Structural evolution of the crust as a means of determining the technical properties of bedrock in the Helsinki capital region

WENNERSTRÖM MARIT[1], AIRO MERI-LIISA[2], ELMINEN TUIJA[3], PAJUNEN MATTI[4] & SALMELAINEN JUHA[5]

[1] *Geological Survey of Finland, Betonimiehenkuja 4, Espoo, FIN-02150, Finland. (e-mail: marit.wennerstrom@gtk.fi)*
[2] *Geological Survey of Finland, Betonimiehenkuja 4, Espoo, FIN-02150, Finland. (e-mail: meri-liisa.airo@gtk.fi)*
[3] *Geological Survey of Finland, Betonimiehenkuja 4, Espoo, FIN-02150, Finland. (e-mail: tuija.elminen@gtk.fi)*
[4] *Geological Survey of Finland, Betonimiehenkuja 4, Espoo, FIN-02150, Finland. (e-mail: matti.pajunen@gtk.fi)*
[5] *Rockplan Ltd, Asemamiehenkatu 2, Helsinki, FIN-00520, Finland. (e-mail: juha.salmelainen@rockplan.fi)*

Abstract: Geological evolution of the crust is the major factor in modifying the technical properties of bedrock. The main purpose of this paper is to highlight the control of the ductile 1.9 - 1.8 Ga old Svecofennian tectonic pattern to brittle structures of bedrock. Findings of the study could be exploited in applications useful for urban infrastructural purposes. Three projects of the Geological Survey of Finland have been carried out in southern Finland, predominantly near the Helsinki Capital region, since the year 1998. Examinations have been based on detailed field observations (ca. 1500 studied outcrops) on lithology, ductile and semi-brittle to brittle faulting and jointing structures. Sophisticated aerogeophysical methods have been used in constructing the ductile crustal structure, on which the more brittle faulting and jointing have been bound. Geophysical methods for determining the regional distribution of brittle structures have been developed in these projects.

Two important fault sets characterize the study area. The older semi-brittle fault set may be linked to the latest Svecofennian deformation events. The later brittle faults form a uniform network in areas of low-angle structural trends or in regions of homogenous granitoids. In steeply deformed terrains brittle faults locally strengthened to intense fault zones. These brittle structures in addition to reactivated ductile to semi-brittle fault and shear zones form technically demanding zones of weakness.

In the Helsinki Capital region jointing geometry involves the control of older deformation on the development of joints and their orientation. At outcrops one joint set often parallels the main foliation course, especially in gneisses with steeply dipping strong foliation. The uniform occurrence of steeply dipping SE-NW and SW-NE trending joint sets implies a regional strain. The joint zones also follow these two regional trends. Combined geological and technical classifications of fracture zones and jointing properties are useful in civil engineering projects.

Résumé: L'évolution géologique de la croûte est le facteur le plus important de la modification des propriétés techniques du substratum rocheux. L'objet principal de cet exposé est de mettre en lumière le contrôle de l'ancien modèle tectonique svécofennien 1.9 - 1.8 Ga ductile sur les structures fragiles du substratum rocheux. Les résultats de l'étude seraient exploités dans des applications utiles à des fins d'infrastructures urbaines. Trois projets du Centre de recherches géologiques de Finlande ont été réalisés dans le sud de la Finlande, principalement près de la région capitale de Helsinki, depuis l'année 1998. Les examens ont été basés sur des observations in situ détaillées (environ 1500 affleurements étudiés) sur la lithologie, les structures de failles et de joints ductiles et de semi-fragiles à fragiles. Des méthodes aérogéophysiques complexes ont été employées dans la construction de la structure croûteuse ductile, à laquelle les failles et les joints plus fragiles ont été liés. Des méthodes géophysiques pour déterminer la répartition régionale des structures fragiles ont été employées dans ces projets.

Deux ensembles importants de failles caractérisent la zone de l'étude. L'ensemble le plus ancien de failles semi-fragiles peut être relié aux cas de déformation svécofennienne les plus récents. Les dernières failles fragiles forment un réseau uniforme dans les régions à tendances structurelles de faible angle ou dans les régions de granitoïdes homogènes. Dans des terrains abruptement déformés, des ensembles de failles fragiles produisent des zones de failles intenses. Ces structures fragiles ajoutées aux zones de failles et de cisaillements ductiles à semi-fragiles réactivées forment des zones de faiblesse techniquement difficiles.

