

## Late Svecofennian shear zones in southwestern Finland

MARKKU VÄISÄNEN<sup>1</sup> and PIETARI SKYTTÄ<sup>2</sup>

Väisänen, M. & Skyttä, P., 2007: Late Svecofennian shear zones in southwestern Finland. *GFF*, Vol. 129 (Pt. 1, March), pp. 55–64. Stockholm. ISSN 1103-5897.

**Abstract:** The bedrock of southwestern Finland is transected by a shear zone network with two dominant directions: ~E–W and ~N–S. The shear activity occurred after peak metamorphism and crustal melting at 1840–1810 Ma. The shear zones began to form as a consequence of north vergent oblique continent–continent collision and accommodated the resulting dextral transpression. The 150–200 km long ~E–W oriented Somero and South Finland Shear Zones acted as dextral strike-slip faults, while the crustal unit between them was transported westward and deformed along the ~N–S oriented reverse faults. The main deformation within these contractional shear zones took place at 1.81–1.79 Ga. After that, extensional faulting took place, tentatively at 1.79–1.77 Ga, 1.64–1.55 Ga and 1.26 Ga.

**Keywords:** contraction, extension, ductile shearing, pseudotachylite, shear sense, strike-slip, transpression, Palaeoproterozoic, Fennoscandian Shield.

<sup>1</sup>Department of Geology, FI-20014 University of Turku, Finland; markku.vaisanen@utu.fi

<sup>2</sup>Geological Survey of Finland, FI-02151 Espoo, Finland; pietari.skytta@tkk.fi

Manuscript received 9 June 2006. Revised manuscript accepted 12 March 2007.

### Introduction

Shear zones are defined as planar or curvilinear zones of intense non-coaxial deformation transecting rocks of lower strain. Depending on temperature, pressure, strain rate and rock composition, localised deformation can produce ductile, brittle-ductile or brittle shear zones (e.g. Ramsay & Huber 1987). The scale of shear zones varies from subgrain-scale to continental-scale; the most prominent may represent present or fossil plate boundaries. Shear zones can provide valuable information on the kinematics of transported crustal blocks, while the less strained areas between the shear zones can be passively transported and may provide little or no evidence of tectonic movements. The progress in understanding kinematic indicators within shear zones (e.g. Simpson & Schmid 1983) provided new methods for studying large-scale tectonics and therefore significantly contributed e.g. to the discovery of lateorogenic extensional collapses since compressional vs tensional deformation became easier to distinguish (e.g. Dewey 1988).

The interest in shear zones in the Svecofennian Domain of the Fennoscandian Shield has steadily increased. Earlier, generally only continental-scale structures were considered (e.g. Halden 1982; Berthelsen & Marker 1986) but later, also single shear zones or shear zone networks have been studied in more detail (e.g. Ploegsma 1989; Kärki et al. 1993; Pietikäinen 1994; Nironen 1995; Talbot & Sokoutis 1995; Heeremans et al. 1996; Lonka et al. 1998; Väisänen & Hölttä 1999; Högdahl & Sjöström 2001; Pajunen et al. 2001; Persson & Sjöström 2003; Torvela & Annersten 2005; Bergman et al. 2006).

In this paper we shortly review previous investigations and present new data on the shear zones in southwestern Finland. The zones in question are mainly steep-dipping and post-date the peak metamorphism in that area. The main emphasis is on

the kinematics and the regional tectonic significance of the shear zones.

### Geological setting

The bedrock of southern Finland belongs to the Southern Svecofennian Arc Complex (SSAC in Fig. 1A; Väisänen et al. 2002), one of the at least three separate terranes that accreted to form the Palaeoproterozoic Svecofennian Orogen in Finland (Rämö et al. 2001). The SSAC consists of two volcanic belts: the Uusimaa belt and the Häme belt intervened with sedimentary basins (Fig. 1B). The age of volcanism within the SSAC is dated between 1.90–1.88 Ga (Patchett & Kouvo 1986; Vaasjoki 1994; Reinikainen 2001; Väisänen & Mänttari 2002; Ehlers et al. 2004; Skyttä et al. 2005). It is inferred that the SSAC collided with the Central Svecofennian Arc Complex (CSAC) at ~1.87 Ga (Väisänen et al. 2002; Ehlers et al. 2004). In the CSAC, the deformation ceased at that time and gave way to post-kinematic A and C-type magmatism (Nironen et al. 2000). In the SSAC, an extensional stage at 1.86–1.84 Ga was followed by a younger period of continent–continent collision (the Svecobaltic orogeny), which caused further crustal shortening (Lahtinen et al. 2005). The resulted regional upright folding and thrusting was simultaneous with high heat flow at low pressures that caused the production of granites and migmatites as crustal melts at 1.84–1.81 Ga (Huhma 1986; Schreurs & Westra 1986; Korsman et al. 1999; Väisänen & Hölttä 1999; Väisänen et al. 2002; Jurvanen et al. 2005; Kurhila et al. 2005; Mouri et al. 2005). Therefore, the zone is also called the Late Svecofennian Granite–Migmatite Zone (LSGM, Ehlers et al. 1993). An extensional tectonic setting for the LSGM has also been proposed (Korja & Heikkinen 1995;

