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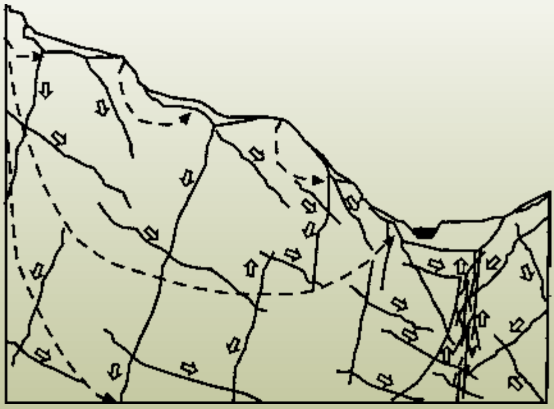

ANNUKKA LIPPONEN

Topographical, structural and geophysical characterization of fracture zones: implications for groundwater flow and vulnerability

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Ulla Haapanen, Finnish Environment Institute
P.O. Box 140
FI-00251 Helsinki, Finland
Fax: +358 9 40300490
e-mail: ulla.haapanen@ymparisto.fi

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MONOGRAPHS OF THE BOREAL ENVIRONMENT RESEARCH

25

Annukka Lipponen

Topographical, structural and geophysical characterization of fracture zones: implications for groundwater flow and vulnerability

Yhteenveto: Ruhjevyöhykkeiden ominaisuuksien arviointi topografisin, rakenteellisin ja geofysikaalisin menetelmin pohjaveden virtauksen ja pilaantumisherkkyyden kannalta

FINNISH ENVIRONMENT INSTITUTE, FINLAND
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Contents

List of original publications and author's contribution

This study synthesizes the following original publications. In addition, some previously unpublished results are presented. The contributions made to the papers by other authors are explained below.

Paper I
Lipponen, A., 2002. Detection of potential pathways for contaminants into the Päijänne Tunnel in Finland. *Norges geologiske undersøkelse, Bulletin* 439: 27–32.

Paper II
Lipponen A., Manninen S., Niini H. & Rönkä E. 2005b. Effect of water and geological factors on the long-term stability of fracture zones in the Päijänne Tunnel, Finland. *International Journal of Rock Mechanics and Mining Sciences* 42: 3–12.

Paper III
Lipponen A. & Airo M-L. 2006. Linking Regional-Scale Lineaments to Local-Scale Fracturing and Groundwater Inflow into Päijänne Water-Conveyance Tunnel, Finland. *Near Surface Geophysics* 4: 97–111.

Paper IV
Lipponen A. & Julkunen A. 2003. Gamma-spectrum measurements in a drilled well in Leppävirta, eastern Finland. In: Stournaras G. (ed.), *1st Workshop on Fissured Rocks Hydrogeology: Proceedings.* IRIS Publishers, Athens. pp. 115–129.

Paper V
Lipponen A., Tossavainen J. & Rönkä E. 2005a. Temperature and fluid conductivity measurements in drilled wells of Leppävirta: comparing hydrogeological environments as indicated by different methods. In: Rönkä E. & Suokko T. (eds.), *Fennoscandian 3rd Regional Workshop on Hardrock Hydrogeology Helsinki, Finland, June 7–9, 2004*. Finnish Environment Institute, The Finnish Environment 790, pp. 19–25.

Paper VI
Lipponen A. Applying GIS to assess the vulnerability of the Päijänne water-conveyance tunnel in Finland. Environmental Geology (in press).

Papers I–IV are reprinted with kind permission of Norges geologiske undersøkelse (I), Elsevier Science (II), EAGE Publishing (III), IRIS Publishers (IV), the Finnish Environment Institute (V) and Springer (VI).

The interpretation of block falls inside the Päijänne Tunnel from a recording made by a submersible robot used in Paper II was carried out by M. Manninen. The author compiled and processed the data and wrote Paper II, which was then commented upon by the co-authors. Paper III was written by the author except for the part on processing and interpretation of aeromagnetic data. Paper IV was written by the author, and the gamma measurements and data processing, including conversions to concentrations, were carried out by Astrock Oy. The water quality measurements taken using a multi-parameter probe described in Paper V were carried out by J. Tossavainen.

A significant proportion of the data on the Päijänne Tunnel were processed and analysed as a part of the study of environmental geology and risks commissioned by the Helsinki Metropolitan Area Water Company (PSV) and undertaken by the Finnish Environment Institute (SYKE), for which the author was the responsible researcher. The results have been published as a report (Lipponen 2001).

In the section of this study consisting of elements complementary to the papers, the author carried out the conductivity measurement in Oitti. The interpretation of the borehole video recording data was made by O. Ikävalko. This was complemented by additional analysis undertaken by J. Klockars. The analysis of the groundwater monitoring results, based on the data of Soil and Water Ltd provided by the PSV, was carried out by the author.

Topographical, structural and geophysical characterization of fracture zones: implications for groundwater flow and vulnerability

Annukka Lipponen

Finnish Environment Institute, P.O. Box 140, Fin-00251 Helsinki, Finland

Lipponen, A. 2006. Topographical, structural and geophysical characterization of fracture zones: implications for groundwater flow and vulnerability, Monographs of the Boreal Enviroment Research No 25, 2006.

The main objective of this study is to evaluate selected geophysical, structural and topographic methods on regional, local, and tunnel and borehole scales, as indicators of the properties of fracture zones or fractures relevant to groundwater flow. Such information serves, for example, groundwater exploration and prediction of the risk of groundwater inflow in underground construction. This study aims to address how the features detected by these methods link to groundwater flow in qualitative and semi-quantitative terms and how well the methods reveal properties of fracturing affecting groundwater flow in the studied sites. The investigated areas are: (1) the Päijänne Tunnel for water-conveyance whose study serves as a verification of structures identified on regional and local scales; (2) the Oitti fuel spill site, to telescope across scales and compare geometries of structural assessment; and (3) Leppävirta, where fracturing and hydrogeological environment have been studied on the scale of a drilled well.

The methods applied in this study include: the interpretation of lineaments from topographic data and their comparison with aeromagnetic data; the analysis of geological structures mapped in the Päijänne Tunnel; borehole video surveying; groundwater inflow measurements; groundwater level observations; and information on the tunnel's deterioration as demonstrated by block falls. The study combined geological and geotechnical information on relevant factors governing groundwater inflow into a tunnel and indicators of fracturing, as well as environmental datasets as overlays for spatial analysis using GIS. Geophysical borehole logging and fluid logging were used in Leppävirta to compare the responses of different methods to fracturing and other geological features on the scale of a drilled well.

Results from some of the geophysical measurements of boreholes were affected by the large diameter (gamma radiation) or uneven surface (caliper) of these structures. However, different anomalies indicating more fractured upper part of the bedrock traversed by well HN4 in Leppävirta suggest that several methods can be used for detecting fracturing.

Fracture trends appear to align similarly on different scales in the zone of the Päijänne Tunnel. For example, similarities of patterns were found between the regional magnetic trends, correlating with orientations of topographic lineaments interpreted as expressions of fracture zones. The same structural orientations as those of the larger structures on local or regional scales were observed in the tunnel, even though a match could not be made in every case. The size and orientation of the observation space (patch of terrain at the surface, tunnel section, or borehole), the characterization method, with its typical sensitivity, and the characteristics of the location, influence the identification of the fracture pattern. Through due consideration of the influence of the sampling geometry and by utilizing complementary fracture characterization methods in tandem, some of the complexities of the relationship between fracturing and groundwater flow can be addressed.

The flow connections demonstrated by the response of the groundwater level in monitoring wells to pressure decrease in the tunnel and the transport of MTBE through fractures in bedrock in Oitti, highlight the importance of protecting the tunnel water from a risk of contamination. In general, the largest values of drawdown occurred in monitoring wells closest to the tunnel and/or close to the topographically interpreted fracture zones. It seems that, to some degree, the rate of inflow shows a positive correlation with the level of reinforcement, as both are connected with the fracturing in the bedrock.

The following geological features increased the vulnerability of tunnel sections to pollution, especially when several factors affected the same locations: (1) fractured bedrock, particularly with associated groundwater inflow; (2) thin or permeable overburden above fractured rock; (3) a hydraulically conductive layer underneath the surface soil; and (4) a relatively thin bedrock roof above the tunnel. The observed anisotropy of the geological media should ideally be taken into account in the assessment of vulnerability of tunnel sections and eventually for directing protective measures.

Keywords: fracture zones, geophysics, lineaments, scale effects, water supply, tunnels, groundwater, inflow, wells, GIS

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1 Introduction

Predicting locations of hydraulically conductive zones in the bedrock is important for community water supply based on groundwater in crystalline rocks, for assessing the risk of groundwater inflow into underground cavities and for groundwater protection. The prediction of likelihood of groundwater inflow and characterization of fracturing are important for minimizing exposure to risk from elevated costs in planning placement of underground constructions due to the sealing and reinforcement measures required. Drawdown of the groundwater table in the surrounding aquifer is one of the possible environmental impacts of groundwater inflows into underground constructions (e.g. Morfeldt 1972, Hagerman 1969).

Yields from drilled wells are commonly sufficient in Finland for supplying water to individual households, but for supporting community water supply, a thorough knowledge of the location of fracture zones is crucial (Rönkä 1993, Leveinen *et al.* 2000). Glacio-fluvial deposits are unevenly distributed throughout the country (Kujansuu and Niemelä 1984) and in cases where there are limitations to their utilization due to, for example pollution, it may be necessary to develop water supply solutions based on groundwater in fractured rock on a local basis. For assessment of bedrock groundwater supply potential, it is important to investigate whether the fracturing is of a type that gives rise to sufficiently productive fractured aquifers.

Nuclear waste repository research in Finland has substantially advanced the knowledge of groundwater conditions in deep, fractured bedrock as well as the development of techniques and methodologies for characterizing fractured rock, including borehole measurements (McEwen and Äikäs 2000). The studies have shown that groundwater conditions in the upper fractured part of the bedrock above a depth of approximately 100 metres, which is the most interesting layer for the purposes of water supply (e.g. Rönkä 1983), differ from those deeper down where (1) the rock is generally less fractured, (2) hydraulic conductivities are lower and (3) groundwater contains higher concentrations of dissolved solids (e.g. Anttila et al. 1999). The superficial part of the bedrock (together with overburden) also has a key role when considering impacts on groundwater resources in fractured rock from contamination sources at the surface.

This study evaluates the application of selected geophysical, structural and topographic methods on regional, local, tunnel and borehole scales as indicators of the properties of fracture zones or fractures relevant to groundwater flow. The respective geometries of assessment vary from two-dimensional planar of the ground surface, sub-horizontal tunnel, to vertical boreholes. The objective was to evaluate how the features detected by these methods link to groundwater flow in qualitative and semi-quantitative terms. In addition to observations on actual hydraulic activity, an estimation was made of how well the methods reveal properties of fracturing that are relevant to groundwater flow in the studied sites. The methods applied in this study included interpretation of lineaments from topographical data and comparing them with aeromagnetic data, analysis of mapped structures in the tunnel, geophysical borehole logging, digital video surveying of borehole wall and fluid logging. In particular, it was assessed how consistent the lineament interpretation, considered indicative of fracture zones, is with actual observations of fracturing observed from inside the Päijänne Tunnel and with regional lineament trends interpreted from aeromagnetic data. The Päijänne Tunnel served as a verification rarely available for aerogeophysical and topographical structural interpretation. The Päijänne Tunnel is a 120-km tunnel conveying water from Lake Päijänne to supply the greater Helsinki region in southern Finland. On the tunnel scale, the spatial relationship between detected inflows and interpreted lineament/fracture zone trends was analyzed. Data such as groundwater inflow measurements, reinforcement descriptions and information on the tunnel's deterioration, as demonstrated by block falls, were provided by the Helsinki Metropolitan Area Water Company. Existing methods were used, but combined and applied in an integrated fashion, demonstrating the use of Geographical Information Systems (GIS) for spatial analysis and spanning over a range of scales.

Some of the geophysical borehole logging methods used in fracture characterization survey the properties of the rock mass, some those of the borehole surface and some those of the water column. One of leading ideas in this work is the recognition of uncertainties related to the methods, many of which are indirect, and suggesting, for example verification using complementary methods for controlling them. The integrated approach considers the connection of fractures to groundwater in the overburden and how the groundwater in superficial deposits responds to changing pressure conditions in the rock mass. This aspect was addressed through analysis of measured drawdowns during the repair of the northern part of the Päijanne Tunnel. It has to be recognised that the tunnel and drilled wells are complex systems as constructed underground environments and hence the dynamics are not fully comparable to natural hydrogeological system.

This study evaluates the selected methods for assessing fracturing and groundwater flow through two case study areas – the Päijänne Tunnel and Leppävirta – in the light of particular constraints arising from the conditions of a tunnel or a drilled well environment, respectively. The community water supply of the municipality of Leppävirta is based on groundwater in fractured rock. The Oitti site provides an illustrative zoom-in to the zone of the Päijänne Tunnel to look at structures at different scales and to assess the differences in the picture of fracturing as observed (1) based on the local surface topography, (2) in boreholes and (3) from inside the tunnel. In Leppävirta, a range of geophysical borehole and fluid logging methods was used to compare the hydrogeological environment in two wells, one with a low and one with a high/moderate yield. In addition to comparing the different logs, indications of fracturing from them were compared with related information on lithological variation and groundwater flow into the well.

In practical characterization of fracturing in the rock mass, even relative predictions of groundwater flow, or determining the likely sites of more substantial groundwater flow may be adequate. When surveying large areas, this is the probable level of knowledge that can be feasibly obtained, and GIS provide a powerful tool for the related spatial analysis.

1.1 Structure of the thesis

The study involves testing of methods for different aspects of fracture zone characterization on regional, local, and tunnel and borehole scales. The methods are evaluated through case studies, highlighting the particular qualities of drilled wells and of tunnel environments and noting constraints.

In Papers I–III and VI, fracturing in the zone of the Päijänne Tunnel and its linkage to geological features and groundwater flow was analyzed on different scales. Paper I demonstrates the use of spatial analysis of geological, environmental and technical datasets for assessing fracturing on a local scale to detect potential pathways for contaminants into the Päijänne Tunnel. In Paper II, it was investigated how the interpreted fracture zones relate to groundwater inflow and damage that has occurred in the tunnel. Paper III presents a comparison of lineaments indicative of fracture zones on regional and local scales interpreted using aeromagnetic and topographic data, respectively, to fractures and foliation measured on the tunnel scale. Paper VI makes suggestions for incorporating the observed hydrogeological heterogeneity into an assessment of vulnerability of a rock tunnel or a fractured aquifer.

Papers IV and V report on geophysical borehole logging of drilled wells in Leppävirta, relating the results of gamma-spectrum measurements to information on fractures and lithologies, and evaluating a set of probes of variable level of sophistication for measuring fluid conductivity and temperature.

The data complementary to the papers presented in this study include (1) a conductivity log and interpretations of fracture occurrence from borehole video recordings from a fuel spill site in Oitti which is located in the zone of the Päijänne Tunnel; (2) the results of a borehole radar survey in two drilled wells in Leppävirta and of multiparameter geophysical borehole logging from one of the two wells and (3) observed drawdowns in wells and monitoring wells in the zone of the Päijänne Tunnel mainly during the repair of the northern part of the tunnel in 2001.

Among the core considerations of this study are (1) the scale aspects (self-similarity and precision), (2) the complementarities of logging fluid properties and rock matrix or borehole wall properties and (3) relating the observed geophysical and geological fracture (or fracture zone) properties to the observed hydraulic activity. The hydraulic properties for this purpose were mainly assessed on the basis of measurements or qualitative/semi-quantitative observations made in the Päijänne Tunnel. On the basis of the results, complementarities of the different methods are identified and recommendations are given on their applicability. The discussion refers to implications of fracturing for groundwater exploration in a terrain of fractured crystalline bedrock, for underground construction and for groundwater protection.

2 Study areas

2.1 The Päijänne Tunnel (Papers I–III, VI)

The Päijänne Tunnel (Fig. 1) was constructed for water conveyance from Lake Päijänne to the Helsinki metropolitan area between 1973 and 1982 and has since been continuously in use, apart from brief periods of repair. Extensive geophysical and geological surveys preceded the tunnel construction (Niini 1968a and b, 1982). The tunnel runs at a depth of 30–130 m under the ground surface (e.g. Lipponen 2001). The cross-section of the tunnel on average is 15.5 m^2, and the current flow in the tunnel is approximately 3.1 m^3/s (2004) under natural pressure. During the repair of the northern part of the tunnel in 2001, observations were made on the geological structures and damage that had occurred during use.

The rock types in the zone of the Päijänne Tunnel comprise early Proterozoic Svecofennian granite and migmatites (Korsman *et al.* 1997), overlain by glacial, glaciofluvial and postglacial overburden. The rocks in the Svecofennian domain are 1.93–1.8 Ga old and metamorphic rocks dominate which are former volcanic plutonic and sedimentary lithologies. The primary distribution of major supracrustal and igneous rock provinces, major structures and metamorphic zones has a strong, almost E-W trend (Koistinen *et al.* 1996). The overlying Quarternary deposits include esker systems and the First and Second Salpausselkä ice marginal deposits (Fig. 1).

The properties of fractures in the rock mass affect the tunnel in several ways. In case of chemical spills or other pollutants getting into groundwater in the zone of the tunnel, the hydraulically conductive fractures expose the tunnel to a risk of contaminant transport (Niini and Ekholm 1976). For many sections in the northern part of the tunnel, the water pressure level in the tunnel is markedly lower than that of local groundwater, which causes groundwater flow towards the tunnel (see the profile of the tunnel, Fig. 1b in Paper II, Annex 3). In the southern part, the pressure level is close to that of the ground surface, even exceeding it in some places (Pokki 1979), which diminishes the inflow. For allocating preventive measures, these hydrogeological data can be used for assessing vulnerability of the tunnel to pollution (Paper I). Furthermore, the weakness of fractured zones makes them prone to the eroding impact of both water that is being conveyed in the tunnel and of groundwater flowing in the fractures (Paper II), which has implications for tunnel maintenance.

To monitor impacts on groundwater caused by construction of the Päijänne Tunnel, the wells, springs and water intake stations near the tunnel were registered and filed, and water stage observations were initiated in 1967. The width of the observation area was 400–2000 metres. Groundwater level decline observed in private wells and monitoring wells located along the tunnel line was restricted to the construction period in most cases (Harjula 1982).

Refraction seismic sounding was employed for example for estimating the bedrock surface elevation in the geological investigations for determining the course of the Päijänne Tunnel (Niini 1967b and 1968a). Rönkkö (1968) and Rönkä (1970) carried out morphological and engineering geological studies for the purpose of locating the main fracture zones along the line of the Päijänne tunnel between Helsinki and Palomaa (approximately 94 km from the southern end of the tunnel), estimating the depth to the bedrock surface in these zones as well as their degree of brokenness and of weathering. Rönkkö (1968) and Rönkä (1970) concluded that the deepest point of the valleys is closer to the side where the bedrock crops out.

The investigations for comparing alternative courses for the Päijänne Tunnel involved studying the following geological criteria: (1) rock types, (2) the topography of the bedrock surface, (3) fractured and weathered zones as well as (4) superficial deposits and groundwater (for example Niini 1990). An analysis of joints and fracture zones in the tunnel zone was made using aerial photographs and geological maps (for example, Soveri 1971). In his study focused on fracturing observed at depths shallower than approximately 100 m, Niini (1968b) observed variation in the occurrence of fracture zones and in the extent of weathering in the bottoms of valleys, grouped by orientation. On the basis of profile forms of the valleys in the southern part of the tunnel zone, Niini estimated that NW–SE valleys, parallel to the movement of continental ice, have been glacially worn down approximately 5 m more than the other valleys.

Pajunen *et al.* (2002a) classified bedrock areas

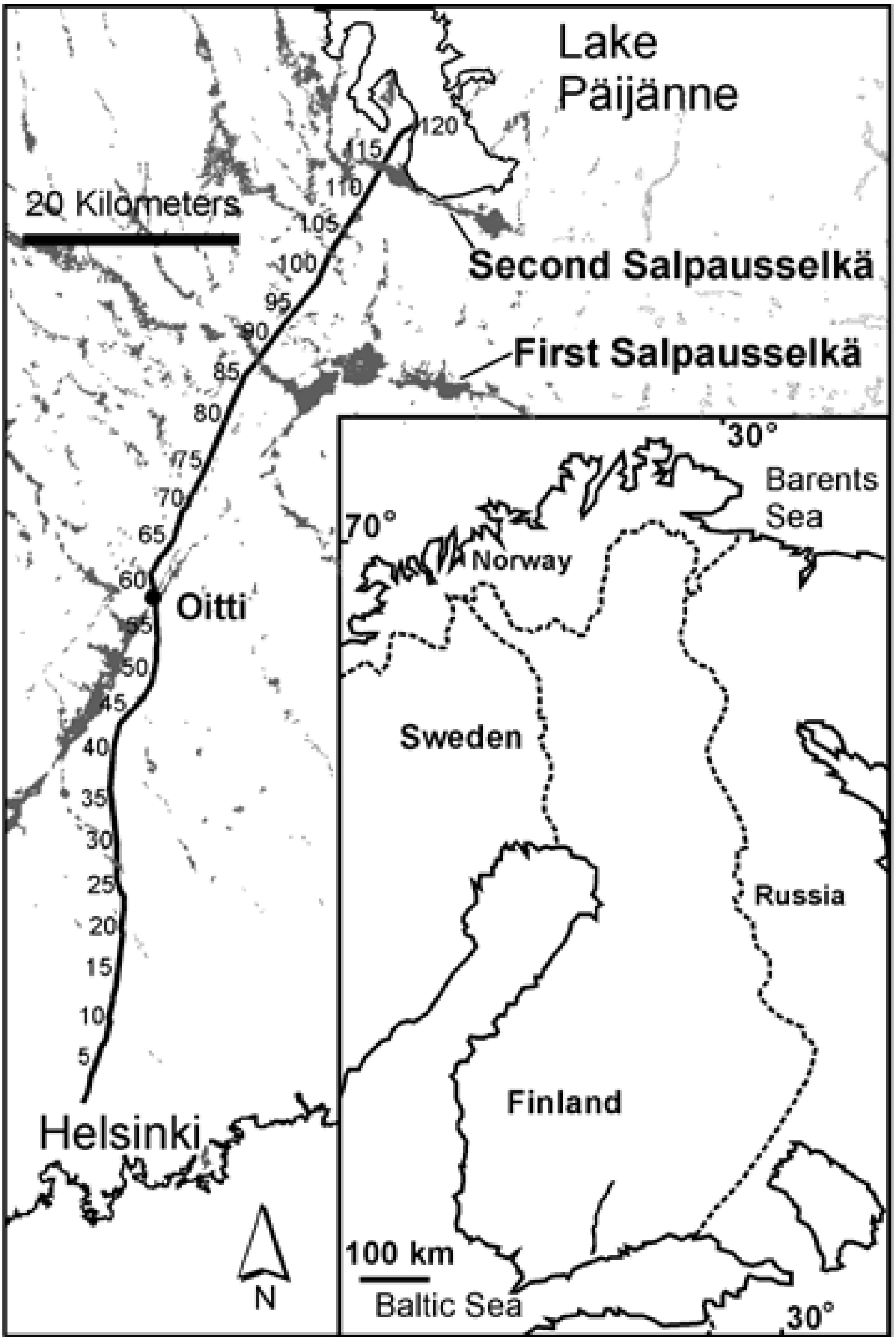

Fig. 1. Päijänne Tunnel in southern Finland conveying water from Lake Päijänne to Helsinki. The numbers denote kilometre readings from the southern end of the tunnel.

