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From ductile to brittle deformation – the structural development and strain variations along a crustal-scale shear zone in SW Finland

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Abstract: This study demonstrates the impact of variations in overall crustal rheology on crustal strength in relatively high P-T conditions at mid- to lower mid-crustal levels. In a crustal-scale shear zone, along-strike variations in the rheological competence result in large-scale deformation partitioning and differences in the deformation style and strain distribution.

Keywords: shear zone, deformation, strain partitioning, terrane boundary, Finland, Palaeoproterozoic.

The structural behaviour of the crustal-scale Sottunga-Jurmo shear zone (SJSZ) in SW Finland is described. The shear zone outlines a significant crustal discontinuity, and it probably also represents a terrain boundary between the amphibolite-to-granulite facies, dome-and-basin-style crustal block to the north and the amphibolite facies rocks with dominantly steeply dipping structures to the south. The results of this study also imply that the late ductile structures (~1.80-1.79 Ga) can be attributed to the convergence of an unknown microcontinent from south, while the influence of the coeval continent-continent-type Nordic orogeny from the west was insignificant. It is further suggested that the ~1.79 Ga magmatism in Åland at least commenced in a compressive/transpressive setting, although later magmatism may have occurred in an extensional setting. The results also support the notion of exhumation and cooling of the crust after ~1.79 Ga so that within and south of the SJSZ the brittle-ductile transition zone was reached somewhat later than within the terrane to the north.

Geological setting

The Fennoscandian shield is an amalgam of crustal domains that cover a time span of over 2400 Ma with several orogenic periods from the Archaean to the Caledonian orogen 450-400 Ma ago (Fig. 1; e.g. Nironen, 1997; Lahtinen *et al.*, 2005). The bulk of the shield (central and southern Finland, central and northern Sweden) was formed during the Palaeoproterozoic orogeny, ca. 2.0-1.85 Ga ago, which is often referred to in literature as the Svecofennian orogeny (Gaál and Gorbatschev, 1987). The main direction of convergence against the Archaean nucleus to the NE (Fig. 1) was toward the NE in northern parts and approximately N-NNW in the southern parts (southern Finland-central Sweden; e.g. Gaál and Gorbatschev, 1987; Ehlers *et al.*, 1993; Nironen, 1997). However, subduction from the NW that eventually closed the ocean between the Fennoscandian and Amazonian plates began during this phase (Lahtinen *et al.*, 2005 and references therein). The Svecofennian period was followed by the Svecobaltic Andean-type orogeny at ~1.84-1.80 Ga, during which the supracrustal Svecofennian belts in SW Finland and central Sweden were offset by crustal-scale shear systems due to continuing convergence and subduction from the S-SSE (Fig 1; Lahtinen *et al.*, 2005, and references therein). The last compressive event before an orogenic collapse was the continent-continent-type Nordic orogeny at ~1.82-

