked to larger fractures - kinematic indicators

Ch. 3: The recognition of deformation zones in boreholes and tunnels - case studies from Äspö (details in Appendix A1)

Ch. 4: Method for the detection of minor deformation zones using new characterization data (details in Appendix A2

Cruden, A.R., 2008. **Emplacement mechanisms and structural influences of a younger granite intrusion into older wall rocks - a principle study with application to the Götemar and Uthammar granites**. Site descriptive modelling, SDM-Site Laxemar. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-138.
- *Ch. 2: review of granite emplacement studies*
- *Ch. 3: Götemar and Uthammar granites - subsurface geometry (petrology, gravity modelling)*
- *Ch. 4: emplacement mechanism (laccolith emplacement model, Fig. 4.1) and implications for the structural development of Laxemar (discussion of large scale - lineaments which may have formed or been reactivated during the elastic bending of the laccolith roof, Fig. 4.2, cf. fracturing associated with flexural-slip folding - see ref. list)*
  - small-scale fracturing and fracture mineralogy not described, discussed

Darcel, C., Davy, P., Bour, O., de Dreuzy, J.-R., 2004. **Alternative DFN model based on initial site investigations at Simpevarp**. Swedish Nuclear Fuel and Waste Management Company (SKB), report R-04-76.

Darcel, C., Davy, P., Bour, O., de Dreuzy, J.-R., 2006. **Discrete fracture network for the Forsmark site**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-06-79.
- alternative expert view of DFN modelling with "emphasis on the definition of the theory and methodology necessary to assess a sound comparison between data taken at different scales, with different techniques."

Darcel, C., Davy, P., Le Goc, R., de Dreuzy, J.R., Bour, O., 2009. **Statistical methodology for discrete fracture model - including fracture size, orientation uncertainty together with intensity uncertainty and variability**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-09-38.

Davis, G.H., Reynolds, S.J., 1996. **Structural Geology of Rocks and Regions. 2nd Edition**. John Wiley & Sons (New York, etc.).
- Parts I and II: modern structural geology text book, concentrating on understanding rock deformation in the crust
Ch. 1: Nature of Structural Geology
Ch. 2: Kinematic Analysis
Ch. 3: Dynamic Analysis
Ch. 4: Deformation Mechanisms and Microstructures
Ch. 5: Joints and Shear Fractures
Ch. 6: Faults
Ch. 7: Folds
Ch. 8: Cleavage, Foliation and Lineation
Ch. 9: Shear Zones and Progressive Deformation
- Part III: useful series of Appendices on methodology and data processing, entitled "How to function in the field, and how to reduce the data":
A. Geological mapping
B. Mapping contact relationships
C. Identifying primary structures
D. Measuring structural orientations with the compass
E. Preparing geological cross-sections
F. Preparing subsurface contour maps
G. Orthographic projection
H. Stereographic projection (superb exposition!)
I. Stereographic evaluation of rotation
J. Determining slip on a fault (orthographic and stereographic)
K. Stereographic relationship of faults to principal stress directions
L. Methods in joint analysis
M. Some additional tips on fold analysis
N. Studying shear zones in the field

Dunne, B., Stewart, I., Turner, J., eds., 2001. **Special Issue: Brittle Microtectonics, Neotectonics, and Archaeoseismology - In honour of Paul Lewis Hancock: Editor-in-Chief, 1979-1985; Founding Editor, 1986-1998**. Journal of Structural Geology, 23, Number 2-3.

Eloranta, P., 2006. **Laboratory testing of gneissic rocks in Olkiluoto borehole OL-KR24**. Posiva Oy, Working Report 2006-80.
- study of effect of anisotropy on different rock mech properties: uniaxial compressive strength, indirect tensile strength, Young's modulus.
App. 2: paired photos of test cylinders, before and after deformation
App. 3: stress/strain curves for all tests

Enescu, N., Cosma, C., Balu, L., 2007. **Seismic VSP investigations at Olkiluoto, 2005**. Posiva Oy, Working Report 2007-72.
- carried out in 4 drillholes in the vicinity of ONKALO (KR8, 27, 29, 38)
- comparison of deformation zone intersections in the access tunnel with the system of intepreted VSP reflectors (see Section 4.5)

Engelder, T., 1993. **Stress Regimes in the Lithosphere**. Princeton University Press (Princeton, N.J.).
Ch. 1: Basic Concepts - stress regimes indicated by laboratory experiments on intact rock, and described in the next three chapters
Ch. 2: Stress in the Crack-Propagation Regime (near-surface regime - formation of joints, veins and dykes, i.e. extensional fracturing)
Ch. 3: Stress in the Shear-Rupture and Frictional-Slip Regimes (SR regime - formation of primary shear fractures in intact rock in lower part of Scholz "schizosphere" or brittle regime of upper crust; FS regime - frictional slip on already formed structures, whether joints or primary shear fractures)
Ch. 4: Stress in the Ductile-Flow Regime (lower crustal regime = Scholz "plastosphere")
- primary shear joints: only form when local conditions allow stress to excede intact rock strength under compression, therefore never form regional patterns, only local and related to large-scale faulting and folding (regional stress is kept down by crack-propagation, joint formation and frictional slip on already formed discontinuities) - for summary joints/shear fractures, read pages 58-60 !

Engström, J., 2006. **Geological mapping of investigation trench OL-TK8 at the Olkiluoto study site, Eurajoki, SW Finland**. Posiva Oy, Working Report 2005-44.
- many BFI and BJIs described and tabulated (App. 3), also 2 mafic dykes (2.5 m thick) documented

Engström, J., Kemppainen, K., 2008. **Evaluation of the geological and geotechnical mapping procedures in use in the ONKALO access tunnel**. Posiva Oy, Working Report WR 2008-77.

Evans, B., Frederich, J.T., Wong, T.-F., 1990. **The brittle-ductile transition in rocks: recent experimental and theoretical progress.** American Geophysical Union, Geophysical Monograph 56, 1-20.
- Introductory paper in the Heard Volume (entitled "The Brittle-Ductile Transition in Rocks"). Focussed on the semi-brittle failure mode from an experimental and fracture mechanics point of view. Figs. 2 and 4 used in Posiva in-house course on brittle deformation, see Milnes 2006b.
- emphasizes throughout the present lack of knowledge of "the semi-brittle regime" and the need for further research focussed on this topic
- see Fig. 2: "semi-brittle" is in the ductile failure mode but is characterised by cataclasis and cataclastic flow - leading to formation of cataclasite? (but Fig. 5D looks like a mylonite to me!)

Fecker, E., 2007. **Rock stress measurements in ONKALO underground characterisation facility at Olkiluoto at depth of 120 m**. Posiva Oy, Working Report 2007-26.
-overcoring technique using CSIRO 3D stress measuring cell, in boreholes in foliated migmatitic gneiss
- of 8 tests, 4 are considered "relatively successful" - sigma1 subhorizontal NW-SE 14.8 MPa

Fettes, D., Desmons, J., eds., 2007. **Metamorphic Rocks. A Classification and Glossary of Terms**. IUGS/Cambridge University Press (Cambridge, UK).

Fossen, H., 2010. **Structural Geology**. Cambridge University Press (Cambridge, UK).
From the Contents:
Ch. 2: Deformation
Ch. 3: Strain in rocks
Ch. 4: Stress
Ch. 5: Stress in the lithosphere
Ch. 6: Rheology (plastic, brittle, ductile)
Ch. 7: Fracture and brittle deformation

Ch. 8: Faults
Ch. 9: Kinematics and paleostress in the brittle regime
Ch. 12: Foliation
Ch. 13: Lineation
Ch. 15: Shear zones and mylonites
App. B: Stereographic projection

Fox, A., LaPointe, P., Hermanson, J., Öhman, J., 2007. **Statistical geological discrete fracture model. Forsmark modelling stage 2.2**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-07-46.
Ch. 3: modelling methodology
Ch. 4: derivation of SDM Forsmark version 2.2 geological DFN statistical model
- first use of the new fracture domain concept - "The conceptual model ....revolves around the concept of orientation sets. For each fracture domain, other model parameters such as size and intensity are tied to the orientation sets" "Intensity statistics are presented for each fracture set in each domain ..."

Fransson, A., 2009. **Literature survey: relations between stress change, deformation and transmissivity for fractures and deformation zones based on *in situ* investigations**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-09-13.

Front, K., Paananen, M., 2006. **Hydrothermal alteration at Olkiluoto: mapping of drill core samples**. Posiva Oy, Working Report WR 2006-59.

Fry, N., 1984. **The Field Description of Metamorphic Rocks**. Geological Society of London Handbook, Open University Press (Milton Keynes).
- Ch. 4: Banding
- Ch. 6: Textures, fabrics, cleavage and schistosity
- Ch. 7: Scattered entities: pods, boudins, augen, pseudomorphs, veins and pegmatites
- Ch. 8: Contacts and reaction zones
- Ch. 9: Faults, mylonites and cataclasites

Fukuchi, T., 2001. **Assessment of fault activity by ESR dating of fault gouge; an example of the 500m core samples drilled into the Nojima earthquake fault in Japan**. Quaternary Science Reviews, 20, 1005-1008.

Fusseis, F., Handy, M.R., Schrank, C., 2006. **Networking of shear zones at the brittle-to-viscous transition (Cap de Creus, NE Spain)**. Journal of Structural Geology, 28, 1445-1467.
- detailed analysis of brittle-ductile shear zones cutting discordantly through the foliation in high-grade paragneisses and schists - mutual (i.e. +/- coeval) overprinting of brittle and ductile (viscous) deformation. Main structure described is ca. 20 m from tip to tip ("ductile beads"). Many figs. scanned, but not used in Posiva in-house course on brittle deformation, see Milnes 2006b.

Fälth, B., Hökmark, H., 2006a. **Seismically induced slip on rock fractures. Results from dynamic discrete fracture modelling**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-06-48.
- magnitude 6 earthquake modelled and its effect on 1.50 m diameter fractures at different distances from the rupture plane - maximum slip 58 mm, at about 200 m

Fälth, B., Hökmark, H., 2006b. **Mechanical and thermo-mechanical discrete fracture near-field analyses based on preliminary data from the Forsmark, Simpevarp and Laxemar sites**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-06-89.
- modelling using the 3DEC codes ("distinct element method" - same as finite element? - at least, not DFN modelling) to investigate fracture shear displacements, fracture normal stress and rock stresses close to openings, in the near field, and thermal stresses between repository and ground level (intact rock, i.e. assuming no fracturing), on the large scale

Gehör, S., 2007. **Mineralogical characterization of gouge fillings in ONKALO facility at Olkiluoto**. Posiva Oy, Working Report WR 2007-33.

Gehör, S., Karhu, J., Kärki, A., Löfman, J., Pitkänen, P., Ruotsalainen, P., Taikina-aho, O., 2002. **Fracture calcites at Olkiluoto. Evidence from Quaternary infills for palaeohydrogeology**. Posiva Oy, report POSIVA 2002-03.