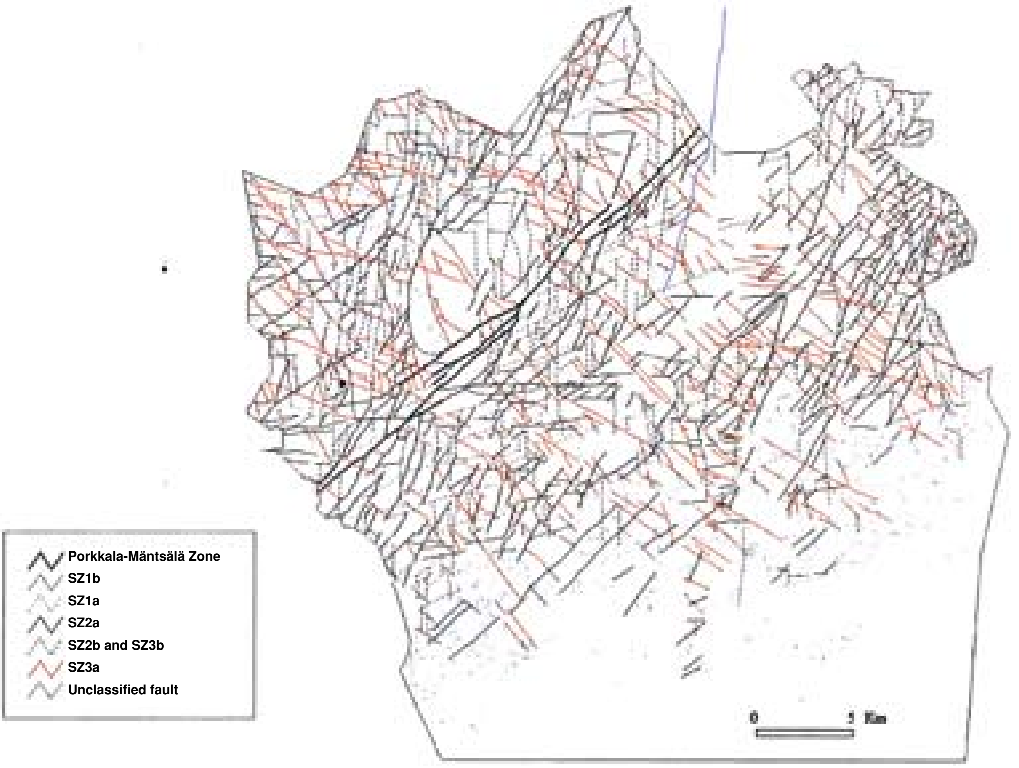

Fig. 2. Geologically classified shear and fault zones in the greater Helsinki region (Pajunen *et al.* 2002a). The Päijänne Tunnel is indicated by a blue line. Key: SZ$_1$– ductile shears and faults, SZ$_2$ – transitional faults, SZ$_3$ – brittle steep faults and SZ$_4$ (not in the figure) – brittle low-angle faults. The 200 km long and 0.1-1 km wide Porkkala-Mäntsälä shear zone (in black) intersects the Päijänne Tunnel further to the northeast along the continuation of the zone (Pajunen et al. 2002c).

in the greater Helsinki region using the geological history and different structure populations as its indicators, including fracturing. Figure 2 shows the distribution of shear and fault zones, divided into classes, resulting from these investigations. This classification of technical properties on the basis of parameterization of lithological and tectonic features does not infer hydraulic properties *per se*, but the research distinguishes structures resulting from plastic and brittle deformation. Brittle and multi-phase fault zones were concluded to be more fractured and the most difficult from the point of view of construction. This has implications for groundwater flow, as brittle fracturing is generally more prone to conducting flow.

Pajunen et al. (2002b) identified brittle steep faults (indicated as SZ$_3$ in Fig. 2) with either NW or N-S trends. The NW trending faults were noted to intersect ductile and transitional structures and to be partly connected to diabase dykes. On the basis of information from tunnels, water (in)flow associated with these NW trending brittle structures was estimated to be rather abundant and that associated with N-S trends to be minor. Some of the ductile, NNE trending SZ$_2$ faults have been later reactivated, probably at the same time when the NW trending SZ$_{3a}$ faults formed (Elminen 2006).

In summarizing the geological observations from the northern part of the Päijänne tunnel (from metre reading 84 800 to 120 000), Laitakari and Pokki (1979) noted the difficulty of estimating the strike and dip of a fracture zone in a small tunnel. They observed that fracture zones in this tunnel section are commonly gently-dipping.

2.1.1 Oitti fuel spill site in relation to the Päijänne Tunnel

Chlorinated ethenes spread into groundwater from the waste pit of an abandoned chemical cleaning shop (Salkinoja-Salonen *et al.* 1995) that operated in the 1950s and 1960s and from the landfill where some of the solvent waste was dumped in Oitti (Fig. 1). Investigations following the discovery led to data collection and analysis, including data on the bedrock surface elevation. The research activities carried out in the wake of the investigations of contamination, including for example geostatistical modelling using expert knowledge carried out by Laine (1998), focusing on quantitative risk from contaminant transport, provided information on the fracturing and hydraulic properties in the superficial part of the bedrock above the tunnel. The soil contaminated by chlorinated solvents in Oitti was remediated in 1996 and the investigations concluded that probable transport direction was mostly away from the tunnel that no threat was posed by the spill to the tunnel water (Laine and Peltoniemi 1997, Soil and Water Ltd 1997).

Detection of the fuel additive methyl-tertiary-butyl ether (MTBE) in three analysed samples of groundwater flowing into the empty northern part of the Päijänne Tunnel in 2001 led to investigations and the eventual discovery of soil contaminated with hydrocarbons at the site of a former service station in Oitti which operated from 1981 to 2002. Contaminants had migrated into groundwater and been transported towards the Tunnel. In analyses of tunnel water, these substances have not been detected and in the magnitude of flow in the Päijänne Tunnel, the concentrations analysed in the sampled groundwater get diluted below detection limit. However, MTBE transport demonstrates flow and transport connection to the Tunnel, which highlights the importance of its protection.

MTBE is soluble in water, does not adsorb well to soil particles, and is relatively slow to biodegrade (for example), Thomson 2000). MTBE is more mobile in the ground than other components of fuel (Nikunen *et al.* 1990). Any estimate of the actual flow and transport channels would be complicated by the fact that they tend to be highly variable and tortuous in fractured rock. Furthermore, the flow and transport conditions have varied because of the repair of the tunnel, which involved emptying the tunnel of water.

Since the detection of the contamination, the soil was excavated and remediated in the framework of SOILI, the national remediation programme of the Finnish Oil and Gas Federation, the Ministry of the Environment and the Association of Finnish Local Authorities. Altogether 8310 cubic metres of contaminated soil were removed. Pump-and-treat of groundwater was continuous from April 2002 to August 2005 (J. Lintu pers. comm. 2005). The planning and supervision of the remediating the soil, including pump-and-treat as well as groundwater quality monitoring were carried out by Golder Associates Oy, as assignment from Oil Industry Service Centre Ltd. The investigations carried out in the area involved, for example drilling, chemical sampling and test pumping of wells (Lintu 2002, Lintu and Takala 2004). In early 2002, a digital borehole video survey of drilled wells was carried out at the fuel spill site by Kivikonsultit Oy (Ikävalko 2002). In August 2005, the pumping of groundwater was stopped with the authorization of Häme Regional Environment Centre. The soil vapour treatment involving sucking and burning catalytically air in the soil pores containing volatile petrol as well as groundwater monitoring were still continued after the pumping ceased (J. Lintu pers. comm. 2005).

2.2 Leppävirta (Papers IV–V)

In Leppävirta and Sorsakoski, the two main centres in the municipality of Leppävirta in eastern central Finland (Fig. 3), a total of 6000 inhabitants are using groundwaters from crystalline bedrock for water supply. The water abstraction is about 1 100 m^3/d (June 2005) from seven wells. This is the first case in Finland where groundwater from fractured crystalline bedrock has been extensively used in community water supply. The investigations for groundwater supply were conducted by the North Savo Regional Environment Centre, the Geological Survey of Finland (GTK) and the municipality of Leppävirta. Since the 1990s, pumping tests, water quality analyses and geophysical surveying have been conducted in different phases. Fracture zones were located by GTK from the topographic maps (Digital Elevation Model, DEM), airborne geophysical data and refraction seismic soundings. Pumping tests were made in 13 wells and the yield varied between 45 and 400 m^3/d (Breilin *et al.* 2003).

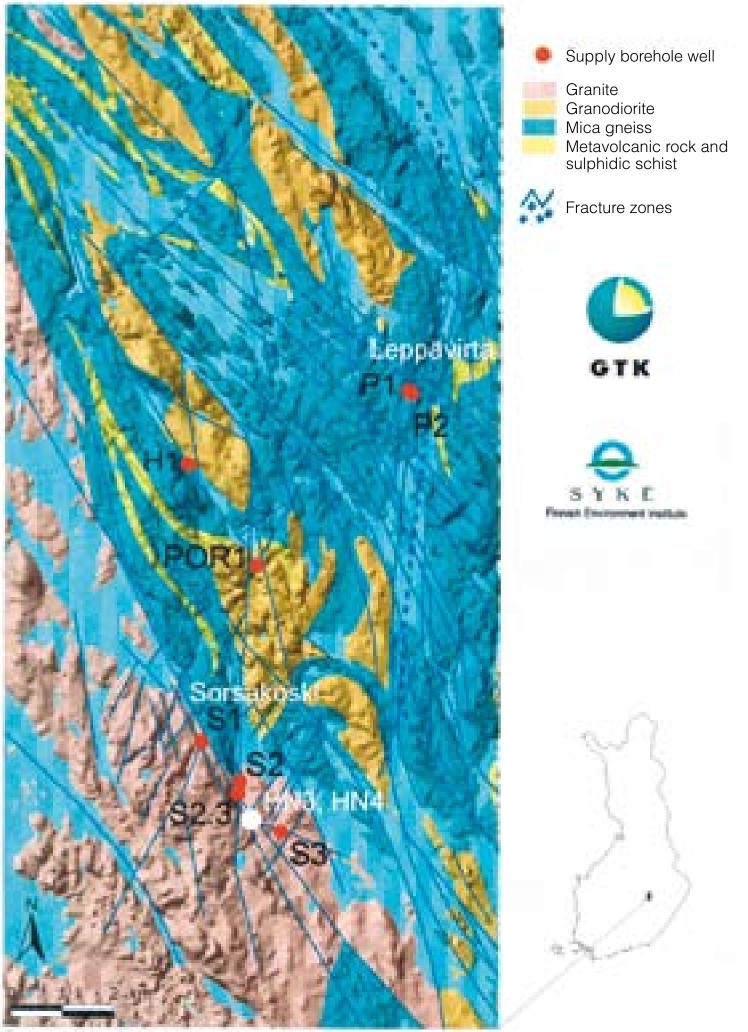

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Fig. 3. The fields of drilled wells in the vicinity of the Sorsakoski and Leppävirta centres the approximate locations of which are indicated by white text (map modified from Klockars and Lipponen 2003). HN3 and HN4 are the wells investigated in this study. Information on the other wells can be found in Klockars (2003).

The crystalline bedrock of the Leppävirta area comprises mainly Svecofennian schists and granitoids (1900–1800 Ma) (Korsman *et al.* 1997). In the wellfield area in Sorsakoski, in the vicinity of wells HN3 and HN4, the bedrock consists of granite and mica gneiss (Fig.3). Approaching the NW-SE fracture zone and lithological contact, which also coincides with the main fractured aquifer in the area, the granite becomes more gneissic in texture and in places is strongly deformed (Klockars 2003). Approximately 500 m^3/d of groundwater is abstracted from the three wells in this NW-SE fracture zone for community water supply. There is also one spare supply well in the zone. The two wells in which the borehole logging survey of this study was carried out are located approximately 30 m apart in the linear depression of the fracture zone. Well HN4, which according to a pump test by the municipality yielded approximately 100 m^3/d, penetrates the contact zone to granite. Well HN3 is a low-yield well entirely within mica gneiss. To the west, the granite is porphyric, with clasts of potassium feldspar. The strike of the cleavage is commonly 150–160°, with a vertical or near-vertical dip. Fracturing occurs both parallel to the cleavage and perpendicular to it (Klockars 2003).

The Pohjukansalo fractured aquifer field, located N/NE from Sorsakoski, has been studied by Leveinen *et al.* (1998) (wells P1 and P2, Fig. 3). The approximately N-striking fracture zones trace sub-vertical shear zones that functioned as feeder channels for mafic dikes and intrusions and probably resulted from a dextral movement along the NW-striking shear zones. This fracture zone pattern is consistent with the regional tectonic models (Talvitie 1971, Ekdahl 1993). The basement is overlain by Pleistocene glacial deposits that consist mainly of tills and clays (Huttunen 1990). Topographical highs are either exposed bedrock or covered by a soil layer a few metres thick. In topographical depressions associated with fracture zones, till deposits are 9–15 m thick (Leveinen 1996, Rainio 1980). The hydraulic conductivities which Leveinen *et al.* (1998) estimated in Pohjukansalo from monitoring well data by type-curve matching and by making simplifying assumptions concerning the extent of the throughflow area and the radial distance along the fracture system are as follows: $1.3*10^{-5}$ to $7.9*10^{-5}$ m/s and $5.0*10^{-6}$ to $2.5*10^{-5}$ m/s for the western and eastern fracture zones, respectively.

The analysis of correlation between yield of the bedrock wells and the seismic velocity of the fracture zone systems in Leppävirta by GTK showed, that the seismic velocity is 3 500 – 3 800 m/s in a fracture zone of the best pumping rate. The pumping rate was also noted to depend on the seismic velocity of the adjacent rocks. The specific discharge was identified as a possible means of assessing variations of the hydraulic conductivity in fracture zone systems. In the Leppävirta area, the hydraulic conductivity in fractured zones is 10^{-7}– 10^{-5} m/s (Breilin *et al.* 2003, Klockars *et al.* 2004).

An overview of groundwater quality in the area can be found in a paper by Klockars and Lipponen (2003). The maximum concentrations of iron, manganese and radon are an order of magnitude higher in the borehole well waters of Leppävirta than the mean values for Finland. The concentrations of radon are highest in the well waters of Sorsakoski, where the gamma radiation survey reported in Paper IV was carried out. With the exception of the two sulphate-dominated wells in Pohjukansalo, the borehole well waters of Leppävirta are bicarbonate waters, which typically occur in Finland (Lahermo *et al.* 1990). Geological factors such as rock type, thickness of the overburden and oxygen balance have an effect on the quality of the groundwater (Klockars 2003).

3 Fracturing and hydraulic properties of crystalline rocks

Direct quantification of flow and transport in fractured crystalline rocks is commonly made on the basis of fracture geometric data coupled with pressure (or flow) and tracer tests (for example Neuman 2005). Reflecting the scope of this work, the review of theory is limited to selected geological and geophysical methods and data that are useful for the qualitative conceptualisation of flow and transport in fractured rocks. In particular, the treatment of geophysical ground surveying is rather descriptive and the focus is on borehole measurements.

It is recognised that fractured rocks generally must be characterized *in situ*, because fracturing of hydrogeologic interest manifests itself on a much larger than laboratory scale and fracture properties are strongly affected by *in situ* fluid distribution and stress conditions (Neuman 2005). Long *et al.* (1997) reviewed fracture heterogeneity, emphasizing the highly channeled nature of fracture flow and the complexity of inter-relation between fracture features on different scales. In order to be hydrologically significant, a fracture must be both open and connected.

Laboratory studies (e.g. Neretnieks *et al.* 1982), field experiments (e.g. Neretnieks 1993) and numerical simulations (e.g. Tsang 1984) suggest collectively (Tsang and Neretnieks 1998) that flow and transport in rough-walled fractures tend to occur in highly variable and tortuous channels forming a braided pattern. The channels are dynamic in that their spatial distribution varies with the externally imposed flow regime.

Only a small portion of fractures in geologically observable fracture networks are water-conducting; for example in Jansson's field experiments, 10–15% of the total number of fractures were water conductive (Jansson 1998). In Olkiluoto the frequency of hydraulically conductive fractures in the depth range 0–150 m varies from 1 to 3 in a 10 m sample length (Hellä *et al.* 2004). A challenge when determining large-scale hydraulic properties of a rock mass is the upscaling of discrete observation points, such as geophysical logs and drill core data used by Saracino *et al.* (2004), into a three-dimensional framework.

Extensive site investigations were carried out from 1983 to 1999 in search of a suitable repository site for final disposal of high-level spent nuclear fuel produced in Finland, which included screening of the whole country for suitable coherent bedrock blocks with minimum fracturing (McEwen and Äikäs 2000). The results from for example Olkiluoto, the chosen nuclear waste repository site that has been investigated by Posiva Oy, indicated clearly that the hydraulic properties of the uppermost 100–200 m of bedrock are distinct from those at greater depth, that is hydraulically conductive fractures are more frequent and several with very high transmissivities exist in this near-surface zone. Based on the results from double-packer tests and flow logging, it is also evident in Olkiluoto that there is a clear decrease with depth in the hydraulic conductivity of the intact rock (Anttila *et al.* 1999). The bedrock in Olkiluoto consists of Paleoproterozoic migmatites (Paulamäki *et al.* 2002).

Hellä *et al.* (2004) demonstrated that it is possible to identify single hydraulically conductive fractures using the difference flow measurements and borehole wall images. The fracture properties identifiable from the borehole wall image include the orientation, openness and shape of the fracture as well as rock type and possible foliation. Difference flow can be used for directly measuring differences of flow along a borehole, which are either seepage from the bedrock into the borehole or flows from the borehole into the bedrock. However, the application requires isolation of test sections from the borehole with rubber discs which are only available for small diameter research boreholes (≤76 mm) (Pöllänen and Rouhiainen 2001, Öhberg and Rouhiainen 2000).

Well yield has been found to correlate positively with parameters such as the cumulative length of topographic lineaments, the number of lineaments and their intersection points per 1 km^2 area within a study area consisting of three ¼ Landsat TM images in south-east Finland (Tossavainen 1992). Based on statistical GIS analyses and numerical groundwater modeling, Lie and Gudmundsson (2002) identified proximity of wells to lineaments and lineament trends as two parameters that affect well yield. Through identification of fractured zones, drilled wells can be located for higher yields.

The more fractured superficial part of the bedrock provides more storage capacity for supplying water. Based on his survey of 700 drilled wells, Rönkä (1983) reported the highest yields to have derived from wells that were approximately 41–50 m deep. Wells deeper than 60 m had clearly lower yields. His investigations based on interpreting maps and studying rock powder and water samples from drilled wells, led him to also conclude that fracturing of the bedrock is a more important factor than the type of rock in question in its effect on the groundwater yield. Rönkä also observed that a thick soil cover caused an increase in the specific yield of the bedrock. For a numerical measure of rock fracturing, in his study Rönkä used weighted classified widths of topographic lineaments determined for an area of approximately 3.5 km^2 around each well.

Tuominen *et al.* (1973) found that the strikes of foliation of the Precambrian schists and gneisses are concentrated into eight dominant trends, each of which parallels a set of lineaments. On a larger scale, the bedrock in northern Fennoscandia is characterized by a relatively large number of major shear zones with NW-SE and N-S strike bordering and cutting post-glacial faults perpendicular to them (Saari 1992). The map of topographic lineaments of Vuorela (1982), presented in Fig. 4, showed lineaments as straight lines to facilitate orientation analysis, but in nature lineaments are commonly curved (Mikkola and Niini 1968). Steeply inclined fracture zones are likely to be prominent for topographic lineament interpretation. According to Saraste (1967), fracture zones can form en-echelon-like features that mark the trace of a larger tectonic feature.