Dans la région capitale de Helsinki, la géométrie de joints implique le contrôle d'une déformation plus ancienne jusqu'au développement des joints et à leur orientation. Aux affleurements, un ensemble de joints est souvent en parallèle avec le cours de foliation principal, en particulier dans les gneiss avec une forte foliation immergeant abruptement. L'existence uniforme d'ensembles de joints dirigés du sud-est au nord-ouest et du sud-ouest au nord-est immergeant abruptement suppose une déformation régionale. Les zones de joints suivent également ces deux tendances régionales. Les classifications géologique et technique combinées des zones de fracture et des propriétés des joints sont utiles dans les projets de génie civil.

Keywords: Ductile deformation, fractures, joints, airborne methods, classification, geotechnical maps.

INTRODUCTION

Geological evolution of the crust is a crucial factor in determining the technical properties of rocks and rock masses. However, the geological approach has not been emphasized enough as a basis for technical solutions and applications in promoting various activities in urban environments. The significance of careful analysis of geological field observations and geophysical data increases especially in the Precambrian Shield areas, where lithology and tectonic structures vary in a very complicated manner as a consequence of polyphase evolution of the crust. Careful lithological mapping accompanied by analysis of magmatic, structural and metamorphic research offers the possibility of constructing models for variation of technical properties in rock masses. Our approach concentrates predominantly on tectonic features like ductile deformation, shear and fault zones and jointing properties. These structures along with lithology predominantly define the regional factors that are important for several applications. This paper summarizes how by analysing the polyphase evolution of the 1.9-1.8-Ga-old Proterozoic Svecofennian crust was used to build up a regional overview on technical properties of rock masses in the vicinity of the Helsinki urban area in southern Finland (Figure 1). One of the main purposes was to develop proper components for geological mapping that are useful for different applications. These results were produced in three projects carried out in the Geological Survey of Finland (GTK) in 1998-2004 in co-operation with the cities of Helsinki Capital area, the Technology Agency of Finland and several private companies (Pajunen et al. 2001a and b). There are many activities in the society that could exploit the applied geological information, for example, underground construction and tunnelling, regional planning, prospecting for rock aggregates or water reserves, prognoses of toxicant transport in bedrock etc. This development work is still in progress, but some preliminary tests have already proved this kind of geologically data to be useful, for example, in underground construction and planning activities.