Gehör, S., Karki, A., Paananen, M., 2007. **Petrology, petrophysics and fracture mineralogy of the drill core sample OL-KR20 and OL-KR20B**. Posiva Oy, Working Report 2007-45.
- one of a series of working reports with the same title: WR 2007-42 to 2007-48, describing the petrology, etc. of the cored boreholes KR08, KR15 and KR19-KR23, respectively
Ch. 2: petrology - lithology, whole-rock geochemistry, petrography
Ch. 3: petrophysics - density and magnetic properties, electrical properties and porosity, P-wave velocity (Appendix 3)
Ch. 4: fracture mineralogy - fillings in pervasive alteration zones, fillings outside pervasive alteration zones, indications of water flow, etc.
- no data on mineral sequence or timing

Glamheden, R., Curtis, P., 2006. **Comparative evaluation of core mapping results for KFM06C and KLX07B**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-06-55.
- conclusion: mostly OK, but some areas need attention: shear zones and how they are recorded, fracture classification (e.g. for rock mass classification, also open vs. sealed fr.)
- critical of the BOREMAP mapping system - SKB has initiated a detailed review of current drill-core mapping routines

Glamheden, R., Fredriksson, A., Röshoff, K., Karlsson, J., Hakami, H., Christiansson, R., 2007. **Rock mechanics Forsmark. Site descriptive modelling Forsmark stage 2.2**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-07-31.
Ch. 3: Mechanical properties of intact rock
Ch. 4: Mechanical properties of fractures
Ch. 5: Rock mass mechanical properties
Ch. 6: In situ state of stress

Glamheden, R., Lanaro, F., Karlsson, J., Lindberg, U., Wrafter, J., Hakami, H., Johansson, M., 2008. **Rock mechanics Forsmark. Modelling stage 2.3. Complementary analysis and verification of the rock mechanics model**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-66.
Ch. 2: Mechanical properties of intact rock
Ch. 4: Evaluation of the rock mass mechanical properties using empirical methods
Ch. 5: In situ state of stress

Gratier, J.P., Renard, F., Labaume, P., 1999. **How pressure solution creep and fracturing process interact in the upper crust to make it behave in both a brittle and viscous manner**. Journal of Structural Geology, 21, 1189-1197.

Groshong, R.H., 1988. **Low-temperature deformation mechanisms and their interpretation**. Geological Society of America Bulletin, 100, 1329-1360.
- somewhat misleading title: only first few and last few pages deal with deformation mechanisms at microscopic scale, rest is essentially brittle microtectonnics, cleavage formation, fault zone fabrics, stress and strain analysis, etc.
- extensive review, also of "brittle microtectonics" (joints, veins, stylolites, etc.)
- fossil Smiley: "rocks do not suffer deformation, they enjoy it"!

Gustafsson, J., Gustafsson, C., 2004. **Forsmark site investigation. RAMAC and BIPS logging in borehole KFM05A**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-04-152.

Habimana, J., Labiouse, V., Descoeudres, F., 2002. **Geomechanical characterisation of cataclastic rocks: experience from the Cleuson-Dixence project**. International Journal of Rock Mechanics and Mining Sciences, 39, 677-693.
- focus on incoherent fault gouge and breccias (crushed rocks), and on rock engineering aspects (mechanical properties, rock mass class., testing methods); protoliths quartzitic sst and phyllitic schists.

Hagros, A., 2006. **Host Rock Classification (HRC) system for nuclear waste diposal in crystalline bedrock**. University of Helsinki, Publications of the Department of Geology D8 (PhD thesis no. 191).

Hagros, A., Äikäs, K., McEwen, T., Anttila, P., 2003. **Host rock classification, Phase 2: Influence of host rock properties**. Posiva Oy, working report WR 2003-04.

Hagros, A., McEwen, T., Anttila, P., Äikäs, K., 2005. **Host rock classification, Phase 3. Proposed classification system (HRC-system)**. Posiva Oy, working report WR 2005-07.

Hagros, A., Johansson, E., Hudson, J.A., 2008. **Time dependency in the mechanical properties of crystalline rocks. A literature survey.** Posiva Oy, Working Report WR 2008-68.

Hakala, M., 2000. **Interpretation of the Hästholmen in situ state of stress based on core damage observations**. Posiva Oy, report POSIVA 2000-01.

Hakala, M., 2006. **Quality control for overcoring stress measurement data**. Posiva Oy, report POSIVA 2006-03.
Ch.2: overcoring methodology
Ch. 3: assumptions, problems, etc.
Ch. 6: case studies - Äspö, AECL URL

Hakala, M., Sjöberg, J., 2006. **A methodology for interpretation of overcoring stress measurements in anisotropic rock**. Posiva Oy, Working Report 2006-99.
- mainly development of computer codes for dealing with overcoring results from transversely isotropic rock (i.e. foliated rock), and analysis of case studies from Sweden and Finland (SKB and Posiva sites)
Ch. 2: stress measurement in anisotropic rock, including effect of anisotropy on stress measurements and determination of elastic constants in anisotropic rock
*Ch. 5: **project conclusions** (including also earlier reports. e.g. **Hakala et al. 2005 (WR 2005-61)** - not in WR 2006-25 - important to study reference list in this report!)*

Hakala, M., Kuula, H., Matinlassi, M., Somervuori, P., Syrjänen, P., Tolppanen, P., 2002. **Analyses of tunnel stress failures at Pyhäsalmi mine**. Posiva Oy, Working Report 2002-28.

Hakala, M., Kuula, H., Hudson, J., 2005. **Strength and strain anisotropy of Olkiluoto mica gneiss**. Posiva Oy, Working Report 2005-61.

Hakami, E., Olofsson, S.-O., 2002. **Numerical modelling of fracture displacements due to thermal load from a KBS-3 repository**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-02-08.
- aim to estimate largest shear displacement which can be expected on pre-existing fracture due to heat release from the deposited waste - rock mass around the fracture modelled as a homogeneous, isotropic, elastic material, with maximum shear displacement expected about 200 years after depostion
- most fracture lengths modelled greater than 700 m in the dip direction (3 models out of 20 use 265, 528, 528 m - see Table 2-1) - totally unrealistic for single fractures!!!
- maximum displacements achieved were about 13 cm, and some recommendations made to confine such effects to <10 cm, which is SKB's magic number

Hakami, E., Frederiksson, A., Lanaro, F., Wrafter, J., 2008. **Rock mechanics Laxemar. Site descriptive modelling, SDM-Site Laxemar**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-57.
Ch. 1: introduction, incl. parameters, nomenclature, abbreviations, symbols, etc.
Ch. 2: Input from other disciplines, incl. geological model overview (with summary defm. zones and GeoDFN)
Ch. 3: mechanical properties of intact rock
Ch. 4: mechanical properties of single fractures
Ch. 5: mechanical properties of rock mass (and fracture domains, deformation zones)
Ch. 6: in situ state of stress
Ch. 7: summary of Chapters 3-6 (title "Summary of the rock mechanics model" - seems to be more a compilation and summary of measured properties)

Hancock, P.L., 1985. **Brittle microtectonics: principles and practice**. Journal of Structural Geology, 7, 437-457.

Hancock, P.L., ed., 1994. **Continental Deformation**. Pergamon Press (Oxford, etc.).
Part 1: Deformation processes and deformation analysis, including
Ch. 1: Ductile deformation processes (Williams, Goodwin, Ralser)
Ch. 2: Palaeostrain analysis (Lisle)
Ch. 3: Brittle crack propagation (Engelder)
*Ch. 4: **Fault slip analysis** and palaeostress reconstruction (Angelier)*
*Ch. 5: Palaeostress analysis of **small-scale brittle structures** (Dunne, Hancock)*
Ch. 18: Neotectonics (Stewart, Hancock)

Hancock, P.L., Engelder, T., 1989**.** **Neotectonic joints**. Geological Society of America Bulletin, 101, 1197-1208.
- neotectonic joints systems are "the most recent joint systems to form within a region of uplift and erosion" and form within the upper 500 m of the crust where the minimum principal effective stress is both tensile and horizontal, and the differential stress is small, due to unloading (uplift, erosion)
- detailed description of the characteristics of neotectonic joints (geometry, architecture , surface spacing, surface markings), based on case studies (Appalachian Plateau, SE-England-NE-France, Arabian Platform, Ebro Basin)

Hartley, L., Hoek, J., Swan, D., Roberts, D., Joyce, S., Follin, S., 2009. **Development of a hydrogeological discrete fracture network model for the Olkiluoto Site Descriptive Model 2008**. Posiva Oy, Working Report WR 2009-61.

Heikkinen, E., Öhman, I., Paulamäki, S., Säävuori, H., Vuoriainen, S., Aaltonen, I., 2009. **Summary of petrophysical analysis of Olkiluoto core samples, 1990-2008**. Posiva Oy, Working Report WR 2009-11.

Hellä, P., Ikonen, A., Mattila, J., Torvela, T., Wikström, L., 2009. **RSC-Programme - Interim Report. Approach and basis for RSC development, layout determining features and preliminary criteria for tunnel and deposition hole scale**. Posiva Oy, Working Report WR 2009-29.
- ? relationship to ReRoC programme (Aalto et al. 2009)

Henderson, I.H.C., Ihlen, P.M., 2004. **Emplacement of polygeneration pegmatites in relation to Sveco-Norwegian contractional tectonics: examples from southern Norway**. Precambrian Research, 133, 207-222.

Hermanson, J., Hansen, L., Wikholm, M., Cronquist, T., Leiner, P., Vestgård, J., Sandahl, K.-A., 2004. **Detailed fracture mapping of four outcrops at the Simpevarp peninsula and Ävrö**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project Report P-04-35.

Hermanson, J., Forsberg, O., Fox, A., LaPointe, P., 2005. **Statistical model of fractures and deformation zones. Preliminary site description, Laxemar subarea, version 1.2**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-05-45.

Hobbs, B.E, Means, W.D., Williams, P.F., 1976. **An Outline of Structural Geology**. Wiley (New York, etc.).
See particularly:
Ch. 1: Mechanical Aspects
Ch. 2: Microfabric
Ch. 5: Foliations
Ch. 6: Lineations
Ch. 7: Joints and Faults

Holmén, J.G., Outters, N., 2002. **Theoretical study of rock mass investigation efficiency**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-02-21.
- essentially an extremely detailed consideration of the parameters necessary for DFN modelling and errors/uncertainties involved in their measurement and initial processing
Ch. 2: Methodology (including statistical tests and sampling bias corrections)
Ch. 3: Estimation of fracture-set mean direction from borehole data
Ch. 4: Estimation of fracture set dispersion from borehole data
Ch. 5: Estimation of fracture density from boreholes and rock surfaces - including matematical and statistical fundament of the "P10Te = approx. P32" method of processing drillhole fracture data
Ch. 6: Estimation of trace-length distribution from rock surface data
Ch. 7: Estimation of fracture-set orientation from fracture traces on rock surfaces
Ch. 8: Limited sensitivity analyses

Holness, M.B., ed., 1997. **Deformation-enhanced Fluid Transport in the Earth's Crust and Mantle**. Chapman & Hall (London, etc.).
Ch. 4: The influence of deformation on the extraction of crustal melts: a consideration of the role of melt-assisted granular flow (Rutter) - incl. formation of dykes and veins
Ch. 5: The role of deformation in the movement of granitic melts: views from the laboratory and the field (Brown, Rushmer) - incl. melt segregation at the outcrop scale (migmatites, folds, boudins, shear zones, veins)
Ch. 9: The geoschemistry of volatile fluid flow in shear zones (McCraig)
Ch.10: Segregation veins: evidence for deformation and dewatering of a low-grade metapelite (Brantley et al.)
Ch.11: Fluid flow in fractured rocks at shallow levels in the Earth's crust: an overview (odling)

Hopgood, A.M., 1984. **Structural evolution of Svecokarelian migmatites, southern Finland: a study of Proterozoic crustal development**. Transactions of the Royal Society of Edinburgh, Earth Sciences, 74, 229-264.

