

Major Palaeoproterozoic shear zones of the central Fennoscandian Shield

A. Kärki*, K. Laajoki and J. Luukas

Department of Geology, University of Oulu, Linnanmaa, 90570 Oulu, Finland

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ABSTRACT

Employing two recently studied crustal-scale shear zones as type examples, this paper summarizes the major Palaeoproterozoic (Svecokarelian) shear tectonics of the central Fennoscandian Shield and demonstrates that this part of the Shield was not as stable during the Svecokarelian Orogeny as commonly assumed.

The collision of the Svecofennian island arc with the Karelian Continent first created numerous NW–SE trending folds and thrusts of stages D₁ and D₂, which were then modified by successive shearing during stages D₃ and D₄. Stage D₃ built up a system of N–S trending shear zones, here named the *Savolappi Shear System*, the type example of which is the Hirvaskoski Shear Zone. This is a dextral strike-slip shear zone at least 150 km long and 10–30 km wide, characterized by blastomylonitic fault rocks and various structures such as hook folds, Z-folds and sheath folds associated with the principal displacement zone, synthetic Riedel shears, and pinnate shears. The traces of the axial planes of F₃ en-echelon folds deviate 15°–30° anticlockwise from the plane of the principal displacement zone. Other members of the Savolappi Shear System are the Pajala Shear Zone in northern Sweden and the Russian North Karelia Shear Zone in the east.

Stage D₄ created a conjugate shear system called the *Finlandia Shear System*, the type example of which is the Oulujärvi Shear Zone. This is a NE–SW trending sinistral strike-slip shear zone more than 250 km long and 20–30 km wide across its southwestern end. It is composed of a NE–SW trending principal displacement zone, synthetic Riedel shears, and pinnate shears with antithetic Riedel shears in a NW–SE direction. Typical fault rocks within these shears are S–C mylonites. The axial-plane traces of F₄ folds of all scales diverge by 20°–40° clockwise from the plane of the principal displacement zone. The Kuopio Shear Zone is a conjugate NW–SE trending counterpart of the Oulujärvi Shear Zone. As a whole, the Finlandia Shear System forms a conjugate network of NW–SE and NE–SW trending shear zones which occupies most of the northern and central Fennoscandian Shield.

1. Introduction

A commonly overlooked feature of the Palaeoproterozoic geology of the Fennoscandian Shield is the tectonic evolution of the Karelian area between the so-called Raahe–Ladoga Zone (cf. Kahma, 1978) and the Lapland Granulite Belt (Fig. 1). Most commonly, this area is considered an Archaean domain covered by anorogenic, intracratonic sedimentary and volcanic rocks, collectively known as the Karelian formations. The present boundary of Archaean crust trends along the Raahe–La-

dogo zone (e.g. Gaál and Gorbatshev, 1987). The early works on the Kainuu Schist Belt, which is situated well inside the “Archaean domain”, nevertheless proved this to be one of the major Proterozoic tectonic zones in the Shield (Wegmann, 1928, 1929; Väyrynen, 1933), a fact verified by numerous later studies (Laajoki 1973, 1991; Kontinen, 1987, 1992; Laajoki and Tuisku, 1990). Väyrynen (1954) emphasized the intense folding of the Proterozoic schists of Finnish Lapland and even considered them a separate orogenic belt which he named the Lappides. The extensive area of granitoids in central Lapland provides more evidence of the orogenic nature of the “Ar-

*Corresponding author.