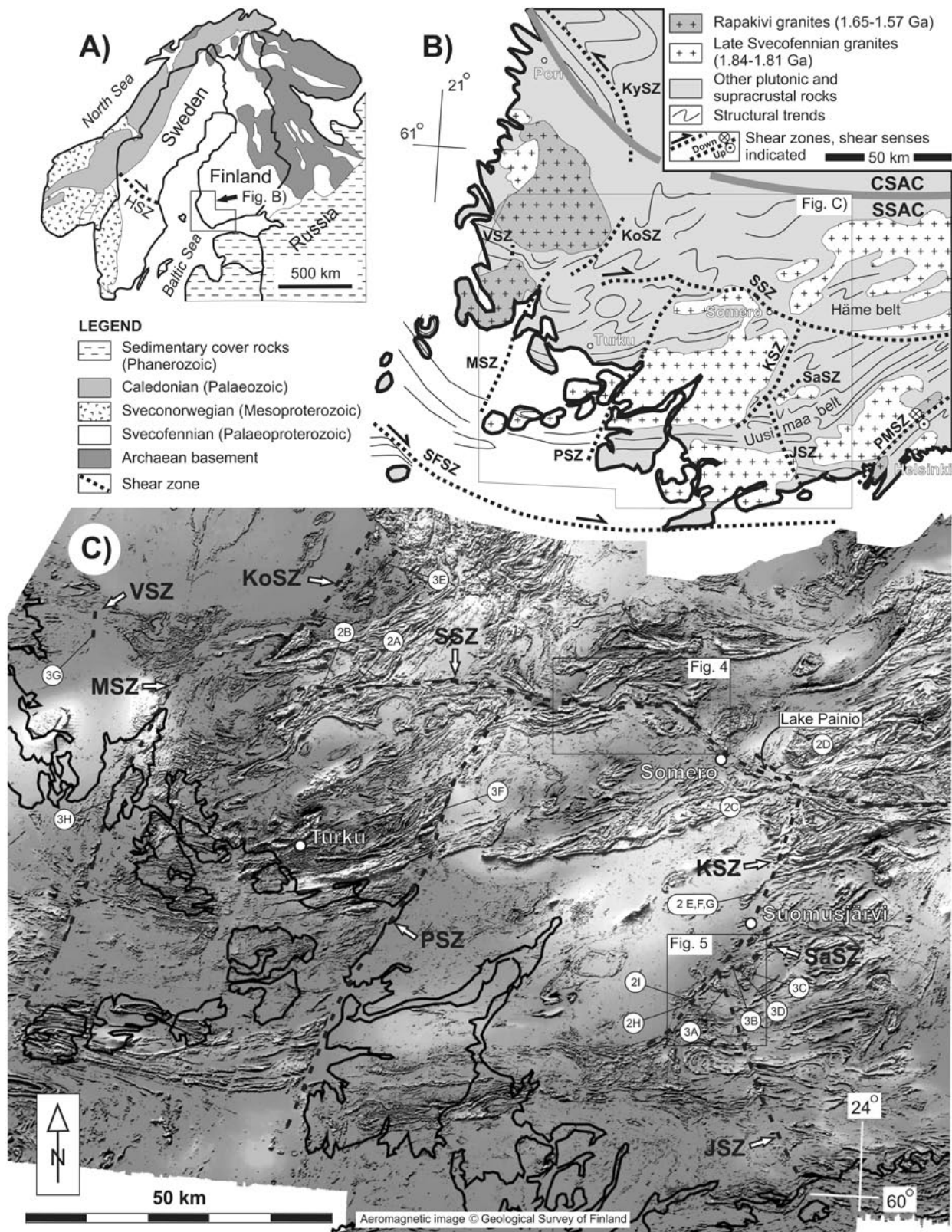


Fig. 1. **A.** An overview of the geological units in the Fennoscandian Shield. HSZ – Hassela Shear Zone (Högdahl & Sjöström 2001). **B.** Generalized geological setting of shear zones in SW Finland. JSZ – Jyly Shear Zone, KSZ – Kisko Shear Zone, KoSZ – Kolinummi Shear Zone, KySZ – Kynsikangas Shear Zone, MSZ – Mynälahti Shear Zone, PMSZ – Porkkala-Mäntsälä Shear Zone, PSZ – Paimio Shear Zone, SSZ – Somero Shear Zone, SaSZ – Salittu Shear Zone, SFSZ – Southern Finland Shear Zone, VSZ – Vellua Shear Zone; CSAC – Central Svecofennian Arc Complex, SSAC – Southern Svecofennian Arc Complex. The thick gray line separating the SSAC and CSAC drawn after Lahtinen (1996). **C.** Low-altitude aeromagnetic map of SW Finland showing the locations and signatures of the shear zones described in this study. Sample sites for the thin sections in Figs. 2 and 3 as well as the locations for Figs. 4 and 5 are indicated.



Nironen 1997). Only small volcanic areas, like the Orijärvi-Keimiö and Enklinge areas were not migmatized (Ehlers & Lindroos 1990; Ploegsma & Westra 1990; Skyttä et al. 2005).

## Shear zones in southwestern Finland

The models for the Svecofennian Orogen in southern Finland emphasize tectonic movements in various stages of the orogeny along gently and steep-dipping zones of ductile deformation, i.e. shear zones (SZs). The early stages of the Svecofennian deformation at ~1.88–1.86 Ga (Väisänen et al. 2002) have been explained by thrust tectonics and stacking of crustal piles during north-vergent deformation. These hypotheses are mainly based on observed recumbent folding (Van Staal & Williams 1983; Ehlers et al. 1993; Korsman et al. 1999; Väisänen & Hölttä 1999) but no major early Svecofennian thrusts have been described so far. After the intervening extensional period at 1.86–1.84 Ga the deformation is related to the post 1.84 Ga convergence (Lahtinen et al. 2005). After the main folding and crustal melting, strain was localised into post-metamorphic steep shear zones that deform the migmatites and granites (Ploegsma 1989; Nironen 1999; Väisänen & Hölttä 1999).

For shear sense determination, we used both field and thin section observations and utilized the methods described e.g. by Passchier & Trouw (1996). It must be emphasized that the shear zones are poorly exposed and many of the conclusions are made on scattered outcrop information. Aeromagnetic maps have therefore been a great supplement to infer the extension of the zones (Fig. 1C).

### Previously investigated major shear zones

*The Kynsikangas Shear Zone (KySZ).* – The KySZ is a major NW–SE zone, among several shear zones in the Pori area. Pietikäinen (1994) and Pajunen et al. (2001) described it as a sinistral strike-slip zone, that later experienced extensional normal faulting. The area evidently has a long history of shearing at different stages (Pajunen et al. 2001).

*The Porkkala-Mäntsälä Shear Zone (PMSZ).* – The PMSZ is a prominent NE–SW shear zone ~20 km east of Helsinki. Heeremans et al. (1996) concluded that field evidence clearly showed that the PMSZ was active during the intrusion of the 1.64 Ga Obbnäs rapakivi granite. Ar/Ar dating, however, yielded 200–250 Ma younger ages (Heeremans & Wijbrans 1999). Elminen et al. (2006) described multistage shearing with initial reverse E-side-up ductile deformation later overprinted by extensional brittle deformation related to the 1.64 Ga magmatism.

*The South Finland Shear Zone (SFSZ).* – The SFSZ is a ~200 km long, E–W shear zone offshore the southern Finland coastline. It is mainly exposed on the islands in the archipelago of SW Finland and continues to eastern Åland where it turns into a NW orientation. The dextral strike-slip with a minimum along-strike displacement of 20 km accommodated the roughly NW–SE compression in a transpressional tectonic setting (Ehlers et al. 1993; Torvela & Annersten 2005). Ehlers et al. (2004) dated the associated intrusive rocks in the shear zone and concluded that the maximum age is provided by strongly deformed ~1865 Ma mafic dykes and the waning stage of deformation by a 1790±6 Ma cross-cutting only weakly deformed granite dyke.

### Shear zones investigated in this study

*The Somero Shear Zone (SSZ).* – The SSZ, previously locally called the Painio shear zone (Stel et al. 1989) and the Riihikoski shear zone (Väisänen & Hölttä 1999), is a major E–W anastomosing vertical to subvertical shear zone located ~100 km north of the SFSZ. It is distinct on the aeromagnetic maps where it can be traced more than 100 km, reflecting its regional significance. In the west the coherent main zone splays into several ENE–WSW discontinuous minor shear zones. We interpret the latter as an imbricate fan at the termination of the shear zone. These minor shear zones are shown in more detail on the geological map of the area (Väisänen 2007). The main SSZ and all the splays show subhorizontal lineations on the mylonitic foliations and they all consistently show dextral kinematic indicators (Fig. 2A and B, and also fig. 5a in Väisänen & Hölttä 1999). Opposing this, Nironen (1999) describes the SSZ as a sinistral shear zone.

In the central part of the SSZ, east of the town Somero where the zone strikes NW–SE, two approximately parallel shear zones 2.5 km apart were identified. The southern one, the main SSZ, displays vertical lineations on mylonitic foliations and kinematic indicators show S-side-down movement direction (Fig. 2C). The northern zone, north of Lake Painio, has a well-developed S–C fabric and an opposite S-side-up movement direction (Fig. 2D). The variable kinematic indicators clearly demonstrate that the tectonic movements along the SSZ zone are complex.

We have no data on the SSZ further to the east of the Somero area.

*The Kisko Shear Zone (KSZ).* – The KSZ is a prominent NNE–SSW striking vertical to steeply E-dipping high strain zone that can be followed ~50 km from Lake Kirkkojärvi in the south towards the north-northeast where it apparently terminates at the SSZ. In the field it consists of several parallel zones intervened with less deformed rocks. The shearing has resulted in protomylonites, mylonites and ultramylonites, which are overprinted by fractures and joints. Concordant and discordant veins of pseudotachylite also exist (Fig. 2E). Lineations on the steep mylonitic foliations are consistently steeply plunging. In addition, there are NE–SW shear zones following the main structural grain, which are considered splays from the main KSZ. Asymmetric right-handed folds associated to the splays suggest a dextral horizontal component.

In general, E-side-up kinematics were prevalent within the KSZ, as observed both in the field (Fig. 2F) and in the thin sections (Fig. 2G). At the same locality with Fig. 2E, one thin section out of the fourteen investigated showed an obvious opposite shear sense. In the southern end of the KSZ a granite dyke with a gently east-dipping mylonitic fabric was also detected. Subhorizontal stretching lineation and asymmetric features indicated top-to-WNW shear (Fig. 2H). However, just one kilometre to the north, at the eastern margin of the KSZ, E-side-down kinematics were also indicated from several thin sections (Fig. 2I). At Suomusjärvi road cut, the same locality studied by Ploegsma (1991) and Lonka et al. (1998), symmetric structures are dominant and we could not determine unambiguous shear senses. Some indicators showed contradictory shear directions, even in the same thin section. We interpret this to indicate pure shear deformation (shortening) with negligible simple-shear components.