Hopgood, A.M., 2000. **Determination of Structural Successions in Migmatites and Gneisses**. Kluwer Academic Publishers (Dordrecht, etc.).
From the contents:
Ch.1: general characteristics of migmatites and migmatite terranes
Ch.2: principles of structural analysis of migmatites
Ch.3: development of migmatite structure: overprinting
Ch.12: principles and practice of determining structural succession

Hudson, J.A., Harrison, J.P., 1997. **Engineering Rock Mechanics. Part I: An Introduction to the Principles**. Pergamon (Amsterdam, etc.).
Ch. 3: Stress
Ch. 4: In situ stress
Ch. 6: Intact rock
Ch. 7: Discontinuities
Ch. 8: Rock masses
Ch.10: Anisotropy and inhomogeneity

Hudson, J.A., Cosgrove, J.W., 2006. **Geological history and its impact on the rock mechanics properties of the Olkiluoto site**. Posiva Oy, Working Report 2006-14.
- *geol history rather sketchy, but serves as an example of what the rock mechanics team expects from the geologists - what is important from a rm point of view (past/present state of stress, bounding lineaments, tectonic history), for char. of rock properties, numerical modelling of rock behaviour, rock stress, monitoring, etc.*

Hudson, J.A., Johansson, E., 2006. **Summary of rock mechanics work completed for Posiva before 2005**. Posiva Oy, report POSIVA 2006-04.
- *80 rock mechanics works tabulated in Appendix with details of data, objectives, methodology and conclusions, and in some cases reproductions of key Figures*
- *categories in Appendix include: **in situ stress** and comparative data from Sweden, **EDZ**, and deformation properties of intact rock, fractures, rock mass and **deformation zones***

Hudson, J.A., Cosgrove, J., Johansson, E., 2008. **Estimating the mechanical properties of brittle deformation zones at Olkiluoto**. Posiva Oy, Working Report WR 2008-67.

Huhta, P., 2007. **Studies of Quaternary deposits of investigation trench OL-TK13 at the Olkiluoto study site, Eurajoki, SW Finland**. Posiva Oy, Working Report 2007-34.
- *no evidence for disturbance related to post-glacial bedrock movements*

Hökmark, H., Fälth, B., 2003. **Thermal dimensioning of the deep repository. Influence of canister spacing, canister powwer, rock thermal properties and nearfield design on the maximum canister surface temperature**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-03-09.
- *graphs are produced which will enable canister spacing to be determined for keeping the canister surface temperature at or below 100^{o}C, for different combinations of site characterisation data (initial undisturbed rock temperature, host rock heat transport properties)*
- *assumes homogeneous rock for thermal conductivity data (linear heat conduction in a homogeneous medium) - for graphs showing the effect of **intact rock thermal conductivity**, see Figs. 5-5 to 5-12 and 8-1 to 8-8*

Ikonen, K., 2003. **Thermal analyses of KBS-3H type repository**. Posiva Oy, report POSIVA 2003-11.
- *thermal properties of rock assumes homogeneous/isotropic material (calculations seem to be a highly simplified version of those in the corresponding SKB study, Hökmark & Fälth 2003)*

Imber, J., Holdsworth, R.E., Butler, C.A., Strachan, R.A., 2001. **A reappraisal of the Sibson-Scholz fault zone model: the nature of the frictional to viscous ("brittle-ductile") transition along a long-lived, crustal-scale fault, Outer Hebrides, Scotland**. Tectonics, 20, 601-624.
- *Outer Hebrides Fault Zone (1-6 km thick, exposed 190 km along strike): role of major influx of hydrous fluids caused phyllonitization and weakening over a wide range of temperatures (depths), so that the "brittle ductile" transition zone can be as shallow as 5 km depth*
- *good critical review of the Sibson-Scholz model; well-documented oveview of the OHFZ (Caledonian reactivated, Precambrian shear zone)*

Jaeger, J.C., 1962. **Elasticity, Fracture and Flow, with Engineering and Geological Applications**. **2nd Edition**. John Wiley & Sons (New York).
- *the classical starting point for understanding rock mechanics (basic mathematics of the theories of elasticity, plasticity, viscosity and rheology, in as elementary form as possible):*

Ch. 1: Stress and strain
Ch. 2: Behaviour of actual materials
Ch. 3: Equations of motion and equilibrium
Ch. 4: Applications

Johannes, W., Ehlers, C., Kriegsman, L.M., Mengel, K., 2003. **The link between migmatites and S-type granites in the Turku area, southern Finland**. Lithos 68, 69-90.

Johansson, R., 2006. **A comparison of two independent interpretations of lineaments from geophysical and topographic data from the Simpevarp area**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-06-53.
- *primary interpretation (GeoVista) and alternative interpretation (GTK) - patterns similar (reproducable), but attributes (length, uncertainty, etc.) differ significantly*
- *key report - well-formulated conclusions! - also that the assignment of significance (e.g. whether lin. is the trace of a deformation zone, etc.) needs drilling and/or field data - cannot be simply assumed*

Juhlin, C., Cosma, C., 2007. **A 3D surface seismic pilot study at Olkiluoto, Finland: acquisition and processing report**. Posiva Oy, Working Report 2007-65.
- *several strong subhorizontal reflection zones at 600-900 m depth, undulating and discontinuous, sometimes apparently offset*
- *also some reflectors dipping 20-30^0 to south, but short and difficult to follow*

Juhlin, C., Bergman, B., Cosma, C., Keskinen, J., Enescu, N., 2002. **Vertical seismic profiling and integration with reflection seismic studies at Laxemar**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-02-04.

Juhlin, C., Bergman, B., Palm, H., 2004. **Oskarshamn site investigation. Reflection seismic studies performed in the Laxemar area in 2004**. Svensk Kärnbränslehantering AB, SKB Projektrapport P-04-215.

Julkunen, A., Kallio, L., Kuusisto, M., 2009. **Drillhole gamma-ray spectrum logging in drillholes .... OL-KR46, OL-KR47....OL-KR48 and ground survey at Olkiluoto in Eurajoki, 2007 and 2008**. Posiva Working Report 2009-68.

Karttunen, P., Kosunen, P., Lamminmäki, T., Pekkanen, J., Pöllänen, J., Tarvainen, A.-M., Toropainen, 2010. **Drilling and associated drillhole measurements of the pilot hole ONK-PH9**. Posiva Oy, Working Report WR 2010-09.

Kemppainen, K., Ahokas, T., Ahokas, H., Paulamäki, S., Paananen, M., Geför, S., Front, K., 2007. **The ONKALO Area Model. Version 1**. Posiva Oy, Working Report 2007-71.
- *first version to contain access tunnel data and to model major deformation zones for future construction purposes*

Kim, Y.-S., Sanderson, D.J., 2005. **The relationship between displacement and length of faults: a review**. Earth-Science Reviews, 68, 317-334.

Kim, Y.-S., Peacock, D.C.P., Sanderson, D.J., 2004. **Fault damage zones**. Journal of Structural Geology, 26, 503-517.

Korhonen, K., Kuivamäki, A., Paananen, M., Paulamäki, S., 2005. **Lineament interpretation of the Olkiluoto area**. Posiva Oy, Working report 2005-34.

Kuivamäki, A., 2000. **Lineament database of the Finnish potential repository sites for the calculation of bedrock movements induced by earthquakes**. Posiva Oy, working report WR 2000-12.

Kuivamäki, A., 2005. **Revision of the lineament interpretation of the Olkiluoto area in the light of acoustic-seismic data from the adjacent marine areas**. Posiva Oy, Working Report 2005-16.

Kukkonen I.T., 2000. **Thermal properties of the Olkiluoto mica gneiss: Results of laboratory measurements**. Posiva Oy, Working Report 2000-40.

Kukkonen, I.T., Suppala, I., Korpisalo, A., 2007. **Rock thermal property measurements with the Posiva TER056 drill hole device in the Forsmark study site**. Posiva Oy, Working Report 2007-83.

- carried out at a test site "for measuring the thermal properties of anisotropic rocks", but does not seem to be any further mention or discussion of the problem of anisotropy (foliation)!

Kuusisto, S., Lehtokangas, M., 2007. **Selected visualizations and summaries of the contents of the fracture database, deformation zone intersection data, and deviation survey measurements regarding boreholes OL-KR1 - OL-KR33B**. Posiva Oy, Working Report WR 2007-07.
- data-mining techniques applied to the heterogeneous collection of fracture information known as the fracture database - aim to characterize the database, not any geological questions

Kuva, J., Voutilainen, M., Timonen, J., Aaltonen, I., 2010. **Tomographic imaging of 12 fracture samples selected from Olkiluoto deep drillholes**. Posiva Oy, Working Report WR 2010-38.

Kärki, A., Paulamäki, S., 2006. **Petrology of Olkiluoto**. Posiva Oy, report POSIVA 2006-02.

Lagerbäck, R., Sundh, M., Svedlund, J.-O., Johansson, H., 2005. **Forsmark site investigation. Searching for evidence of late- or post-glacial faulting in the Forsmark region. Results from 2002-2004**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-05-51.

Lahti, M., Ahokas, T., Nordbäck, N., Paananen, M., Paulamäki, S., Vaittinen, T., 2009. **The ONKALO Area model, version 1.1**. Posiva Oy, Working Report WR 2009-113.
Ch. 4: Lithological Model
Ch. 5: Brittle Deformation Model (5.1: Interpreted brittle deformation zones cross-cutting the tunnel; 5.3: Tunnel cross-cutting fractures TCF)
App. 2: Geological, geophysical and geohydrogeological characteristics of site-scale structures
App. 4: Collected fault-slip data from TCFs in ONKALO, chainage 0-2300
App. 6: Vertical sections through the ONKALO model volume

Laing, W.P., 2004. **Tension vein arrays in progressive strain: complex but predictable architecture, and major hosts of ore deposits**. Journal of Structural Geology, 26, 1303-1315.

Lampinen, H., 2007. **Terminology report: respect distance. The use of the term respect distance in Posiva and SKB**. Posiva Oy, Working Report 2007-69.
- cf. Cosgrove et al. 2006 - useful but contains some misconceptions and misrepresentations.

Lanaro, F., Bäckström, A., 2006. **Empirical characterisation of the rock mass along borehole KBH02 and comparison with the results of the EXPECT project. Site descriptive modelling, Laxemar stage 2.1**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-06-67.
- borehole running parallel to Äspö Tunnel: rock mass characterisation according to the Q and RMR system compared with data on fracturing and deformation zones in the corresponding part of the Äspö access tunnel as described in the EXPECT report (SKB R-06-39)

Lanyon, G.W., Marschall, P., 2006. **Discrete Fracture Network modelling of a KBS-3H repository at Olkiluoto**. Posiva Oy, report POSIVA 2006-06.
Ch. 2: representation of the geosphere - basically the input data used for the modelling, provided by Posiva (e.g. uses the old bedrock model of Vaittinen et al. 2003 as basis)

LaPointe, P.R. & Hudson, J.A., 1985: **Characterization and interpretation of rock mass joint patterns**. Geol. Soc. Amer. Spec. Paper 199, 37 p..
- whole technique of scanline joint surveys explained, on two scanlines at right angles, measuring orientation and length at every crossing point removes all systematic biases

LaPointe, P.R., Cladouhos, T.T., 1999. **An overview of a possible approach to calculate rock movements due to earthquakes at Finnish nuclear waste repository sites**. Posiva Oy, report POSIVA 99-02.

LaPointe, P.R., Cladouhos, T.T., Outters, N., Follin, S., 2000. **Evaluation of the conservativeness of the methodology for estimating earthquake-induced movements of fractures intersecting canisters**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-00-08.

LaPointe, P.R., Hermansson, J., 2002. **Estimation of rock movements due to future earthquakes at four candidate sites for a spent fuel repository in Finland**. Posiva Oy, report POSIVA 2002-02.

LaPointe, P.R., Olofsson, I., Hermanson, J., 2005. **Statistical model of fractures and deformation zones for Forsmark. Preliminary site investigation, Forsmark area - version 1.2**. Swedish Nuclear Fuel and Waste Management Company (SKB), report R-05-26.