The type of fracturing that tends to develop depends to some degree on the rock type. In some early investigations, it was observed that granitic rocks conduct water better than gneisses, and that water commonly flows in joints between two rock types, for example along a diabase dyke (e.g. Hagerman 1969). In Fjällveden, Sweden, situated in the Svecofennian domain, hydraulic conductivity was found to be at most 10^{-6} m/s in granite gneiss, the most pervious rock type, and lower in other tested rocks (Ahlbom et al. 1991, Fig. 5.).

Fig. 4. Topographical lineaments in the whole of Finland (a) and in the Kuopio region (b). Source: Leveinen (1996), adopted from Vuorela (1982) and Talvitie (1971). In (b), Leppävirta is indicated with a circle. In (b), only lineaments from the ground have been indicated and lakes have been left white, although they commonly represent concentrations of fracture zones.

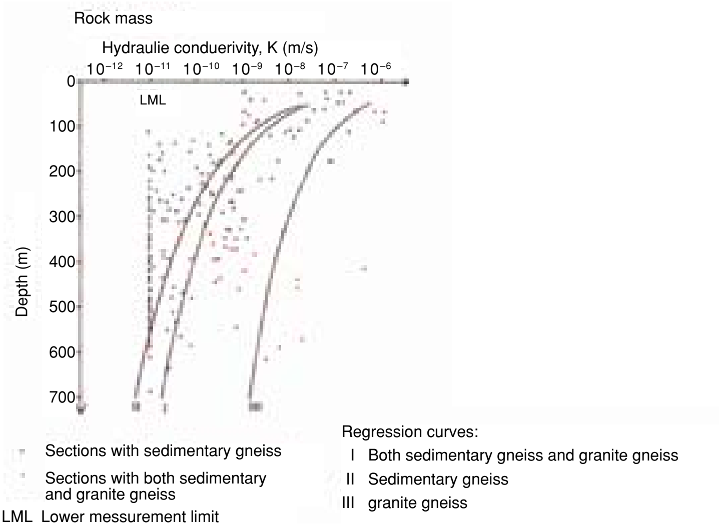

Fig. 5. Hydraulic conductivity as a function of depth with regression curves for different rock types, simplified from Ahlbom (1991) by Mälkki (2003). This study is mainly concerned with the upper 130 m of rock mass which is the maximum depth of the Päijänne Tunnel. The superficial part of the bedrock is also commonly the most fractured.

Fracture frequency determined from the assessment of a rock mass depends on the direction of observation. For example, Niini *et al.* (2001) observed that both the degree of weathering and the fracture frequency observed on the excavated rock faces in a migmatitic Precambrian belt in southern Finland were about twice as high as observed on the natural outcrop surface.

Sampling geometry is a potential source of bias in determining the hydraulic properties of both fracture zones and rock mass. Predictions of groundwater inflow into a tunnel using for example packer test data from boreholes may be constrained by bias from the geometry of sampling when the orientations of the planned tunnel and testing boreholes differ (Thapa *et al.* 2003). The results of Thapa *et al.* (2003) showed no clear correlation between mapped inflows into the Borman Park Tunnel, Indiana (in Devonian carbonates and interbedded shales overlying Silurian dolomite) and fracture density, that is, a fracture swarm did not lead to higher inflows.

Niemi *et al.* (2000) investigated hydraulic properties and up-scaling characteristics of low-permeability fractured rocks at Romuvaara, Finland. Based on systematic well test data from three different measurement scales they inferred that a borehole representing a one-dimensional sample of the medium can be more sensitive to the sampled low conductivities and may to some extent underestimate the overall conductivity in comparison to the two-dimensional reality where more pathways can be formed.

3.1 Inflow into a tunnel

Tunnels and other underground cavities create a negative pressure change in the interstitial water of the soil above, and in consequence water flows into the tunnel along fractures in the bedrock (Soveri 1971). The amount of water seeping down into rock joints and fractures strongly depends on the transmissivity of the soil covering the bedrock. As in the case of glaciated terrain, the soil layer closest to the bedrock is commonly compact bottom moraine with a low transmissivity for infiltrating water (e.g. Soveri 1971). Olofsson (2000) showed that the soil type is one of the most determining factors in regulating the drawdown of the groundwater level as a consequence of the excavation of a tunnel.

Long-term drawdown resulting from inflow into a tunnel can affect vegetation, the groundwater supply and the groundwater chemistry, and when leading to subsidence, ground settling can damage buildings (e.g. Morfeldt 1972, Hagerman 1969, Olofsson 1991). In the case of the Päijänne Tunnel, Niini and Ekholm (1976) identified four main environmental and economic effects from the tunnel construction: (1) water leakage into the tunnel hampers the contruction work, (2) leakage causes lowering of the groundwater level, affecting vegetation and approximately 1000 wells in the tunnel zone, (3) the tunnel will leak where its hydraulic pressure exceeds the groundwater pressure and (4) drilling through confining clay formations has made arable land wet.

Various factors influence the sensitivity of the environment to impacts from groundwater inflow. Based on his study of effects on groundwater from the construction of the Bolmen tunnel in Sweden, Olofsson (1991) concluded that there is a strong conformity between the groundwater level fluctuations in rock and in the soil cover along a valley which was primarily formed by tectonic events. He reported the distance from the tunnel to be the most important single variable affecting drawdown, but that it still only explains a small part of the variation. The various parameters used in the Multiple Linear Regression Analysis explained a minor part (15 %) of the drawdown in soil (Olofsson 1991). Based on results from a multiple regression analysis of data from the Bolmen Tunnel, Cesano *et al.* (2000) observed that the number of leakages increased with the depth of the tunnel, which they attributed to an increasing radius of drainage area of the construction as its depth increases. Results on different scales turned out to be different, for example on the 500-m scale topographical and soil parameters alone could explain 15% of the major leakage. The fact that the number of fractures together with the number of pregrouting is the most important parameter for the occurrence of minor leakage was interpreted to indicate that minor leakage is more related to drainage of the water that is mostly stored in the fractures (Cesano *et al.* 2000).

A mean value of inflow measurements for more than 100 kilometres of tunnel sections in Precambrian granite, gneiss, diorite and gabbro in Sweden is 60 L/(min km), reported by Morfeldt (1972). A mean inflow value from one section of the Bolmen tunnel in Sweden is 7.4 L/(s km) (that is, 44.4 L/

min/100 m), considered not markedly different in comparison with other sections (Olofsson 1991).

Inflow into a tunnel is commonly associated with a rough surface of the rock, which results from fracturing in the bedrock, and with inadequate shotcrete (Ritola and Vuopio 2002). The observations and results from measurements of groundwater inflow into a tunnel are affected by the applied reinforcement measures such as grouting (for example Sievänen 2002). Assessment of the hydraulic properties of fractured rock based on measurements of inflow to tunnels could be hampered by the skin effects around tunnel walls (Olsson 1992). If a grouted zone with a lower hydraulic conductivity than that of the rock mass is introduced, the control by the skin effect has the result that the hydraulic properties determined in the tunnel do not reflect the actual hydraulic conductivity of the rock mass. These potential limitations to quantifying rates of inflow must be acknowledged when assessing the hydraulic properties of fracture zones using observations from a tunnel.

The number of inflows from three tunnels in the Helsinki metropolitan area has been reported to correlate approximately with the pressure level of groundwater. A study of rock quality at points of inflow (n=156) showed that the inflows clearly concentrate in zones of fractured rock. Inflows were observed to concentrate around tubes fitted through shotcrete to channel flow in leaking zones, with 77 percent of the inflows falling within two metres of a tube (Ritola and Vuopio 2002).

Before the construction of the Päijänne Tunnel, an attempt was made by Soveri (1971) to predict the effects of bedrock groundwater leaks on the groundwater situation along the tunnel line. The sizes of influence areas and drainage areas were compared, including the rate of formation of groundwater and the density of joints and fractures in the bedrock. The methodological approach of Soveri is available, but results were not published. Groundwater inflow to the Päijänne Tunnel per tunnel drive was measured both at the time of construction for the whole tunnel and during the repair for the northern part (Lipponen 2001).

Data assembled by Bäckblom (2002) on groundwater inflow to underground facilities in Sweden shows a total inflow reduction in the order of 0.3–1% per month. On the basis of his review that concentrated on the improvements of water tightness by means of grouting, he concluded that the reasons for these reductions are not understood. Rhén *et al.* (1997) reported a decrease of inflow with time to a tunnel section of the Äspö Hard Rock Laboratory, which is an underground testing laboratory for nuclear waste repository studies. In Olkiluoto, chemical precipitation in the leaking fractures and the closing effects of rock stresses in the surrounding rock mass have been suggested as possible reasons for the observed decrease in leakage with time (Anttila *et al.* 2001).

3.2 Impacts of the stress regime on fracturing

The relations of large and secondary fractures as well as horizontal and vertical dislocations in the Päijänne Tunnel area generally were discussed by Niini (1987). His mechanical model explains the high conductivity variations in the large fracture zones such as the Porkkala-Lahti zone.

Based on results from earthquake fault plane solutions, Uski *et al.* (2003) named two main far-field stress sources presently prevailing in Finland: the North Atlantic ridge-push causing the prevailing NW-SE oriented horizontal compression and extension related to post-glacial crustal rebound. The stress relief related to post-glacial rebound related is a second-order stress source, but, importantly, it causes horizontal fracturing. The NW-SE oriented compression tends to keep fault systems sub-parallel to the prevailing stress field and horizontal fractures open and hydrologically conductive.

Based on the analysis of horizontal crustal deformations using observations from the Finnish triangulation network, Chen (1991) concluded that the Svecofennian domain (relevant to the Päijänne Tunnel) has a general strain pattern with its maximum compression in the NW-SE direction. Leppävirta lies in a zone where Chen (1991) considers deformations to be insignificant in the context of presenting the general structure of the strain patterns in Finland.

Although the dominant direction of horizontal stress in Finland is NW-SE, orientations markedly different from this orientation occur locally, particularly in the upper part of the bedrock (< 300 m) (Stephansson *et al.* 1991, Tolppanen and Särkkä 1999). According to the results of Mononen (2003) from model-based estimates of *in situ* stress distribution in the rock mass of the greater Helsinki area, zones of weakness have a strong influence on the orientation of principal stresses. The influence on their magnitude is smaller but acts over a greater distance. Mononen (2003) also found that the boundary between different rock types had little effect on rock stress distribution. An extensive review of results of the research on the complex overall structural development and multi-phase deformation of southern Finland, which lays the foundation for the behaviour of the rocks under stress, was presented by Pajunen (2002a).

Neotectonic movements have generally followed old faults and fracture zones in the bedrock, which have repeatedly been reactivated during geological time, leaving the blocks between the faults tectonically undisturbed (Saari 1992). The old deformed or fractured zones potentially channel contemporary movements under a changing stress regime. Post-construction movements in the rock mass can cause fracturing in shotcrete, which is one of the identified reasons for the occurrence of inflows in tunnels (Ritola and Vuopio 2002).

3.3 Scale aspects of fracturing

The methods applied to fracture characterization for the purpose of assessing hydraulic properties use a different volume for the assessment. Core sections, particularly in heterogeneous fractured media, do not provide a representative volume for assessing the properties of an aquifer. Neuman and Di Federico (2003) have demonstrated with a number of examples hydrogeological variables exhibiting isotropic and directional dependencies on scales of measurement, observation, sampling window, spatial correlation and spatial resolution.

In modeling groundwater flow and transport, a representative elementary volume, REV has been reached when the macroscopic properties of geological formations (for example hydraulic conductivity or porosity) become independent of the volume over which the averaging of the microscopic properties takes place (Bear 1972, 1993). Hard rocks in general have been found to have very large REV or to lack REV, particularly if matrix blocks are considered (Gustafsson and Krásný 1994). In addition to crystalline rocks investigated in this study, “hard rocks” include sedimentary, highly cemented and/or folded rocks (Krásný 1996a). Erratic fluctuations in macroscopic medium properties are known to exist on all scales (Neuman and Di Federico 2003), and attempts have been made to eliminate them with REV. The recent methodological development, reviewed by Neuman (2005), in their treatment limits the applicability of the REV concept.

As observed by Krásný (1996b) from results in the Bohemian Massif, individual transmissivity (and also permeability) values of hard rocks determined by pumping tests in drilled wells often vary over three or even four orders of magnitude, but regionally averaged transmissivity values usually do not differ very much in distinct types of hard rocks and in distinct areas. Superimposed upon this regional background are “inhomogeneity elements” such as fault zones or tectonically strongly affected zones or belts of regionally higher permeability along river valleys (Krásný 1996b). Based on his statistical study of aquifer test results, Krásný (1996b) concluded that the greater the size of the tested area or considered domain, the smaller the variability in test results of hydraulic conductivity or transmissivity caused by inhomogeneity elements of a certain size.

Based on an analysis of twelve fracture networks, ranging from 1 m to 30 km and mapped on different sites and scales, (Bossart *et al.* 2001) concluded that fracture networks at Äspö are not self-similar with regard to fracture geometry and mechanistic principles. Therefore a large-scale fracture network cannot be derived from a small-scale fracture network, for example for the purposes of modeling. This was inferred to result from the multi-phase deformation history. A higher degree of self-similarity would be expected for a more simply deformed area where, for example, only one brittle deformation phase has occurred. At Äspö the results also suggest a high structural and also hydraulic interconnectedness of fractures in a rock mass lying between major water-conducting faults. The small-scale fracture network outside fracture clusters is somewhat chaotic and patternless, whereas regional features are largely linear (Bossart *et al.* 2001). The fault geometries at Äspö differ on different scales; even fracture mineralizations and wallrock alterations indicate that most larger scale faults, have at least episodically been water-conducting although structural evidence in the form of gouges shows that all these structures have been reactivated only recently. The rocks in Oskarshamn, where Äspö is located, are mainly granitic, 1800–1850 Ma in age (Hammarström and Olsson 1996).

According to the review of Nieto-Samaniego *et al.* (2005) concerning the self-similar geometry of fracture arrays, quoting for example Cowie *et al.* (1995), direct observations, analog models and numerical simulations indicate that fracture linkage is a fundamental mechanism responsible for the scale invariance of fracture length distributions. Large fractures can accommodate more deformation and more efficiently than small ones. Findings from their analysis of photographs support the evolution of fracture systems to accommodate deformation in larger faults (Nieto-Samaniego *et al.* 2005).

3.4 Geophysical properties of fractures

The geophysical surveying techniques provide valuable information on features relevant to groundwater flow, particularly in mapping bedrock surface topography and complex underground geological structures. In his essay on the recent developments of borehole and surface-based geophysics in hydrogeology, Guérin (2005) considered scale and depth characterization as well as resolution as the key research and development focus area for future geophysics. As a part of Posiva's detailed investigation programme for the nuclear waste repository, borehole logging surveys have included the use of for example the following methods: magnetic susceptibility, natural gamma radiation, gamma-gamma density, single point resistance, Wenner-resistivity, borehole radar and full waveform sonic (Lahti and Heikkinen 2004).

The utilisation of aerogeophysics in the preliminary stage of hydrogeological investigations, as reviewed by Mattsson (2001), has resulted in important progress. In aeromagnetic data, plastic deformation and folding are generally marked by magnetic patterns which tend to be curved and continuous and stratigraphy-related, whereas brittle deformation results in discordant magnetic patterns. Changes such as hydrothermal alteration in deformed bedrock zones, which is commonly controlled by structural and tectonic features, can be detected using analysis of aeromagnetic data (Airo 2002).

Geophysical ground surveying is important for validating aerogeophysical anomalies and delineating groundwater exploration targets in more detail. The relevant theory is covered here more from the point of view of borehole logging application. A thorough review of geophysical techniques used in groundwater investigations was presented by for example Sporry (2004), and Meju (2002) reviewed the application of electrical and electromagnetic methods in, for example groundwater exploration. In Finland, earlier systematic treatments of geophysical methods for groundwater application and of geophysical properties of fracture zones include the work of Vesterinen *et al.* (1988) and Dammert and Väätäinen (1986), respectively.

Due to the fact that fracture zones contain water, clay minerals and dissolved ions, their resistivity is lower than that of the surrounding fresh rock (assuming that there are no sulphide- or graphite-bearing rocks). The practical indications of fracture zones depend on the width of the zone, masking formations (for example overburden) and the resolution of the method itself (Lanne *et al.* 2002). Seismic refraction sounding was applied for determining the depth to the bedrock surface and for choosing the sites for drilling when planning the course of the Päijänne Tunnel, but it also provided information about the quality of bedrock and of mineral soil as well as about the groundwater level (Niini 1967a, b and 1968a, b; Pokki 1969).

As noted by Paillet and Reese (2000), both lithologic and geophysical logs are limited in the sense that neither provides a direct estimate of the hydraulic properties of aquifer materials.

However, there are a number of benefits in using geophysical logging for the documenting lithologies and fracturing in the bedrock. With an expense that is small in comparison to the drilling costs, an amount of information which far exceeds that extractable from the core samples can be obtained. The logging techniques also determine the properties from a much larger volume than a drill core and a representative sample is often difficult to obtain. In addition, logging techniques can even be employed in old boreholes or wells, and measurements are repeatable, adjustable for accuracy. In addition, some of the techniques can be applied in wells with casing, with drilling mud or with a low groundwater level.

Geophysical borehole logging methods employed in hydrogeological investigations are well described with numerous examples in Keys (1997), and techniques with particular relevance to fractured rocks are referred to in for example Kobr *et al.* (1996) from the point of view of application in the Bohemian Massif in the Czech Republic which has been consolidated by the Variscan orogeny (320–280 Ma, Krasny 1997). Fractured aquifers in carbonate, igneous and metamorphic rocks are indicated for example on spontaneous potential logs by narrow and comparatively sharp negative anomaly produced mainly by electrokinetic potentials. Other possible indications include major or minor cavities on caliper logs or zones with a lower bulk density on formation density logs, owing to the presence of fractures and cracks filled with water. On formation resistivity logs fractured aquifers appear as conspicuous conductive zones in contrast to solid rock blocks showing relatively high resistivities ranging from one to tens of kΩ m (Kelly and Mares 1993). Cross-hole correlation studies and tomography with radar are means of tracing lithological units or continuation of fractures between different boreholes.

It is crucial to integrate the use of geophysical methods with other methods for assessment of fracturing in bedrock. Paillet and Reese (2000) emphasized that characterization of the hydraulic properties of heterogeneous aquifers needs to be an integrated and an iterative process. They considered it critical to aquifer characterization to integrate descriptions of lithologies and geophysical well logs for identifying the optimal locations for aquifer tests. Schürch and Buckley (2002) carried out an integrated geophysical and hydrochemical investigation (downhole and discharge samples) of four boreholes in the Chalk in the UK using geophysical borehole logs and optical imaging logs. They identified the combination of fluid and flowmeter logging and videoscan imaging of the borehole wall is a powerful technique for examining flow horizons.

Recently published Olkiluoto Site Report (Posiva Oy 2005) integrates geology, rock mechanics, hydrogeology and hydrogeochemistry, and describes the surface conditions in the site for a repository of spent nuclear fuel. The suitability of this location for a repository of spent fuel with high-level of radioactivity has been investigated by means of ground and airborne geophysical methods and from shallow and deep (300–1000 m) boreholes.

3.5 Significance of groundwater flow in fractured rock

The risk of groundwater inflow must be considered in the context of planning and construction of underground tunnels and caverns. Larger volumes of inflow increase the construction costs, and seepage into the excavation after construction causes problems in use, depending on its nature, and may eventually cause damage.

The Rock Engineering System of Hudson (1992) was applied by Ritola and Vuopio (2002) in analyzing factors influencing the water-tightness of underground excavations. The analysis involves a systematic assessment of interactions between different factors, both from the point of view of water-tightness and from that of managing the hydrogeological environment. The matrix of interactions demonstrates the various factors involved and the complexity of their interactions (Table 1). The lower row represents ways in which construction affects the rock mass. The cause-effect co-ordinates of each factor as calculated from the matrix content determine the factor's location in the Cause-Effect diagram presenting the intensity and dominance of the three rock mechanics

Table 1. RES matrix of interactions (applying Hudson's original system) between bedrock conditions and construction affecting the water-tightness of underground constructions (Ritola and Vuopio 2002).

rock structure P1	fractures affect the orientations and values of stresses	fracture network governs the secondary permeability	fracture orientation can influence the orientation or size of excavations
stresses can open and close fractures as well as create new ones	rock stress P2	high normal stress may decrease water permeability	high stress state can cause construction failures
flow of water washes away fracture fillings/changes fracture properties	water pressure decreases normal stress in/on fractures	water flow P3	large inflows make the excavation more difficult → grouting
excavation causes fracturing/opens old fractures	in the vicinity of excavations the principal stresses are altered	excavation below the groundwater table changes the flow conditions	construction P4

parameters (rock structure, *in situ* stress and water flow) as they relate to construction. According to the results for the general case, Construction (P4) is the factor most active via the interactions in the system describing the bedrock conditions. The Rock Structure (P1) influences the other factors most and, conversely, the other factors have only a small influence on the Bedrock structure itself. The Rock Stress (P2) and Water Flow (P3) are most prone to influences resulting from changes in the bedrock conditions.

4 Materials and methods

The methods applied in this study include interpretation of lineaments from topographical data and comparing them with a lineament interpretation based on aeromagnetic data, analysis of structures mapped in the tunnel, geophysical borehole logging, digital video surveying of borehole wall, fluid logging, groundwater inflow measurements, drawdowns of groundwater level in monitoring wells and information on tunnel deterioration as demonstrated by block falls. Existing methods were used, but combined and integrated in a novel way, demonstrating the innovative use of the GIS. Spatial analysis was used in Papers I–III and in Paper VI. Geophysical borehole logging was employed in Papers IV and V.