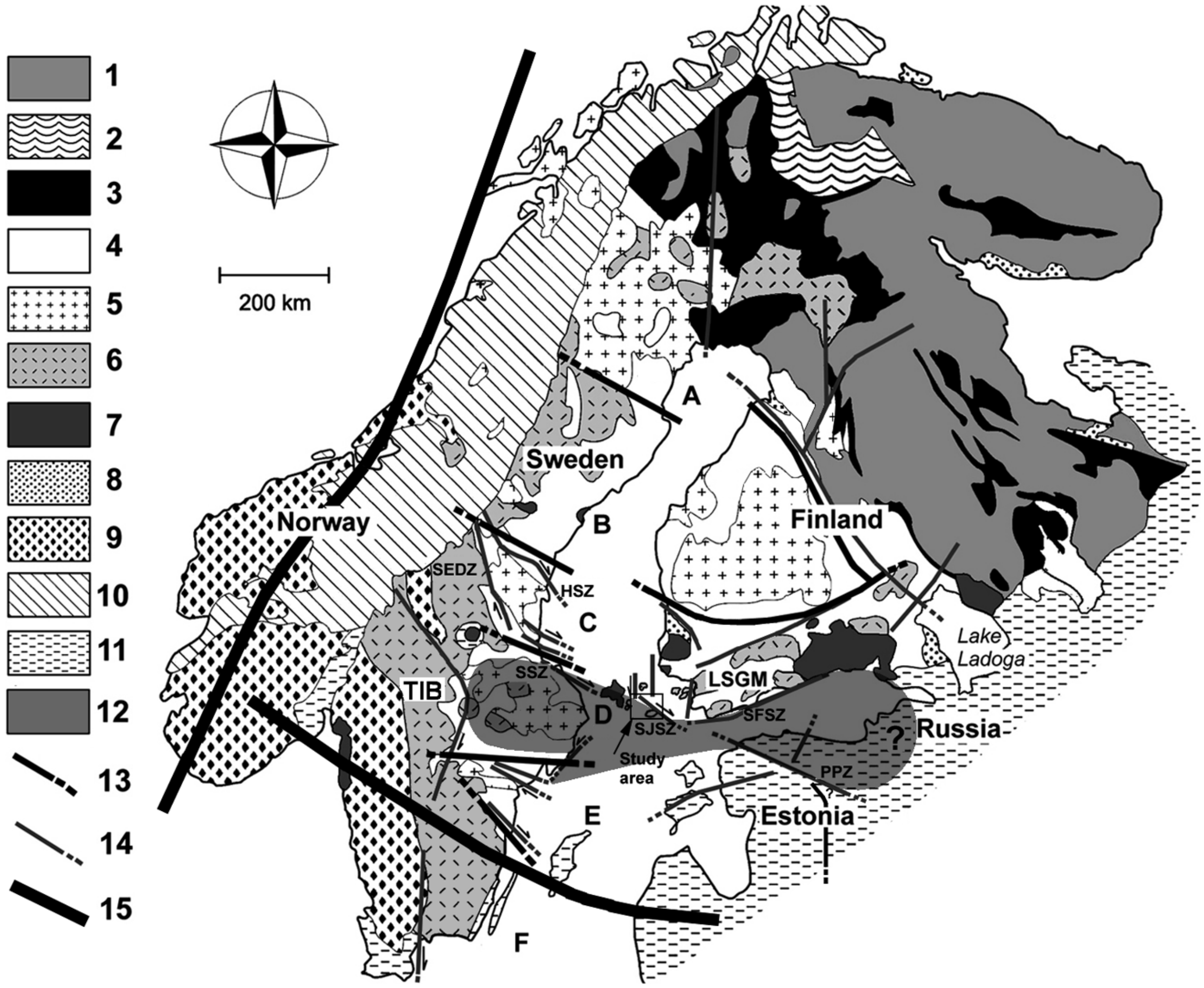

Figure 1. Generalised geological map of the Fennoscandian shield. Key: 1) Archaean rocks 3.2-2.5 Ga; 2) Lapland granulite 2.2-1.9 Ga; 3) Karelian supracrustals 2.5-1.8 Ga; 4) Svecofennian supracrustals 2.0-1.85 Ga; 5) Svecofennian magmatic rocks 1.95-1.84 Ga; 6) Svecofennian lateorogenic granites and migmatites; 7) Anorogenic rapakivi granites 1.65-1.4 Ga; 8) Sandstones 1.5-0.57 Ga; 9) Sveconorwegian rocks 1.25-0.9 Ga; 10) Caledonian rocks 0.6-0.4 Ga; 11) Phanerozoic sedimentary cover <0.57 Ga; 12) Mainly amphibolite facies terrains 13) Domain borders; 14) Major Palaeoproterozoic deformation zones; 15) Approximate locations of active plate boundaries at 1.87-1.80 Ga; LSGM: Late Svecofennian Granite Migmatite zone; TIB: Trans-Scandinavian Igneous Belt; A-F: Palaeoproterozoic, granulite to amphibolite facies bedrock domains in Sweden (from Sjöström and Bergman 1998); SFSZ: South Finland shear zone; SJSZ: Sottunga-Jurmo shear zone; PPZ: Paldiski-Pskov shear zone; HSZ: Hassela shear zone; SEDZ: Storsjön-Edsbyn deformation zone; SSZ: Singö shear zone; Modified from a map compiled from Korsman *et al.* (1997).