LaPointe, P., Fox, A., Hermanson, J., Öhman, J., 2008. **Geological discrete fracture network model for the Laxemar site. Site descriptive modelling, SDM-Site Laxemar**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-55.
- *"The conceptual model ..... revolves around the identification of fracture domains based on relative fracture set intensities, orientation clustering, and the regional tectonic framework (including deformation zones)." (from the Abstract)*
- *calculates P32 from drillhole fracture data using the Wang method (Wang 2005 - PhD thesis) which was first used in the Forsmark version 2.2 geol. DFN modelling in 2006 and 2007*

Ch. 2: data and software used (incl. listings of data used in the definition of fracture domains)
Ch. 3: modelling methodology, including fracture domain model (3.2), orientation model (3.3), size model (3.4), intensity model (3.5), and spatial distribution model (3.6)
Ch. 4: derivation of DFN model for Laxemar site (4.1 fracture domain model, 4.2 orientation model, 4.3 coupled size-intensity model) - uses a "global" orientation model (i.e. 4 sets which are constant in all domains, but vary in intensity from domain to domain)
Ch. 5: verification and validation of the derived Laxemar DFN model
Ch. 6: uncertainty - identification of sources and evaluation of impacts
Ch. 7: summary and conclusions, e.g.: fracture domain concept reduces uncertainty because fr. intensity varies more between domains than within one domains; difference between fr. domains is not due to changes in fr. orientation but to changes in intensity of individual sets; fr. termination relationships suggest that the N-S set formed earliest, the other 3 sets later.
App. B: contoured stereoplots used in defining fracture domains
App. E: fracture intensity as a function f depth

Le Maitre, R.W., ed., 2004. **Igneous Rocks. A Classification and Glossary of Terms. 2nd Edition**. Cambridge University Press (Cambridge, UK).

Lee., H.-K., Kim, H.S., 2005. **Comparison of structural features of the fault zone developed at different protoliths: crystalline rocks and minerals**. Journal of Structural Geology, 27, 2099-2112.
- *good diagram of the architecture of a **semi-brittle fault zone** cutting granite gneiss (core zone and damage zones), with series of thin-section and rock slab photos of **cataclasites** (Fig. 2 in Posiva in-house course on brittle deformation, see Milnes 2006b)*
- *Keumwang fault zone, Korea, sinistral strike-slip, up to 200m thickness, 25 km length, displacement and movement history not yet known*

Lehtonen, T., Tarvainen, A.-M., 2006. **Mise-a-al-masse surveys of the EDZ-holes at Olkiluoto 2006**. Posiva Oy, Working Report 2006-86.
- *"EDZ-holes" in ONKALO are boreholes ONK-PP12 - PP57 mise-a-la-masse surveys carried out in 12 holes, for comparison with resistivity logging in 9 holes and optical imagery in 18 holes - each EDZ hole is about 3 m long*
- *a test to see whether mise-a-la-masse could be used for study of "unbrokeness" of rock in the ONKALO access tunnel after blasting*

Lehtonen, T., Mattila, J., 2007. **The identification of the continuity of the long fractures by mise-a-la-masse surveys. A test work at ONKALO**. Posiva Oy, Working Report 2007-02.
- test negative - "interpretation of the results difficult and ambiguous" - "needs to test and improve to be a suitable system of rock characterisation"

Lindberg, A., 2007. **Search for glacio-isostatic faults in the vicinity of Olkiluoto**. Posiva Oy, Working Report 2007-05.
- 619 fractures observed/measured (> 4 m trace length), 30 considered as fault planes or narrow fault zones (but photos unconvincing - seems to mix height of fracture scarp with evidence for post-glacial displacement!)
- clear evidence not observed, but in some cases a post-glacial component of movement could not be excluded
- cites an early work by Edelman 1949 - also Ojala et al. 2004
***Appendix: photo collection on CD** shows many good examples of migmatites, veins, granitic rocks and different brittle structures, well-exposed on wave-washed outcrops on the islands surrounding Olkiluoto, and on some Åland islands (rapakivi bedrock)*

Lindberg, A., 2010. **Geological mapping of investigation trench OL-TK17 at the Olkiluoto Study Site, Eurajoki, SW Finland**. Posiva Oy, Working Report WR 2010-01.

Lisle, R.J., Leyshon, P.R., 2004. **Stereographic Projection Techniques for Geologists and Civil Engineers. 2nd Edition**. Cambridge University Press (Cambridge, UK).

Lisle, R.J., Orife, R.J., Arlegui, L., Liesa, C., Srivastave, D.C., 2006. **Favoured states of palaeostress in the Earth's crust: evidence from fault-slip data**. Journal of Structural Geology, 28, 1051-1066.

Lockner, D.A., 1995. **Rock failure**. In: Rock Physics and Phase Relations. A Handbook of Physical Constants. American Geophysical Union (Washington DC), Reference Shelf 3, 127-147.

Lund B., 2005. **Effects of deglaciation on the crustal stress field and implications for endglacial faulting: a parametric study of simple Earth and ice models**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report TR-05-04.

Lund, B., 2006. **Stress variations during a glacial cycle at 500 m depth in Forsmark and Oskarshamn: Earth model effects**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-06-95.
- large-scale dynamic modelling: Earth model of 100 km thick elastic plate overlying viscoelastic half-space, with complexity introduced by inserting horizontal layers of different properties in the plate and in the half-space
- stresses produced by glacial loading/unloading studied wrt. fault stability at repository sites - fault stability significantly higher at Forsmark - Oskarshamn site shows "long periods of decreased fault stability during interstadials and at the end of deglaciation"

Lund, B., Schmidt, P., Hieronymus, C., 2009. **Stress evolution and fault stability during the Weichselian glacial cycle**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report TR-09-15.

Löfgren, M., Neretnieks, I., 2002. **Formation factor logging in-situ by electerical methods. Background and methodology**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-02-27.
- focus on methodology of wireline logging using electrical methods (resistivity, etc.), especially with regard to the formation factor as a parameter governing matrix diffusion
- new technique presented and compared with SKB techniques used up to now - tested in Laxemar deep borehole KLX02
- problem of water-conducting fractures and their effects on the resistivity logs addressed

Majapuro, J., 2006a. **Optical imaging of the boreholes KR37, KR37B and KR38 at Olkiluoto 2005**. Posiva Oy, Working Report 2006-17.

- details of equipment, specifications and methodology, test of new procedures
- complete set of images on enclosed CD (not in e-copy)

Majapuro, J., 2006b. **Geophysical borehole logging of the boreholes KR37, KR37B and KR38, at Olkiluoto**. Posiva Oy, Working Report 2006-30.
- wireline logging, including natural gamma, gamma-gamma, magnetic susceptibility, single point res., normal res., fluid temp. and res., caliper, full waveform sonic - equipment described, with specifications
- Appendix with complete logs in colour

Marchal, D., Guiraud, M., Rives, T., 2003. **Geometric and morphologic evolution of normal fault planes and traces from 2D to 4D data**. Journal of Structural Geology, 25, 135-158.
- Oklo fault system (outcrop studies, seismic surveys, analogue modelling) - reconstruction of faut zones "in the real world" - curvature, splays, fault terminations, relay zones, etc. (used as illustration in Posiva course and in WR 2006-25)

Martel, S.J. Munier, R., Hokman, H., 2004. **Respect distances – rationale and means of computation**. Swedish Nuclear Fuel and Waste Management Company (SKB), report R-04-17.

Martin, C.D., Christiansson, R., Söderhäll, J., 2001. **Rock stability considerations for siting and constructing a KBS-3 repository. Based on experiences from Äspö HRL, AECL's URL, tunnelling and mining**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-01-38.
*- Ch. 2: Overview of failure modes around underground openings in hard rocks (including discussion of **bulk rock mass strength**)*

Martin, C.D., 2007. **Quantifying in situ stress magnitudes and orientations for Forsmark. Forsmark stage 2.2**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-07-26.
Ch. 2+3: geological framework for interpreting stress data, geological framework of Forsmark
Ch. 4+5: indicators of stress state at Forsmark, and stress measurement campaigns (hydrofrac, overcoring)
Ch. 6+7: interpretation of in-situ stress data and estimation of Forsmark stress state
- sigma1 = sigmaH orient 145^{o}+/-15-20, most likely magn at 500 m = 41 MPa
- sigma2 = sigmah orient 055^{0}+/-15-20, most likely magn at 500 m = 23 MPa
- sigma3 = sigmaV orient vertical, calc as 0.0265z at 500 m = 13 MPa

Mattila, J., 2006. **A system of nomenclature for rocks in Olkiluoto**. Posiva Oy, Working Report 2006-32.

Mattila, J., 2009. **Constraints on the fault and fracture evolution at the Olkiluoto region**. Posiva Oy, Working Report WR 2009-130.
Ch. 3: Brittle Deformation and Palaeostress/-strain Analysis (3.1 methodology of joint and fault-slip analysis; 3.2 Results, as applied to mafic dykes, hydrothermal fractures, and fractures in rapakivi granite and mafic dykes)
Ch.4: Data Interpretation and Discussion

Mattila, J., Aaltonen, I., Kemppainen, K., Talikka, M., 2007. **Geological mapping of the investigation trench OL-TK11, the Storage Hall area**. Posiva Oy, Working Report 2007-27.
- important report! - v.detailed fracture mapping of the cleared and cleaned area where the core storage facility now stands (area equidimensional, ca. 1500 m^3)
- classic example of areal mapping and also architecture of a small brittle fault zone (fault core and both damage zones) - the Storage Hall fault - and the surrounding averagely fractured intact rock
- intact rock includes a mappable high grade deformation zone which is displaced by the SH fault
- successful kinematic analysis of the SH fault carried out: good teaching example

Mattila, J., Aaltonen, I., Kemppainen, K., Wikström, Paananen, M., Paulamäki, S., Front, K., Gehör, S., Kärki, A., Ahokas, T., 2008. **Geological model of the Olkiluoto Site. Version 1.0**. Posiva Oy, Working Report 2007-92.
Ch. 2: Data Sources and Evaluation of Database
Ch. 3: Geological Evolution of the Bedrock
Ch. 4: Geological Model
Ch. 5: Confidence Assessment
App. III: Preliminary fault analysis
App. VI: Lineament analysis and interpretation
App. VII: Description of modelled site-scale deformation zones
App. VIII: Description of modelled local-scale deformation zones
App. IX: Horizontal and vertical serial corss-sections through the model volume

Mauldon, M., Dunne, W.M., Rohrbaugh, M.B., 2001. **Circular scanlines and circular windows: new tools for characterizing the geometry of fracture traces**. Journal of Structural Geology, 23, 247-258.

Mazurek, M., 2000. **Geological and hydraulic properties of water-conducting features in crystalline rocks**. In: Hydrogeology of Crystalline Rocks (Stober, I., Bucher, K., eds.), Kluwer (Amsterdam), 3-26

McClay, K.R., 1987. **The Mapping of Geological Structures.** Geological Society of London Handbook, Open University Press (Milton Keynes).
Ch. 4: Foliations
Ch. 5: Lineations
Ch. 6: Faults and shear zones
Ch. 7: Joints, veins and stylolites

McEwen, T., 2002. **Host rock classification. Phase 1: The factors that determine the location and layout of a repository - a review**. Posiva Oy, Working Report 2002-36.
- very useful review including the following topics:
*Ch. 2: Factors that influence **repository siting** (overview)*
Ch. 3: Factors that influence the location of tunnels and disposal holes (overview)
*Ch. 4: Fracture zones and R-structures (including 4.2: **Structure of fracture zones** and faults, including the damage zone concept and the phenomenon of foliation-guided fracture zones; 4.3-4.4 **Respect distance** - development of the concept and determining factors)*
Ch. 5: Hydraulically conductive features (HCFs) and other conductive fractures
*Ch. 6: **In situ stress** and rock strength*
*- in Ch. 4.2, **case studies**, including: Lewisian of NW Scotland (foliation-guided fracture zones?); Pori shear zone project; Finnsjön fracture zone project (also e.g. of foliation-guided fracturing?);*
*- in Ch 4.3-4.4, **case studies**, including; NAGRA crystallines in NCH: AECL and Canadian URL; NIREX and the Sellafield case - very useful summary!*

Miller, W., Alexander, R., Chapman, N., McKinley, I., Smellie, J., 2000. **Geological Disposal of Radioactive Wastes and Natural Analogues**. Pergamon (Amsterdam, etc.).
Ch. 1: The issue of radioactive waste disposal
Ch. 2: Radioactive waste types and repository designs
Ch. 3: Varieties of analogue studies
Case histories: Sweden and Finland (Box 1), Forsmark SFR (Box 3), Palmottu (Box 16)

Milnes, A.G., Gee, D.G., 1992. **Bedrock stability in Southeastern Sweden. Evidence from fracturing in the Ordovician limestones of Northern Öland**. Swedish Nuclear Fuel and Waste Management Company (SKB),Technical Report TR 92-23.