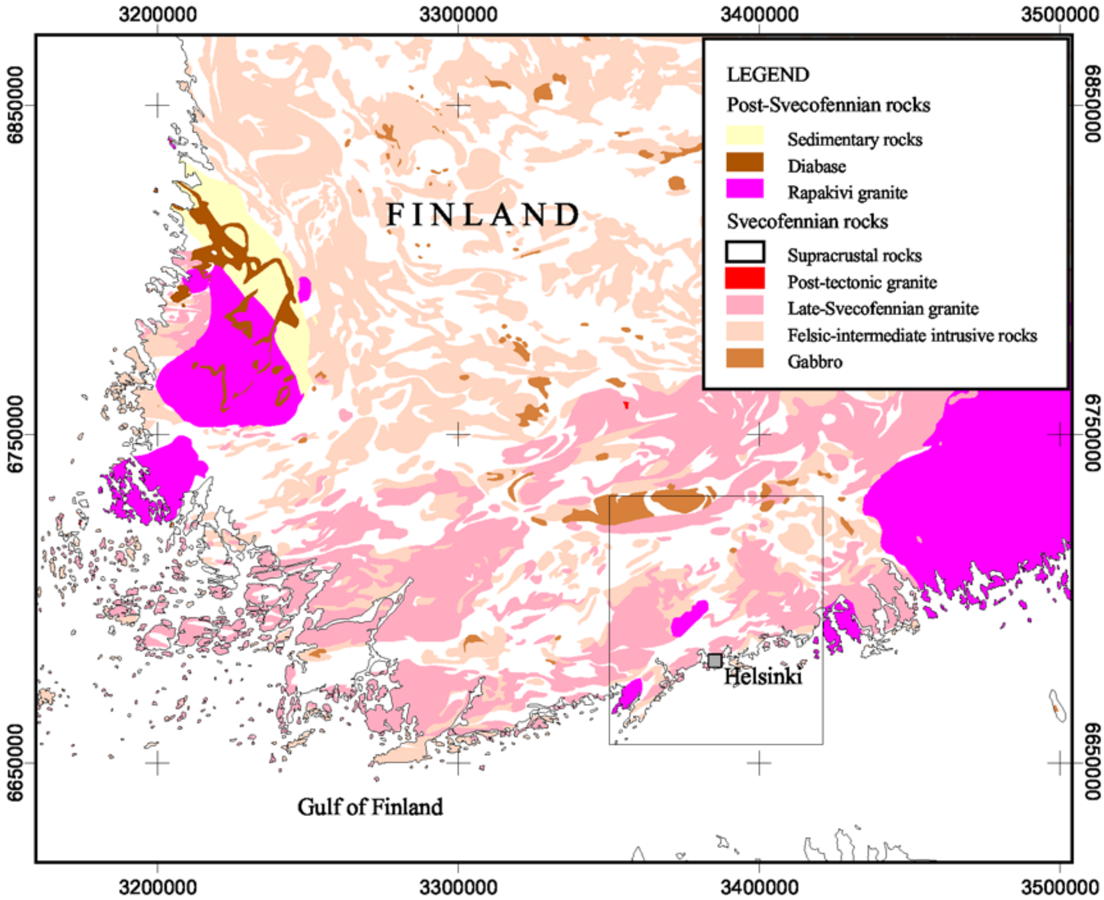

Figure 1. Location of the study area in southern Finland (box) modified from Koistinen et al. (2001)

DATA

The study is based on field observations on ca. 1500 outcrops, where comprehensive lithological and structural data were collected. Collected lithological data include normal lithological mapping of rock type and their age relations. In addition all the pre-existing geological maps and databases of the GTK were benefitted. Thorough information was collected on ductile structures to analyse the sequences of polyphase deformation events. The rough estimates of intensity of foliation versus lineation were done for average estimates on type and amount of strain. The structures were analyzed using the method of Hopgood (1999). Characterization of ductile structures forms the basis for terrane division for technical classification.

This study puts great attention on shearing and faulting structures at outcrops, because they, even though often minute, act as windows to the characters of the neighbouring covered zones of weakness. The type of fault rocks reflects the physico-chemical conditions at the time of their formation, and the characterizing properties can be identified in the microstructures of fault rocks (e.g. Wise et al. 1984 and Higgins 1971). The fault properties collected are fault rock type, fault dimensions and orientation, age relations, alteration processes and amount and trend of movement. Pre-existing rock mechanically classified tunnel data from zones of weakness were gathered for comparison and classification of observed faults.

Jointing properties were gathered from joint sets, namely, direction of joints in the joint set may vary 15º in strike and 20º in dip. The following properties of these joint sets, generally three to four sets at outcrops, were collected, that is, joint trace length, joint spacing, joint zone, joint set number, joint wall outline, joint wall roughness and joint type. These properties were chosen to correspond with the parameters in the Q system of engineering classification of rock masses (Barton et al. 1974). Whenever possible, the relationships of joints to other tectonic structures at outcrops were studied for further prediction of jointing patterns in neighbouring outcrops.

Geophysical airborne data was processed for regional analyses. Much weight was put on diminishing the non-geological noise and identifying brittle faulting and jointing features.

GEOLOGICAL BASIS FOR TECHNICAL ANALYSIS

Characteristics of Svecofennian orogeny

The Svecofennian bedrock in southern Finland shows a complex pattern of supracrustal and magmatic lithology formed in different events during the 100 million years crustal evolution (Figure 2). Post-tectonic granites at 1.8 Ga cut the ductile Svecofennian structures. Later thermal pulse at 1.65-1.5 Ga ago produced significant amounts of rapakivi granites and diabase dykes. Rift-related sedimentation was accompanied by diabase magmatism at 1.25 Ga ago. There are well documented evidences of fluid activity in pre-existing faults during the Caledonian orogeny (Vaasjoki 1977). Some faults in deformed bedrock and in the overlying post-glacial sequences have been associated with small-magnitude earthquakes indicating the occurrence of modern tectonic activity.