1.79 Ga that closed the ocean between the Fennoscandian shield and the Amazonia to the west, resulting in large-scale granitoid magmatism (TIB in figure 1), but which also converged an unknown microcontinent from the south with present southern Finland-central Sweden (approx. domain F in figure 1; Lahtinen *et al.*, 2005, and references therein).

A more than a kilometre wide, NW-SE-striking shear structure, the Sottunga-Jurmo shear zone (SJSZ), is a part of the large-scale shear system that dextrally offsets the Svecofennian supracrustal and magmatic rocks in southern Finland and central Sweden (Fig. 1). The shear zone formed under the transpressive stress fields of the Svecofennian and Svecobaltic orogenies (e.g. Ehlers and Lindroos, 1990; Ehlers *et al.*, 1993; Lahtinen *et al.*, 2005; Torvela, 2007) and shows an apparent offset of the order of some tens of kilometres. In the NW parts, the exposed SJSZ terminates against the late-orogenic, 1.79 Ga Mosshaga pluton and the anorogenic, ca. 1.58 Ga Åland rapakivi granite batholith (Fig. 2). The approximately coeval, dextral Hassela and Storsjön-Edsbyn shear zones (HSZ and SEDZ) and/or Singö shear structures

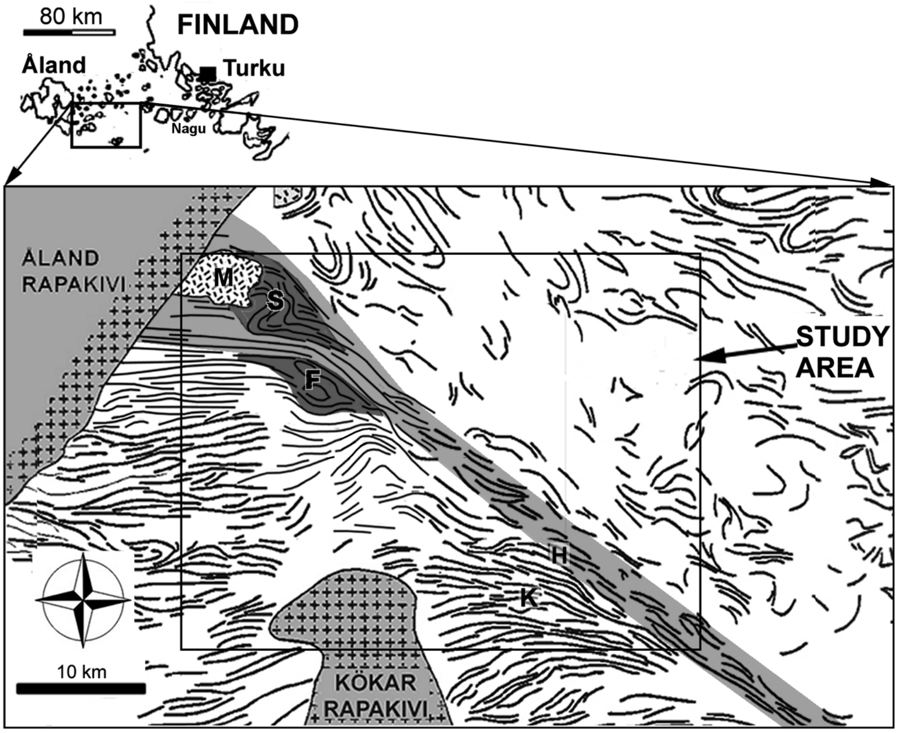

Figure 2. Foliation map of Åland (modified from Ehlers and Lindroos 1990). The SJSZ is marked in light grey and the more rigid Finnö and Sottunga lenses in dark grey (see text). K: Kökar, H: Hellsö, F: Finnö, S: Sottunga, M: Mosshaga pluton.

(SSZ) in central Sweden as well as the yet poorly studied PPZ in Estonia are likely to belong to the same large-scale trans-Fennoscandian deformation zone as the SJSZ (Fig. 1).