Milnes, A.G., 2002. **Swedish deep repository siting programme. Guide to documentation of 25 years of geoscientific research (1976-2000)**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-02-18.

Milnes, A.G., 2006a. **Understanding brittle deformation at the Olkiluoto site. Literature compilation for site characterization and geological modelling**. Posiva Oy, Working Report 2006-25.
Ch. 1: Rock Deformation: Basic Principles
Ch. 2: Fabric of Intact Rock
Ch. 3: Brittle Deformation in Experiment and Nature
Ch. 4: Fracture Data Acquisition and Processing
Ch. 5: Brittle Deformation Zones (Fracture Zones)
Ch. 6: Regional Geological Framework of the Olkiluoto Site
*- the **Posiva in-house course "Brittle Deformation of Hard Rock"** given at Olkiluoto by A.G. Milnes on 20-21 September 2006, was largely based on the material summarized in this report and contained in the cited literature*

Milnes, A.G., 2006b. **Brittle Deformation of Hard Rock**. Posiva Oy, CompactDisc containing a complete set of PowerPoint presentations given in Posiva in-house course at Olkiluoto, 20-21 September, 2006

Milnes, A.G., Hudson, J.A., Wikström, L., Aaltonen, I., 2006. **Foliation: geological background, rock mechanics significance, and preliminary investigations at Olkiluoto**. Posiva Oy, Working Report 2006-03.

Milnes, A.G., Wikström, L., Aaltonen, I., Front, K., Gehör, S., Kemppainen, K., Kärki, A., Mattila, J., Paananen, M., Paulamäki, S., 2007. **Geological data acquisition for site characterisation at Olkiluoto: framework for the phase of underground investigations**. Posiva Oy, Working Report 2007-32.
Ch. 1: Background (geological modelling, starting points, guidelines)
Ch. 2: Characterisation of Intact Rock
Ch. 3: Characterisation of Deformation Zone Intersections
Ch. 4: Characterisation of Individual Fractures

Milnes, A.G., Stephens, M.B., Wahlgren, C.-H., Wikström, L., 2008. **Geoscience and high-level nuclear waste disposal: the Nordic scene**. Episodes, 31, 168-175.

Milord, I., Sawyer, E., Brown, M., 2001. **Formation of diatextite migmatite and granite magma during anatexis of semi-pelitic metasedimentary rocks: an example from St. Malo, France**. Journal of Petrology, 42, 487-505.

Moisio, K., Kaikkonen, P., 2004. **The present day rheology, stress field and deformation along the DSS profile FENNIA in the central Fennoscandian Shield**. Journal of Geodynamics, 38, 161-184.

Munier, R., 2004. **Statistical analysis of fracture data, adapted for modelling Discrete Fracture Networks - version 2**. Swedish Nuclear Fuel and Waste Management Company (SKB), report SKB R-04-66.

Munier, R., 2006. **Using observations in deposition tunnels to avoid intersections with critical fractures in deposition holes**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport SKB R-06-54.
- deals with the problem of "critical" (i.e. very long single) fractures - a first discussion of one of the main themes/results of the EXPECT project (see also Cosgrove et al. 2006)

Munier, R., 2010. **Full perimeter intersection criteria. Definitions and implementations in SR-Site**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report TR-10-21.

Munier, R., Hökman, H., 2004. **Respect distances – rationale and means of computation**. Swedish Nuclear Fuel and Waste Management Company (SKB), report R-04-17.

Munier, R., Stigsson, M., 2007. **Implementation of uncertainites in borehole geometries and geological orientation data in Sicada**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-07-19.
Ch. 3: sources of error and uncertainty in parameters such as borehole deviation, borehole diameter, magnetic field variations, correlation of BIPS imagery and core mapping, dip/dip direction of foliation, fractures, etc.
Ch. 4: implementation of algorithms in Sicada and BOREMAP to compute geometric uncertainties
Ch. 5: quantification of changes to orientation data

Munier, R., Stenberg, L., Stanfors, R., Milnes, A.G., Hermanson, J., Triumf, C.-A., 2003. **Geological site descriptive model. A strategy for the model development during site investigations**. Swedish Nuclear Fuel and Waste Management Company (SKB), Report SKB R-03-07.

Mänttäri, I., Taikka, M., Paulamäki, S., Mattila, J., 2006. **U-Pb ages for tonalitic gneiss, pegmatitic granite, and diabase dyke, Olkiluoto study site, Eurajoki, Finland**. Posiva Oy, Working Report 2006-12.
- tonalitic gneiss 1863+/-6, pegm granite between 1.86 and 1.823, dating of mafic dyke failed

Mänttäri, I., Aaltonen, I., Lindberg, A., 2007. **U-Pb ages for two tonalitic gneisses, pegmatitic granites and K-feldspar porphyries, Olkiluoto study site, Eurajoki, SW Finland**. Posiva Oy, Working Report 2007-70.
- TTG ages from two different localities 1851+/-5 and 1856+/-5 (compared with earlier age det. 1863+/-6
- because of inherited zircon and later radiogenic lead loss, PGR ages more difficult to interpret: most likely 2 samples at ca. 1830 and one somewhat younger, with min. age at around 1823
-for K-fel. porphyries, same only more so: no clear interpretation

Mänttäri, I., Pere, T., Engström, J., Lahaye, Y., 2010. **U-Pb ages for PGR dykes, KFP, and adjacent older leucosomic PGRs from the ONKALO Underground Research Facility, Olkiluoto, Eurajoki, SW Finland.** Posiva Oy, Working Report 2010-31..
- results are thought to date the D3 and D4 events in the Olkiluoto migmatites at ca. 1.83-1.82 Ga and 1.81-1.80 Ga resectively
- compilation of all age results so far

Nasseri, M.H.B., Rao, K.S., Ramamurthy, T., 2003. **Anisotropic strength and deformational behaviour of Himalayan schists**. International Journal of Rock Mechanics and Mining Sciences, 40, 3-23.

Mänttäri, I., Mattila, J., Zwingmann, H., Todd, A.J., 2007. **Illite K-Ar dating of fault breccia samples from ONKALO underground research facility, Olkiluoto, Eurajoki, SW Finland**. Posiva Oy, Working Report 2007-67.
Ch. 2: samples for dating, including samples from Storage Hall fault (from access tunnel chainage 522 and 901 m)
Ch. 3: Theory and methodology
Ch. 4: detailed mineralogy (SEM, XRD, TEM)
Ch. 5: results - 2 samples from SH fault both give identical Precambrian ages (1385+/-27, 1373+/-27), others give younger ages - youngest 550+/-11 (lower Cambrian)

Müller, G., Dahm, T., 2000: **Fracture morphology of tensile cracks and rupture velocity**. Journal of Geophysical Research, 105 (B1), 723-738.

Müller, G., 2001. **Experimental simulation of joint morphology**. Journal of Structural Geology, 23, 45-49.

Nielsen, U.T., Ringgaard, J., Vangkilde-Pedersen, T., 2006. **Forsmark site investigation. Geophysical borehole logging in boreholes KFM09A, KFM07B, HFM25, HFM27 and HFM28**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-06-22.
- example of the final description of the geophysical logging (wireline) carried out in each drillhole in the SKB site investigations

Niinimäki, R., Aaltonen, I., 2006. **Rock mechanical tests of the deep drillholes KR1 and KR12 at Olkiluoto 2006**. Posiva Oy, Working Report 2006-106.
- point load tests, strength and elastic properties on/for 26 samples from KR1 and 19 samples from KR12, both fresh and subject to varying degrees of hydrothermal alteration
- aim: rock mechanics significance of alteration
- uses RMF number to classify foliated samples - no effect using alteration alone, but some trend to weaker rock towards RMF 3 (for use of RMF number, see Milnes et al. 2007)

Nordbäck, N., 2007. **Geological mapping of investigation trench OL-TK14 at the Olkiluoto study site, Eurajoki, SW Finland**. Posiva Oy, Working Report 2006-51.
--> 2.5, 3.4, 5.4

Nordbäck, N., 2010. **Outcome of the geological mapping of the ONKALO underground research facility access tunnel, chainage 1980-3116**. Posiva Oy, Working Report WR 2010-42.

Nordbäck, N., Talikka, M., 2006. **Geological mapping of investigation trench OL-TK9 at the Olkiluoto study site, Eurajoki, SW Finland**. Posiva Oy, Working Report 2006-51.
- deformation zone intersections include 4 BJI, 1 BFI, 1 SFI (semi-brittle?) and 1 DSI

Nordbäck, N., Engström, J., 2006. **Geological mapping of investigation trench OL-TK12 at the Olkiluoto study site, Eurajoki, SW Finland**. Posiva Oy, Working Report 2006-104.
App. 4: deformation zone intersections tabulated, including 2 SFI
Section 2.1 Lithology (2.2 Ductile deformation)
Section 2.3 Fracturing
Section 2.4 Deformation zone intersections

Nordbäck, N., Engström, J., 2010. **Outcome of the geological mapping of the ONKALO underground research facility access tunnel, chainage 990-1980**. Posiva Oy, Working Report WR 2010-41.

Nordbäck, N., Engström, J., Kemppainen, K., 2008. **Outcome of the geological mapping of the ONKALO underground research facility access tunnel, chainage 0-990**. Posiva Oy, Working Report WR 2008-84.

NRC/CFCFF 1996. Rock **Fractures and Fluid Flow. Contemporary Understanding and Applications**. Report of the Committee on Fracture Characterization annd Fluid Flow, National Research Council, National Academy Press (Washington D.C.).
Ch.1: Rock fractures and fluid flow: practical problems.
Ch.2: Physical characteristics of fractures and fracture patterns.
Ch.3: Physical properties and fundamental processes in fractures.
Ch.4: Fracture detection methods.
Ch.5: Hydraulic and tracer testing in fractured rocks.
Ch. 8: Case histories (incl. Stripa SCV project and URL low angle fracture zone project).

Ojala, V.J., Eilu, P., Turunen, P., Julkunen, A., Gehör, S., 2007. **The use of gamma spectrometry in mapping alteration zones in Olkiluoto**. Posiva Oy, Working Report 2007-64.
- test on core OL-KR27: very variable TH/K ratio is a reasonably good indicator of alteration zones even in migmatitic gneisses

Olofsson, I., Simeonov, A., Stigsson, M., Stephens, M.B., Follin, S., Nilsson, A.-C., Röshoff, K., Lindberg, U., Lanaro, F., Fredriksson, A., Persson, L., 2007. **Site descriptive modelling, Forsmark stage 2.2. A fracture domain concept as a basis for the statistical modelling of fractures and minor deformation zones, and interdisciplinary coordination**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-07-15.

- first report discussing the concept of fracture domains in the intact rock between the major deformation zones (based on fracture frequency variations amongst the different fracture sets, and tested for various types of control - lithological, structural, etc.), and its application in the areas of hydrogeology, hydrogeochemistry and rock mechanics
Ch. 2: terminology
Ch. 3: available primary data
Ch. 4: fracture data in boreholes, incl. fracture frequency distribution in each borehole
Ch. 5: fracture domain concept
Ch. 6: hydrogeological data in the context of fracture domains and deformation zones
Ch. 8: rock mechanics data in the context of fracture domains and deformation zones

Oye, V., Bungun, H., Roth, M., 2005. **Sources parameters and scaling relations for mining-related seismicity within the Pyhäsalmi ore mine, Finland**. Bulletin of the Seismological Society of America, 95, 1011-1026.