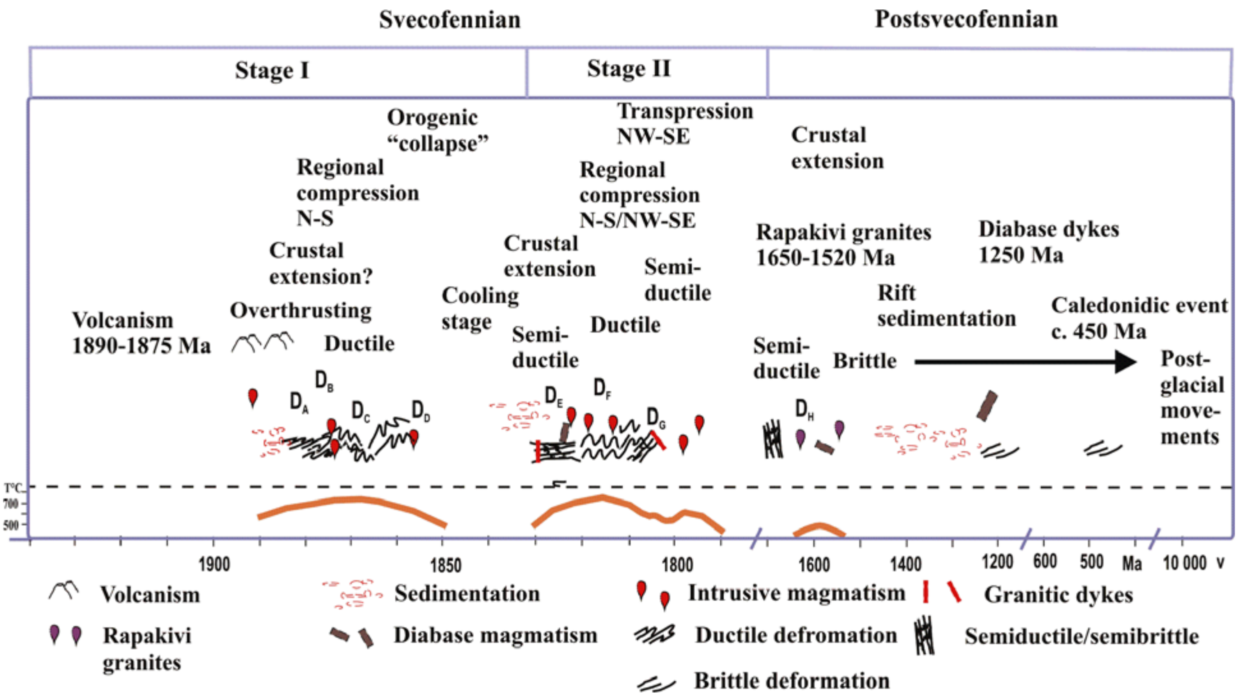

Figure 2. Geological evolution of the Svecofennian bedrock in southern Finland

The Svecofennian lithology is composed of predominantly migmatitic supracrustal gneisses representing various primary origins and varying intrusive rocks. The granitoids, granites, granodiorites and tonalites form in southernmost Finland a continuous 100 km wide, WSW trending zone. Several magmatic pulses occurred during the complex compressional, extensional and transpressional tectonic events. Magmatic rocks representing different stages differ in their composition and structure - the older ones are generally foliated and migmatitic medium-grained tonalites, whereas the later ones are less deformed granodiorites and granites, often pegmatitic or porphyritic in character. Strain, the amount of which can be approximated from the strengths of foliation, lineation and folding, is an important factor determining the anisotropy of rock masses, and along with the mineralogical composition it determines, for example, the breaking strength of rocks. Technical properties of intrusive rock material are related to tectono-metamorphic processes that existed during their formation. In particular, the latest Svecofennian granites and later rapakivis show quite homogeneous technical characters over wide areas. Conversely, the strongly foliated and folded supracrustal rocks are very variable and are technically more anisotropic. Supracrustal associations are composed of mafic to felsic volcanic rocks and widespread pelitic-psammitic mica gneisses. Although generally migmatitic, they still often show primary features that allow their origin to be established.

The Svecofennian tectono-metamorphic evolution in the study area consists of two major high to medium grade geotectonic stages (I and II) with a cooling stage in between them. The situation in Figure 2 is simplified, because conditions in the tectonically active crust varied with crustal depth. Deeper in the crust heat production was high and deformation was ductile with contemporaneous metamorphism and magmatism. Simultaneously, low-temperature brittle events like faulting and dyke formation occurred in the upper crust. A cooling stage between the main stages I and II was accompanied by the development of semi-brittle structures that, however, were mostly hidden by the later stage II high temperature processes. On the present erosion level the rocks from different crustal depths and representing varying tectono-thermal histories, are tectonically juxtaposed. The Svecofennian crust in the study area can thus be divided into differently developed terranes, which have rather coherent internal tectonic, metamorphic and magmatic characteristics. The technical classification of rock masses by using the jointing properties was fixed to these tectonically established terranes.

The terranes are bordered by high-strain shear zones and faults, which often appear as sub-linear valleys (lineaments) in the topography. During the latest events of the Svecofennian evolution, deformation turned to more partitioned semi-ductile shearing and brittle faulting. The Svecofennian major ductile shear zones generally were reactivated during the post-Svecofennian faulting events. These Svecofennian zones formed suitable locations for the later kinetic energy to dissipate. They represent nowadays the most important crustal zones of weakness, for example, the Porkkala-Mäntsälä polyphase shear/fault zone is a good example.