4.1 Spatial analysis

Technical and geological data from the extensive engineering-geological investigations for determining the course of the tunnel (Niini 1967b) were collected and converted into a GIS compatible format for spatial analysis as overlays using ArcView GIS software with the Spatial Analyst extension. In addition, the study utilized the largely unpublished technical reports on the planning and construction of the tunnel provided by the Helsinki Metropolitan Area Water Company (PSV), together with regional datasets. The latter were mainly from the Finnish Environmental Administration. The data, which are described in detail in Paper I, included the following: (1) rock types, structures and reinforcement details from inside the tunnel; (2) geophysical measurements, mainly refraction seismic sounding for extracting bedrock surface elevations; (3) drill logs for the thickness of overburden and for stratigraphy; (4) digital elevation model (25-m grid DEM, National Land Survey of Finland, NLS); (5) digital map of Quaternary deposits (scale 1:20 000, Geological Survey of Finland, GTK); (6) locations of measured groundwater inflow during construction and complementary information from the repair of the tunnel; and (7) groundwater areas, groundwater levels and drawdown of groundwater level. The use of technical tunnel data, as well as the distribution of inflows and block falls in the spatial analysis, are presented in Paper II.

4.2 Structural methods

Fractures and cleavage or foliation were measured inside the Päijänne Tunnel during its construction by GTK (Suominen 1979, and 1983; Laitakari and Pokki 1979) and during repair work of the northern part of the tunnel in 2001 by the consulting companies Soil and Water Ltd and Viatek Ltd. The aims of the mapping of fractures during the repair work were engineering-geological. The mapping was carried out somewhat irregularly in response to needs of repairing the tunnel or where the advancement of work allowed and therefore the data do not necessarily represent a continuous series of the tunnel sections. The analysis of structures from selected tunnel sections was made on spherical plots, distinguishing water-conducting ones when possible, and on rose diagrams. This facilitated comparison with structures observed on more general scales (Paper III). The theory on the construction of spherical plots applied in the presentation of the structural observations can be found in for example Billings (1972) or in Hobbs *et al.* (1976). The video recordings of fracture openness and frequency made by Ikävalko (2002) in drilled wells at the fuel spill site in Oitti were analysed.

4.3 Topographical methods

A superficial deposit relief map was developed by combining a digital elevation model (NLS) and a Quaternary geology map (GTK), using a method similar to that used by Palmu (1999) for tracing linear depressions indicative of fracture zones. Lineament tracing as a method has earlier been used for example by Mikkola and Niini (1968). The topography of the bedrock surface was reconstructed from seismic profiles and drill logs, and converted into a point coverage, and into grid files covering the areas, where the observation density was considered adequate for interpolating a continuous surface. This information on bedrock topography was mainly used for visual aid and for elaboration of the fracture zone interpretation. Data on the reinforcement as an indirect indication of weakness in the bedrock were visualized in GIS and used iteratively in the topography-based fracture zone interpretation (Lipponen 2001).

4.4 Groundwater inflow measurements during construction and repair of the Päijänne Tunnel

Groundwater inflow to the Päijänne tunnel per tunnel drive (mean length approximately 2.6 km) was measured both at the time of construction for the whole tunnel and during repair for the 12 northernmost pairs of tunnel drives extending over the tunnel section 58 900–120 000 m (Lipponen 2001). At the time of the construction, groundwater inflow into the tunnel was measured with a Thompson weir, located by the access tunnels at the lowest point of each drive. The values represent the situation when the tunnel was kept free of water by pumping and when resulting changes in hydraulic conditions may have affected flowpaths, depending on the amount of drawdown.

Uncertainties related to the inflow measurements have been discussed in Paper II. The volumes are potentially affected by for example drilling waters (estimated minor), water used for rinsing the tunnel walls, leaks from water mains and rainwater inflow along entry drives. Furthermore, the volumes are based on reports of the contractors.

4.5 Groundwater monitoring during construction and repair of the Päijänne Tunnel

The groundwater level observations were made in dedicated monitoring wells in general during the period from 1976 to 1993 for the southernmost 25.6 km. For the northernmost 35.2 km, monitoring observations started from 1973 and continued until 1993. The observed drawdowns indicate the quality of the hydraulic connection between the overburden and the tunnel. Groundwater level in private wells may also have been influenced by water use, whereas the monitoring wells are free from this uncertainty. Therefore, mainly monitoring wells were considered in this study. The changes in the groundwater level, when identified as temporally linked with the tunnel construction, were estimated from regression curves to the data points. The values of drawdown used for the statistical and spatial analyses are essentially the calculated differences of the groundwater level just before the emptying started and the lowest level of the main drawdown effect.

During the repair of the northern half of the tunnel in 2001, Soil and Water Ltd. monitored groundwater level initially in 102 wells and 93 monitoring wells in the tunnel zone (Öhberg 2002). A set of monitoring wells was selected where either an influence or non-influence was identified. The lowering of the groundwater level was generally estimated down to the lowest level of the main drawdown effect at the beginning of the emptying of the tunnel. The emptying started on August 27, 2001 and the northern part of the tunnel was kept empty of water for the duration of the repair. Altogether the pressure of the tunnel water was below normal for almost four months, including a period of approximately three weeks for both emptying and filling the tunnel. Compared with the construction the repair period was short, which must be taken into consideration when comparing the drawdown effects on groundwater. Potential correlation of the amount of drawdown was spatially analysed in relation to distance from the tunnel and to the occurrence of topographically interpreted fracture zones.

4.6 Geophysical methods

4.6.1 Aeromagnetic method

A lineament interpretation based on aeromagnetic data covering the zone of the Päijänne Tunnel by M-L. Airo was compared with the interpretation of topographic lineaments in Paper III, which also describes technical features of the data. Changes in the abundance and in the grain fabric of magnetic minerals as a result of hydrothermal alteration are reflected in the aeromagnetic signatures of altered rock units (Airo 2002). Faults were interpreted on the basis of dislocations, offsets, terminations or alignments of magnetic anomalies. Extremely weak magnetic lineaments with systematic trends, particularly observed in weakly magnetic units, were interpreted to be expressions of shallow structures and small scale fracturing.

4.6.2 Borehole measurements

Borehole geophysical measurements in two wells (HN3 and HN4) in Sorsakoski, in the Leppävirta municipality (Fig. 3), commissioned by the Finnish Environment Institute were carried out by Astrock Oy using Wellmac logging equipment of Malå Geoscience. A detailed description of the equipment can be found for example in Nilsson and Gustafsson (2003). The techniques included the following: resistivity (electrode configurations: Wenner and short-normal), spontaneus potential, single-point resistance, induced polarization (Wenner), magnetic susceptibility, gamma-gamma density, natural gamma, gamma-spectrum, caliper and borehole radar. Borehole radar assesses the properties of the rock mass, some other methods the borehole surface and some the actual water column (fluid logging). Filling, presence of water and compositional differences all affect the responses of the different methods to fracturing. Potential constraints for applying the methods include borehole properties such as diameter, surface, and presence of casing. The radar survey and fluid logging were carried out in wells HN3 and HN4 (Paper V), whereas the other measurements were carried out only in HN4. The gamma radiation survey is reported in Paper IV.

The different geophysical methods – more commonly applied in small-diameter research boreholes – were tested to the case of a large-diameter drilled well in order to obtain information about their applicability and potential constraints. The results of the measurements were compared with information on the lithologies and groundwater inflow, documented during the drilling. Samples from the coarsest fraction of the drill cuttings from selected depth intervals were analysed chemically and compared with the gamma log (Paper IV).

4.6.2.1 Borehole radar

The description of the radar method and of the results largely follow the presentation in Lipponen *et al.* (2004) in which technical details on the equipment set-up are also presented. Data processing, filtering for removing clear disturbance signals and reflector interpretation were performed by A. Julkunen (Astrock Oy). The field equipment used for storing the data was RAMAC GPR/BH manufactured by MalåGeoScience, Sweden.

In addition to reviewing the theory of the borehole radar method, Saksa *et al.* (2001) also tested the radar's functioning in indicating the properties of rock in comparison to borehole data. The applicability of borehole radar to mapping structures in bedrock is based on the identification of reflecting features in the rock mass. Electromagnetic radiowaves are reflected from contact surfaces where the resistivity of the rock or dielectric permittivity changes. Such surfaces may be represented by fracture groups, water-conducting structures or conducting minerals. The analysis of the positioning and characterizing of the reflecting surfaces is based on the principle of determining dielectricity and conductivity using attenuation and velocity. Reflection in a radar image can be caused by a fracture inside a structure. Therefore, the orientation of an individual reflector is not necessarily the same as that of the zone of weakness.The distance and general position of major structural features can still be obtained based on prominent reflectors in radar data.

The nominal frequency used in the survey was 100 MHz. Frequency affects the propagation, attenuation and reflection of electromagnetic radiowaves. In general, a wave propagates well in resistive bedrock, but in a conductive environment the radius of investigation is markedly smaller. The known distance of 30 m between the two wells surveyed in reflection mode, HN4 and HN3, in Leppävirta allowed the calculation of the average wave velocity in the rock mass for converting times to distances.

The interpretation is affected both by sensor technical and geometrical factors. The measuring system is cylinder symmetric. In interpreting reflectors, angles and intersections were calculated assuming planar geometry, from which deviations may occur. The interpretation, focused on planar reflectors, was experimentally made separately for reflectors within the near-field domain (<5 m from the wells) and for the far-field domain (dipole field, >5 m) with different dipole antenna fields (Lipponen *et al.* 2004).

4.6.2.2 Caliper

The **caliper** log measures the diameter of the borehole mechanically, providing information about for example open fracturing. Changes in borehole diameter may be related to both drilling technique and lithology. Caliper logs are useful for interpreting other logs, because most types of logs are affected by changes in well diameter (Keys 1997) .

The caliper probe of Astrock consists of three arms, one of which was used in the measurement. The resolution of the probe is approximately 0.2 mm and depends on the position of the arms. The probe was calibrated before and after measurement with calibration jigs of known diameter.

4.6.2.3 Magnetic susceptibility

Magnetic susceptibility, indicating the degree to which the mineral particles can be magnetized, reflects the mineral composition of the rock and the concentration of magnetic minerals (that is, mainly magnetite or magnetic pyrrhotite in Precambrian terrains) (Airo 1995). The magnetic minerals present carry both induced and remanent magnetization. The former is a temporary effect, acquired by a susceptible material when located in a magnetic field, and the latter a permanent setting of for example the magnetic fabric of a rock acquired upon formation or re-heating during metamorphism. Remanent magnetism can also be related to the formation of new magnetic mineral or existing minerals can be altered, broken etc. (Airo and Loukola-Ruskeeniemi 2004). The proportions of induced and remanent components can only be determined by petrophysical laboratory measurements (Sporry 2004).

The calibration of the susceptibility probe was carried out using calibration pads of known magnetic susceptibility. Adjustment of the base level was performed manually using other borehole and laboratory measurements made for comparable rock types as a reference. The base level of the measurement result may be somewhat higher than in reality, but approximately 1000 µSI was chosen by Astrock as the base level. The volume of investigation in the measurement of magnetic susceptibility is approximately 5–10 cm in rock.

Density, magnetic susceptibility and intensity of remanent magnetization for hand samples of rocks (J. Klockars) from the Sorsakoski area, measured by the Geophysical Laboratories of GTK, was compared with the susceptibility measured in the borehole.

4.6.2.4 Electric logs

All electrical methods are based on the ability of minerals and rock to conduct electricity. As the probes must be in electrical contact with the surrounding rock formation, electrical methods cannot be run in empty boreholes, boreholes with nonconductive mud or boreholes with casing. (e.g. Nilsson and Gustafsson 2003).

Spontaneous potential (SP) is a record of potentials or voltages that develop at the contacts between dissimilar rock types where they are penetrated by a drill hole. It is a function of the chemical activities of fluids in the borehole and adjacent rocks, the temperature, and the type and amount of clay present; it is not directly related to porosity and permeability. Rapid oscillations in the log commonly indicate depth intervals at which water is moving in or out of the well (Keys 1997). Any change in the salinity of the borehole fluid or of the formation water will cause a change in the SP log which is largely a function of their relation. An increase in borehole diameter or depth of invasion decreases the magnitude of the SP recorded (Keys 1997).

Single-point-resistance logs that measure the resistance between two electrodes, in ohms, cannot be used for quantitative interpretation, but they provide information on lithology (Keys 1997). The equipment of Astrock measured the resistance between the electrode in the well and an electrode at the surface. Effective porosity and fluid salinity have a much greater effect on resistance or resistivity than does mineralogy, even if some conductive minerals are present, and surface conduction on clay can contribute to current flow in most rocks (Keys and MacCary 1985). Hellä *et al.* (2004) used **single point resistance** measurements as supportive information to choose the most probable fractures to conduct the flow. Single-point resistance logs are known to be greatly affected by changes in borehole diameter, partly because of the relatively small volume of investigation and the effect of surrounding water. The effect of a larger diameter is a decrease in apparent resistance (Keys and MacCary 1985).

Resistivity measurement with the **Wenner**

electrode array gives apparent resistivity from the surrounding rock. The volume of investigation in the resistivity measurements is a few tens of centimetres. Essentially with increasing electrode spacing, a greater volume of investigation is achieved. For the **short-normal** resistivity device used by Astrock the electrode spacing was 41 cm. The measurement of resistivity with normal configuration is less sensitive to variations in fluid resistivity than with Wenner, which is why it is commonly used under conditions with high concentrations of dissolved solids (Poikonen 1983). As the response of resistivity logs is related to effective porosity (e.g. Kukkonen et al. 1992, Keys 1997), increased porosity through fracturing is probably associated with negative anomalies in the resistivity logs.

The principle of **induced polarization** (IP) is based on running a current into the ground and switching it off, and then observing the decaying potential difference after the moment of current switch-off. When the current is switched off, the bound ionic charge does not immediately disappear, but decreases in time due to diffusion back into the pore water. The electrode polarisation is generally the strongest effect and is particularly generated by sulphidic minerals. However, the membrane polarization is particularly generated by clay particles and is therefore useful in groundwater investigations. A qualitative evaluation of IP data will reveal the presence of conductive faults or fracture zones, which may contain groundwater (Sporry 2004). The electrode configuration used by Astrock in the measurement was the Wenner configuration.

4.6.2.5 Nuclear logs

In the gamma-gamma **density** measurement, the *in situ* density is determined by the radiation from a gamma source in the probe, after it has been attenuated and backscattered in the borehole and surrounding rocks (Keys 1997). The volume of investigation in the measurement is approximately 10–30 cm. As the calibration was made for rock, large variations result from open fractures where much less dense water displaces rock.

Two **gamma** logging methods were used: 1) ordinary natural gamma and 2) total gamma count to the energy window 0.4–3 MeV used by the spectrometer. Natural gamma radiation mainly reflects the uranium, thorium and potassium contents of the rock. Reported examples on the use of borehole gamma measurement include distinguishing granites of different radioactivity (Kobr *et al.* 1996). The equipment, the extent of the measurement and the data processing involving a correction of count rates with equations is described in detail in Paper IV.

4.7 Fluid logging

Fluid conductivity (the reciprocal of fluid resistivity) or resistivity logs are records of the capacity of the borehole fluid that enters the probe to transmit electric current. These logs provide data related to the concentration of dissolved solids and movement within the fluid column (e.g. Keys 1997).

In addition to the measurements using Wellmac, temperature and electrical conductivity measurements were carried out with a multi-parameter probe (MiniSonde, series 4 by Hydrolab) and a conductivity-T probe (YSI Model 3000 Temperature-Level-Conductivity Meter). The multiparameter probe was also used to measure oxygen, oxygen saturation percentage, depth, pH and chloride (Cl^-) concentration. More details on the fluid logging methods are provided in Paper V. The conductivity-T probe was also used in well KP5 in Oitti and the fluid conductivity log was compared with information on fracturing in the well obtained from a borehole video recording.

4.8 Borehole video surveying

A survey of wells KP2-KP7 in the Oitti site using a digital videocamera was assigned by the Golder Associates Oy to O. Ikävalko (Kivikonsultit Oy) to investigate engineering-geological properties of the rock at the site. These data on the nature and frequency of fracturing were compared with (1) measured dips of fractures and foliation in the tunnel and with (2) local lineament trends assessed from the topography. Interpretation of depth of fractures, their relative steepness (when available) and characteristics from borehole video recordings was performed by O. Ikävalko and complemented by J. Klockars.

The depth of the features was determined from a measuring tape attached to the video camera. The camera recorded the structures with a camera of 40 mm from a very short distance and hence in great detail. The camera captured via a mirror a 33° sector of the borehole wall measuring approximately 3 x 4 cm in a 140 mm borehole (Nyberg 2003).

Ideally the depth, dip of fracture as well as its quality (for example open vs. closed, presence of filling) can be estimated from a borehole video recording. Also information on lithologies, rock quality, cleavage/foliation, zones of weakness, fracturing and weathering can be obtained. However, the level of information is subject to the image quality, clarity of water, etc. The uneven rotary-drilled surface of wells possibly affected the quality of the image. Palmen (2003) applied digital optical imaging of borehole wall in determining foliation type and intensity as well as in mapping rock types.

In order to determine accurately the dip direction, the upper or lower flexion of the fracture should be visible. Based on the curvature of the line of intersection, it may be possible to determine with relatively good precision the location and direction of the flexion point. For determining the angle of intersection, the distance between the upper and lower flexion is required as well as the diameter of the borehole. As such information was commonly incomplete, the accuracy of the estimated angles is limited. Due to the small picture area (3 x 4 cm), the bending point of a fracture is not necessarily recognized as such and the fracture can be interpreted as horizontal. Due to the previously mentioned factors, only main groupings of relative steepness were considered appropriate to analyse and present.

4.9 Vulnerability assessment

Vulnerability of groundwater is a relative, nonmeasurable, dimensionless property that is used in **groundwater protection**. The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against natural and human impacts, especially contamination. Vulnerability is an intrinsic (or natural) property of a groundwater system that depends on the sensitivity and/or ability of that system to cope with human and natural impacts. Groundwater vulnerability is commonly assessed using the following variables: net recharge, soil property, unsaturated zone lithology and thickness, groundwater level below ground, aquifer media, aquifer hydraulic conductivity and topography. A comprehensive discussion of the concept and its presentation is provided by Vrba and Zaporozec (Vrba *et al.* 1994), and a review of the recent developments of assessment methodology is given in Witkowski (2004). The GIS have been used for developing groundwater vulnerability maps by, for example, Barrocu and Biallo (1993) and Hrkal (2001).

Relevant datasets for assessing vulnerability of the Päijänne Tunnel were reviewed and their application was demonstrated Paper I. Different options for taking into account the observed hydrogeological heterogeneity in assessing vulnerability are considered in Paper VI.

5 Review of papers

Paper I

The use of GIS for assessing the occurrence of cross-cutting fracture zones as potential pathways for contaminant transport into the largely rock-surfaced Päijänne Tunnel is demonstrated in Paper I. The paper presents the method for analysing factors governing groundwater inflow into a tunnel including the following: fracturing and its continuation, topography, the distribution and types of superficial deposits, difference between the pressure level in the tunnel and the groundwater level in the environment.

The study combined geological and geotechnical information as well as environmental datasets as overlays for spatial analysis in GIS. The superficial deposits relief map developed by combining a digital elevation model and a digital soil map formed the basis for tracing topographic lineaments indicative of fracture zones. Although the coverage of seismic profiles and drill logs is nonuniform, in areas of high observation point density, approximate interpolations of the bedrock surface were made also taking into account the elevation data from bedrock outcrops.

Inferred area of influence of the tunnel was considered based on individual observations on drawdown of the groundwater level during the construction of the tunnel from 1973 to 1982, as well as on topography and the extent of superficial deposits. Risks to the tunnel from the infrastructure and the identified risk activities in the tunnel zone were assessed in qualitative terms using the spatial relationships with hydrogeological features.

Paper II

The distribution of block falls inside the Päijänne Tunnel was compared with both measured and semi-quantitatively documented groundwater inflow and characteristics of fracture zones intersecting the tunnel (Paper II). GIS was used to analyse the distances and spatial correlations between the locations of blockfalls, of inflows and the interpreted fracture zones. The relationships were analysed in order to test whether the factors appear to have been influencial in triggering damage. The results showed that the rate of inflow appears to correlate to some degree positively with the level of reinforcement, both being connected with fracturing in the bedrock. Several individual sections in which many falls of large blocks had occurred, all showed groundwater inflows, foliation strike sub-parallel to the tunnel and occurrence of block falls outside the heavily supported sections. The variability in the observed correlations demonstrated that a number of factors contributed to the occurrence of damage.

Fracture zones appearing as linear depressions in topography are potentially difficult from the rock support or groundwater inflow management points of view and should be taken into account in planning underground constructions. Horizontal and gently-dipping fractures can significantly contribute to inflow, was inferred in the case of some mainly granitic sections of the Päijänne Tunnel, and may be difficult to identify and locate.

The hydraulic properties of fracture zones were inferred to contribute to the deterioration in the tunnel, as with difficulty quantifiable but probably as a relatively minor factor compared with the rock support solutions and structural orientation sub-parallel to tunnel. Orienting a tunnel sub-parallel to foliation should be avoided when possible, as in the case of the Päijänne Tunnel it seems to be linked to the occurrence of large block falls. On the basis of the observed variation in inflow when linked to the strike of the fracture zone, it was inferred that the orientation of fractures also plays a role in the distribution of hydraulic activity.