Pseudotachylites cross-cut even the joints (Fig. 2E), and therefore indicate a late reactivation of the KSZ.

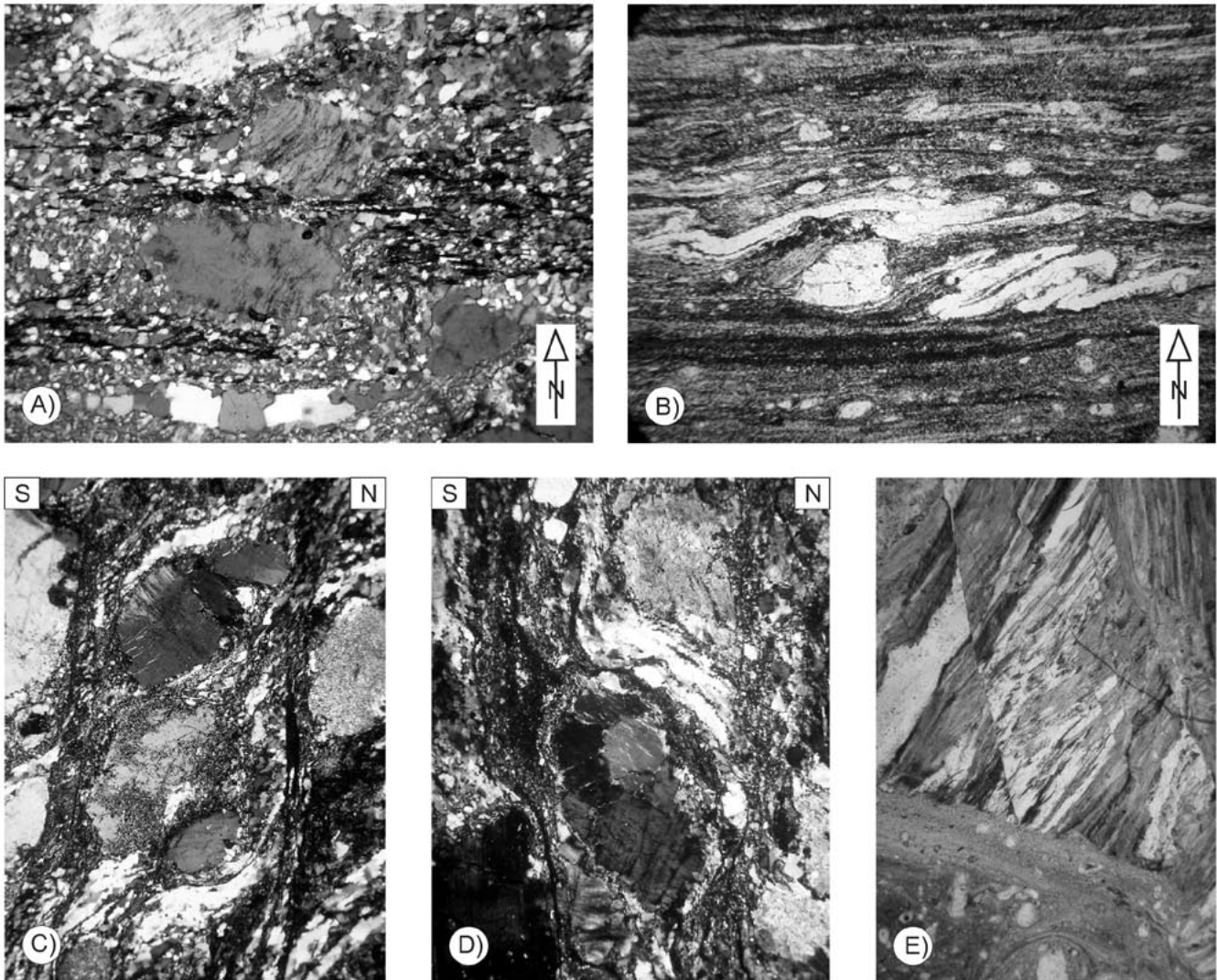


Fig. 2. **A.** Thin section of a mylonite from a granite in the main SSZ shows dextral stair-stepping and S-C structures. Horizontal section. Base of the photo is 5 mm. **B.** Intramytonitic folds, feldspar porphyroclasts and stair-stepping in a granodiorite all show dextral shear sense in the horizontal thin section from one of the splays out of the SSZ. Base of the photo is 2 mm. **C.** A granite with well-developed S-C structure and oblique recrystallized quartz grains in a vertical thin section from the SSZ showing S-side-down shear sense. Base of the photo is 3 mm. **D.** Well-developed S-C structure and asymmetric K-feldspar porphyroclasts in a thin section of a granodiorite from the northern SSZ shows an S-side-up movement sense. Vertical section. Base of the photo is 5 mm. **E.** Ductile mylonite in felsic volcanic rock overprinted by brittle microfaults (on the top), both later cross-cut by a pseudotachylite vein (at the bottom). Base of the microphotograph is 4 mm. KSZ.

*The Jyly Shear Zone (JSZ).* – The JSZ is a few kilometres wide network of ~N–S to NNW–SSE shear zones (Fig. 5) that can be traced approximately 35 km from the southern coastline to the join with the KSZ in the north. Four approximately parallel mylonitic zones were recorded in the field, intervened with apparently less deformed domains composed of folded rocks (Skyttä et al. 2006). The mylonite zones are here referred to as the Jyly I (westernmost), II, III and IV (easternmost).

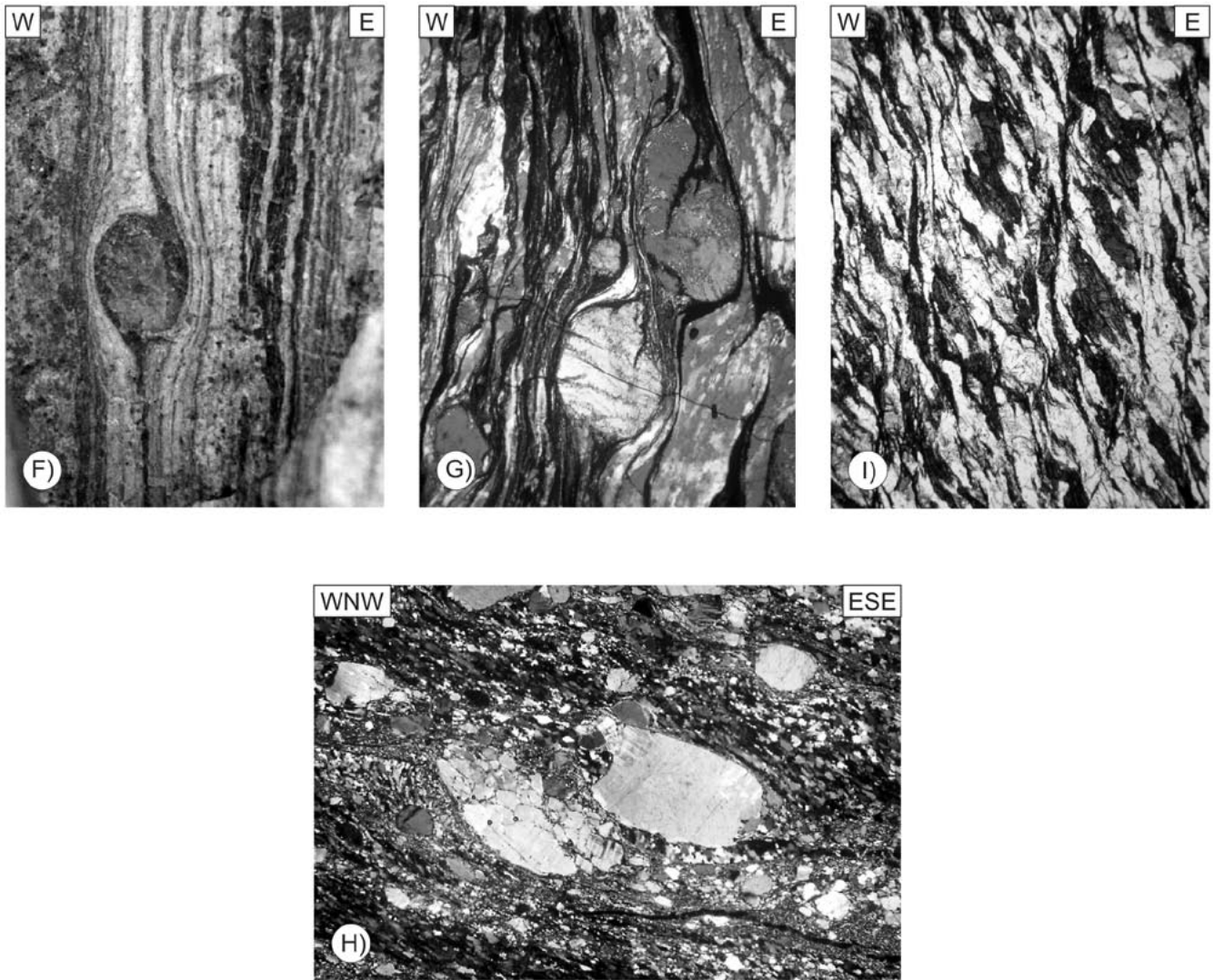
The JSZ I is considered as the main shear zone, since it is the widest (a few hundred meters) and also easiest to observe in the field as a terrain depression partly filled with elongate small lakes. It is vertical to steeply E-dipping and affects the 1.84–1.81 Ga granites common in the surroundings. Mylonitic lineations are plunging steeply. Kinematic indicators show consistent