Paananen, M., Kuivamäki, A., 2007. **Regional lineament analysis of the southern Satakunta area**. Posiva Oy, Working Report 2007-04.
- rather general overview and interpretation, check against Paulamäki & K. 2006!

Paananen, M., Paulamäki, S., Gehör, S., Kärki, A., Front, K., Aaltonen, I., Ahokas, T., Kemppainen, K., Mattila, J., Wikström, L., 2006. **Geological model of the ONKALO area, version 0**. Posiva Oy, Working Report 2006-13.

Paananen, M., Lehtonen, T., Korhonen, K., 2007. **Electrical model of Olkiluoto**. Posiva Oy, Working Report 2007-49.
- composite electrical model combining 4 geophysical methods: mise-a-la-masse (MAM), SAMPO EM soundings, Slingram (HLEM) and single-hole electrical soundings
- basic premise: sulphide-rich and graphitic zones (good electrical conductors) mark brittle deformation zones
Ch. 3: MAM methodology, interpretation of results
Ch. 4: Slingram surveys and interpretation of results
Ch. 5: SAMPO soundings
Ch. 6-7: correlation and block modelling - 11 structures modelled on basis of MAM and discussed, then general resistivity models of central part of Olkiluoto presented

Palmén, J., Tammisto, E., Ahokas, H., 2010. **Database for hydraulically conductive fractures - update 2009**. Posiva Oy, Working Report 2010-13.

Passchier, C.W., Trouw, R.A.J., 1996. **Microtectonics**. Springer (Berlin).
*- key textbook on the microscopic-mesoscopic aspects of rock deformation (deformation mechanisms, **foliation/lineation, ductile shear zones, mylonites and other fault rocks, etc.); basically analysis of flow in rock (also in brittle regime - cataclastic flow)***

Passchier, C.W., Myers, J.S., Kröner, A., 1990. **Field Geology of High-Grade Gneiss Terrains**. Springer-Verlag (Berlin, etc.).
Ch. 2: Mapping in gneiss terrains
Ch. 3: Fabric development in gneiss terrains
Ch. 4: Interpretation of structures and fabrics
Ch. 5: Metamorphic history of gneiss terrains
Ch. 6: Geochemistry, isotope geochemistry, and geochronology: application to field studies
Ch. 7: Origin and evolution of high-grade gneiss terrains

Paterson, M.S., 1978. **Experimental Rock Deformation - the Brittle Field**. Springer-Verlag (Berlin, etc.).

Paulamäki, S., 2007. **Geological mapping of the region surrounding the Olkiluoto site**. Posiva Oy, Working Report 2007-30.

- Part 1: structural evolution of the Olkiluoto region - important synthesis of the structural history of the Olkiluoto migmatite complex, particularly ductile structural history D_1-D_5, with numerous illustrations of structural relations
- Part 2: geology of the Eurajoki rapakivi stock, including description of NW-SE lineaments which intersect the intrusion (post-intrusive defm zones?)

Paulamäki, S., Kuivamäki, A., 2006. **Depositional history and tectonic regimes within and in the margins of the Fennoscandian Shield during the last 1300 million years**. Posiva Oy, Working Report 2006-43.
- sister report to report POSIVA 2002-04: "Structure and geological evolution of the bedrock of southern Satakunta, SW Finland".

Paulamäki, S., Paananen, M.,Gehör, S., Kärki, A., Front, K., Aaltonen, I., Ahokas, T., Kemppainen, K., Mattila, J., Wikström, L., 2006. **Geological model of the Olkiluoto site, version 0**. Posiva Oy, Working Report 2006-37.

Pere, T., 2009. **Fault-related local phenomena in the bedrock of Olkiluoto, with particular reference to fault zone OL-BFZ100**. Posiva Oy, Working Report WR 2009-125.

Petersson, J., Berglund, J., Wängnerud, A., Danielsson, P., Strahle, A., 2004. **Forsmark site investigation. Boremap mapping of telescopic drilled borehole KFM05A**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-04-295.

Petersson, J., Skogsmo, G., von Dalwigk, I., Wängnerud, A., Berglund, J., 2006. **Forsmark site investigation. Boremap mapping of cored borehole KFM09A**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-06-130.
- example of the definitive geological logging (offsite, in the core archive, with BIPS and geophysical data studied side-by-side) carried out in each drillhole in the SKB site investigations

Pollard, D.D., Aydin, A., 1988. **Progress in understanding jointing over the past century**. Geological Society of America Bulletin, 100, 1181-1204.
- extensive survey of the development of ideas on joints and jointing in the past 100 years, with complete bibliography (selected from the 11 000 scientific papers which have been published on this topic between 1785 and 1987!)
- the word "joint" should be restricted to those fractures with field evidence of dominantly opening displacements, and no discernible lateral displacement (although features which would indicate such displacement may be absent)
- strong criticism of the term "shear joint" - "the concept of shear joints is sheer nonsense" (p. 1186)
- fracture mechanics approach to the formation and propagation of joints

Pollard, D.D., Fletcher, R., 2005. **Fundamentals of Structural Geology**. Cambridge University Press (Cambridge, UK).
From the Contents:
Ch. 2: Structural mapping techniques and tools (incl. GPS)
Ch. 3: Physical quantities, fields, dimensions, scaling
Ch. 6: Force, traction and stress
Ch. 9: Brittle behaviour
Ch.12: Model development and methodology (idealization of field observations, selection of boundary conditions, model construction in structural geology)

Posiva Oy, 2006. **Expected evolution of a spent nuclear fuel repository at Olkiluoto.** Posiva Oy, report POSIVA 2006-05.
- long list of corrections to the text, bound into report!
- updates envisaged in 2009 and 2011
Ch. 2: present conditions at the site, incl. geology, hydrogeology
Ch. 5: climate scenarios
Ch. 8: evolution during the glacial phase
Ch. 9: behaviour of initially defective canisters

Posiva Oy, 2008.. **Safety Case Plan 2008**. Posiva Oy, report POSIVA 2008-05.
- including Ch. on management of uncertainties (in concepts, models and data) and management of quality (quality control, review system, expert judgement)

Posiva 2009. **Olkiluoto Site Description 2008**. Posiva Oy, report POSIVA 2009-01.
- Ch. 4: Bedrock geology (regional, site-specific, GSM v. 1.1)
- Ch. 5: Rock mechanics (incl. in situ stress)
- Ch. 6: Hydrogeological flow model (site-scale hydro-zones, DFN model)
-->1.1, 2.5, 5.4, 5.5

Priest, S.D., 1993. **Discontinuity Analysis for Rock Engineering**. Chapman & Hall (London, etc.).
Ch. 1: Introduction to discontinuities (natural mechanical defects in rock masses which possess "the common characteristics of low shear strength, negligible tensile strength (main criterion- my italics) and high fluid conductivity compared with the surrounding rock material"), including 1.3: Discontinuities and their origins (faults, joints bedding, cleavage,fissures, etc. - foliation also mentioned, contributes to anisotropy, but is not usually a plane of negligible tensile strength)
Ch. 2: Measurement of discontinuity characteristics (core logging, scanline logging, and rock mass classification, for latter also Appendix C)
Ch. 3: Discontinuity orientation
Ch. 4: " frequency
Ch. 5: " spacing
Ch. 6: " size
Ch. 7: Stresses on discontinuities
Ch. 8: Analysis of rigid blocks
Ch. 9: Discontinuities and rock strength
Ch.10: Discontinuities and rock deformability
Ch.11: Fluid flow in discontinuities

Ramsay, J.G., 1967. **Folding and Fracturing of Rocks**. McGraw-Hill (New York, etc.).
- classical text book on strain analysis and analysis of superimposed deformation (ductile rock deformation in nature), but some more general chapters of application to brittle deformation (Ch. 1: Orientation analysis; Ch. 2: Stress; Ch. 6: Relationship between stress and strain)

Ramsay, J.G., Huber, M.I., 1987. **The Techniques of Modern Structural Geology. Volume 2: Folds and Fractures**. Academic Press (London, etc.).
Sessions 23-25: Faults and fault analysis
Session 26: Ductile and brittle shear zones
Session 27: Joints

Ramsay, J.G., Lisle, R., 2001. **The Techniques of Modern Structural Geology. Volume 3: Applications of Continuum Mechanics to Structural Geology**. Academic Press (London, etc.).
Ch. 30: Finite element analysis: 1. Modelling stress fields
Ch. 31: Finite element analysis: 2. ***Inhomogeneous and anisotropic rocks*** *(including sections on Transverse isotropy, Finite element modelling of anisotropy, Some models involving anisotropy, e.g. stresses in rocks with parallel discontinuities, Key references).*
Ch. 32: ***Fault slip analysis*** *and stress tensor calculations*

Ranalli, G., 1995. **Rheology of the Earth. 2nd Edition**. Chapman & Hall (London, etc.).

Reches, Z., Lockner, D.A., 1994. **Nucleation and growth of faults in brittle rocks**. Journal of Geophysical Research, 99 (B9), 18159-18173.

Remes, H., Kuula, H., Somervuori, P.,, Hakala, M., 2009. **ONKALO rock mechanics model (RMM), version 1.0**. Posiva Oy, Working Report 2009-55.
Ch. 3: Rock mass quality
Ch. 4: Rock mech properties of brittle deformatuion zones

Ch. 5: (Intact) rock strength
Ch. 6: In situ stress

Rudzki, M.P., 2003. **On the propagation of an elastic surface wave in a transversely isotropic medium**. Journal of Applied Geophysics, 54, 185-190. (In Special Issue "Advances in seismic anisotropy")

Röshoff, K., Cosgrove, J., 2002. **Sedimentary dykes in the Oskarshamn-Västervik area. A study of the mechanism of formation**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-02-37.

Saari, J., 2008. **Seismicity in the Olkiluoto area**. Posiva Oy, report POSIVA 2008-04.
- including map with Finnish fault plane solutions

Saksa, P., Lehtimäki, T., Heikkinen, E., 2007. **Surface 3D reflection seismics - implementation at the Olkiluoto site**. Posiva Oy, Working Report 2007-10.
- glossary of commonly used "seismic" terms p. 6-7
- aim of report: to study possibilities and problems of carrying out a 3D reflection seismic survey at Olkiluoto, both theoretically and by study of case studies of 2D and 3D reflection seismics in crystalline rock (incl. SKB) - basically a desk study.

Sawyer, E.W., 1998. **Formation and evolution of granite mgmas during crustal reworking: the significance of diatexites**. Journal of Petrology, 39, 1147-1167.

Sandström, B., Tullberg, E.-L., Smellie, J., MacKenzie, A.B., Suksi, J., 2008. **Fracture mineralogy of the Forsmark site. SDM-Site Forsmark.** Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-102.

Schmid, S.M., Handy, M.R., 1991. **Towards a genetic classification of fault rocks: geological usage and tectonophysical implications**. In: Controversies in Modern Geology (Müller, D.W., McKenzie, J.A., Weissert, H., eds.), Academic Press (London), 339-361.

Scholz, C.H., 2002. **The Mechanics of Earthquakes and Faulting, 2nd Edition**. Cambridge University Press (Cambridge, U.K.).
Ch. 1: Brittle fracture of rock (incl brittle-plastic transition and semi-brittle behaviour)
Ch. 2: Rock friction (incl stick-slip and stable sliding)
Ch. 3: Mechanics of faulting (incl. fault rocks and strength of fault zones)
Ch. 4: Mechanics of earthquakes
Ch. 5: The seismic cycle
Ch. 6: Seismotectonics (incl. induced seismicity around underground facilities)
Ch. 7: Earthquake prediction and hazard analysis

Segall, P., Pollard, D.D., 1983b**. Joint formation in granitic rock of the Sierra Nevada**. Geological Society of America Bulletin, 94, 563-575.
- important paper on the geometry and genesis of jointing in crystalline rock, on the example of an area showing a single joint set in the Mount Givens granodiorite in the Sierra Nevada
- deposition of epidote and chlorite in a set of extension joints, later shearing superimposed on already formed minerals
- single set of subvertical, chlorite/epidote joints studied: extensional joints (amount of extension ca. 10^{-4}), some joints later sheared (strike slip); fracture length/frequency relations, tensile stress for initiating joint growth estimated at 1-40 MPa (-> fracture toughness of granodiorite - compatible with expt. data)
- detailed outcrop map of single set jointing, area ca. 70m x 30 m, genesis of fractures discussed in detail

SKB 2008a. **Site investigations Forsmark 2002-2007**. Swedish Nuclear Fuel and Waste Management Company (SKB), Summary Report, 142 p..