Shearing and faulting structures

Closure of the Svecofennian orogeny in the study area occurred at ca. 1.8 Ga ago. Due to temperature decrease, deformation changed from penetrative to more partitioned shearing and faulting. Tectonic movements occurred first along wider ductile shear zones and with decreasing temperature the tectonic movements were concentrated into narrower semi-ductile, semi-brittle and finally brittle faults. The results of fault movements vary also due to crustal depth (Figure 3). This fault deformation was caused by rapid tectonic uplift after the Svecofennian orogeny.

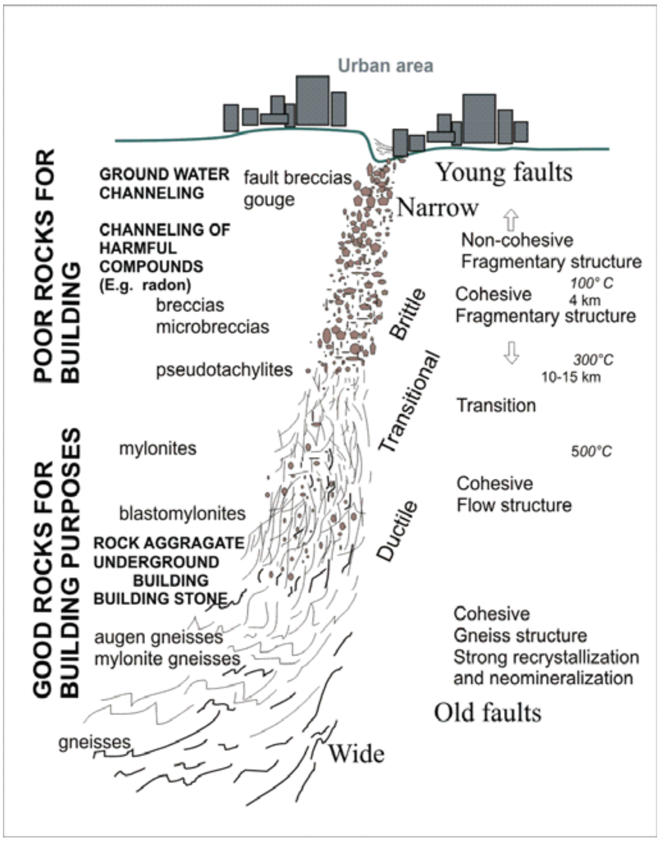

Figure 3. Fault profile with geological fault rock terminology and rock applicability. Our today bedrock surface has imprints of faults formed since Svecofennian times, so they represent different crustal levels

Metamorphic observations and dating information establish ca. 3-6 km of tectonic erosion from the latest Svecofennian metamorphic peak, which occurred at a depth of ca. 12-15 km, to the post-orogenic granite event. The intrusion depth of rapakivis was ca. 5 km (Figure 2) (cf. Korsman et al. 1999). Brittle faults in rapakivis and faults bordering the rift-related sandstones offer evidence of still later intense faulting movements.

The earlier researches were mainly based on lineament analyses of fault patterns in the crust using satellite images or topographic and geophysical maps (Aarnisalo 1978 and Härme 1961). The first attempts to link different type fault rocks and structures to the regional structural succession were presented by Pajunen (1986). Ploegsma (1991) gave detailed descriptions and isotopic datings for the faults in Suomusjärvi close to study area. The regional pattern of shear zones and faults in the study area was constructed by using processed topographic and geophysical maps along with the field observations and microscopic analyses of fault rock characteristics. According to field observations several different types of faults were identified; certain types of faults were concentrated in certain directions that means that their kinematic setting is somehow systematic. The kinematic analysis of the fault systems is in progress and the first results provide evidence of least two major extensional faulting events in the area. There is a direct connection of fault types to different applications, foe instance, brittle fault zones are often good water conductors, but may cause problems in underground construction, whereas certain ductile shear zones locally represent first class rocks for aggregates (Figure 3). The fault types identified in the study area, based of 460 fault observations in the field, are as follows:

- Porkkala-Mäntsälä shear/fault zone: Major, steep, NE-trending shear zone; mylonite gneisses to breccias; alteration and weathering; slickenside planes; large regional sinistral bend of structures; polyphase, roots in Svecofennian ductile deformation (D_{F-G}) and reactivation continuing during the rifting-stage at 1.25 Ga ago; > 20 km long; generally < 1 km in width including undeformed slices.
- SZ_{1a}: Svecofennian, steep, ductile, ENE trending shear zones and faults; mylonites; generally <10 km long.
- SZ_{1b}: Svecofennian, steep, ductile, E trending shear zones and faults; mylonites; polycataclastic - overprinted by SZ_3 with slickensides and local gouge; early foliation bends into zones; on average 1-2 km long; generally <2m wide.
- SZ_{2a}: Late-Svecofennian, steep to moderate, semi-ductile, NNE trending shears/faults; mylonites, ultramylonites and pseudotachylites; Reactivation in SZ_{2b}–phase: breccias; slickensides; locally straight jointing along the large faults; 5-15 km long zones, often fragmented; generally >2m in width.
- SZ_{2b}: "Rapakivi-related", steep to moderate, semi-brittle, NE and NNE trending faults; breccias, slickensides overprinted by SZ_{3b}; on average 10 km long; generally up to 5 m wide.
- SZ_{3a}: "Rapakivi-related", steep, brittle, NW and WNW trending faults; breccias, fault breccias and joint zones; often related to diabase dykes of the rapakivi-stage; on average 4 km, sometimes 10 km long; 2 m several 5-20 m wide.
- SZ_{3b}: Steep brittle N trending faults; fault breccias and joint zones; overprints ductile to semi-brittle shears/faults; dimensions not established with respect to SZ_2.
- SZ_4: Late low-angle - dip <45º, brittle faults with dipping directions of 10º, 100º, 190º and 280º; fault breccias, alteration and weathering; up to several kilometres long, but not coherently; width 1.5-4 m, sometimes up to 11m.

These shear and fault zones represent the major zones of weakness in the area and their technical classification was based on the described field characteristics and dimensions along with the some rock mechanical data (see below).

Jointing

According to Grad and Luosto (1992) the fractured bedrock continues in the Finnish Precambrian to a depth of ca. 1-2 km. Research work on jointing properties in Finland has mostly concentrated on local sites of investigation (Paulamäki & Koistinen 1991, Anttila 1992 and Anttila et al. 1999). The first regional approach to link jointing patterns to the Svecofennian ductile structure was done by Pajunen et al. (2001a) in the Pori area. In this study the geophysical airborne magnetic data was processed to highlight the weak brittle fracturing features. The data was correlated with the observed jointing patterns in the field. The method turned out useful especially when the anomalies define the areas of contrasted anomaly patterns caused by ductile structures.

It is already an old observation that the major "lineaments" in the Finnish Precambrian bedrock often show a systematic setting into NE and NW directions. These directions also characterize the jointing pattern in the study area, the joints occurring independently of the lithology in the area. The systematic array of joints postulates generation by a very homogeneous stress field, which affected a large area, but the tectonic event causing the pattern is not so far known.

Several observations show that tectonic structure defines the orientation of jointing (e.g. Pajunen et al. 2001a and b); for example, in the study area the NNE trending joints are related to the SZ_2-faults in the same direction. Mostly the joint density increases when approaching the major faults. Thus, the observations on joint directions and densities could give us information on the hidden zones of weakness. In the strongly foliated rocks, like in the gneisses and mylonite gneisses of the Porkkala-Mäntsälä zone, there is generally a joint set following the foliation planes. In the Pori area there is normally dense jointing perpendicular to the strong Svecofennian stretching lineation (Pajunen et al. 2001a), but due to the different strain pattern in the study area such lineation is generally weak and similar relations are not established. The jointing pattern in the homogeneous granitoid areas is more systematic and is characterized by long horizontal joints and joint zones. The horizontal joints following the preset erosion level in large road cuts postulate their generation by late (post-glacial?) release of load pressure.

There are preliminary observations on the kinematic control of joints by the faults of the rapakivi-stage (SZ_{2-3}). At least the joints, sometimes a bit altered, that lie in the same direction and are outcropping in the same terrane as the constantly WNW oriented rapakivi-related diabase dykes, suggest that at least at 1.65 Ga ago the bedrock behaved in so brittle way that jointing was able to form. The decrease in temperature after the Svecofennian orogeny was quite rapid and faulting deformation became more brittle. It is thus very plausible that some kind of initial jointing was generated already at this very early stage.

FROM GEOLOGICAL TO TECHNICAL CLASSIFICATION

It is a demanding challenge to transform geological observations in such a way that they are useful in applied purposes. Our approach was to form classifications compatible with the pre-existing rock mechanical classifications for zones of weakness (RG) (Gardemeister et al. 1976) and the Q system for joints (Barton et al. 1974). In practice there was only limited possibilities to collect all such data necessary for these classifications from the outcrops polished by glacial ice characteristic in Finland. Only road cuts and quarries are suitable for collecting such data.