Paper III

As presented in Paper III, documented observations on fracturing and groundwater inflow from inside the Päijänne Tunnel provide subsurface information on the fractures and their hydraulic properties. Regional and local-scale lineaments indicative of fracture zones determined from aeromagnetic and topographic data, respectively, were compared to tunnel scale structural characteristics in the Päijänne Tunnel. In general, there is considerable agreement between the trends identified with the topographic and aeromagnetic methods. They complement each other, especially in areas where either one is of limited applicability. For example, aeromagnetic data is useful for recognizing regional trends of structures, in particular where a thick overburden covers the bedrock or where the topography is relatively flat. In areas of poor magnetic contrast, topography may reveal bedrock structures more clearly than the magnetic method. The regional magnetic trends serve as an indicator for local scale investigations of fracturing. Based on the aeromagnetic interpretation, bedrock fractures intersecting the tunnel are part of a regional fracture network and their evolution can be connected to the main tectonic stages in southern Finland. The distribution of bedrock fractures is lithologically controlled and reflects the rock type and its structure. On more detailed scales, a superficial deposit relief map is a powerful tool for more accurate location of fracture zones and for evaluating their connection to superficial deposits which are more substantial groundwater reservoirs. Depending on the scale, integrated interpretation using both topographic and aeromagnetic data gives the best results, particularly when supported by independent verification such as the observed fracturing inside the tunnel.

Many of the locations where water-conducting fracturing occurs, or where groundwater inflow has been measured, were associated with intersecting or individual topographically interpreted fracture zones, especially NW-SE trending zones. In the magnetic data, the NW-SE orientation was displayed as (1) swarms of short, faint signatures indicating brittle, shallow features and (2) extended, broad, linear magnetic gradients denoting block boundaries. The observed coincidence and the parallel orientation of these two magnetic features of different scales suggest their evolutionary relationship: the faulted block boundaries were reactivated at later tectonic stages, resulting in brittle fracturing along the same, old structural weakness zones.

Paper IV

The purpose of the study presented in Paper IV was to assess the applicability of gamma measurements to investigating radioactivity and lithology in a large-diameter (160 mm) drilled well HN4 in Leppävirta. The wells in the vicinity have elevated radon (^{222}Rn) concentrations, up to 900–2900 Bq/L (Klockars 2003).

Potential limitations to applying gamma spectrometry for quantitative analysis include disequilibrium in the uranium decay series, abundance of energy peaks, degradation of photon energy and geometry of the measuring instrumentation and well constructions (Keys and MacCary 1985). In Paper IV, the results of the measurement were compared with the drill cutting samples, and potential constraints arising from the well geometry, dimensions and construction were evaluated. Natural gamma and gamma spectrometer logging of well HN4 demonstrated the usefulness of the methods in distinguishing between the local rock types granite and mica gneiss, and detecting changes in soil even through iron casing. This is particularly useful because such information from rotary percussion drilling is limited. The method was also sensitive to alteration related to fracturing that involves mobilisation of radioactive elements. An anomalous zone with the main uranium and thorium peaks was detected close to the bottom of the well. Due to the large diameter of the well, a layer of water between the detector and borehole wall caused attenuation of gamma radiation. The calculated relative contributions of potassium, uranium and thorium to the total gamma count provide mainly qualitative information on the variation of radiation.

The benefits of carrying out gamma logging in a borehole include a greater volume of rock, compared with studying a core sample or recording by a digital borehole video camera. The results from the gamma-spectral logging of HN4 showed that the granitic rock unit at the depth of 52–68 m is the type with a higher uranium concentration and hence with more potential for emitting radon to groundwater. The concentrations indicated by the gamma spectrum log are not absolute and calibration for the actual borehole diameter would help to account for the attenuation, which is probably less than the calculated maximum attenuation in the order of 20–40%. Commonly, it is more important to obtain information on the variations and to distinguish between rock types than to know the absolute concentrations of radioactive elements. The fact that the natural gamma log suggests less lithological variation than the drill log demonstrates the usefulness of the method for distinguishing visually not very distinct rock types and in conditions where information from the rotary drilling method used is limited.

Paper V

The results of fluid electric conductivity and temperature (T) measurements were assessed by (1) a conductivity- T probe, (2) a multi-parameter probe and (3) a geophysical logging system in reflecting the hydrogeological environment. The aspects considered in Paper V include both the level of information delivered by the different methods and the differences of the hydrogeological environments in a well with a sufficient yield for water supply (HN4) and a low yield drilled well (HN3) in Sorsakoski, Leppävirta municipality. The results were evaluated to assess any differences in the extractable information by the different methods.

A slight increase in T as a function of depth in well HN3 was captured by all the methods. The more dynamic conditions in the higher-yield well (HN4) stand out in, for example the fluid conductivity logs as interrupted, less consistent increase in fluid conductivity as a function of depth. Furthermore, the paper identified as potential challenges in the application of specialized geophysical logging the appropriate calibration for and sensitivity to the parameters, and discussed constraints arising from the well dimensions. Relative variation within a well and between wells can be measured with greater certainty than absolute values. For quantitative measurements, cross-validation by another method is recommended.

On the basis of the results, it was concluded that even the common conductivity-T probes can deliver indications of differing groundwater flow conditions in the wells. Measurement of ionic parameters can extend knowledge of groundwater conditions, but independent verification from analysis should be used for proofing, preferably by sampling at different depths because a pumped mixed sample from the well only represents an average chemical signature weighted according to the transmissivity of the water-producing zones. Borehole geophysical parameters that provide information on rock mass properties such as fracturing may complement surveying with probes explicitly detecting changes in the water column, and are also rather insensitive to seasonal changes.

Paper VI

The observed heterogeneity in the occurrence of superficial deposits, in fracturing in the rock mass and in hydraulic activity in the zone of the Päijänne Tunnel were used in Paper VI to recommend alternatives for (1) focusing an assessment of vulnerability and eventual protective measures; and (2) delineating the recommended zone of caution for protection of tunnel water. Central criteria in identifying vulnerable locations are the spatial distribution of interlinked highly localized groundwater inflows measured inside the tunnel and the iteratively interpreted fracture zones. Among the relevant considerations for assessing risk are the large volume of flow in the tunnel, the irregular distribution of potentially hazardous human activities, and the interplay of natural and human-influenced factors, that is, the effect of the tunnel's use on groundwater conditions.

To improve groundwater vulnerability assessments for formations or systems involving fractured aquifers or risks to water conveyance tunnels, crucial aspects can be given more weight, for example in the following ways: (1) linking the observed variation in inflow into the study, that is, focusing on the hydraulically active zones where it is more likely that a contaminant could get transported into the tunnel; (2) defining the extent of permeable superficial deposits, that is, vulnerability in the overburden focusing on the preventive action, emphasizing immediate risk; (3) describing in more detail the areas with existing risk activities, abundant infrastructure, and more densely populated areas with industrial or residential land-use; and (4) using the occurrence of fracture zones in the bedrock as indicators of potential pathways for contaminant transport. These factors could be incorporated in determining the geometry or introducing a weighting to vulnerability zoning.

6 Additional results

6.1 Hydrogeology in the Oitti fuel spill site

MTBE was found in 2001 in samples of groundwater inflow to the empty northern part of the Päijänne Tunnel, at metre readings 60 930 (102 µg/L MTBE), 61 120 (925 µg/L) and 61 210 (120 µg/L). The latter two samples also contained tert-amyl-methyl ether (TAME), 30.00 and 1.56 µg/L, respectively. These sites lie NE and ESE from the spill site (Fig. 6a), which demonstrates a flow and contaminant transport connection through fractures in bedrock, over a distance of approximately 170 m horizontally and at least 70 m vertically in rock, down to the level of the tunnel at approximately 15 m.a.s.l. Well KP7 (Fig. 6a), where MTBE was also detected, is located approximately 10 metres from the line of the Päijänne Tunnel horizontally. At km-metre reading 61, the tunnel runs quite deep at a depth of 95 m below ground surface.

Immediately after the remediation of the soil (change of the soil mass in January 2004), elevated concentrations of MTBE were still detected in wells KP1, KP6 and KP7, but not after March 2004. Wells KP1 and KP6 are located close to the contamination source and KP7 is in the direction of groundwater flow (J. Lintu, pers. comm. 2005).

The bedrock in Oitti is predominantly granite (Suominen 1979). Close to the km-reading 60 which is in the vicinity of the spill site (Fig. 6a), bedrock is fractured. In the depression of the fracture zone, the thickness of overburden is 14–33 m, and at its thickest there is even 15 m of clay. At around the km-reading 61, the bedrock is also fractured. Sorted water-conducting soil types from the north-west extend to the vicinity (Lipponen 2001). The general stratigraphy of the spill site is as follows: On top, there are 1–2 metres of sand and underneath it there are 3–4 metres of clay. Below the clay, there are 4–5 metres of fine sand and below that more than 5 metres of mixed sand and gravel. The bottommost layer on the bedrock surface is gravel (Lintu 2002).

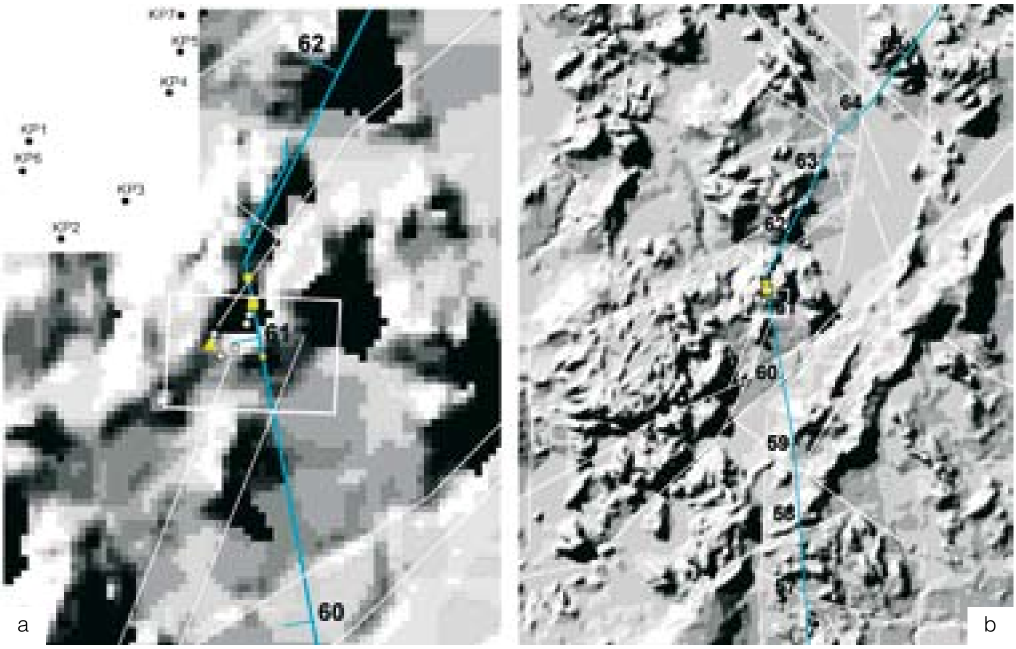

Fig. 6. (a) Plane view of the Oitti fuel spill site (yellow triangle) and the immediate surroundings. The km-readings of the tunnel (blue line) indicate the scale. The white rectangle shows the extent of the 3-D section in Fig.7. The yellow squares indicate the sites where MTBE was detected in samples of groundwater inflow into the Päijänne Tunnel (the size of the symbol is in proportion to the concentration of MTBE, see the text). The relative locations of wells (circles) are indicated in the upper left corner. (b) Areal view of the surroundings of Oitti, showing the local topographic lineament orientations (white lines). The topographic interpretation was extended only a few kilometres from the tunnel at most.

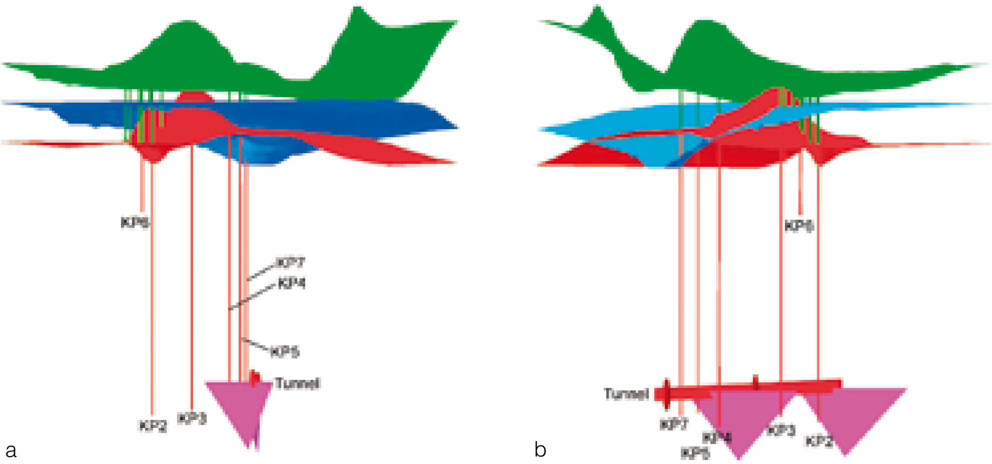

Fig. 7. A 3-D view of the Oitti fuel spill site (a) along the Päijänne tunnel facing north and (b) facing south-east, showing the land surface (green, interpolated by triangulation from a digital elevation model of the National Land Survey), groundwater surface in 2002 (blue, modelled by Golder Associates Oy) and estimated bedrock surface (red) interpolated by the natural neighbor method using bedrock surface elevations of drilling sites using GMS 3.0. software (S. Tuominen). Pink triangular planes represent cleavage measured in the tunnel. The red cylinders indicate the locations in the tunnel where MTBE was detected in groundwater samples. Five-fold vertical exaggeration. The diameter of wells is not to scale. In plane view, the locations of wells and samples are indicated in Fig. 6a.

6.1.1 Regional fracture trends vs. orientation of fractures in wells

In parts of the Oitti topography, the terrain is low-lying and clay-covered, which limits the accuracy of determination of trends in topographical lineaments commonly indicative of fracture zones. However, several regional sets of lineaments indicative of fracture zones can be identified (Fig. 6b). One strikes NW-SE and another NE-SW, the prominence of which may be due to the parallel cleavage. NE-SW is the predominant cleavage strike along the tunnel section shown in Fig. 6a. The third regional-scale pattern strikes N-S at the surface and may be due to or linked with the cleavage orientation which is close to a km-reading of 61 in the tunnel turns almost N-S.

When the dip orientations of structures measured in the tunnel are divided into classes of ten degrees and compared in a rose diagram (Fig. 8), it can be seen that the fracture orientations show three distinct dip directions: NW, SW and NE. Few N-S fractures are known to have been documented in this section of the tunnel. The depth of measurements made in the tunnel (from metre reading 60 000 to 61 700) ranges from approximately 65 to approximately 95 m below the ground surface (Lipponen 2001). Variation in the relative steepness of fracture dips in each drilled well in different depth ranges are presented in Table 2. The fractures observed in the boreholes lie mostly at relatively small angles. In Oitti, granite is the dominant rock type which typically develops prominent surface-parallel fracturing.

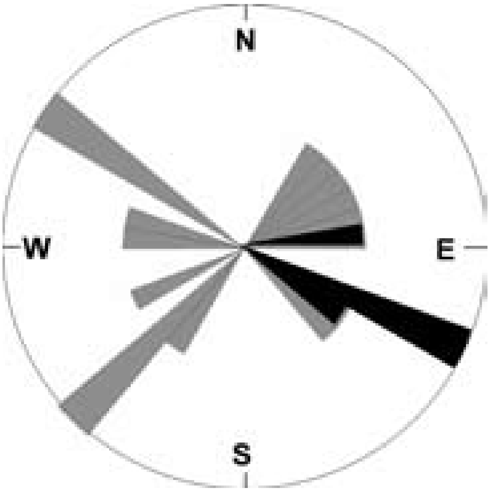

Fig. 8. Rose diagram of dip directions of geological structures detected in the tunnel section in the vicinity of the Oitti site. Black – cleavage (n=4), grey – fractures (n=17).

In both the ground surface topography and bedrock surface elevation, boreholes KP4, KP5 and KP7 lie low (Fig. 6a), the location in a topographic depression possibly suggesting more fractured bedrock. However, on the basis of the borehole video interpretation, the bedrock in KP4 is only sparsely fractured. In KP3, KP5 and KP7, open fracturing is

Table 2. Relative steepness of dip in drilled wells in the Oitti site, interpreted from borehole video recordings. If no depth range is indicated in parentheses, the orientation was observed to occur through out the borehole. In well KP1, there was only one open fracture. The locations of the wells are shown in Fig. 6a.

well	diameter (mm)	well depth (m)	dip angles
KP1	140	25.9	moderate
KP2	140	98.8	gently-dipping
KP3	140	98.9	Horizontal (11 m); gently-dipping (>50 m); moderate (<40 m)
KP4	140	98.8	moderate
KP5	63	94.0	moderate (20 m, 95 m); gently-dipping (<30 m); steep (<40 m)
KP6	140	40.8	moderate
KP7	64	96.1	gently-dipping -moderate; moderate (>/=65 m)

most abundant. When compared with the steepness of fractures interpreted from the borehole videos, the fractures measured in the tunnel are steeper-dipping at a mean angle of 70 degrees.

The fractures in KP5 are steeper-dipping than, for example, in KP2 (Table 2). The few open fractures in KP2 are gently-dipping. Both open and closed fractures in KP3 are gently-dipping. In KP7, the fractures generally dip at moderate angles. The detected fractures in KP7 are mainly open and only two closed structures were documented. In general, relatively few closed fractures were observed. It is possible that closed fractures more easily disappear among patterns caused by changes in mineralogy, scours, other structures and striations possibly caused by the drilling. The borehole image was at times blurry but, in general, it was of sufficient quality for the interpretation. For a part of the recording in well KP4, interpretation could not be made due to staining of either lense or mirror.

The most open fracturing appeared to be in boreholes KP3, KP5 and KP7. On the other hand, boreholes KP1 and KP6 are the shortest, and consequently there was less video recording.

The locations, where MTBE was detected in groundwater in the tunnel level, lie NE and ESE from the source. As the groundwater flow direction is towards NE, lateral transport may have occurred in the overburden and near-vertical transport may have occurred from above the tunnel. But as the data indicates, there are NE-SW striking fractures that may contribute to the flow paths as well as the NW-SE trending fractures. Or even intersections of NE and SE dipping structures could result in occurrence of linear features with an eastward dip that might play a role in the transport. The data presented here leaves many possible routes of flow and transport open and further investigations would be required to identify the pathways.

6.1.2 Electric conductivity and the frequency of fracturing in well KP5

The conductivity log of well KP5 (Fig. 9) demonstrates the following features. When compared with information on the number of fractures per metre, it can be observed that kinks (that is, changes in the fluid conductivity log) at the depths of, for example 20.0 m, 33.5 and 43.5 m, correspond with one-metre sections where there was either no fracturing or a single fracture observed in the borehole video data. The zone between the depths of 26 and 29.5 m demonstrates very uniformly conductivity values from 392 to 396 µS/cm (values temperature-corrected to 25°C), and appears – apart from the central part – abundantly fractured. At highest, up to 20 fractures per metre were interpreted from the borehole video data. It seems likely that some inflow and mixing or vertical flow is taking place in this part of the well. The factors that potentially affect the result of the conductivity measurement with a conductivity-T probe are discussed in, for example Paper V, in which measurements in Leppävirta were carried out by the same method.

Based on the number of fractures per metre from the borehole video data, plotted in Fig. 9, fracturing appears somewhat (but not significantly) more abundant in the upper part of the well. The number of fractures estimated by O. Ikävalko (2002) as open or probably water-conducting is clearly higher in the superficial part of the bedrock traversed by the borehole. Interestingly, these open fractures apparently do not necessarily fall into sections that seem to have the highest fracture frequencies.

6.2 Groundwater inflow into the Päijänne Tunnel: geological factors

When the total groundwater inflow rates measured per tunnel drive of the northern part of the tunnel (58 900–120 000 m) from the time of tunnel construction are compared with those measured during the repair in 2001 (Lipponen 2001), an overall decrease of 1.9 L/(min 100 m) or approximately 18 percent appears to have occurred, even though the values from the construction period do not include rainwater inflow along the entry drives. Of the monitoring wells along the northern part of the tunnel for which measured drawdown was available both from the time of construction and repair (n=16), drawdown was greater during repair only in one case. In the others, the drawdown during repair was less than 50 percent compared with that during construction on average. This may be influenced by the fact that the period over which the pressure of the tunnel water was below normal due to the repair was relatively short (almost four months, inclusive of three weeks for both emptying and filling the tunnel) compared with that needed for the construction. During the repair the groundwater storage therefore may have drained

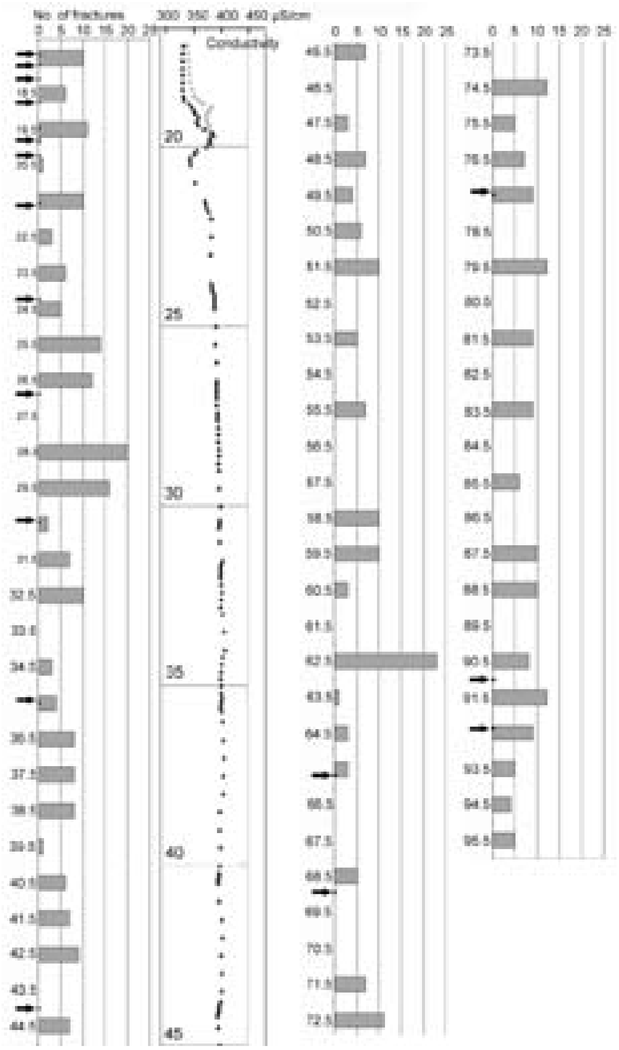

Fig. 9. The conductivity log measured in well KP5 in Oitti, shown against the number of fractures per one metre section (horizontal columns), interpreted by O. Ikävalko (2002) from a borehole video recording. Notably the fractures classified as open or probably water conducting (black arrows), more abundant in the superficial part, do not necessarily coincide with concentrations of fractures.

less. Precipitation of minerals in fractures or rock stresses may also have contributed to the decrease of inflow. However, the water use in the tunnel operations and the measurement technologies also involve uncertainties.