SKB 2008b. **Site description of Forsmark at completion of the site investigation phase. SDM-Site Forsmark**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-08-05.
Ch. 1: introduction, background, project methodology, objectives, strategy
Ch. 2: investigations, available data and other prerequisites for modelling
Ch. 3: evolutionary aspects, incl. geological history bedrock, Quaternary development
Ch. 4: surface system, surface-bedrock interactions
Ch. 5: bedrock geology, incl. rock domains, deformation zones and fracture domains, disc. of ductile defm (fol., lin.), summary DFN model
Ch. 6: bedrock thermal model, incl. measurement of anisotropy
Ch. 7: rock mechanics, incl. intact rock, rock mass and fracture properties, in situ stress
Ch. 8: bedrock hydrogeology, incl. hydraulic conductor and hydr. rock domains
Ch. 9: bedrock hydrogeochemistry, incl. fracture mineralogy
Ch.10: bedrock transport properties (as Ch. 8,9, based on rock and fracture domains)
Ch.11: summary present site understanding, incl. rock domains, brittle deformation, rock stress, bedrock hydraulic properties, and "overall confidence"
- fulfillment of objectives, remaining issues, implications for underground construction
References
App. 1: topography, geological names
App. 2: nomenclature
App. 3: tabulated references to primary data
App. 4: property tables for deformation zones

SKB 2008c. **Confidence assessment. Site descriptive modelling, SDM-Site Forsmark**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-82.

SKB 2009. **Site description of Laxemar at completion of the site investigation phase. SDM-Site Laxemar**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-09-01.
Ch. 1: introduction, background, project methodology, objectives, strategy
Ch. 2: investigations, available data and other prerequisites for modelling
Ch. 3: evolutionary aspects, incl. geological history bedrock, Quaternary development
Ch. 4: surface system, surface-bedrock interactions
Ch. 5: bedrock geology, incl. rock domains, deformation zones and fracture domains, incl. summary of DFN model
Ch. 6: bedrock thermal model, incl. measurement of anisotropy
Ch. 7: rock mechanics, incl. intact rock, rock mass and fracture properties, in situ stress
Ch. 8: bedrock hydrogeology, incl. hydraulic conductor and hydr. rock domains
Ch. 9: bedrock hydrogeochemistry, incl. fracture mineralogy
Ch.10: bedrock transport properties (as Ch. 8,9, based on rock and fracture domains)
Ch.11: summary present site understanding, incl. rock domains, brittle deformation, rock stress, bedrock hydraulic properties, and "overall confidence"
Ch.12: conclusions - fulfillment of objectives, remaining issues, implications for underground construction
References
App. 1: topography, geological names
App. 2: nomenclature
App. 3: tabulated references to primary data
App. 4: WellCAD logs for cored boreholes
App. 5: property tables for deformation zones

Snoke, A.W., Tullis, J., Todd, V.R., 1998. **Fault-related Rocks. A Photographic Atlas**. Princeton University Press (Princeton, NJ). **
- 140 photographic plates, each accompanied by explanatory notes by the expert who provided the photographs, grouped according to the following themes:
- Geomentrical characteristics and microstructures - brittle behaviour
- Cataclasis and gouge development
- Pseudotachylyte
- Fluid-related features - brittle behaviour

- Geomentrical characteristics and microstructures - semi-brittle behaviour
- Fluid-related features - semi-brittle behaviour
- Foliation development
- Composite foliations in mylonites
- Fluid-related features - ductile behaviour

Stephens, M.B., Fox, A., LaPointe, P., Simeonov, A., Isaksson, H., Hermanson, J., Öhman, J., 2007. **Geology Forsmark. Site descriptive modelling, Forsmark stage 2.2**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport SKB R-08-64.
Ch. 2: Available data, previous geological models, model volumes
Ch. 3: Evaluation of primary geological and geophysical data, incl.rock alteration, deformation zone character and kinematics,
Ch. 4: Rock domain model
Ch. 5: Model of deterministic deformation zones
Ch. 6: Statistical model for fractures and minor deformation zones
App. 3: Primary geological and geophsical data and the single hole interpretation of cored boreholes
App. 8: Outcrop maps and fracture orientation derived from detailed fracture mapping of excavations
App. 9: Orientation of fractures inside possible deformation zones on a borehole-to-borehole basis
App. 11+12+17: Mineral coating and mineral filling along fractures inside possible deformation zones on a borehole-to-borehole basis, and inside different sets of modelled deformation zones
App. 13: Rock domains, deformation zones and fracture domains in each cored borehole
App. 15+16: Properties of regional, local and minor deformation zones included in the deterministic models

Stephens, M.B., Simeonov, A., Isaksson, H., 2008. **Bedrock geology Forsmark. Modelling stage 2.3. Implications for and verification of the deterministic geological models based on complementary data**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport SKB R-08-64.
- includes results of additional high-resolution ground magnetic data and data from three cored boreholes, carried out after 2.2 data freeze + character and kinematics of defm. zones and fracture mineralogy
Ch. 4: prediction-outcome study, borehole KFM08D intersects central part of 2.2 modelled volume - verification "highly satisfactory"

Stephens, M.B., Bergman, T., Isaksson, H., Petersson, 2008. **Bedrock geology Forsmark, modelling stage 2.3. Description of the bedrock geological map at the ground surface**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-128.
- superb report - detailed description and reconstruction of the Forsmark ground surface, 2D model of the top surface of the model block, concentration on intact rock (very well illustrated) and major deformation zones
- detailed bedrock map of the target area, with form lines and structural data
- list of SKB data reports bearing on the composition and age of Forsmark rock types

Sundberg, J., Wrafter, J., Back, P.-E., Rosén, L., 2008. **Thermal properties Laxemar. Site descriptive modelling, SDM-Site Laxemar**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-61.
Ch. 3: overview and assessment of investigation data on intact rock, including section on anisotropy of thermal conductivity due to foliation (3.8) - factor may be as high as 1.15 (higher parallel to foliation)
- no discussion of effect of fractures, fracturing, fracture zones .....

Söderbäck, B., ed., 2008. **Geological evolution, palaeoclimate and historical development of the Forsmark and Laxemar-Simpevarp areas. Site descriptive modelling, SDM-Site**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-19.

Ch. 2: bedrock evolution - including two subsections on far-field tectonic activity causing brittle deformation (2.2.2), and timing of brittle deformation (2.2.3), and separate sections summarising bedrock evolution at Forsmark (2.3) and Laxmar-Simpevarp (2.4)
- six tectonic domains described from Ljusdal in north to Kalmar in south (Figs.2-3 and 2-5 - FM lies in TD2, LX in TD5) - but all overview maps show also Olkiluoto (probably lies in TD1)
Ch. 3: geological evolution, glaciation history and climate during the Quaternary period
Ch. 4: palaeoseismicity and evidence for faulting in the Quaternary, present seismicity and deformation of the Earth's crust

Talikka, M., 2005. **Geological mapping of the Olkiluoto 3 construction site**. Posiva Oy, Working Report 2005-32.
- geol. map 1:12000 presented, but cross-cutting mafic dykes noted seem to be missing (!?), no fracture zones described/observed

Tammisto, E., Palmén, J., Ahokas, H., 2009. **Database for hydraulically conductive fractures**. Posiva Oy, Working Report 2009-30.

Tarvainen, A.-M., 2007a. **Optical imaging of borehole PR10 at Olkiluoto 2006**. Posiva Oy, Working Report 2007-13.
- test and technical description of the OBI 40 slimhole optical televiewer (borehole wall imagery)

Tarvainen, A.-M., 2007b. **Optical imaging of drillholes OL-KR40, OL-KR41, OL-KR41B, OL-KR42, OL-KR42B, OL-KR43 and OL-KR43B at Olkiluoto, 2006 and 2007**. Posiva Oy, Working Report 2007-14.
- application and technical description of optical televiewer OBI 40

Tarvainen, A.-M., Heikkinen, E., 2008. **Geophysical drillhole logging and optical imaging of the drillholes.....OL-KR46.....OL-KR47....OL-KR48.....at Olkiluoto 2007 and 2008**. Posiva Working Report 2008-61.

Thunehed, H., Keisu, M., 2004. **Forsmark site investigation. Interpretation of borehole geophysical measurements in KFM05A, HFM14, HFM15 and HFM19**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-04-154.

Tiensuu, K., Heikkinen, E., Lahti, M., 2009. **Acoustic imaging of the drillholes.....OL-KR46.....at Olkiluoto 2008**. Posiva Working Report 2009-41.

Tonon, F., Amadei, B., 2003. **Stresses in anisotropic rock masses: an engineering perspective building on geological knowledge**. International Journal of Rock Mechanics and Mining Science, 40, 1099-1120.

Torben Nielsen, U., Ringgaard, J., 2004. **Forsmark site investigation. Geophysical borehole logging in borehole KFM05A and HFM19**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project report P-04-153

Toropainen, V., 2007. **Core drilling of deep borehole OL-KR46 at Olkiluoto in Eurajoki 2007**. Posiva Oy, Working Report 2007-74.
- example of cored borehole drilling report (on-site core logging, preliminary fr. data collected for rock engineering purposes)
- 46A hole length 600 m, plunge 70^0 towards 180^0
- core orientation 96% successful (using Ezy-Mark system, details in App. 8.18)
- in App. 8, also lithology (8.12), degree of alteration (8.13, called "weathering"), foliation (8.14, incl. type and intensity), list of fractures (8.15), fr. frequency, RDQ (8.16), and fractured zones, core loss (8.17), tabulated

Toropainen, V., 2008a. **Core drilling of deep borehole OL-KR48 at Olkiluoto in Eurajoki 2007**. Posiva Oy, Working Report 2008-05.
- *example of cored borehole drilling report (on-site core logging, preliminary fr. data collected for rock engineering purposes)*
- *hole length 530 m, vertical (pilot hole for 3.5 m diameter shaft)*
- *no core orientation*
- *in App. 8, also lithology (8.11), degree of alteration (8.12, called "weathering"), foliation (8.13, incl. type and intensity), list of fractures (8.14), fr. frequency, RDQ (8.15), and fractured zones, core loss (8.16), tabulated*

Toropainen, V., 2008b. **Core drilling of deep borehole OL-KR47 at Olkiluoto in Eurajoki , 2007-2008**. Posiva Oy, Working Report 2008-13.
- *example of cored borehole drilling report (on-site core logging, preliminary fr. data collected for rock engineering purposes)*
- *47A hole length 1009 m, plunge 70^0 towards 270^0*
- *core orientation 94% successful (using Ezy-Mark/Ori-Block, details in App. 8.18)*
- *in App. 8, also lithology (8.12), degree of alteration (8.13 called "weathering"), foliation (8.14, incl. type and intensity), list of fractures (8.15), fr. frequency, RDQ (8.16), and fractured zones, core loss (8.17), tabulated*

Tuominen, V., Hella, P., Vaittinen, T., 2006. **Statistical model of fractures based on data from OL-TK7, OL-TK11, OL-KR24, OL-PH1 and ONKALO PL0m - PL140m**. Posiva Oy, Working Report 2006-22.
- *aim: by studying fracture statistics from the first 140 m of the ONKALO access tunnel (including surrounding drillholes and trenches) to provide a DFN-based flow model for the next tunnel segment pilot hole PH2 - block size ca 250 x 200 x 100 m (actual model size 26 x 26 x 26 m) - to be tested against outcome*