Fault structures

Classification of observed geologically classified faults was based on the RG classification modified for Finnish rocks by Gardemeister et al. (1976). The fault observations at outcrops were correlated with the corresponding fault structures in tunnels, where technically classified data includes much information that is difficult to obtain during mapping, for example, data on water flow, alteration, fracture filling (e.g. clay minerals) or weathering properties. The principles for the technical classification of zones of weakness into three classes are shown in Table 1. If there is decreasing the rock strength at the outcrops, brittle and altered fault rocks, large water flow, cross-cutting faults or dense joint sets, the quality class of zone is decreased. Also information on thickness of soil cover was taken into account in establishing and classification of zones of weakness.

Table 1. Typical properties of faults zones in different technical classes. Class 1 is the most intact, class 3 is the most fractured. Rp and Ri abbreviations concern the Finnish RG classification (Gardemeister et al. 1976).

Class	**Rock structures affect on**		
	Blasting/quarrying	Stabilization	Stopping
1	Rock quality non-weathered or slightly weathered, (Rp0-1). Joints open or filled by clay. Joints with slickensides. Small joint openings (<2 mm). Rock quality RiIII-RiIV	Moderate block size, (>30 dm^3). Clearly visible jointing system. Small dimensions of zone, (<2 m)	Small water conductivity of jointing. Small underground water pressure
2	Rock quality slightly or strongly weathered, (Rp1-2). Joints open or filled by clay. Joints with slicken- sides. Moderate joint openings (2-5 mm).Rock quality RiIV	Moderate-small block size, (30-10 dm^3). Weakly visible jointing system. Moderate dimensions of zone, (2-5 m)	Moderate water conductivity of jointing. Moderate underground water pressure
3	Rock quality strongly or penetratively weathered, (Rp0-1). Joints open or filled by clay. Joints with slickensides. Small joint openings (<2 mm). Joints filled by rock grains or clay. Wide joint openings (>5 mm). Rock quality RiIV-RiV	Small block size (<10 dm^3). Jointing system not visible. Large dimensions of zone (>5m)	High water conductivity of jointing. High underground water pressure

The geologically classified shear zones and faults are used in the classification in the Table 2. The classification of the observed zones was established to describe the worst possible rock quality, whereas the zones without such information were classified using the criteria in Table 1. Figure 4 shows the faults in the study area classified according to these technical properties. They were classified into two categories: zones of weakness with observed properties are separated from those predicted from corresponding data nearby using geophysical airborne, topographic and structural information.

Our observations show that it is not possible to characterize and predict the technical properties of the zones of weakness by using only the dimensional information that is easy to compile from topographic or geophysical maps. The evolution of shear/fault zones differ remarkably from place to place and from direction to direction. Faults may be polycataclastic showing a very complex internal structure or they may be simple faults with solid totally recrystallized structure - their technical properties are absolutely different. For example, in the study area the 2-5 km long SZ_{1a}, SZ_2, SZ_{3b} faults are mostly class 1, whereas the SZ_{1b} faults of same dimensions are class 2. Thus, it is not possible to attain reliable information from the shear/fault structures from the less known areas without geological observations. The possibilities improve a lot if there is reliable data on the kinematics of faulting and good information on the present stress field of the area. Unfortunately, this kind of kinematic analysis needs careful research and comprehensive data on the major fault structures; this is certainly a time-consuming process, but when done it gives possibilities to make interpretations for quite large areas and for different applications.

Table 2. Table for determining the technical class of a fault. The RG classification (geotechnical properties, Gardemeister et al. 1976) varies in different geological fault classes (SZ). By combining the geological classification, and the dimension for the fault in question, the technical class can be estimated.

SZ class	**PM-zone**	**SZ_{1a}**	**SZ_{1b}**		**SZ_{2a}**	**SZ_{2b} and SZ_{3b}**	**SZ_{3a}**		**SZ_4**
RG-classification	Strongly weathered and fractured	No tunnel observation	Rp1-3 RiIII-IV		Rp1-2 (3) RiII / IV	Rp0-2 RiIV-V	Rp1-2 RiIII-IV		Rp0-2 RiI-V
Water			Minute		Moderate	Minute	Rather abundant		Rather abundant
Size--> Technical class		**Length**	**Width**	**Length**	**Length**	**Length**	**Width**	**Length**	**Width**
1		2-5 km	< 2 m	< 2 km	2-5 km	2-5 km	< 2 m	< 2 km	< 1 m
2		> 5 km	2-5 m	2-5 km	> 5 km	> 5 km	2-5 m	2-5 km	1-2 m
3	always class 3	> 5 km + factors decreasing class	> 5 m	> 5 km	> 5 km + factors decreasing class	> 5 km + factors decreasing class	> 5 m	> 5 km	> 2 m
Other properties	(Properties from the drilling data)		If fault breccia, strong alteration or weathering exist the primary class is decreasing						