When the tunnel sections are grouped according to the dominant rock type (Table 4), no significant differences in the inflow are observed. Figure 10 highlights the wide range of values of more abundant measured inflows. These are clearly elevated compared to the average inflow rates into the tunnel sections and they have been identified as clear rises on the cumulative inflow measurement curves. These more abundant flows, identified from the cumulative inflow curves, were commonly observed to occur over relatively short distances. The differences between the groups are not distinct. Based on this coarse assessment on this scale, the rock type appears to have no influence on the volume of inflow.

Table 4. Thirty-four sections of the Päijänne Tunnel, each approximately 2.6 km in length (12 of the sections are double, having a northern and a southern drive), classified according to the dominant rock type and related inflow statistics. The rock types have been determined from the generalized 1:1 000 000 digital map of the GTK (Korsman *et al.* 1997).

dominant rock type in the section	mean inflow (L min^{-1} 100 m^{-1})	standard deviation	median inflow	min	max	n
granite (gn)	13.8	8.1	12.0	3	32	18
felsic metasediments or metavolcanics	14.9	8.9	14.5	1	31	10
mafic or intermediate volcanics	10.0					1
phyllites or schists (schist)	12.5	3.8	11.0	10	18	4
dominantly intermediate plutonic rocks (ign)	21.0					1

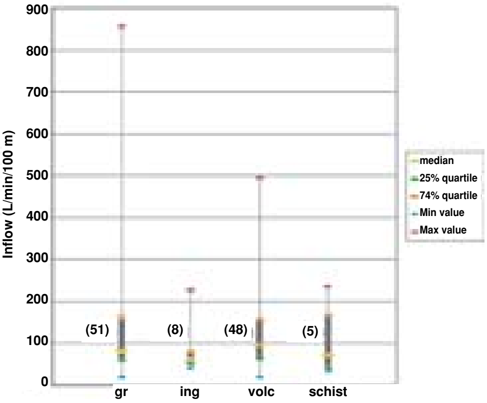

Fig. 10. Measured groundwater inflows (n=112) grouped by rock type (dominant from 1:1 000 000 digital map of the GTK (Korsman et al. 1997) at the mid-point of each inflow) at the locations of measured groundwater inflows. The class "volcanics" (volc) includes both felsic metasediments and metavolcanics as well as mafic and intermediate volcanics. For a key to the other rock types, see Table 4.

6.3 Results from groundwater monitoring during emptying of the tunnel

The response of the groundwater level to the pressure decrease in the tunnel upon emptying reflects the quality of the hydraulic connection. The response is likely to be affected by distance from the tunnel, by the soil at the level of the well screen and at the interface of bedrock, and by the distribution of fracturing in the rock. In the assessment of monitoring results, the lowering of the groundwater level had to be at least 0.1 m and meaningfully temporally linked to the tunnel operation, in order for the well or monitoring well to be classified as affected. This threshold value is mainly applicable to monitoring wells that were not affected by water use. The drawdown values were noted in general to be lower than those estimated by Soil and Water Ltd that carried out the monitoring. This probably results from the fact the company used the long-term average level of groundwater level as reference level in an attempt to reflect the overall impact and to avoid including seasonal influence. In this study, the immediate response to the decrease of pressure was of more interest. For these reasons, the values of drawdown considered here are not representative of any possible influence that occurred for the duration of the repair operation and in general the groundwater level recovered after the filling of the tunnel (Öhberg 2002). The only monitoring well drilled into bedrock in the sample was not included in the scatter plots, because it was not considered fully comparable to dug wells in terms of response. The drawdown in this drilled well, located approximately 70 m from the tunnel, amounted to seven metres. The majority of the observed drawdowns (41 out of 51, that is, 80%) in wells was less than a metre. In 21 out of 51 wells the drawdown was ≤ 0.5 m.

The dynamics of emptying the tunnel for repair partly determined the response of the groundwater level in the monitoring wells. In the beginning of emptying the northern part of the tunnel, the two-day gravitational pressure drop decreased the pressure, not uniformly to any set level. Once the pumping was initiated with a series of pumps, lasting more than 3 weeks, the water level decreased gradually and uniformly.

From the monitoring wells surveyed during the repair in 48 monitoring wells, a drawdown was observed. The average drawdown was 0.4 m. The mean head in comparison to the pressure level in

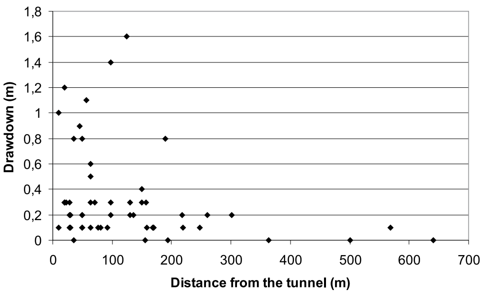

Fig. 11. The drawdown observed in monitoring wells (n=54, including six monitoring wells with no drawdown observed) during emptying of the Päijänne Tunnel in 2001 versus distance from the tunnel.

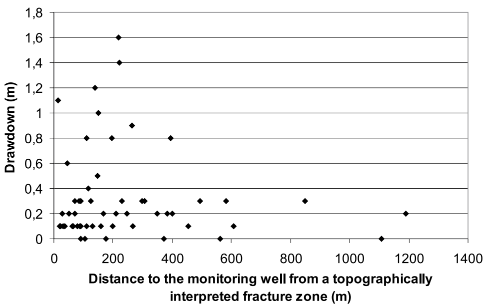

Fig. 12. The drawdown observed in monitoring wells (n=54, including six monitoring wells with no drawdown observed) during emptying of the Päijänne Tunnel in 2001 versus distance from topographically interpreted fracture zones

the tunnel is 20.4 m when the tunnel is in use that is when the pressure level of the tunnel is +42 south or +78 m.a.s.l. north of the Kalliomäki pumping station (located 56.2 km N from southern end of the tunnel).

The observed changes in the groundwater level have to be viewed against the background of hydrological events. In August 2001, it rained relatively little in the Häme region that the tunnel traverses, and typically for the season, the groundwater levels decreased. In September the groundwater levels mainly remained low, even though in Pirkanmaa it rained more than usual (Finnish Environment Institute 2005). The groundwater table decreased at the four groundwater monitoring stations of the Environmental Administration located in the area (Siuntio, Karkkila, Orimattila and Tullinkangas) from June until October in 2001 with the exception of Karkkila where the decrease turned by September (Finnish Environment Institute 2005). Due to the overall situation with precipitation, the observed values of drawdown include some groundwater level decrease that is typical to the season. Locally, however, even increases in groundwater level as a result of autumn rains were observed in the monitoring wells (Öhberg 2002).

In general, the largest values of drawdown occurred closest to the tunnel (Fig. 11). Figure 12 demonstrates that the largest values of drawdown in monitoring wells also commonly occurred close to the topographically interpreted fracture zones.

The appropriate reference elevation of the head for the two tunnel halves was different: south from the Kalliomäki pumping station the pressure level was decreased only by ten metres to approximately +32 m.a.s.l. whereas north from Kalliomäki the tunnel was emptied of water, making the tunnel floor a more appropriate reference level. When dividing the drawdown data from the monitoring wells collected during the repair into two groups based on the pressure level of the tunnel water (Fig. 13), it can be observed that the head values are higher north from Kalliomäki. Higher values of drawdown were also measured in the north. The rates of inflow in general, however, are higher in the south (Lipponen 2001). A potential explanation to the higher heads is the greater elevation of terrain in the north leading to higher head values in relation to the tunnel (see the profile of the tunnel, Fig. 1b in Paper II). Naturally the fact that the pressure level in the south was only decreased by 10 m also had an influence.

The mineral soils at the surface at the sites of wells and monitoring wells in which drawdown was observed during the tunnel's repair were characterized by the dominance of fine-grained soils. One potential explanation of the large proportion of fine-grained soils is their common occurrence in topographic lows, where the bedrock is usually also more fractured. In these locations, a good flow connection in the rock is more likely. The observed drawdown may also result from the fact that the groundwater storage in the fine-grained soils is typically small and, consequently, drainage into the tunnel below may have a prominent influence.

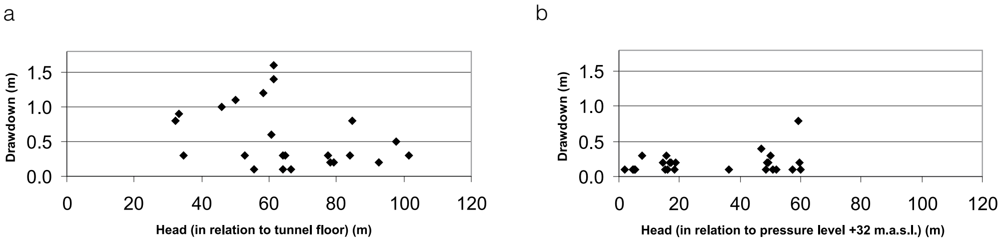

Fig. 13. Scatter plots of head vs. observed drawdown in monitoring wells during the Päijänne Tunnel's repair in 2001. Head is the difference between the pressure level in the tunnel and groundwater level in the monitoring wells (a) north and (b) south of the Kalliomäki pumping station. Note the different reference level for determining the head, which derives from the fact that the pressure level in the southern part was decreased only by 10 m to approximately 32 m.a.s.l. from the level prevailing during normal use, which partly explains the lower head values.

6.4 Geophysical properties of fractures: borehole logging

As described in the methods section, a number of geophysical logs were recorded in Sorsakoski in addition to those reported in Papers IV and V: borehole radar, induced polarization, caliper, gamma-gamma density, resistivity (electrode configurations: Wenner and short normal), single-point resistance, spontaneous potential. The main well surveyed was HN4 (Fig. 3), with a depth of 78 m. This depth, corrected according to the supplementary information from the contractor, differs from the depth of 72 m previously reported in Paper IV. The discrepancy was probably due to a noting error by the drilling supervisor. The greater depth is supported by the depth measurements of Astrock Oy that exceeded 72 m during the geophysical logging. Implications of this difference in depth for the logging interpretation in paper IV are inferred to be minor, because a linear depth correction was employed, assigning the log to correspond to the drilling depth. The maximum possible error is 7.7%. However, it is likely to be smaller because the log was recorded to a depth of 77 m. Two of the samples representing 2–3 m sections analysed in Paper IV, 52–54 and 69–72, are from close to boundaries of lithological units, as indicated by the gamma log. Paper V concentrates on fluid logging of the top 50 m in the well and the results are therefore not affected.

6.4.1 Borehole radar

Borehole radar is useful for obtaining an overview of fracturing in the rock mass in a drilled well where no drill core remains and the vertical resolution of observations during the rotary drilling is limited. The effect of multiple reflecting on the radar data, already substantial in borehole HN4 with a diameter of 160 mm, was markedly decreased by filtering. A few of the reflectors can be traced as far as 25 to 33 metres from the borehole, indicating resistive bedrock. The radius of penetration is similar to that reported by Carlsten and Stråhle (2001), ranging from 1–2 metres to 20–25 metres with a frequency of 100 MHz.

Abundant groundwater inflow was observed during drilling at the depth of approximately 65 m which coincides with the extension of the reflectors intersecting the well approximately at the depth of 65–70 m. The most prominent reflector (Fig. 14) hence appeared to be connected to a fracture zone that is probably important to groundwater inflow (Lipponen *et al.* 2004). Planar reflectors were clearly much more frequent higher up in the depth zone 15–30 m, which the caliper log measuring the hole diameter mechanically also indicated to be more fractured (Fig. 17).

The field strength distribution of the dipole antenna allows the interpretation of the near-field domain also to detect steeper and weaker reflectors (Fig. 15a). The interpretations for the near- and far-field domains were therefore complementary in detecting reflectors around drilled wells.

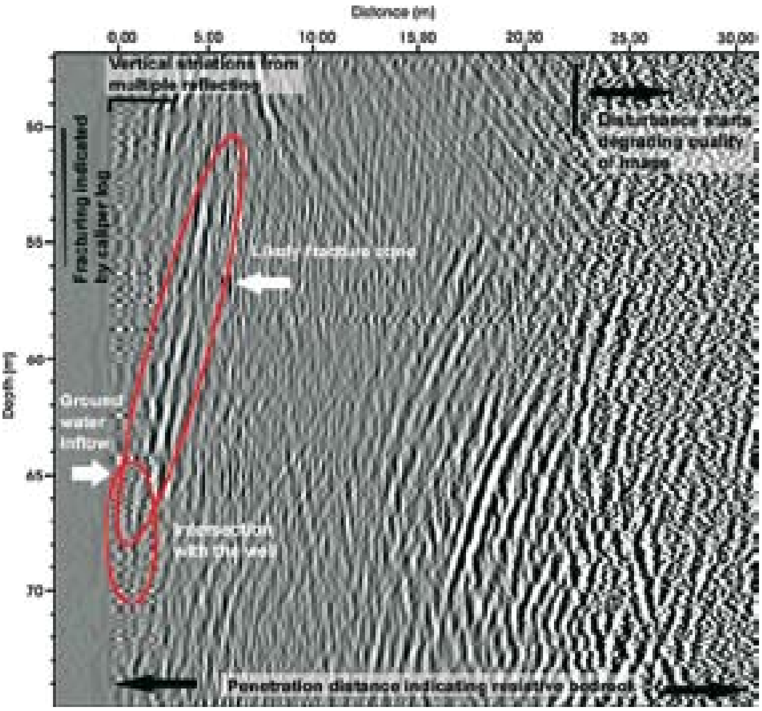

Fig.14. Reflection image of the lower part of well HN4 with specific features indicated.

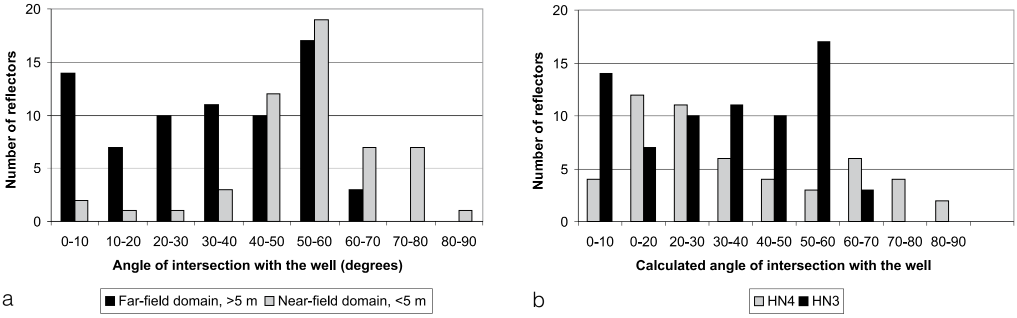

Fig. 15. (a) The field strength distribution of the dipole antenna allows the interpretation of the near-field domain (<5 m) in well HN3 also to detect reflectors at larger angles to the borehole and weaker reflectors (Lipponen et al. 2004). (b) Well HN4 appeared to have more reflectors at small angles to the well whereas in HN3 there was a wider scatter, although reflectors at 40–60 degrees to the well also occurred.

6.4.2 Magnetic susceptibility

The *in situ* measurement of magnetic susceptibility ranged from less than 900 to 1100 µSI units (Fig.16). Compared with susceptibilities determined from samples in the area (Table 5), the measured values are slightly higher, but in the same order of magnitude. Adjusting the base level of the magnetic susceptibility probe to the level determined from the samples would probably yield more quantitative results. The observed variation within the borehole probably results from compositional variation in the rock.

The magnetic susceptibilities of the samples

Table 5. Petrophysical parameters of hand samples (J. Klockars) from Sorsakoski, Leppävirta municipality. Measurements by Geophysical Laboratories, GTK. The sample locations are indicated in Annex 1.

sample	rock type	density (kg/m^3)	susceptibility (µSI)	intensity of remanent magnetization (mA/m)
8-JJK-01	granite	2668	300	10
13B-JJK-01	mica-gneiss	2720	270	60
13D-JJK-01	granite	2577	20	10
14A-JJK-01	mica-gneiss	2722	290	10
14B-JJK-01	tonalitic dyke	2594	20	0
18a-JJK-01	granite (foliated)	2633	210	20
18b-JJK-01	granite (foliated)	2694	370	70
20B-JJK-01	granite	2759	490	10
22a-JJK-01	porphyric granite	2643	160	20
22b-JJK-01	porphyric granite	2655	200	10

are very low (Table 5). Such low levels of magnetic susceptibility may result from the presence of paramagnetic silicates or hematite (Airo 1999), and no magnetic minerals are necessarily present. The remanence values are close to the detection limit. In the paramagnetic (that is, weakly magnetic) category of samples in the petrophysical database of the GTK (131 000 samples in total), the mean magnetic susceptibility is 334 µSI. The samples from Sorsakoski fall on both sides of the mean; more commonly below than above. The ferrimagnetic category of the database contains strongly magnetic samples (Säävuori and Airo 2001).

6.4.3 Caliper

The uneven surface of the borehole wall, typical of a rotary-drilled well, causes some small amplitude variation in the caliper log (Fig. 16) and consequently small fractures may go unnoticed.

According to the caliper measurement, substantial fracturing in the bedrock does not coincide with a depth of 53 m where the density changes, interpreted as the granite-mica gneiss contact, but rather below the upper contact, where the most abundant inflow of groundwater was observed at a depth of approximately 60 m, within the granitic rock unit. Based on the caliper log, fracturing appears to occur particularly in the zone from the bottom of the casing (14.7 m) down to a depth of approximately 30 m.

6.4.4 Nuclear logs

The markedly different levels of **gamma** radiation in HN4 indicated by the log, as presented in Paper IV are most probably associated with a change in rock type or in rock composition. The section with a higher level of gamma radiation appears to have a higher calculated uranium concentration, based on the gamma spectra. In a rotary drilled well where depth determination during the drilling is inaccurate, a gamma log provides a reference for other logs. It seems that the method provides a useful validation to observations made during the drilling, because the drill log (Paper IV) suggests more lithological variation, leading to the inference that these rock types are not easily distinguishable visually.

Substantial variation can be observed in the gamma-gamma **density** log (Fig. 16), which is probably caused by the large diameter of the well in relation to the volume of investigation. The large volume of water in a large-diameter well can cause disturbance. The density log indicates a change in the rock type at approximately 53 m and again at 69 m. Some clear negative peaks can be identified, especially below the bottom of the casing, which appear to be caused by fracturing. Water displacing rock in fractured zones causes density anomalies.

6.4.5 Electric logs

Disturbance from the metal casing in the well can be observed in the top part of the **spontane-**

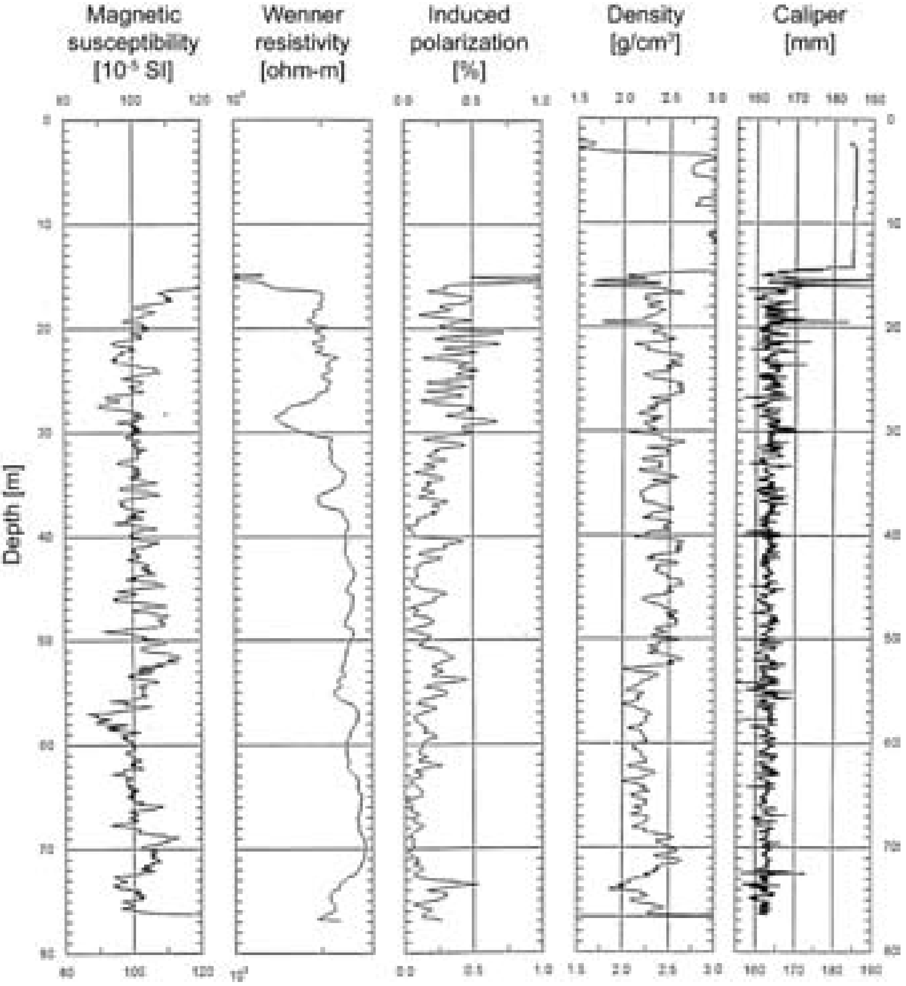

Fig. 16. Geophysical logs of well HN4 in Sorsakoski (from the left): magnetic susceptibility, Wenner resistivity, induced polarization, gamma-gamma density and caliper.

ous potential log (Fig. 17) down to the depth of approximately 15 m. Noisy intervals on spontaneous potential logs potentially indicate sections where water is entering or exiting a borehole (Keys 1997). Such intervals can be observed at the depth of 54–58 m, at 60–62 m and above the depth of 32 m (Fig. 17).