E-side-up movements (Fig. 3A). Sillimanite was occasionally found on the shear planes indicating high temperatures at low pressure conditions. Also Ploegsma (1989) reported the presence of sillimanite in his study.

The JSZ II is an approximately 100 m wide vertical zone, also with steep stretching lineations. Shear zone rocks range from protomylonites to cataclasites. Most of the samples show E-side-down kinematics (Fig. 3B), but in one thin section the opposite movement was observed.

The JSZ III is dipping 60° to the east and occurs within mafic and ultramafic volcanic rocks. Shearing is most obvious in granite dykes. Stretching lineation plunges down-dip and the rocks contain many different kinds of kinematic indicators consistently showing E-side-up shear sense (Fig 3C).





**F.** A felsic volcanic rock containing sigma-shaped porphyroclast of quartz with well-developed asymmetric wings shows an E-side-up shear sense. Vertical section. Clast is c. 8 mm long. Outcrop photo. KSZ. **G.** Asymmetric feldspar porphyroclasts, shear bands and oblique grains in a granite all show a consistent E-side-up shear sense. Vertical section. Base of the photo is 3 mm. KSZ. **H.** Stair-stepping and oblique grains in granite show a top-to-WNW shear sense. Vertical section. Base of the photo is 5 mm. KSZ. **I.** Shear bands in a mafic volcanic rock reveal the E-side-down shear sense at the eastern border of the KSZ. Vertical section. Base of the microphotograph is 3 mm.

The JSZ IV was observed at one locality where a NNW–SSE trending, W-dipping shear zone affected a granite dyke. Kinematic indicators show a W-side-up shear sense, i.e. opposite to the main shear sense within the JSZ. Like in the JSZ I, the mylonite has sillimanite on the shear planes.

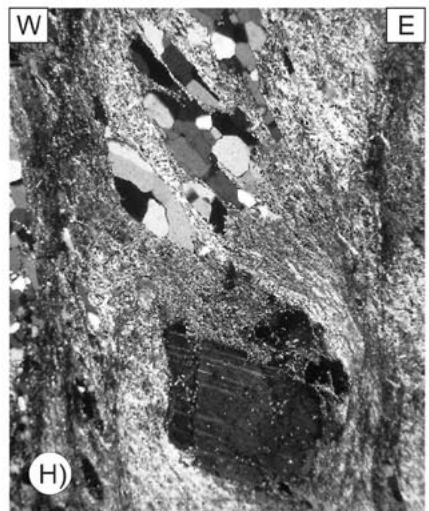
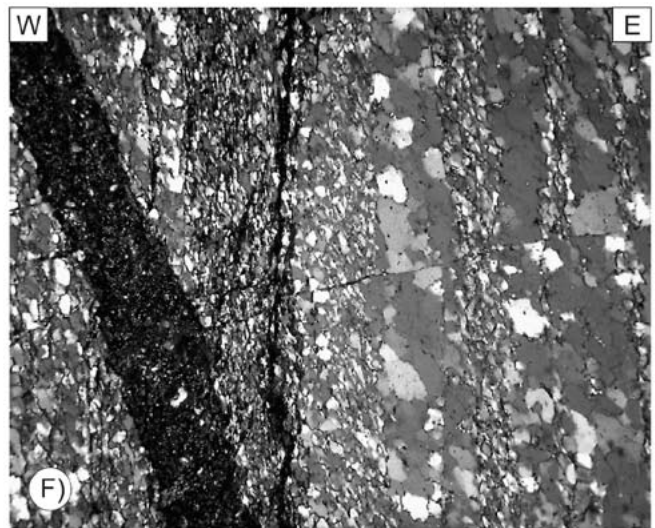
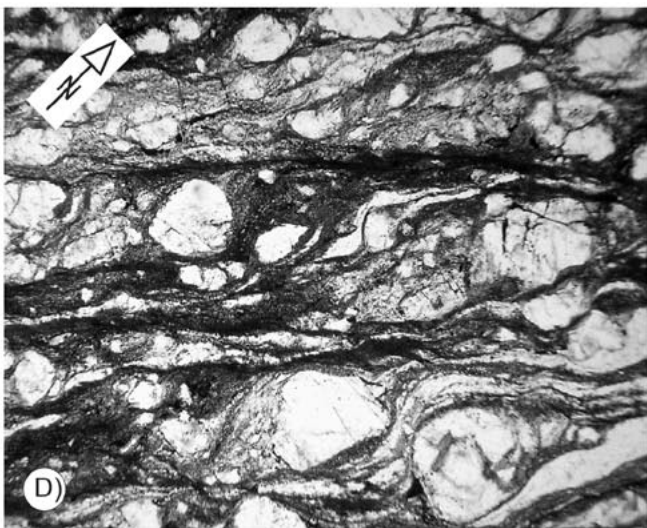
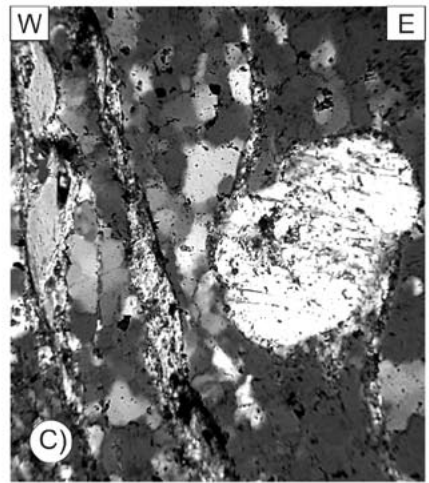
In summary, the JSZ is evidently a wide structure where strain was partitioned into sheared domains and folded domains. Folding and the presence of occasional sillimanite within the shear zones indicate that shearing initiated during ductile, high-temperature conditions. The early evolution also included a sinistral sense of movement before the dominant E-side-up reverse movement (Skyttä et al. 2006).

*The Salittu Shear Zone (SaSZ).* – The SaSZ is located within

the picritic volcanic rocks. The mylonitic fabric was easiest to recognise in a granite dyke where a few tens of metres wide NE–SW vertical shear zone with a horizontal stretching lineation was developed. Shear sense indicators are consistently dextral (Fig. 3D).