The rocks within the SJSZ are dominantly felsic and intermediate intrusive granitoids with steeply dipping foliations. More mafic lenses that are sometimes brecciated by felsic material exist locally within the granitoids. The rocks show early-Svecofennian magmatic ages of ~1.88-1.89 Ga (Suominen, 1991; Ehlers *et al.*, 2004; Torvela *et al.*, 2008). SW of the shear zone, the lithology is very similar to the main zone but the rocks are much less deformed, the steep foliations striking mainly E-W. To the NE of the SJSZ are exposed the structurally overturned, subhorizontal, extensively migmatised supracrustal rocks of the late-Svecofennian Granite-Migmatite Zone (LSGM). Thus, the SJSZ runs roughly along the boundary between the unmigmatised, structurally steep-featured, amphibolite facies granitoids to the south, and the granulite facies, dome-and-basin-style LGSM. An obvious spatial connection between the LGSM and the SJSZ (and SFSZ; Fig. 1) can be observed. Stålfors and Ehlers (2005) suggest that the emplacement and fractionation of the ~1.83 Ga LSGM Nagu granites (40 km NE from Kökar) were shear-assisted processes, and propose a model where vertical crustal-scale shear zones functioned as transport channels for the magmas.

The SJSZ has been repeatedly reactivated, starting with periods of regional, ductile shearing that produced striped gneisses. The ductile deformation is locally followed, in places overprinted, by higher strain-rate, ductile to semi-ductile deformation producing mylonite zones of variable widths. The time frame for the polyphase ductile deformation within the SJSZ has been quite well established (Suominen, 1991; Ehlers *et al.*, 2004; Torvela *et al.*, 2008). The first ductile phase within SJSZ, possibly with shearing, existed at ~1.85 Ga, while a separate deformation phase occurred at ~1.83 Ga, by which time the shear zone was already well developed (Torvela *et al.*, 2008). This age coincides with the Svecobaltic orogeny (Lahtinen *et al.*, 2005). The last active deformation phase within the ductile regime took place at ~1.79 Ga (corresponding to the late stages of the Nordic orogeny of Lahtinen *et al.*, 2005), with coeval granitoid magmatism, after which the rocks cooled and entered the brittle-ductile transition zone (Torvela *et al.*, 2008). The SJSZ was reactivated at least once within the (semi)brittle regime, as witnessed by cataclasites and pseudotachylytes that formed in several places along the shear zone. The pseudotachylytes may be related to the intrusion of the ~1.58 Ga anorogenic rapakivi granite plutons close to the study area, although this is still somewhat ambiguous (Torvela *et al.*, 2008).

Structures in gneisses – an overview

It is possible to follow the changes in the deformation style, strain intensity, strain distribution and the orientation of the deformation fabrics from areas south of the main shear zone northeastwards into the zone of the highest strain, but also along the zone from SE to NW. The overall deformation type within the SJSZ is that of general shear with both pure shear (coaxial) and simple shear (non-coaxial) components, resulting from the transpressive nature of the late-Svecofennian orogeny (e.g. Ehlers *et al.*, 1993). The ductile structures observed imply a similar tectonic stress regime, i.e. transpression from S-SSE, for the Åland area during the subsequent 1.85-1.79 Ga events.

A simplified sketch illustrating the typical structures, deformation distribution and (re)folding patterns in the study area is given in figure 3. The overall vertical kinematic movement along the shear zone was SW side up, so the rocks SW of the shear zone were thrusted toward NW. The rocks display a succession of folding, refolding and shearing of the early, steeply-dipping gneissic foliations as the regional deformation progressed. In general terms, the dominantly E-W- to ENE-WSW-striking foliations have been folded and refolded along roughly E-W- to ENE-WSW-trending fold axes (Fig. 3). As the shear zone is approached, the early folds get tighter and eventually refold into open folds against the SW margin of the main SJSZ, both in outcrop scale and in map scale. These meso- to macroscale 'margin folds' formed as a result of a strong partitioning of coaxial (D3) deformation, while the non-coaxial components mainly partitioned into shear zones (main SJSZ and mesoscale shear zones both parallel and conjugate to the SJSZ).