The level of **single point resistance** is lower in the fractured upper part of the bedrock down to the depth of approximately 30 m than below. There is a negative anomaly at the depth of approximately 26–29 m, coinciding with, for example Wenner resistivity and induced polarization anomalies.

The **Wenner resistivity** log essentially shows a generalized mirror image of the induced polarization (IP) log (Fig. 16). Negative anomalies can be detected immediately below the casing (bottom at 14.7 m), at the depth of approximately 15–17 m, at 27–31 m, at 35–37 m, at 54–56 m and at the very bottom of the well (approximately 73–77 m). The resistivity minimum at 27–31 m corresponds approximately with a density minimum (Fig. 16). Some groundwater inflow was also observed approximately at this depth during drilling. Both features support the occurrence of fracturing.

Short normal resistivity shows a negative

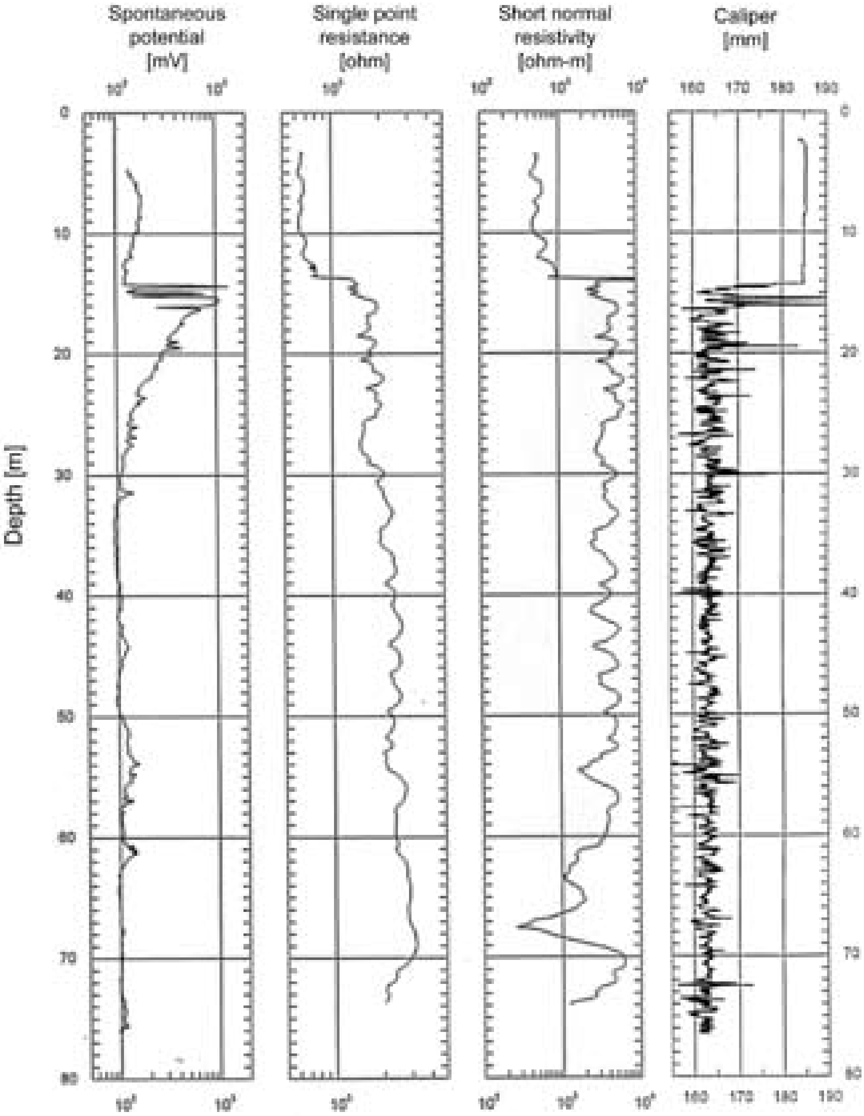

Fig. 17. Electric logs of well HN4 in Sorsakoski (from the left): spontaneous potential, single point resistance, short-normal resistivity, and for reference caliper.

anomaly at the bottom of the well at a different depth from those observable, for example in the logs Wenner resistivity, IP, gamma-gamma density and caliper.

The **induced polarization** (IP) log measured in well HN4 (Fig. 16) displays a positive peak towards the bottom of the well at 73 m as well as at 54 m. In the top part, from the bottom of the casing at the depth of approximately 15 m down to the depth of 30 m, the level of IP is clearly elevated at 0.3–0.4 %, probably resulting from more fractured rock because, for example, density log does not indicate a change in rock type. Below the depth of 30 m IP is variable but at a lower level (0.1–0.15 %).

The Wenner minima appear to correspond with density minima, but the density minima are less prominent. In the case of HN4, largely the same features can be identified in the short normal resistivity as in the Wenner log, although the negative anomalies are more prominent in the latter. An exception is the most prominent negative anomaly in short normal resistivity, which does not have a clear equivalent in the Wenner log. The negative resistivity anomaly at the bottom of the well occurs above the anomalies indicated, for example by the IP, density and caliper logs.

7 Discussion

Underground construction influences the groundwater flow conditions, thus posing a challenge to managing infrastructure functions while striving to mitigate adverse impacts on the hydrogeological environment. Identifying the probable conduits of groundwater flow in the bedrock allows the planning of cost-effective location of underground cavities, improved preparedness for potentially problematic areas in construction and prioritization of measures for protecting groundwater resources and water conveyance from risk activities. Scale and resolution of the tested methods for characterization of fractures in this study are relevant considerations for all these applications.

In the zone of the Päijänne Tunnel, a great deal of agreement was found between the regional magnetic trends correlating with orientations of topographic lineaments commonly indicative of fracture zones (e.g. Fig. 3 in Paper III, Annex 2). The geological/tectonic history makes the zones of weakness in the bedrock prone to repeated movements. Due to the suggested evolutionary relationship of block boundaries activated later, remotely-sensed regional-scale structures serve as indicators in the identification of fracture zones on a local scale or of fractures on site scale. However, the late geological development influencing the water-conducting properties of fractured zones, including weathering, may have resulted in different properties. Tunnel-scale measurements of fracturing are possibly not an equal pointer to predicting inflow compared with telescoping into detailed scales from the regional framework of structures.

Due to the recent methodological developments and the availability of aeromagnetic data of increasingly high resolution (dense line spacing), predictions of fracture orientations and groupings have proved quite accurate upon verification on the ground (pers. comm. M-L. Airo 2005). Furthermore, one of the strengths of aeromagnetic data is their continuous nature, compared with somewhat patchy geological data which are subject to occurrence of outcrops.

Linear depressions in topography are commonly indicative of fracture zones and their tracing serves identification of locations with a risk of groundwater flow to underground cavities, or with groundwater potential for water supply. However, the interpretation is complicated by for example superficial deposits and lithological variation which does not necessarily have hydrogeological significance. The reliability of topographic interpretations of fracture zones is improved by verifying observations by results from independent methods such as ground geophysical surveys, for example seismic methods and drilling. Knowing the relationship between fracturing, cleavage and the orientation of lithological units – results of the geological history and processes – is the key to the lineament interpretation on the basis of which prioritization for probable fracture zones can be made.

The surface expression of a gently-dipping fractured zone may be wide, with fracturing occurring to a different degree and therefore difficult to locate accurately. On the other hand this may make the feature more prominent for detection from topographic or aeromagnetic data. The continuation of these structures in depth dimension and the resulting lateral displacement at different depths from the surface expression remains difficult to assess, due to curving of planes.

The difficulty of linking groundwater inflow – particularly in a quantified way – to the other properties of fractures or fracture zones lies in the sheer number of contributing factors. The amount of inflow into a tunnel is not a function of the fracture zone's hydraulic conductivity only. It also depends on the availability of groundwater storage in the overburden, permeability of the contact between the overburden and the top of bedrock, and the pressure difference, that is, hydraulic head, that drives the groundwater flow. Therefore, from the point of view of all the applications considered here, it is crucial to consider the overburden and fractured rock jointly.

When assessing the measured inflows in the Päijänne Tunnel, it must be noted that the measurements have been carried out at the time when the tunnel was kept free of water by pumping. The potential impact on flow paths and inflow from the

Table 6. Overview: specific considerations related to the methods of fracture characterization. Note that the scale is given here as applicable to the methods used in this study (ground-surveying varieties also exist). Some complementary comments are added from Keys (1997).

method (scale)	application	complications	interpretation and validation or supporting information required
aeromagnetic (regional)	structure detection; distinguishing lithological units; identifying ductile and brittle structures	impact of ductile deformation and compositional differences may dominate; difficult to link to actual individual structures locally due to the scale difference	requires specific geophysical expertise; ideally relationship with local fracturing to be verified
topographic (regional/ local)	identification and location of probable fracture zones	superficial deposits, bedding, variations in lithology	interpretation can be improved by additional information on structures or maps of lithologies and superficial deposits; Insensitive to variation in hydraulic properties
borehole radar (borehole)	Provides an overall distribution of reflectors (structures) from a large rock mass and their cylindersymmetric orientations	compositional differences in lithology: sulphides, conductors; reflector orientation not necessarily the same as that of fracture	calculations involved, requires specific software; matching with observed directions of actual fracturing from, for example outcrops or a televiewer for absolute orientations; tomography
caliper (borehole)	direct indicator of fracturing; good in uncased hardrock	uneven borehole surface may hide small fractures	fluid conductivity and temperature (or flow meter) indicate whether hydraulic activity associated
induced polarization (borehole)	Identification of conductive fractures which may contain groundwater	sulphidic minerals may cause more prominent response	interpretation supported by information on the occurrence of sulphides or clay
natural gamma radiation/ gamma spectrum (borehole)	provides information on lithology which is helpful for distinguishing units, even visually similar ones; also on cased sections and well beyond the borehole wall	attenuation takes place in a large borehole; quantitative measurements require corrections and references	gamma spectrometry allows distinguishing contributions of elements, but specific software required; quantitative interpretation requires accounting for attenuation; useful when fracturing is clearly associated with a rock type, or where the lithological contacts are prone to develop fracturing
magnetic susceptibility (borehole)	distinguishing magnetically different rock types	in areas with potential for good quality groundwater rocks generally have low magnetization; If present, magnetite masks the potential influence of magnetic pyrrhotite	samples and reference measurements are good for setting an appropriate base level
density (borehole)	location of fractured zones; distinguishing rock types with a density contrast	uneven surface, water replacing rock can cause marked variation	information on lithological variation can be used to rule out its possible influence
electric logs (borehole)	detection of conducting fractures	conductivity anomalies caused by sulphides, graphite may complicate interpretation if indications of water and clay sought after	information on the occurrence of graphite and sulphides useful; fluid resistivity can be used to improve estimation of formation's resistivity
borehole video (borehole)	locating fractures, estimation of orientation, quality (filling, aperture)	distinguishing visually similar rock types problematic; angles of fractures can only be estimated if flexions are visible; image quality affected by borehole conditions	different geophysical methods for fracture detection or for distinguishing rock types or fluid flow measurements provide support to interpretation
water quality logging (borehole)	can aid chemical sampling	seasonal effects; information can only be obtained from below groundwater level	knowledge of the hydraulic system important for interpretation
fluid conductivity (borehole)	selection of water sampling depths (Keys); identifying origin of poor quality water; easier to use and better available than water quality logging equipment	interpretation requires knowledge of flow regime within the borehole (Keys); seasonal variation	knowledge of the hydraulic system important for interpretation

pressure difference is diffcult to evaluate. Tunnels that have been subject to pre-grouting and reinforcement measures and boreholes are modified hydrogeological environments and values of hydraulic properties determined in these environments do not represent the properties of an unaltered rock mass. However, these estimates indicating the magnitude may be the best ones available and sufficient for many purposes.

Hydraulic properties of fracturing vary significantly, and selected methods for estimating relevant factors that affect them were tested here. It was possible to identify a number of factors that may indicate associated groundwater flow such as brittle deformation, resistivity or conductivity anomalies. When groundwater flow occurs in locations where the bedrock structure changes, for example at a lithological boundary or in a fracture zone, there is a contrast of properties that can be detected. For radar reflections or for resistivity anomalies, clay and sulphides can cause similar anomalies. Many anomalies are not unambiguous and hence complementary methods are needed for optimal results in order to rule out some alternative causes. An overview of particularities of the tested methods with regard to application is presented in Table 6.

Due to the existing well construction and hydrogeological conditions, several borehole logging methods may be of limited applicability or may provide information only from the part of the well below the groundwater level or from the uncased part of the well:

- Due to the uneven surface and the large borehole diameter, the possibilities for using packers for sampling per section or flow metering are limited. Therefore, indirect indicators of fracture properties are needed. The greater amplitude of variation resulting from the uneven surface of rotary-drilled wells can mask smaller-scale fracturing in the caliper log.
- By contrast, compared with fluid-logging, formation-logging or measurement data on properties of the rock mass are not season-dependent. Fluid logging can be complementary, though, in assessing water quality as a function of depth, helping, for example, to infer more or less dynamic flow conditions.
- How the diameter compares to the radius of investigation of a particular method is a potential constraint to the level of extractable information. Methods such as natural gamma radiation are potentially sensitive to enhanced attenuation effects in a large-diameter drilled well, especially when the diameter varies. In a 160 mm diameter borehole – commonly used for drilled wells in Finland – attenuation of gamma radiation up to a few tens of percent could be expected from the layer of water. If samples or appropriate references are available, corrections for the borehole diameter can be applied to, for example susceptibility and density measurements. Nevertheless, even information about relative variation within a borehole or between a group of boreholes in an area, which can be measured with greater certainty, may be helpful, depending on the purpose of the hydrogeological investigation.

Information available from direct observations during rotary drilling of a well is limited and no drill core remains for cross-checking. Therefore, borehole logging with a technique such as natural gamma can be used to produce a continuous log indicative of the lithology in a case where the rock types differ in this sense. This allows identification of rock types that are visually not very distinct and verification of the depth of a contact, which during drilling is potentially problematic.

The radar measurement provides information on a large volume of rock and on continuation of structures, but due to the cylindrical symmetry, the 3-D position of the reflectors cannot be determined using radar data alone without complementary information. Based on the radar data, the distance and position of major structural features (such as more important fracture zones) can be obtained, which necessarily do not stand out from scattered borehole surface observations. The capacity of the radar to detect structures that intersect the well at large angles is limited, although the near-field interpretation is somewhat more sensitive. A planar surface is assumed in the interpretation, but in reality curving of the surfaces is likely.

The shape and orientation of the investigated space influences the resulting picture of fracture or fracture zone orientations: For example the fact that the topographic interpretation was made for a narrow NNE zone of the tunnel to some extent undervalues the importance of NW-SE trending lineaments which nevertheless are prominent in the landscape if the length of the lineaments is used as a weighting factor (Paper III, Fig. 3, Annax 2). Structures from the tunnel and from boreholes have been determined from a smaller volume, showing typically more scatter.

Admittedly, the sites studied here are individual cases, even though the Päijänne Tunnel provides a 120-km traverse, and hence generalizations based on the results must be made with caution. More in-depth parts of the study are based on selected representative tunnel sections (Paper III) or sites (Oitti, Leppävirta). Furthermore, the applied methods are only a selection of those available for fracture zone characterization.

The observed heterogeneity in hydraulic activity in the rock mass and in the overburden – manifested by, for example the spatial distribution of abundant groundwater inflows into the tunnel (Paper III), the variable magnitude of inflows (Paper II) and by the irregularity of fracturing indicated by the caliper log – can be used as a basis for improving vulnerability assessments of groundwater in crystalline rock or of rock tunnels. In practice these elements could be incorporated through for example geometrically weighted interpolation following an assessment through geostatistical methods, as applied by Laine (1998). The relevant considerations include both the natural (intrinsic) vulnerability resulting from the geology and hydrogeology and the risk posed by the current land use and existing risk activities which evolve with time. The large magnitude of flow in the Päijänne Tunnel, irregular distribution of potentially hazardous human activities, and the interplay of natural and human-influenced factors are among the relevant considerations when assessing vulnerability.

7.1 Future research needs

A more detailed assessment of the potential influence of the rock type or rock composition or of lithological contacts on the occurrence of fracturing and groundwater flow into the Päijänne Tunnel could advance hydrogeological knowledge. Such a study might reveal relationships that this study on a generalized scale could not verify. For example, an evaluation could be made of whether any correlation exists between boundaries of lithological units on different scales or compositional variation which may have local significance for fracture development, and the occurrence of groundwater flow.

A geostatistical study of distances between interpreted fracture zones and inflows as well as of different parameters related to the monitoring wells might provide additional valuable information about the interdependencies, even though the sample size may limit the choice of possible methods.

In the MTBE spill site in Oitti, modelling flow and transport in fractured rock could be very informative about contaminant transport and pathways in hardrock, influenced by the tunnel dynamics. The model would need to take into account the soil-rock interface, the saturated and unsaturated zone.

It would be interesting to calculate and compare hydraulic conductivity based on the inflow measurements made inside the Päijänne Tunnel, with hydraulic conductivities determined from pumping tests in Oitti.

If data on mineral soil at the actual monitoring well sites in the zone of the Päijänne Tunnel, including the overburden thickness and stratigraphy, could be assembled, the potential influence of these factors on the observed drawdown could be investigated. This would advance knowledge about the hydraulic connection between the overburden and fractured rock.

8 Summary and conclusions

This study contributes to knowledge about the complex relationships of fracturing on regional, local, tunnel and borehole scales and its linkage to groundwater flow. The methods applied in this study for fracture characterization included interpretation of lineaments from topographical data and comparing it with interpretation based on aeromagnetic data, analysis of mapped structures in the tunnel, groundwater level observations, geophysical borehole logging, digital borehole video surveying and fluid logging.

Fracture trends appear to align similarly on different scales in the zone of the Päijänne Tunnel. For example, there is in general a great deal of agreement between the trends identified with the topographic and aeromagnetic methods. The regional magnetic trends can serve as indicators to local-scale fracturing because they correlate well with the orientation of topographic lineaments, but a verification of the hydraulic properties is required, which are not necessarily self-similar across scales. The coincidence and parallel orientation of short brittle features and extended gradient in the aeromagnetic data suggest an evolutionary relationship, that is reactivation of block boundaries. Later movements, potentially more significant to groundwater flow, may have occurred along the same zones of weakness. The same structural orientations as those of the larger structures on local or regional scales have been observed in the tunnel, even though a match could not be made in every case. Fracture zone/lineament orientation should be viewed in the context of the stress pattern and geological history of the area, as these have an influence on the hydraulic activity.

A lineament interpretation based on topography is arguably the basic tool for obtaining an overview of the probable fracture zone orientations on a local scale, despite the complexity added by the depth dimension. The quality of the resulting interpretation can be improved by iterating with complementary information. For improved lineament interpretation, it is important to distinguish the contributions of bedrock surface and superficial deposits to the topography, and for this purpose spatial analysis by GIS provides a useful tool.

The topographic and aeromagnetic methods complement each other due to the limitations emerging from, for example the occurrence of superficial deposits, terrain being flat or from orientation of lithological units in the case of topographic interpretation and low magnetization in the case of aeromagnetic interpretation. The methods are not sensitive to variations in hydraulic properties as such, but magnetic data also carries information about the plastic or brittle nature of the features. The contribution of the aeromagnetic data to assessment of fracturing could be: (1) to identify any brittle nature in fracturing and to distinguish plastic features; or (2) in areas where the lithological variation is not well known, to help in mapping boundaries which due to differences in rigidity may have developed fracturing, even hydraulically conducting; or 3) to indicate linear orientations where topography is flat.

The locations with water-conducting fracturing and with measured large-scale groundwater inflow in the zone of the Päijänne Tunnel are commonly associated with intersecting or individual fracture zones, interpreted from the topographic data. NW-SE trending single fracture zones were observed particularly within the investigated tunnel sections 64–80 and 84. In the tunnel section 64–80, the NW-SE trend can be considered pervasive, from fracturing on the tunnel scale up to topographic lineaments and to a weak magnetic trend. The NW-SE oriented compression tends to keep fault systems subparallel to the prevailing stress field and horizontal fractures open and hydrologically conductive. Despite the relatively small number of observations from the tunnel, it can generally be concluded that the strikes of water-conducting fractures are commonly at large angles to the dominant cleavage. The conducting structures also appear to be gently-dipping rather than steeply dipping.