*The Kolinummi Shear Zone (KoSZ).* – The NE–SW KoSZ is located at the SE margin of the Laitila rapakivi batholith. East of the main KoSZ another parallel SZ was detected. We interpret this as an offset. In the northeastern end the KoSZ turns into a N–S orientation towards the KySZ. The KoSZ is subvertical or steeply SE-dipping and close to the 1.57 Ga Kolinummi anorthosite (Vaasjoki 1977), which intrudes the KoSZ. Both steep down-dip and moderately NE-plunging lineations were







detected. Both SE-side-up (Fig. 3E) and dextral horizontal shear senses were identified, therefore defining the zone as an oblique-slip shear zone. The KoZS is apparently the southern extension of the KySZ.

*The Paimio Shear Zone (PSZ).* – The PSZ is a NNE–SSW vertical narrow zone cross-cutting the ENE–WSW structural grain of southern Finland. Väisänen & Hölttä (1999) documented an E-block-down movement along the zone. Observations in this study verified the previous interpretation and also identified pseudotachylites (Fig 3F).

*The Vellua Shear Zone (VSZ).* – The VSZ is a N–S less than 50 m wide vertical zone of intense localised deformation north of the Vehmaa rapakivi batholith, which apparently cuts the VSZ. The VSZ is exposed at a length of ~7 km and displays features of both ductile and brittle deformation including pseudotachylites. Re-evaluation of the thin sections used in Väisänen & Hölttä (1999) showed clear evidences of E-side-up movements along the VSZ (Fig. 3G). Randomly oriented posttectonic micas overprint the mylonitic foliation. As the VSZ defines a metamorphic boundary zone which separates the cordierite + sillimanite + K-feldspar rocks to the west from the garnet + cordierite + sillimanite ± K-feldspar rocks to the east (Väisänen & Hölttä 1999), it is obvious that the eastern side of the VSZ exposes a slightly deeper section of the crust.

*The Mynälahti Shear Zone (MSZ).* – The NNE–SSW MSZ on the eastern side of the Vehmaa rapakivi batholith is clearly visible on aeromagnetic maps and continues at least 60 km to the south below the Baltic Sea. The sporadically exposed portions in the northern part of the MSZ are a few tens of metres wide zones consisting of steeply E-dipping mylonites with down-dip lineations. Microstructures verify the previous interpretation of the E-side-down movement (Fig. 3H; also fig. 5c in Väisänen & Hölttä 1999). Randomly oriented posttectonic micas overprint the mylonitic foliation, identical to that described above from the VSZ.

*Fig. 3. A.* Asymmetric K-feldspar porphyroclast and oblique grains in a granite from JSZ I show E-side-up shear sense. Vertical section. Base of the microphotograph is 4 mm. *B.* Synthetic microfaults deforming K-feldspar and oblique grains on the left side show E-side-down shear sense in a granite from JSZ II. Vertical section. Base of the microphotograph is 4 mm. *C.* Granite from JSZ III where a delta-porphyroclast of quartz (on the right), mica-fish (on the left) and weakly oblique grains (in the top centre) all indicate E-side-up shear sense. The low clast-matrix ratio of the mylonite indicates high shear strain, therefore suggesting that the quartz-rich domains experienced static recrystallization at relatively high temperatures after the shearing, as shown by the nearly equant shapes of the quartz grains. Base of the microphotograph is 1 mm. Vertical section. *D.* S-C structure, asymmetric K-feldspar porphyroclasts and stair-stepping in a granite from SaSZ show dextral shear sense. Horizontal section. Width of the view is 3 mm. *E.* S-C structure in a mica-gneiss from KoSZ defines the SE-side-up shear sense. Vertical section. Base of the microphotograph is 4 mm. *F.* Oblique grains in a granite from PSZ define an E-side-down shear sense. A pseudotachylite vein discordantly cuts the mylonitic foliation. Vertical section. Base of the microphotograph is 3 mm. *G.* Asymmetric mineral aggregate porphyroclast in a mica-gneiss from VSZ displays E-side-up shear sense. Randomly oriented micas overprint and postdate the mylonitic foliation. Vertical section. Base of the microphotograph is 2 mm. *H.* S-C structure in a granite from MSZ shows E-side-down shear sense. Vertical section. Base of the microphotograph is 2 mm.

## Discussion

The shear zones from southwestern Finland form a pattern where two 150–200 km long ~E–W trending shear zones (the SFSZ and the SSZ) are connected by shorter ~N–S trending shear zones. The E–W zones mainly show dextral strike-slip kinematics whereas the ~N–S zones exhibit dominantly dip-slip kinematics with variable shear senses. This pattern can be explained by a two-stage evolutionary model, which involved formation of shear zones first during a contractional stage and later during an extensional stage.

### *The contractional stage*

The late Svecofennian evolution of the crust in southern Finland is modelled as a result of a continental collision when presumably Sarmatia collided with Fennoscandia at c. 1.84 Ga and onward (Elming et al. 2001; Lahtinen et al. 2005). Oblique collision led to ~N–S crustal shortening expressed as refolding of the earlier structures and renewed thrusting towards approximately NW during dextral transpression (Ehlers et al. 1993). At the late stage of this deformation, steep shear zones initiated as a consequence of deformation partitioning into folded vs. sheared domains (Väisänen & Hölttä 1999; Skyttä et al. 2006) and, therefore, the highest strain was concentrated into the E–W and ~N–S oriented shear zones.

The Somero Shear Zone acted as a strike-slip zone along which the crustal unit to the south was transported towards west. This is indicated by the ubiquitous gently-plunging lineations associated with dextral shear senses in the western segment of the shear zone. Deflection of the magnetic anomalies is also obvious and the formation of contractional duplexes is indicated (Fig. 4). We interpret that a NW–SE oriented segment of the shear zone around Somero town is a site of transtension. This accounts for the vertical lineations and the south-side-down displacement in that area (Fig. 4; see Woodcock & Fisher (1986) for model and terminology). The other parallel shear zone to the north showing an opposite shear sense is not easy to explain. We tentatively propose that this zone preserves an earlier northward-directed tectonic transport. Similarly, the Southern Finland Shear Zone also accommodated the transpression in a dextral strike-slip zone (Ehlers et al. 1993). Therefore, we interpret that these two shear zones formed a pair of parallel shear zones that were active simultaneously.

Of the ~N–S oriented shear zones (SZ) the Kolinummi, the Kisko, the Porkkala-Mäntsälä and the Jyly SZs all have in common that the mylonitic zones are surrounded by wide parallel zones of other ductile deformation, including folding. This indicates that at least some of the folding is shear-induced (Skyttä et al. 2006). All these zones showed dominantly E-side-up movements, i.e. they accommodated the westward-directed tectonic transport as reverse faults and thrusts (Fig. 2H) approximately perpendicular to the transport direction. In the Jyly SZ, where several parallel shear zones were detected, the shear zones apparently form a positive flower structure (Fig. 5). We interpret the Salittu Shear Zone there as a transfer fault.

Although the E-side-up reverse movements were most dominant, a few thin sections with opposite shear senses were also observed. Firstly, there are ductile E-side-down microstructures, and secondly, there are semiductile to brittle E-side-down microstructures that we interpret to have formed temporally later. The ductile structures were observed from the Kisko and Jyly SZs.