Ch. 2: fracture data used
Ch. 3: geological setting and fracturing, leading to defn. of fracture sets (short Ch. 4)
Ch. 5: short discussion of fracture size distribution and fracture intensity P32
- *based on FRACMAN methodology of Dershowitz et al. 1994, potentially a good teaching example of possibilities and pitfalls of DFN*

Turner, F.J., Weiss, L.E., 1963. **Structural Analysis of Metamorphic Tectonites**. McGraw-Hill (New York, etc.).
- *classical work on analysis of ductile deformation structures, including theoretical and experimental basis and statistical analysis of foliation, lineation, folds, and single-phase and polyphase deformation; definition of statistically homogeneous domains as the key to structural analysis of complex associations; all scales from microscopic analysis to analysis of large-scale features*

Part I: The Tectonite Fabric and its Geometric Analysis
Ch. 3: Structural anaylsis using stereographic projection
Ch. 4: Outcrop scale, incl. foliation and lineation
Ch. 5: Fabric domains and statistical homogeneity
Part II: Deformation of Rocks: Theory and Experiment
Ch. 7: Stress and strain
Ch. 8: Experimental deformation of minerals and rocks, incl. brittle behaviour
Part III: Interpretation of Tectonite Fabrics

Twiss, R.J., Moores, E.M., 1992. **Structural Geology**. W.H. Freeman & Co. (New York).
- *modern advanced text on structural geology and structural analysis, with equal emphasis on brittle and ductile deformation*

Part II: Brittle deformation (8 chapters, including fractures, joints and faults, geometry-kinematics-dynamics, theoretical and experimental background)
Part III: Ductile deformation (7 chapters, including 2 chapters on foliation/lineation - but rather special nomenclature, not always accepted or acceptable)

Vaittinen, T., Ahokas, H., Nummela, J., 2009. **Hydrogeological structure model of the Olkiluoto site - update in 2008**. Posiva Oy, Working Report WR 2009-15.

Vaarma, M., Vuokko, J., 2009. **Geological mapping of investigation trench OL-TK15 and OL-OK16 at the Olkiluoto study site, Eurajoki, SW Finland**. Posiva Oy, Working Report 2009-52.

Vernon, R.H., Paterson, S.R., 2001. **Axial-surface leucosomes in anatectic migmatites**. Tectonophysics, 335, 183-192.

Vignersee, J.-L., 1999. **Should felsic magmas be considered as tectonic objects, just like faults or folds**. Journal of Structural Geology, 21, 1125-1130.

Vigneresse, J.L., Tikoff, B., 1999. **Strain partitioning during partial melting and crystallizing felsic magmas**. Tectonophysics, 312, 117-132.

Viola, G., Venvik Ganerud, G., 2007a. **Structural analysis of brittle deformation zones in the Simpevarp-Laxemar area, Oskarshamn, southeast Sweden**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project Report P-07-41.

Viola, G., Venvik Ganerud, G., 2007b. **Structural characterisation of deformation zones (faults and ductile shear zones) from selected drill cores and outcrops from the Laxemar area - Results from Phase 2**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project Report P-07-227.

Viola, G., Venvik Ganerud, G., 2008a. **Structural characterisation of deformation zones (faults and ductile shear zones) from selected drill cores from the Laxemar area**. Swedish Nuclear Fuel and Waste Management Company (SKB), Project Report P-08-07.

Viola, G., 2008b. **Ductile and brittle structural evolution of the Laxemar-Simpevarp area: an independent analysis based on local and regional constraints**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-124.

Ch. 2: regional structural situation (in contrast to SKB interpretation) in ductile regime is major sinistral EW shear zones (Oscarshamn, Mederhult) with equivalent of C′ shear structures between (e.g. Äspö sz) following NE-SW trends - shortening (greatest compressive stress) oriented NW-SE

Ch. 3: fault slip analysis (theory and practice, application to core data from Laxemar - 3 "conjugate sets" recognized, plus low-angle faults), and brief study of some outcrops on Öland (also interpreted as conjugate sets - outcrops studied: Jordhamn, Hagudden, Gillberga - basically too little data and too spread geograhically to make sense)

Ch. 4: synthesis and comparison with schemes of Söderbäck 2008, and Talbot & Munier 1993, to arrive at an overall tectonic evolution, Fig. 3-56.

Vrolijk, P., Van der Pluijm, B.A., 1999. **Clay gouge**. Journal of Structural Geology 21, 1039-1048.

Väisänen, M., Skyttä, P., 2007. **Late Svekofennian shear zones in southwestern Finland**. GFF, 129, 55-64.

- mainly relates to Turku area, but overview map contains Olkiluoto (but does not show its location

- main ductile deformation in shear zone network with EW and NS striking components took place under crustal shortening in the interval 1810-1790 Ma

Wahlgren, C.-H., Curtis, P., Hermanson, J., Forssberg, O., Öhman, J., Fox, A., LaPointe, P., Drake, H., Triumf, C.-A., Mattsson, H., Thunehed, H., Juhlin, C., 2008. **Geology Laxemar. Site descriptive modelling, SDM-Site Laxemar**. Swedish Nuclear Fuel and Waste Management Company (SKB), Rapport R-08-54.

Summary: subdivided under the following headings (main emphasis of report) - geological history and geological processes (very little, if any!); analysis and modelling of geological data; rock domains and deformation zones in the focussed volume; fracture domains and geological DFN modelling

Ch. 1: introduction, including a summary of the geological history

Ch. 2: available data (see App. 1), previous geological models, model volumes, and nomenclature
Ch. 3: evaluation of primary geological and geophysical data - investigation methods applied and selection of results, much of the necessary geological description for the modelling in Ch. 4-6 is hidden in this chapter! and in the many Appendices!
Ch. 4: rock domain model (for description of lithologies, see 3.4, and subord. rock types also App. 5, 6 and 9, alteration App. 7, ductile structures App. 8 and 9)
Ch. 5: model for deterministic deformation zones (modelled structures App. 10 and detailed descriptions App. 14)
Ch. 6: statistical model for fractures and minor deformation zones (no Appendices - see separate report)
App. 1 - report list (data acquisition and processing)
App. 2 - rock type nomenclature
App. 3 - primary borehole data and single-hole interpretations
App. 4 - volume % different rock types
App. 5 - thickness distribution of veins
App. 6 - orientation of veins
App. 7 - type and degree of alteration outside defm zones
App. 8 - orientation of foliation
App. 9 - comparison of orientation of foliation and veins
App. 10 - modelled rock domains, deformation zones and fracture domains in boreholes
App. 11 - rock domains - confidence, uncertainty, properties
App. 12 - prediction/outcome studies
App. 13 - borehole control of seismic reflection profiles 3 and 5
App. 14 - tabulated descriptions and properties of deformation zones

Whitehouse, P., 2009. **Glacial isostatic adjustment and sea-level change. State of the art report**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report TR-09-11.
- basic introduction to sea-level change modelling, including a detailed review of the approaches and solutions of the major research groups in this field - a modern text and reference book on the subject
- GIA modelling (glacial isostatic adjustment)

Whitmeyer, S.J., Nicoletti, J., De Paor, D.G., 2010. **The digital revolution in geology mapping**. GSA Today, 20, doi: 10.1130/GSATG70A.1.
- 3D-visualization
- case study of geologic maps from Western Ireland based on digital data assembled in Google Earth (all available from GSA Supplementary Data item 2010102 from www.geosociety.org/pubs/ft2010.htm)

Wibberley, C., Petit, J.P., Rives, T., 2000. **Micromechanics of shear rupture and the control of normal stress**. Journal of Structural Geology, 22, 411-427.
--> 3.1

Wilkins, S.J., Gross, M.R., Wacker, M., Eyal, Y., Engelder, T., 2001. **Faulted joints: kinematics, displacement-length scaling relations and criteria for their identification**. Journal of Structural Geology, 23, 315-327.
--> 3.2

Winberg, A., Andersson, P., Hermansson, J., Byegård, J., Cvetkovic, V., Birgersson, L., 2000. **Final report of the first stage of the tracer understanding experiments**. Swedish Nuclear Fuel and Waste Management Company (SKB), Technical Report SKB TR-00-07.
- updated structural model of the TRUE site, including conceptual model for Feature A (open fracture lined filled with fault gouge, rock fragments and minerals, following a mylonite zone but also in contact with altered and fresh Äspö diorite), also refinement of parameters for DFN modelling based on work done during the parallel Fracture Classification and Characterisation (FCC) project - see Äspö ICR reports 96-04 and 96-05 - for details of whole characterisation and modelling process, see Andersson et al 2002

Zwingmann, H., Offler, R., Wilson, T., Cox, S.F., 2004**. K-Ar dating of fault gouge in the northern Sydney Basin, NSW, Australia - implications for the breakup of Gondwana**. Journal of Structural Geology, 26, 2285-2295.

Äikäs, K., Hagros, A., Johansson, E., Malmlund, H., Sievänen, U., Tolppanen, P., Ahokas, H., Heikkinen, E., Jääskeläinen, P., Ruotsalainen, P., Saksa, P., 2000. **Engineering rock mass classification of the Olkiluoto investigation site**. Posiva Oy, report POSIVA 2000-08.

Öhberg, A., 2006. **Investigation equipment and methods used by Posiva**. Posiva Oy, Working Report 2006-81.

Ch. 2: drilling, but no mention of core orientation!
Ch. 3: hydrogeological investigation methods in use
Ch. 4: geophysical methods - ground surveys, borehole techniques (incl. OPTV), tunnel investigations
Ch. 5: "rock mechanics" - high precision GPS, microseismic monitoring, rock stress measurement

Öhberg, A., Heikkinen, E., Hirvonen, H., Kemppainen, K., Majapuro, J.,Niemonen, J., Pöllänen, J., Rouhiainen, P., 2006a. **Drilling and associated borehole measurements of the pilot hole ONK-PH3**. Posiva Oy, Working Report 2006-20.

- example of standard borehole measurements carried out in each of the ONKALO pilot holes
- borehole measurement includes difference flow logging, geophysical logging, optical borehole wall imagery, borehole radar
- core logging for rock engineering purposes (Q-system) + rock strength and deformation tests on samples
- core oriented in hole (about 69% successful): fractures oriented using OPTV when core orientation not successful

Öhman, I., Heikkinen, E., Lehtimäki, T., 2006. **Seismic 2D reflection processing and interpretation of shallow refraction data**. Posiva Oy, Working Report 2006-114.

- using 2D reflection processing methods, aimed at locating gently dipping reflectors in bedrock - successful down to ca. 400 m
- identified reflectors match well with fracture zones in some cores (KR4, KR7, KR24, KR38)
- "....seismic measurements intended for refraction interpretation can also be successfully processed using reflection seismic processing methods....."

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Fault gouge and incohesive fault breccia in the core of as small fault in migmatitic bedrock, Flatanger, west coast of Norway (Photo: A.G. Milnes).

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Systematic mapping of fractures, lithological contacts and foliation in the heterogeneous, migmatitic bedrock exposed in the ONKALO access tunnel, Olkiluoto (Photo: Posiva).

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A very long fracture cutting through poorly foliated migmatitic gneisses on a shore outcrop near Olkiluoto (Photo 2006-63.1A from the Appendix "Outcrop Photographs" in Lindberg 2007, scale bar 15 cm). Towards the waterline the joint intersects the mafic dyke shown on page 17. Post-glacial movement on this joint of 2-4 cm (height difference of the glacially striated surface on either side) cannot be excluded (see Pere 2009, p. 3 and Fig. 3).

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Pegmatite vein cutting through mica-gneiss in a shore outcrop near Olkiluoto (Photo 2006-48.4B from the Appendix "Outcrop Photographs" in Lindberg 2007, scale bar 15 cm).