Orientation of the studied sample – a borehole or an elongated tunnel zone – may introduce a bias, and the sensitivities of the methods to the orientation of fractures also vary. The observed differences in the picture of fracturing, resulting from the different orientation of observation spaces in Oitti, reflect the prominence of steep structures in the near-horizontal tunnel and sub-horizontal structures in boreholes. The capacity of the radar to detect structures that intersect the well at large angles is limited, although the near-field interpretation proved to be somewhat more sensitive for detecting reflectors at larger angles to the borehole. Structures are not necessarily oriented favourably in relation to the greatest sensitivity of the methods, but knowing the limitations, the surveying can be oriented accordingly. It was observed in Oitti that open or likely water conducting fractures do not necessarily coincide with concentrations of fractures. It can be concluded that the size and orientation of the observation space (patch of terrain at the surface, tunnel section, borehole), as well as the characterization method, with its typical sensitivity, influence the identification of the fracture pattern.

To some degree the rate of groundwater inflow shows a positive correlation with the level of reinforcement, both being connected with fracturing in the bedrock. The hydraulic properties of fracture zones are inferred to contribute to the deterioration of the tunnel (manifested by block falls), but their influence remains difficult to quantify. However, the hydraulic properties of fractures is probably a relatively minor factor compared with the rock support solutions and with orientation of the tunnel sub-parallel to foliation.

As indicated by the inflow measurements at the time of construction and repair of the Päijänne Tunnel, less inflow was reported at the time of the repair. This may be influenced by the relatively shorter time that the tunnel was empty, but the water use in the tunnel operations and the measurement technologies also involve uncertainties. The pressure level in the water tunnel influences the relationship with groundwater, and the quality of connection is indicated by the results of groundwater monitoring in the tunnel zone. In general, the largest values of drawdown occurred in monitoring wells closest to the tunnel and the largest values of drawdown also commonly occurred close to the topographically interpreted fracture zones.

Of the borehole methods sensitive to fracturing tested in well HN4, caliper is a direct method for locating fracturing, although smaller variation may be hidden by an uneven borehole surface. Wenner resistivity appears to highlight anomalies that probably represent conductive fractures, Wenner anomalies appearing more prominent than the respective anomalies in short normal resistivity. A fractured zone appearing in a drilled well, for example as an induced polarization and Wenner anomaly, as well as in the caliper log, demonstrates the possibility of using different methods for their detection. Verification by another or several methods decreases the uncertainty involved in using these indirect methods. The lower level of Wenner resistivity and single point resistance in the same zone appear to provide supporting evidence that the top part of the bedrock penetrated by the well is more fractured. The flow conditions are more dynamic in that section, as indicated by the fluid conductivity log.

In the borehole radar data, planar reflectors were observed to occur clearly much more frequently higher up in the depth zone of 15–30 m in well HN4, which the caliper log measuring the hole diameter mechanically also indicated to be more fractured. The most prominent reflector appeared to be connected to a fracture zone that is probably important to groundwater inflow. The substantial effect of multiple reflecting on the radar data in the large-diameter wells could be markedly decreased by filtering.

For the purposes of assessing groundwater flow or even fracturing, usefulness of distinguishing lithologies is variable: At the Leppävirta site there was some indication of fracturing close to the lithological contacts. In the zone of the Päijänne Tunnel the significance of lithological contacts for hydraulic activity should be assessed. Based on a coarse assessment on the scale of tunnel drives classified according to the dominant rock type, the rock type appears to have no marked influence on the volume of inflow. Information on the lithologies is particularly important in cases when some rock types have high conductivities or when the lithological boundaries are prone to fracturing. Lithological variation can be detected by gamma measurement, as demonstrated, but, for example in the case of well HN4, magnetic susceptibility was uniformly low and therefore not helpful in distinguishing rock units. In large granitic and gneissic terrains where many physical properties of rocks properties vary only slightly, methods that detect fracturing directly are likely to yield better results. A continuous geophysical log sensitive to differences in the lithologies in question is a particularly useful verification when samples from rotary drilling are limited to drill cuttings per section, and when the depth estimates of contacts etc. made during drilling are not accurate.

In the assessment of vulnerability and eventually for directing protective measures, the anisotropy of the geological media should ideally be taken into account, giving more weight or extent to fracture zone orientations identified as linked with groundwater flow, or to the geometry of more permeable deposits in the overburden. In addition to the properties of the hydrogeological environment and its capacity to mitigate pollution, the vulnerability of a pressurized rock tunnel is also influenced by whether the tunnel is in use and by risks posed by human activities such as land use, infrastructure and potentially hazardous activities. Several geological features were considered to increase the vulnerability of rock tunnel sections to pollution in the case of the Päijänne Tunnel, especially when several factors affected the same locations. These factors include fractured bedrock, particularly with associated groundwater inflow, thin or permeable overburden above fractured rock, a hydraulically conductive layer underneath the surface soil and a relatively thin bedrock roof above the tunnel.

The difficulty of linking the interpreted fracture zones to groundwater inflow and to different geological characteristics lies in the sheer number of contributing factors. Despite the similarities of alignment of fractures observed on different scales, no match could be made in every case between regional or local pattern and orientations on a detailed scale. A range of methods can be applied to detection of fracture properties relevant to groundwater flow, ideally seeking verification by another method and with a due consideration to the variable constraints, geometries, sensitivities and scales.

Yhteenveto

Tutkimuksen päätavoite oli arvioida tiettyjä geofysikaalisia, rakenteellisia ja topografisia menetelmiä pohjavettä johtavien ruhjevyöhykkeiden ja rakojen indikaattoreina. Tarkastelu käsitti alueellisen, paikallisen sekä tunneli- ja porareikämittakaavan. Tällainen tieto palvelee esimerkiksi pohjaveden etsintää vedenhankinnan tarpeisiin ja pohjavesivuotoriskien arviointia kalliorakentamisessa.

Tutkimuksessa tarkasteltiin, miten näiden menetelmien avulla havaitut piirteet liittyvät kvalitatiivisesti ja semikvantitatiivisesti määritettyyn pohjaveden virtaukseen. Työssä selvitettiin myös sitä missä määrin menetelmät paljastavat sellaisia kallion ominaisuuksia, jotka vaikuttavat pohjaveden virtaukseen. Tutkimusalueet olivat (1) Päijänne-tunneli, jossa tehdyillä havainnoilla oli mahdollista varmentaa alueellisesti tai paikallisesti tulkittuja rakenteita, (2) Oitti, jossa öljyhiilivetyjä oli päässyt maaperään ja jossa rakenteiden geometriaa vertailtiin eri mittakaavoissa; ja (3) Leppävirta, jossa rakoilua ja hydrogeologista ympäristöä tutkittiin porakaivon mittakaavassa.

Tutkimuksessa käytettiin seuraavia menetelmiä: topografiaan perustuvaa lineamenttitulkintaa ja tulosten vertaamista aeromagneettisesta aineistosta tehtyyn tulkintaan; Päijänne-tunnelissa kartoitettujen geologisten rakenteiden analyysia; porakaivojen reikäkuvausta; vesivuotomittauksia tunnelissa; pohjaveden pinnan korkeushavaintoja; tietoja tippuneista kivistä tunnelin kunnon heikkenemisen indikaattoreina. Tutkimus yhdisti geologista ja geoteknistä tietoa pohjaveden virtaukseen vaikuttavista tekijöistä ja rakoilun ilmenemisestä sekä ympäristötietoaineistoja paikkatietojärjestelmää hyväksi käyttäen.

Leppävirralla vertailtiin geofysikaalisten reikämittausten ja reikäveden ominaisuuksien mittauksien reagointia rakoiluun ja muihin geologisiin piirteisiin porakaivon mittakaavassa. Joidenkin geofysikaalisten reikämittausten tuloksiin vaikutti reiän suuri halkaisija (gamma-säteily) tai sen epätasainen pinta (reiän halkaisija). Koska rinnakkaiset menetelmät osoittivat kallion olevan rikkonaisempaa pinnasta kuin syvemmältä, voidaan todeta, että useampia menetelmiä on mahdollista käyttää rakoilun havainnointiin.

Päijänne-tunnelin vyöhykkeessä havaittiin rakojen suunnissa yhtäläisyyksiä eri mittakaavoissa. Esimerkiksi alueelliset magneettiset suuntaukset korreloivat varsin hyvin ruhjevyöhykkeiden ilmentyminä tulkittujen topografisten lineamenttien kanssa. Myös tunnelissa havaittiin samoja rakenteellisia suuntauksia kuin suuremmissa rakenteissa paikallisessa tai alueellisessa mittakaavassa, vaikkakaan aina yhteyttä eri mittakaavojen välillä ei ollut mahdollista havaita. Havainnoitavan tilan (maa-alue, tunnelijakso tai porareikä) koko ja suuntaus, tutkimusmenetelmä ja sen herkkyys sekä tutkittavan kohteen ominaispiirteet vaikuttavat rakojakauman tunnistamiseen. Näin ollen voidaan todeta, että ottamalla huomioon havainnointigeometrian vaikutukset ja käyttämällä toisiaan täydentäviä menetelmiä voidaan rakoilun ja pohjaveden virtauksen monimutkaisia suhteita selvittää paremmin.

Oitissa todettiin yhteys matalan pohjaveden ja Päijänne-tunnelin välillä. Näin ollen myös haitta-aineiden kulkeutuminen tunneliin on mahdollista kallion rakojen kautta, mikä korostaa tunnelin suojelun tärkeyttä.

Pohjaveden pinta laski tilapäisesti tunnelin korjauksen aikaisen paineen alentumisen seurauksena. Yleisesti ottaen suurimmat pohjaveden pinnan alenemat havaittiin lähimpänä tunnelia ja/tai lähellä topografian perusteella tulkittuja ruhjevyöhykkeitä. Näyttää siltä, että tunneliin vuotavan veden määrä korreloi jossain määrin lujituksen kanssa, koska molemmat liittyvät kallion rakoiluun.

Seuraavat tekijät lisäsivät tunnelijaksojen herkkyyttä haitta-aineiden kulkeutumiselle erityisesti silloin, kun useampi näistä tekijöistä ilmeni samassa paikassa: (1) rakoillut kallio, erityisesti mikäli siihen liittyy pohjaveden virtausta; (2) ohut tai vettä hyvin läpäisevä maapeite kallion päällä; (3) hydraulisesti johtava kerros pintamaan alla; ja (4) suhteellisen ohut kalliokatto tunnelin yläpuolella. Havaittu geologisen aineksen anisotropia tulisi ottaa huomioon tunnelijaksojen pilaantumisherkkyyden arvioinnissa ja suojaavien toimenpiteiden kohdentamisessa.

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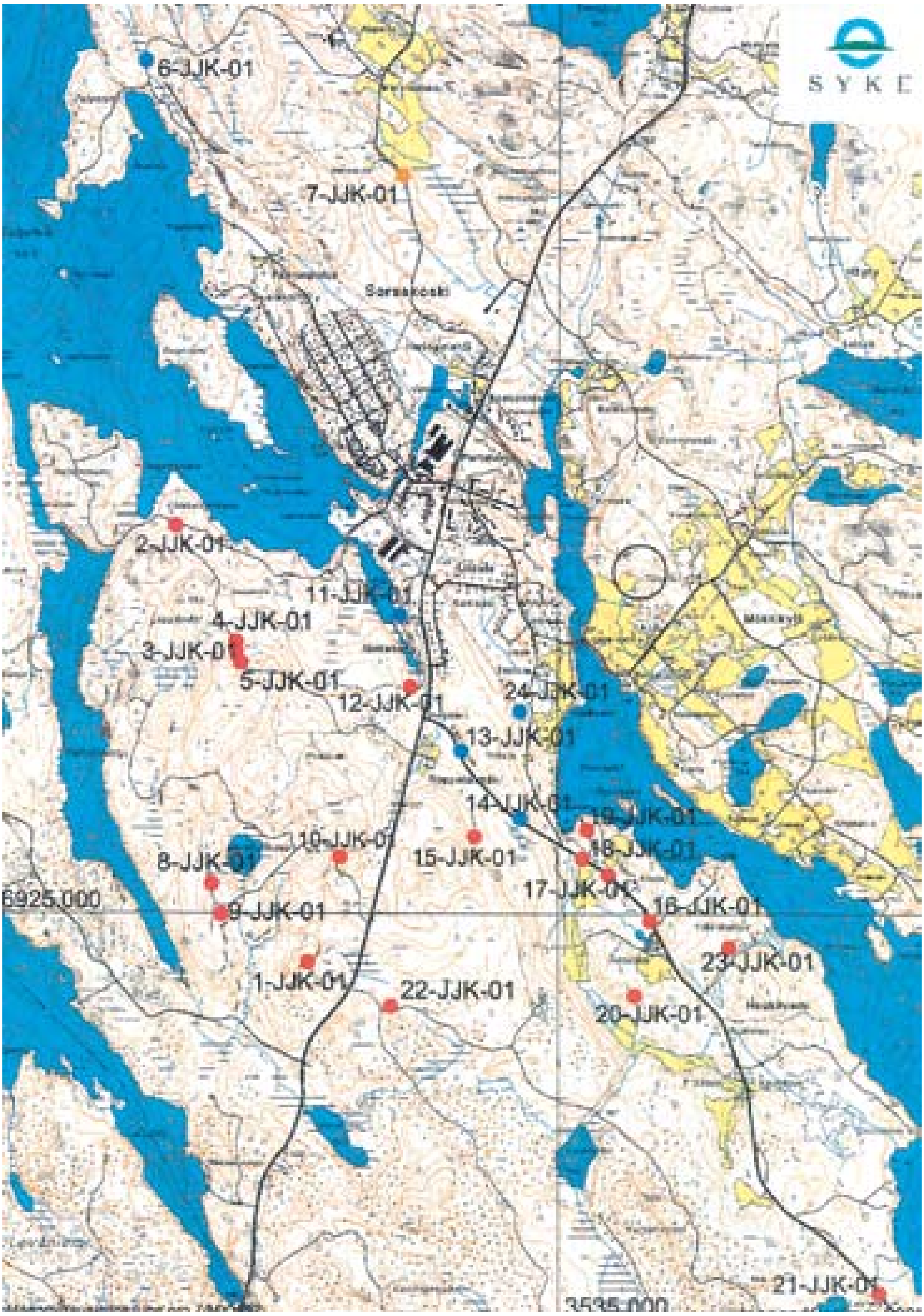
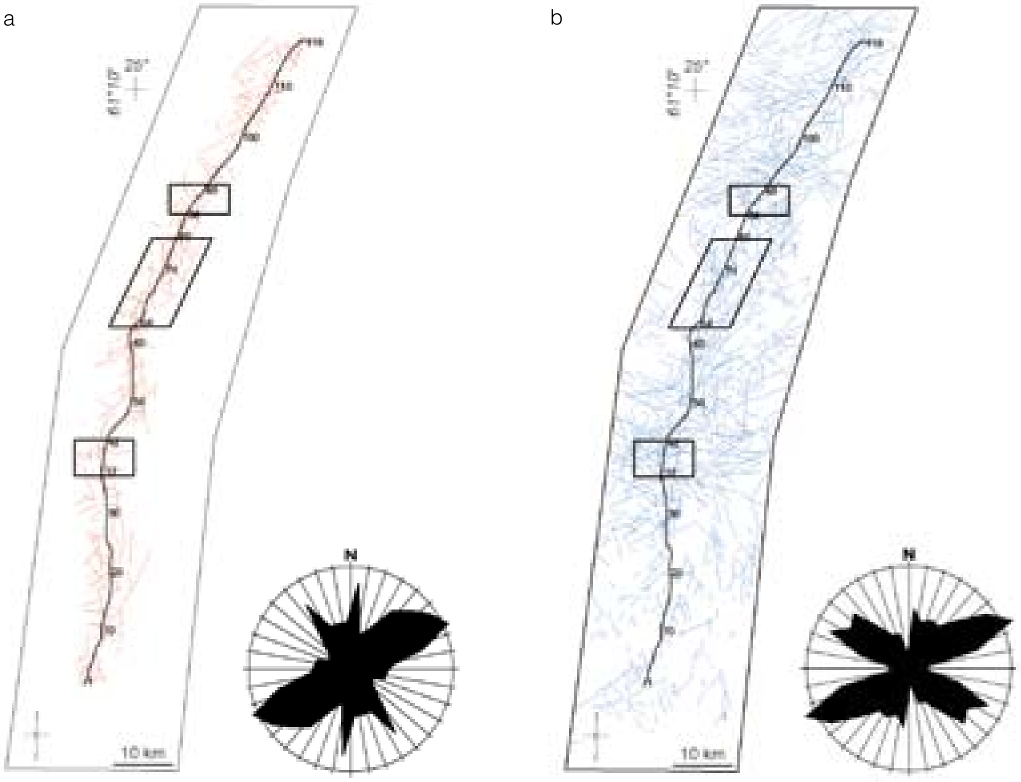
Annex 1

Locations of petrophysical samples for measurements of magnetic susceptibility. Legend: red – porphyric granite; blue – mica gneiss; orange – granodiorite (Klockars 2003)



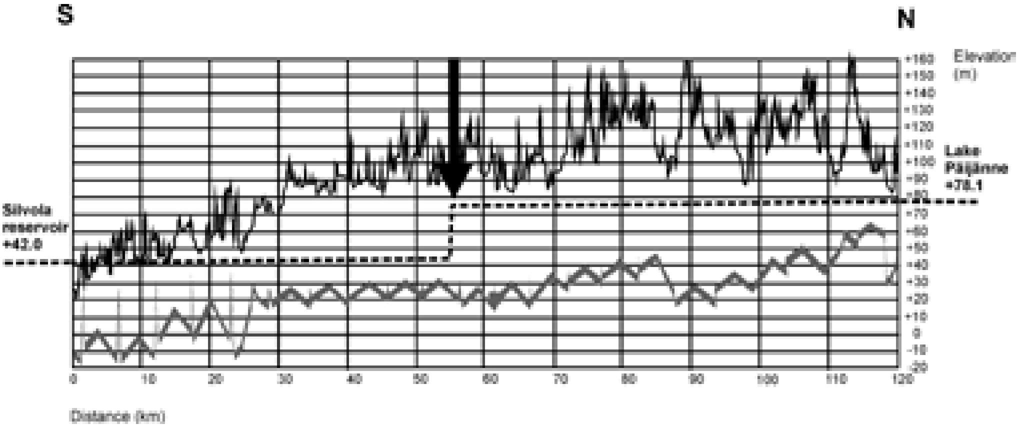
Annex 2

Paper III, Figure 3. Lineaments and fracture zones interpreted from (a) topographic and (b) aeromagnetic data. The rose diagrams below are based on orientation and length of the interpreted features (pers. comm. M. Paananen, GTK). Reprinted with permission from EAGE Publishing.



Annex 3

Paper II, Figure 1b. The tunnel section showing the variation of the ground surface topography (black line) and that of the tunnel elevation (grey line). The pressure level of the tunnel water with the current capacity of 2.9 m^3/s is indicated by the dashed line. The pressure level change at the pumping station is indicated by the arrow. Note the exaggerated vertical scale. The diagram is modified from the original of the Helsinki Metropolitan Water Company, edited by A. Wegelius. Reprinted with a permission from Elsevier Science.



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Provide the title in full, the author's name (firstname in full), affiliation and present address if different from affiliation. If the title is longer than 50 characters, provide a short title for use as a running header.

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Maximum 150 words in one paragraph.

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Gather under one heading, before References.

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- Should fit on A4-sized page.
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Number each equation in parentheses on the right. Use a decimal point not comma. Vectors are set in **boldface**, other one-letter symbols in *italic*.

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Geographic nomenclature

Always use internationally recognised names; in doubtful cases check if names you intend to use are listed in the *Times Atlas of the World* or *Merriam-Webster's Geographic Dictionary*. Usage of coordinates is strongly recommended.

References

In the text, reference to other publications should be made with name(s) and years, e.g. Tamminen and Starr (1990) or (Tamminen and Starr 1990). If there are more than two authors, use e.g. Cosby *et al*. (1986). Use suffixes a, b, etc. to distinguish works by the same author in the same year. Only published works, or publications in press, should be included in the References. Arrange all references in alphabetical and chronological orders at the end of the manuscript. Note that the initials follow the name; all names are mentioned. Names of journals and titles of books should be set in *italics*. Abbreviate journal names if a common abbreviation is known. For references which are not in English, an English title should be provided, only if it is given in the publication. For publications in Russian, give transliterated and original (in Cyrillic) authors' names. Give translated (not transliterated!) title within brackets [] (if not translated in original publication). The following examples show the general format to be used.

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Tikkanen T. 1986. *Kasviplanktonopas* [*Phytoplankton guide*], Gaudeamus, Helsinki. [In Finnish].

Journal articles

Cosby B.J., Homberger G.M., Wright R.F. & Galloway J.N. 1986. Modeling the effects of acid deposition: control of long term sulfate dynamics by soil sulfate adsorption. *Water Resour. Res*. 22: 1238--1291.

Korbut V.V. [Корбут В.В.] 1989. Nest building of hooded crows. 1. Utilisation of different substrata. *Zool. Zh*. 68: 88--95. [In Russian with English summary].

Book chapters

Tamminen P. & Starr M. 1990. A survey of forest soil properties related to soil acidification in Southern Finland. In: Kauppi P., Anttila P. & Kenttämies K. (eds.), *Acidification in Finland,* Springer, Berlin, pp. 237--251.

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Postal addresses of the editors

Outi Heikinheimo
Finnish Game and Fisheries Research Institute
P.O. Box 2 (Viikinkaari 4)
FI-00791 Helsinki, Finland

Dr. Veli-Matti Kerminen
Finnish Meteorological Institute, Air Quality Research
P.O. Box 503
FI-00101 Helsinki, Finland

Dr. Johanna Mattila
Åbo Akademi University, Departmentof Biology
Environmental and Marine Biology
Akademigatan 1
FI-20500 Turku, Finland

Dr. Raija Laiho
P.O. Box 27
FI-00014 University of Helsinki, Finland

Dr. Timo Huttula
Environmental Consulting
Ilvestie 1
FI-36100 Kangasala, Finland

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