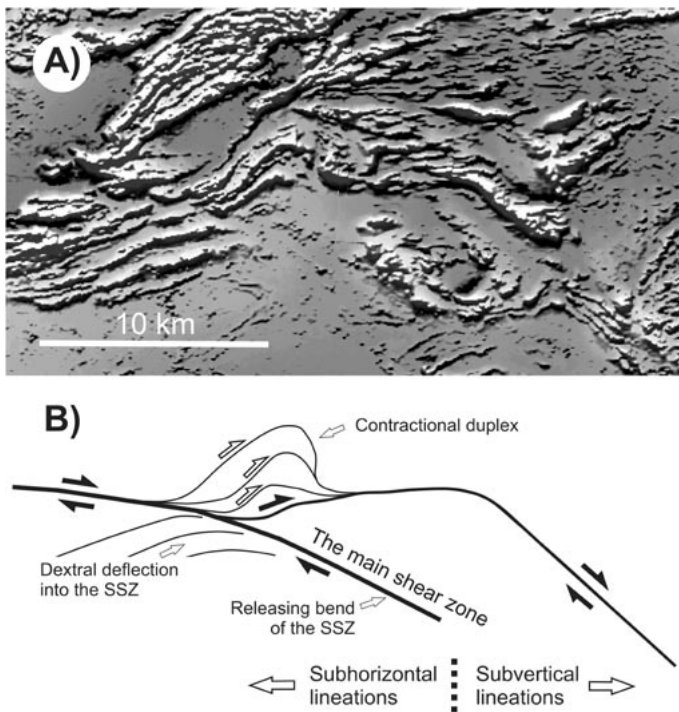


Fig. 4. **A.** Detail of the aeromagnetic image in Fig. 1C. **B.** Structural interpretation of A. The images illustrate the contractional duplex structure along the Somero Shear Zone. Also note the dextral deflection of the magnetic fabric into the shear zone. Thick dashed line marks the change in plunge of the lineations from subhorizontal in the west to subvertical in the east.

This might indicate fluctuating contractional forces with periodic release of stress, which allowed the opposite movements.

In Fig. 6A we provide a model for the evolution of the shear zones in SW Finland during the contractional stage. The model resembles that of Cagnard et al. (2006) in overall tectonic transport directions, but differs in that we also considered the reverse ~N–S shear zones that were missing in their model.

### The extensional stage

The Vellua, Mynälahti and Paimio SZs differ from the other ~N–S zones described above in that they are narrower, usually discordantly cut the regional structural grain and only locally deflect older structures. Microstructures often show brittle deformation. The Mynälahti and Paimio SZs show E-side-down sense of movements similar to the few E-side-down displacement directions found in the Kisko and Jyly SZs. Since these movement directions are opposite to the main movements, we interpret these to represent later extensional deformation structures. Brittle overprinting of ductile fabric is common in most of these shear zones and is previously documented e.g. from the Kynsikangas Shear Zone (Pajunen et al. 2001) and the Porkkala-Mäntsälä Shear Zone (Elminen et al. 2006). We believe that the later extension reactivated all the contractional shear zones at least to some extent.

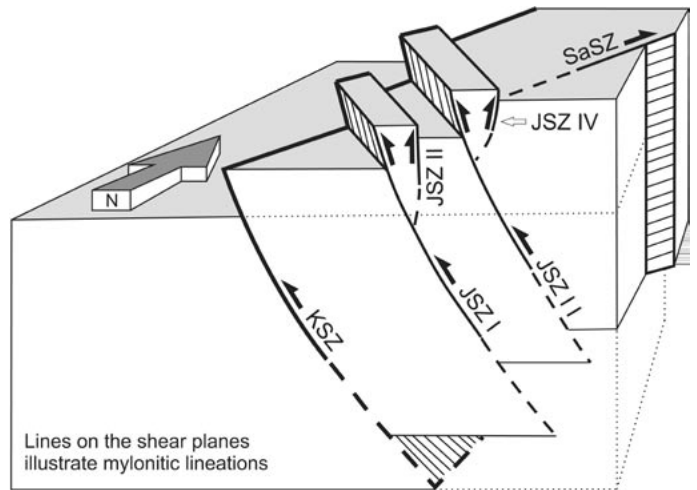


Fig. 5. Block diagram illustrating the geometric and kinematic relationships of the Kisko, Jyly and Salittu Shear Zones. Dotted lines show the shape of the box prior to shearing.

The Vellua Shear Zone north of the Vehmaa rapakivi granite makes an exception, as it is an E-side-up shear zone although otherwise similar to the mylonites of the extensional stage. This can be explained by the horst-graben geometry of faults at least close to the rapakivi granites.

The shear zones interpreted as related to the extensional stage are mainly vertical or steeply-dipping (60–90°). As pointed out by Stel et al. (1993), crustal thinning by vertical faulting does not require an extensional setting. However, seismic profiles (Korja & Heikkinen 1995) and recent modelling (Lahtinen et al. 2005) favour an extensional setting. The amount of extension must, however, have been small as indicated by the thick crust remaining (Korja et al. 1993). In Fig. 6B we provide a model for the evolution of the shear zones in SW Finland during the extensional stage.

### Timing of shearing

As the shear zones are not dated in this study, we must rely on indirect data concerning the timing of shear activity. Maximum ages of the shear zones are indicated by the ~1.83 Ga granites, which are affected by the shearing. The presence of sillimanite in the Jyly Shear Zone demonstrates the high temperature conditions of the shearing. Since the peak metamorphic conditions at the nearby West Uusimaa granulite area were dated at 1830–1815 Ma (Mouri et al. 2005), the 1815 Ma can be considered as the maximum age of shearing in that area.

Ehlers et al. (2004) dated the cross-cutting but still weakly deformed granite dyke at  $1790 \pm 6$  Ma from the South Finland Shear Zone. Torvela & Mänttari (2006) verified this by the 1.79 Ga titanite ages from the same shear zone. From these age data we can conclude that the most intensive shearing during the contractional stage took place at ~1.81–1.79 Ga. This time span roughly coincides with the time of shearing along the major shear