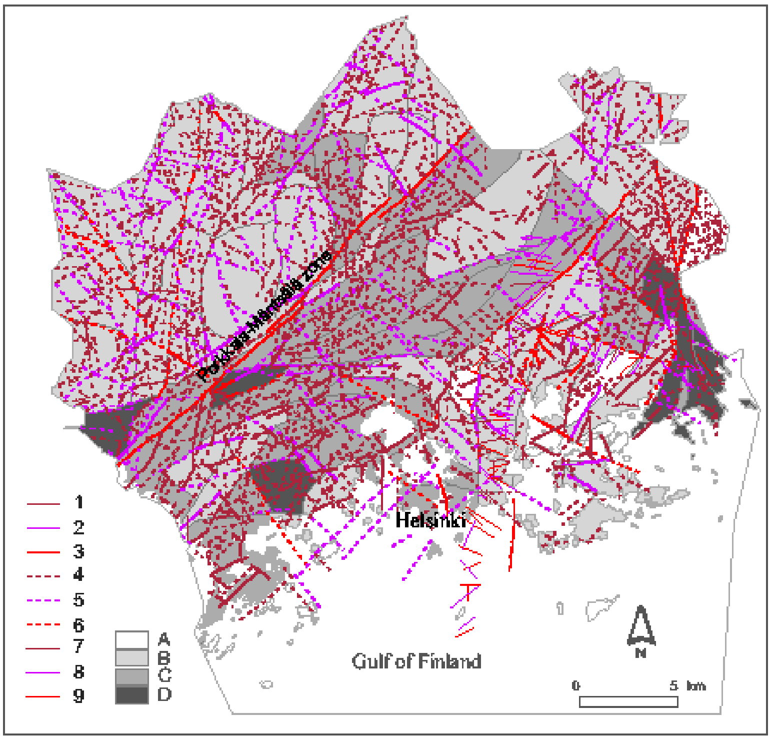

Figure 4. Classified zones of weakness (1-3 observed properties; 4-5 interpreted; 7-9 tunnel data; colours refer for the degree of brokenness, brown is the most intact) and jointing properties (from A to D brokenness increases)

Jointing

As an example of the construction potential of bedrock, jointing data of ca. 2420 joint sets on 700 outcrops were used. They represent a uniform observation net that was planned to cover all the different geotectonic terranes (see above) in the study area. The classification of observation points was based on three main properties, that is, spacing of jointing, joint trace length and the number of joint sets. The class limits for the quality factors were picked from the statistically analyzed distributions for these properties. The construction potential, quality classes based on the main properties decreased, if there were some other predominant quality-decreasing properties at the outcrops. These are tightly spaced jointing, slickenside planes, open jointing, planar jointing, smooth jointing, intensely altered or strongly weathered joint surfaces and clay- or soil-filled or weathered joints. The rock quality of the terrains was classified accoirdong to their jointing properties into four classes A, B, C and D (Table 3, Figure 4).

Table 3. Classification of jointing

Class	**A**	**B**	**C**	**D**
Spacing	> 1 m	> 0.5 - 1 m	0.5 - 0.3 m	< 0.3 m
Length	< 10 m	< 10 m	< 20 m	> 20 m
Number of sets (s=random)	1-2 (Jn: 2-4)	2+s or 3 (Jn: 6-9)	3+s (Jn: 12)	4 -> (Jn: 15)
Slickenside (appear)	No	Single	Moderate	Numerous
Tightly spaced	no	If predominates class decreases	If predominates class decreases	
Other properties	no	If predominates class decreases	If predominates class decreases	

Regional distribution of the rock quality is shown in Figure 4. This concept does not tell the fracturing pattern fixed in certain directions, but gives an overall concept of the quality of rock masses. If we want to reliably predict the jointing patterns in new areas we need information on kinematic relationships between joints and ductile and faulting structures. As noted, these are preliminary observations on the systematic array of joints within some faults and strongly lineated zones.

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Corresponding author: Mrs Marit Wennerström, Geological Survey of Finland, Betonimiehenkuja 4, Espoo, FIN-02150, Finland. Tel: +358 2055020. Email: marit.wennerstrom@gtk.fi.

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