Deformation partitioning is evident not only across but also along the shear zone. In the SE parts (Kökar and Kyrkogårdsö areas), the deformation is relatively distinctly partitioned throughout into zones dominated by coaxial deformation (folds and other compressive structures vs. zones with a significant non-coaxial, subhorizontal flow component (shear zones, subhorizontal margin folds; figure 3). Toward the NW (no figure), the deformation is more evenly distributed and non-coaxial structures are consequently more subtle and less pronounced; for example the

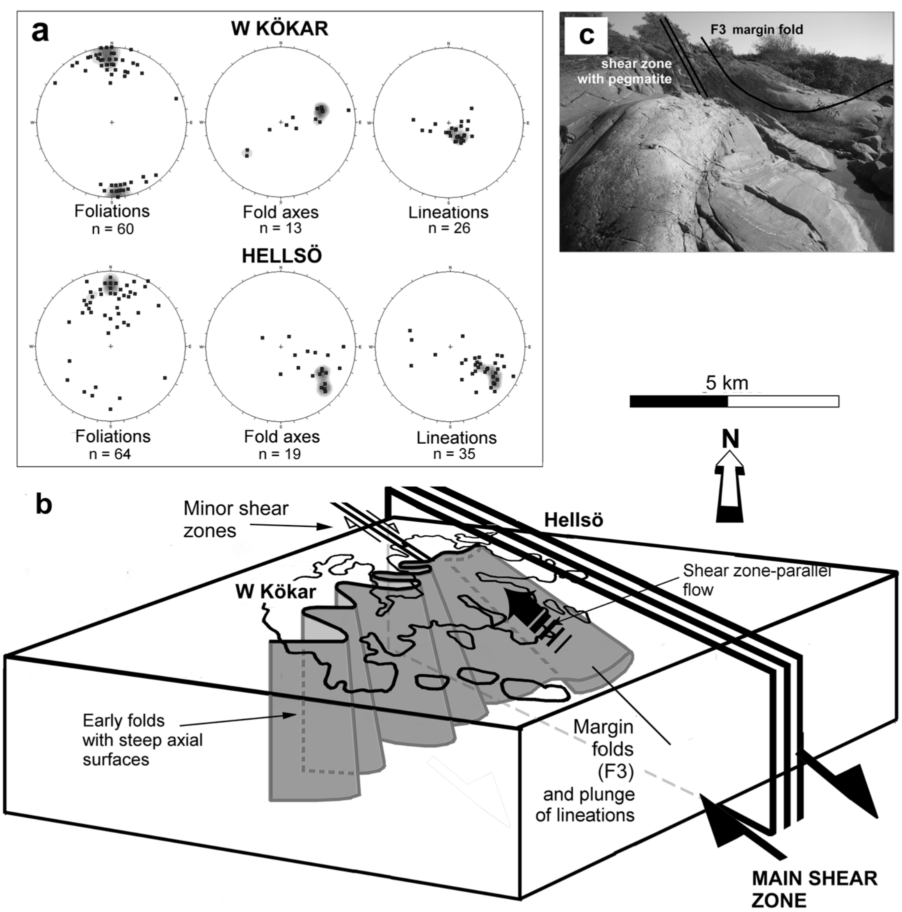

Figure 3. (a) Equal-area projections (lower hemisphere) of the structural observations on Kökar and Hellsö. The isolines represent Fisher concentrations of 10% or higher of total per 1.0% area, (b) a schematic 3D sketch illustrating the structural interpretation of the Kökar area (see text for discussion), (c) a photo from Hellsö of a margin fold with a fold axis plunging gently toward SE. In the northern fold limb (left side of the picture) a minor shear zone, dipping steeply toward the south has developed; it is intruded by a pegmatite dyke; the southern contact cannot be observed (under water). The same structural pattern (margin folds with SE plunging axes bound by steeply dipping deformation zones) is repeated throughout Hellsö. Length of compass ca. 15 cm, view toward SE.

mylonite zones that are common in the SE and evidence of high strain rates and significant deformation partitioning become rare in the NW. The SJSZ instead becomes wider toward the NW and upright sheath folds appear, marking a locally important increase of the vertical stretching in the overall general shear. The change in the strain distribution is attributed to the variations in the lithologies along the shear zone, so that the overall competence of the rocks increases from SE (dominantly felsic gneisses) to NW (increasing amount of intermediate and mafic rocks). As a result, the rigid lenses caused variations in strain distribution along the zone (Finnö and Sottunga lenses in figure 2), and the gently SE dipping axes of the F3 margin folds in the SE (Fig. 3) become steep toward the NW while the folds themselves become larger and more open. The SJSZ-parallel mesoscale shear zones in figure 3, which often follow the flanks of the F3 folds consequently rotate and become conjugate to the SJSZ.