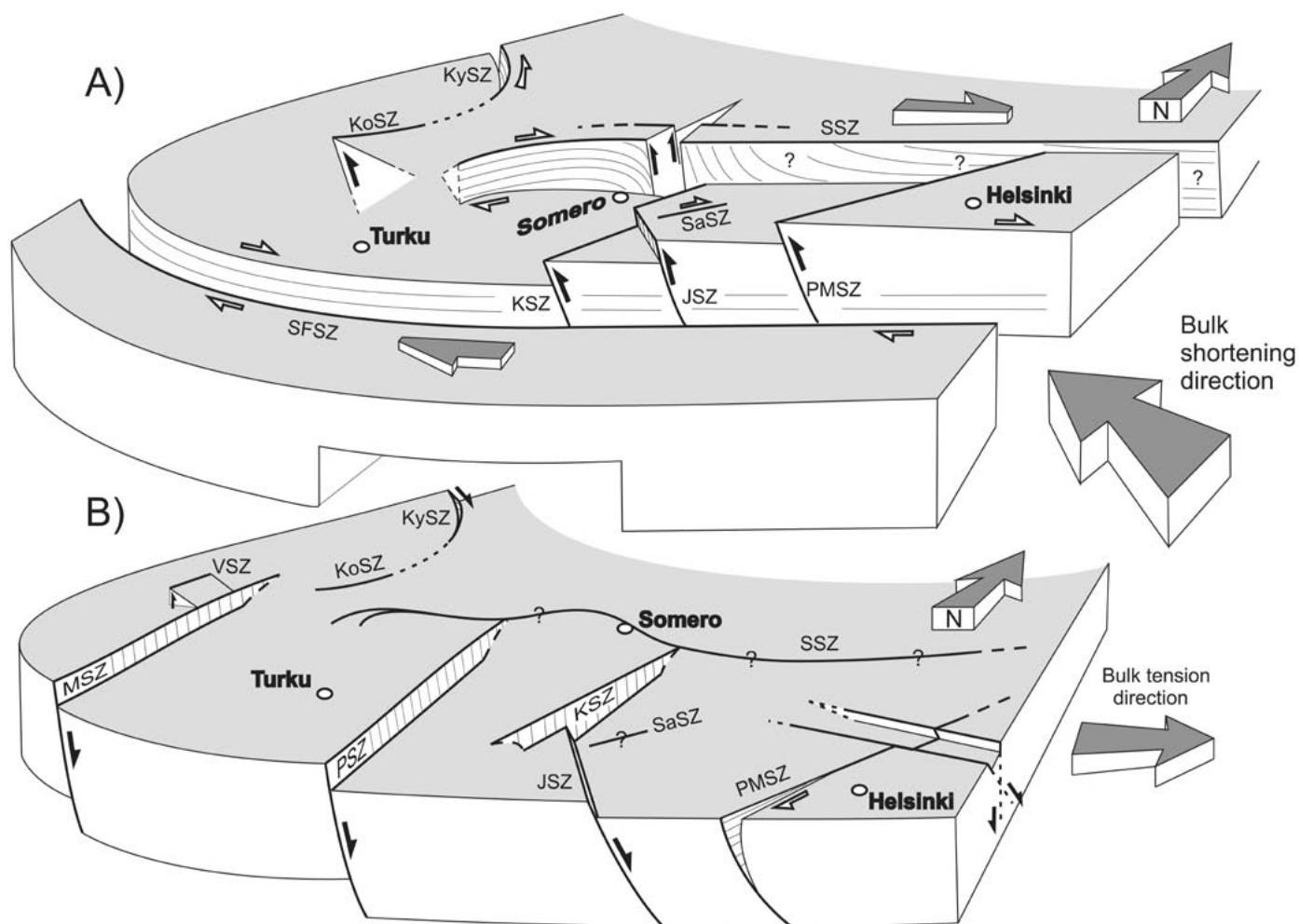


Fig. 6. Schematic block diagram model for the evolution of the shear zones in SW Finland. **A.** The contractional stage at ~1.83–1.79 Ga. SE–NW contraction leads to a transpressional regime along the E–W trending Southern Svecofennian Arc Complex. Tectonic strain was partitioned into the major strike-slip shear zones at the margins and into steep reverse dip-slip shear zones between the strike-slip zones. **B.** The extensional stages at ~1.79–1.77 Ga, 1.64–1.55 Ga and/or 1.26 Ga. The MSZ, VSZ and PSZ were formed and the other SZs were reactivated. Lines on the shear planes illustrate mylonitic lineations. The block south to the SFSZ is omitted for clarity. See Fig. 1B. for abbreviations.

zones in central Sweden (Högdahl & Sjöström 2001; Persson & Sjöström 2003).

We can only speculate about the precise ages of shearing during the extensional stages. However, the Mynälahti and Vellua Shear Zones close to the Vehmaa rapakivi granite are overprinted by post-tectonic micas, which obviously is the effect of the contact metamorphism of the rapakivi magmatism (Heilimo 2005). This indicates that the faulting preceded the rapakivi magmatism. The tectonic model by Lahtinen et al. (2005) infers an orogenic collapse at 1.79–1.77 Ga. Although we do not have any age data from that period, it would be natural to consider that the extensional shear zones were active then. From the Porkkala-Mäntsälä shear Zone it is obvious that it was active at 1.64 Ga (Elminen et al. 2006) and still later during the Jotnian time at 1.26 Ga (Mertanen et al. 2001). Since the pseudotachylites clearly belong to some late and cold deformation, we tentatively consider them Mesoproterozoic or younger.

*Acknowledgements.* – We warmly thank Karin Högdahl and Håkan Sjöström for the thorough reviews which greatly helped in improving the manuscript. PS was funded by the Finnish Graduate School in Geology and the Geological Survey of Finland. This study also received funding from K.H. Renlund Foundation to MV. Antti Joutsen is thanked for assistance in the field and Arto Peltola for making most of the thin sections.

## References

- Bergman, S., Billström, K., Persson, P.-O., Skiöld, T. & Evins, P., 2006: U–Pb age evidence for repeated Palaeoproterozoic metamorphism and deformation near the Pajala shear zone in the northern Fennoscandian shield. *GFF* 128, 7–20.
- Berthelsen, A. & Marker, M., 1986: 1.9–1.8 Ga old strike-slip megashear in the Baltic Shield, and their plate tectonic implications. *Tectonophysics* 128, 163–181.
- Cagnard, F., Durrieu, N., Gapais, D., Brun J.-P. & Ehlers, C., 2006: Crustal thickening and lateral flow during compression of hot lithospheres, with particular reference to Precambrian times. *Terra Nova* 18, 72–78.
- Dewey, J.F., 1988: Extensional collapse of orogens. *Tectonics* 7, 1123–1139.
- Ehlers, C. & Lindroos, A., 1990: Early Proterozoic Svecofennian volcanism and associated plutonism in Enklinge, SW Finland. *Precambrian Research* 47, 307–318.

- Ehlers, C., Lindroos, A. & Selonen, O., 1993: The late Svecofennian granite-migmatite zone of southern Finland – a belt of transpressive deformation and granite emplacement. *Precambrian Research* 64, 295–309.
- Ehlers, C., Skiöld, T. & Vaasjoki, M., 2004: Timing of Svecofennian crustal growth and collisional tectonics in Åland, SW Finland. *Bulletin of the Geological Society of Finland* 76, 63–91.
- Elminen, T., Airo, M.-L., Niemelä, R., Pajunen, M., Wasenius, P. & Wennerström, M., 2006: Extensional brittle structures and their relations to the bimodal 1.6 Ga magmatism in the Helsinki region, southern Finland. The 27<sup>th</sup> Nordic Winter Geological Meeting, 9–12.1. 2006 Oulu, Finland. *Bulletin of the Geological Society of Finland, Special Issue 1*, 31.
- Elming, S.-Å., Mikhailova, N.P. & Kravchenko, S., 2001: Palaeomagnetism of Proterozoic rocks from the Ukrainian Shield: new tectonic reconstructions of the Ukrainian and Fennoscandian shields. *Tectonophysics* 339, 19–38.
- Halden, N.M., 1982: Structural, metamorphic and igneous history of migmatites in the deep levels of a wrench fault regime, Savonranta, eastern Finland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* 73, 17–30.
- Heeremans, M., Stel, H., van der Beek, P. & Lankreijer, A., 1996: Tectono-magmatic control on vertical dip slip basement faulting: An example from the Fennoscandian Shield. *Terra Nova* 8, 129–140.
- Heeremans, M. & Wijbrans, J., 1999: Late Proterozoic tectonic events in southern Finland, constrained by <sup>40</sup>Ar/<sup>39</sup>Ar incremental heating and single spot fusion experiments on K-feldspars. *Terra Nova* 11, 216–222.
- Heilimo, V., 2005: *Vehmaan rapakiven kontaktimetamorfoosi*. M.Sc. thesis, Department of Geology, University of Turku. 58 pp.
- Högdahl, K. & Sjöström, H., 2001: Evidence for 1.82 Ga transpressive shearing in a 1.85 Ga granitoid in central Sweden: implications for the regional evolution. *Precambrian Research* 105, 37–56.
- Huhma, H., 1986: Sm-Nd, U-Pb and Pb-Pb isotopic evidence for the origin of the Early Proterozoic Svecofennian crust in Finland. *Geological Survey of Finland, Bulletin* 337, 48 pp.
- Jurvanen, T., Eklund, O. & Väisänen, M., 2005: Generation of A-type granitic melts during the late Svecofennian metamorphism in southern Finland. *GFF* 127, 139–147.
- Kärki, A., Laajoki, K. & Luukas, J., 1993: Major Palaeoproterozoic shear zones of the central Fennoscandian Shield. *Precambrian Research* 64, 207–223.
- Korja, A. & Heikkinen, P., 1995: Proterozoic extensional tectonics of the central Fennoscandian Shield: results from the Baltic and Bothnian Echoes from the Lithosphere experiment. *Tectonics* 14, 504–517.
- Korja, A., Korja, T., Luosto, U. & Heikkinen, P., 1993: Seismic and geoelectric evidence for collisional and extensional events in the Fennoscandian Shield – implications for Precambrian crustal evolution. *Tectonophysics* 219, 129–152.
- Korsman, K., Korja, T., Pajunen, M., Virransalo, P. & GGT/SVEKA Working Group, 1999: The GGT/SVEKA Transect: Structure and Evolution of the Continental Crust in the Paleoproterozoic Svecofennian Orogen in Finland. *International Geology Review* 41, 287–333.
- Kurhila, M., Vaasjoki, M., Mänttari, I., Rämö, T. & Nironen, M., 2005: U-Pb ages and Nd isotope characteristics of the lateorogenic, migmatizing microcline granites in southwestern Finland. *Bulletin of the Geological Society of Finland* 77, 105–128.
- Lahtinen, R., 1996: Geochemistry of Palaeoproterozoic supracrustal and plutonic rocks in the Tampere-Hämeenlinna area, southern Finland. *Geological Survey of Finland, Bulletin* 389, 113 pp.
- Lahtinen, R., Korja, A. & Nironen, M., 2005: Paleoproterozoic tectonic evolution. In M. Lehtinen, P.A. Nurmi & O.T. Rämö (eds.): *Precambrian geology of Finland: key to the evolution of the Fennoscandian Shield*, 481–531. Developments in Precambrian Geology 14. Elsevier.
- Lonka, H., Schulmann, K. & Venera, Z., 1998: Ductile deformation of tonalite in the Suomusjärvi shear zone, south-western Finland. *Journal of Structural Geology* 20, 783–798.
- Mertanen, S., Pajunen, M. & Elminen, T., 2001: Applying palaeomagnetic method for dating young geological events. *Geological Survey of Finland, Special Paper* 31, 123–129.
- Mouri, H., Väisänen, M., Huhma, H. & Korsman, K., 2005: Sm-Nd garnet and U-Pb monazite dating of high-grade metamorphism and crustal melting in the West Uusimaa area, southern Finland. *GFF* 127, 123–128.
- Nironen, M., 1995: Block boundary at the southeastern margin of the Paleoproterozoic Central Finland Granitoid Complex. *Geological Survey of Finland, Bulletin* 382, 91–115.
- Nironen, M., 1997: The Svecofennian Orogen: a tectonic model. *Precambrian Research* 86, 21–44.
- Nironen, M., 1999: Structural and magmatic evolution in the Loimaa area, south-western Finland. *Bulletin of the Geological Society of Finland* 71, 57–71.
- Nironen, M., Elliott, B.A. & Rämö, O.T., 2000: 1.88–1.87 Ga post-kinematic intrusions of the Central Finland Granitoid Complex: a shift from C-type to A-type magmatism during lithospheric convergence. *Lithos* 53, 37–58.
- Pajunen, M., Airo, M.-L., Wennerström, M., Niemelä, R. & Wasenius, P., 2001: Preliminary report: the “Shear zone research and rock engineering” project, Pori area, south-western Finland. *Geological Survey of Finland, Special Paper* 31, 7–16.
- Passchier, C.W. & Trouw, R.A.J., 1996: *Microtectonics*. Berlin: Springer-Verlag. 289 pp.
- Patchett, P.J. & Kouvo, O., 1986: Origin of continental crust of 1.9–1.7 Ga age; Nd isotopes and U-Pb zircon ages in the Svecofennian terrain of South Finland. *Contributions to Mineralogy and Petrology* 92, 1–12.
- Persson, K.S. & Sjöström, H., 2003: Late-orogenic progressive shearing in eastern Bergslagen, central Sweden. *GFF* 125, 23–36.
- Pietikäinen, K.J., 1994: *The geology of the Paleoproterozoic Pori shear zone, southwestern Finland, with special reference to the evolution of veined gneisses from tonalitic protoliths*. Ph.D. thesis, Michigan Technological University. 129 pp.
- Ploegsma, M., 1989: *Shear zones in the West Uusimaa area, SW Finland*. Ph.D. thesis, Vrije Universiteit te Amsterdam. 134 pp.
- Ploegsma, M. & Westra, L., 1990: The Early Proterozoic Orijärvi triangle (southwest Finland): a key area on the tectonic evolution of the Svecofennides. *Precambrian Research* 47, 51–69.
- Rämö, O.T., Vaasjoki, M., Mänttari, I., Elliott, B.A. & Nironen, M., 2001: Petrogenesis of the post-kinematic magmatism of the Central Finland Granitoid Complex I; radiogenic isotope constraints and implications for crustal evolution. *Journal of Petrology* 42, 1971–1993.
- Ramsay, J.G. & Huber, M.I., 1987: *The Techniques of Modern Structural Geology. Volume 2: Folds and Fractures*, 309–700. London: Academic Press.
- Reinikainen, J., 2001: Petrogenesis of Paleoproterozoic marbles in the Svecofennian Domain, Finland. *Geological Survey of Finland. Report of Investigations* 154, 84 pp.
- Schreurs, J. & Westra, L., 1986: The thermotectonic evolution of a Proterozoic, low pressure, granulite dome, West Uusimaa, SW Finland. *Contributions to Mineralogy and Petrology* 93, 236–250.
- Simpson, C. & Schmid, S.M., 1983: An evaluation of criteria to deduce the sense of movement in sheared rocks. *Geological Society of America Bulletin* 94, 1281–1288.
- Skyttä, P., Käpyaho, A. & Mänttari, I., 2005: Supracrustal rocks in the Kuovila area, southern Finland: structural evolution, geochemical characteristics and the age of volcanism. *Bulletin of the Geological Society of Finland* 77, 129–150.
- Skyttä, P., Väisänen, M. & Mänttari, I., 2006: Preservation of Palaeoproterozoic early Svecofennian structures in the Orijärvi area, SW Finland – Evidence for polyphase strain partitioning. *Precambrian Research* 150, 153–172.
- Stel, H., Cloetingh, S., Heeremans, M. & van der Beek, P., 1993: Anorogenic granites, magmatic underplating and the origin of intracratonic basins in a non-extensional setting. *Tectonophysics* 226, 285–299.
- Stel, H., Veenhof, R., Huizenga, J.M., Timmerman, M. & Hartsink, J.M.H., 1989: Infra-supra structure relations of the microcline-granite dome in the Somero area, Svecofennides, SW Finland. *Bulletin of the Geological Society of Finland* 61, 131–141.
- Talbot, C.J. & Sokoutis, D., 1995: Strain ellipsoids from incompetent dykes; application to volume loss during mylonitization in the Singö gneiss zone, central Sweden. *Journal of Structural Geology* 17, 927–948.
- Torvela, T. & Annersten, H., 2005: PT-conditions of deformation within the Palaeoproterozoic South Finland shear zone: some geothermobarometric results. *Bulletin of the Geological Society of Finland* 77, 151–164.
- Torvela, T. & Mänttari, I., 2006: Styles and timing of deformation within the Southern Finland shear zone, SW Finland. The 27<sup>th</sup> Nordic Geological Winter Meeting, January 9–12.2006. Oulu, Finland. *Bulletin of the Geological Society of Finland, Special Issue 1*, 62.
- Vaasjoki, M., 1977: Rapakivi granites and other postorogenic rocks in Finland: their age and the lead isotopic composition of certain associated galena mineralizations. *Geological Survey of Finland, Bulletin* 294, 64 pp.
- Vaasjoki, M., 1994: Valijärven hapan vulkaniitti: minimi Hämeen liuskejaksion iäksi. Summary: Radiometric age of a meta-andesite at Valijärvi, Häme schist zone, southern Finland. *Geologi* 46, 91–92.
- Väisänen, M., 2007: *Mynämäki. Geological map of Finland 1:100 000, pre-Quaternary rocks, sheet 1044*. Geological Survey of Finland, in press.
- Väisänen, M. & Hölttä, P., 1999: Structural and metamorphic evolution of the Turku migmatite complex, southwestern Finland. *Bulletin of the Geological Society of Finland* 71, 177–218.
- Väisänen, M. & Mänttari, I., 2002: 1.90–1.88 Ga Ga arc and back-arc basin in the Orijärvi area, SW Finland. *Bulletin of the Geological Society of Finland* 74, 185–212.
- Väisänen, M., Mänttari, I. & Hölttä, P., 2002: Svecofennian magmatic and metamorphic evolution of southwestern Finland as revealed by U-Pb zircon SIMS geochronology. *Precambrian Research* 116, 111–127.
- Van Staal, C.R. & Williams, P.F., 1983: Evolution of a Svecofennian-mantled gneiss dome in SW Finland, with evidence for thrusting. *Precambrian Research* 21, 101–128.
- Woodcock, N.H. & Fischer, M., 1986: Strike-slip duplexes. *Journal of Structural Geology* 8, 725–735.