Mylonites – an overview

The last ductile reactivation of the SJSZ occurred at ~1.79 Ga (Torvela *et al.*, 2008). This phase did not apparently result in any large-scale refolding of the earlier folds, although some coaxial deformation still affected the rocks both within and south of the SJSZ. The deformation at this stage was still largely gneissic, but at least some protomylonites were formed simultaneously. The large-scale mylonitisation therefore initiated ~1.79 Ga, although locally some mylonites probably formed earlier (~1.83 Ga) as a result of competence differences between rock layers (Torvela *et al.*, 2008).

The mylonites record the late stages of the ductile and semi-ductile, late- to post-orogenic, high strain rate deformation within the SJSZ. Further data is needed before the exact age(s) and the mechanisms of the large-scale mylonitisation can be deciphered. There seems, however, to be a rather large jump in PT-conditions to the next, brittle deformation phase that locally produced pseudotachylytes and cataclasites, both only rarely observed. This may be due to rapid exhumation of rocks from the ductile and semi-ductile conditions into the brittle regime and/or indicate a pause in regional tectonic activity while the rocks were being exhumed.

Discussion and conclusions

The SJSZ outlines a major geological discontinuity where ductile shearing along the main shear zone produced gneissic and mylonitic rocks that show overall dextral kinematics on various scales. The overall vertical kinematic movement along the shear zone was SW side up. The scale of the weakness zone along which the SJSZ formed is so large that it is suggested here, bearing in mind the lithological and structural differences as well as the differences in the metamorphic grade on both sides of the shear zone, that the SJSZ defines a terrain boundary.

Metamorphic and intrusive ages around 1.79 Ga are also common in non-sheared rocks close to the study area and also elsewhere in SW Finland (e.g. Suominen, 1991). The cause and nature of this metamorphic event has not been widely speculated on in literature. Lahtinen *et al.* (2005) recently concluded that the ~1.80-1.77 Ga regional magmatism in southern Finland and central Sweden was due to an orogenic collapse and related decompression and extension at the late stages of and after the Nordic orogeny (1.82-1.79 Ga). It has also been suggested that exhumation in southern Finland (LSGM) to pressures of ~2 kbar occurred as early as between 1.81-1.80 Ga (Väisänen *et al.*, 2000). Recent analytical evidence (Torvela *et al.*, 2008) and structural observations (Torvela, 2007; Torvela and Ehlers, 2010), however, show that within and south of the SJSZ, compressive/transpressive ductile deformation, probably related to the convergence of a microcontinent from south as suggested by Lahtinen *et al.* (2005), continued at ~1.79 Ga. This also implies that the coeval granitoid magmatism occurred at least partly in a compressive/transpressive setting. The ductile-brittle transition in this area was therefore not reached before ~1.79 Ga, i.e. later than suggested for the LSGM.

As a summarising statement, we suggest that:

1) The SJSZ represents a terrain boundary between the LSGM of southern Finland and the amphibolite facies rocks SW of the SJSZ.

2) The overall vertical component for the shearing was SW-side up, the block SW of the SJSZ thus representing a deeper crustal level than the LSGM.

3) The ductile deformation within the area occurred in several phases between ~1.85 Ga and ~1.79 Ga and that each phase produced both large- and small-scale structures that can be recognised and mapped in the field.

4) The deformation was partitioned both across and along the SJSZ in such a way that the early, domi-

nantly coaxial deformation phases produced the large-scale F1-F3 folds observable in the field; simultaneously –at the latest during D3 and probably even earlier– there was a significant non-coaxial component involved that was mainly accommodated by the main SJSZ and minor shear zones, however so that the deformation was overall more evenly distributed in the NW due to large-scale variations in rheological competence.

5) The SJSZ area was exhumed and cooled somewhat later than the LSGM.

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