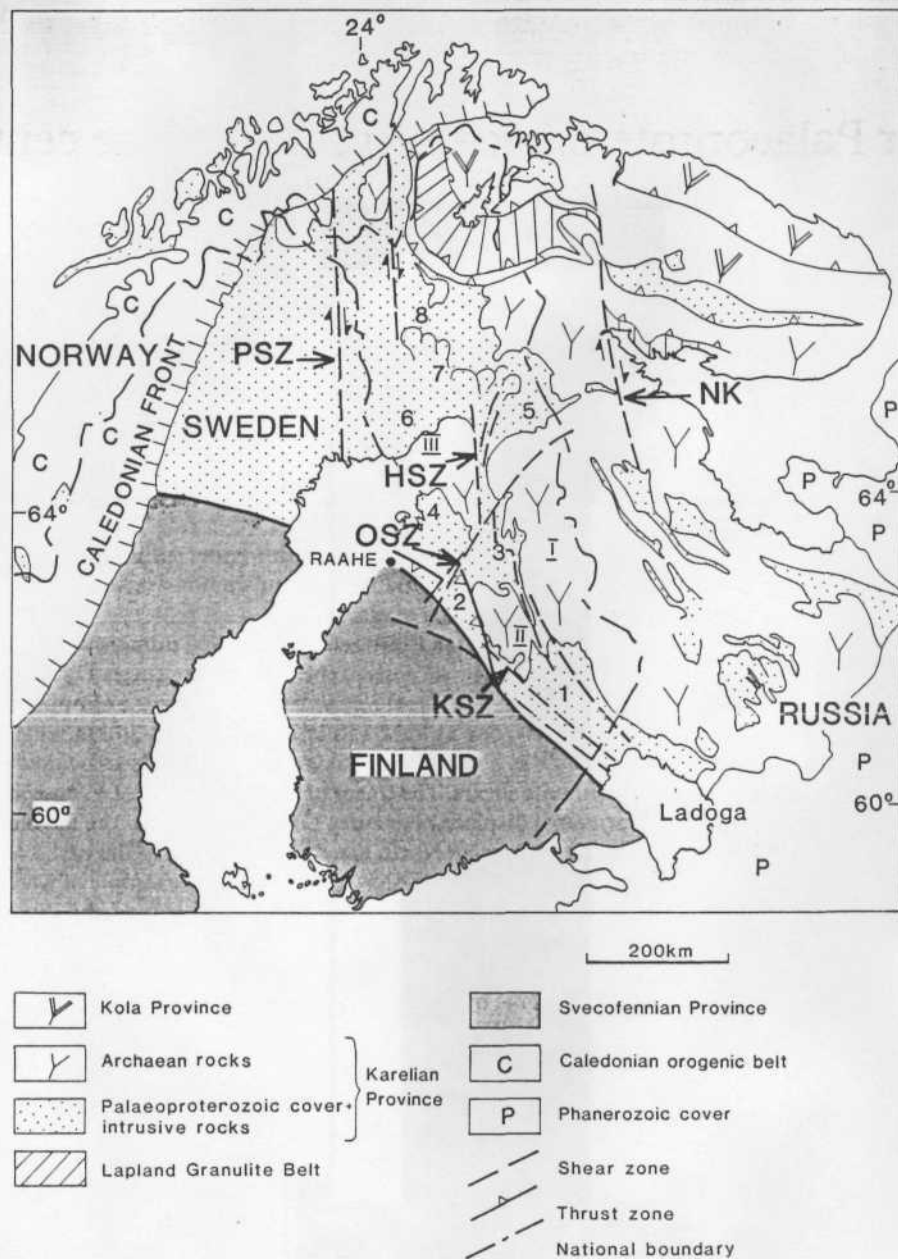


Fig. 1. Simplified geological map of the Baltic Shield showing the major shear zones and geological units: *I*=Kuhmo Complex; *II*=Iisalmi Complex; *III*=Pudasjärvi Complex; *I*=North Karelia Schist Belt; *2*=Savo Schist Belt; *3*=Kainuu Schist Belt; *4*=Northern Pohjanmaa Schist Belt; *5*=Kuusamo Schist Belt; *6*=Peräpohja Schist Belt; *7*=Kemijärvi Complex; *8*=Kittilä Greenstone Belt; *HSZ*=Hirvaskoski Shear Zone (see Fig. 2); *KSZ*=Kuopio Shear Zone; *OSZ*=Oulujärvi Shear Zone (see Fig. 4); *NK*=Russian North Karelia Shear Zone; *PSZ*=Pajala Shear Zone.

chaean domain", which was intensely deformed and reworked by Palaeoproterozoic orogenic processes both in Finland and in northern Sweden (e.g. Witschard, 1984).

The theory of thrust tectonics was applied to the Finnish part of the Fennoscandian Shield as early as in the 1920's by Wegmann (1928,

1929), and was developed further by Väyrynen (e.g. 1939), recalled by Gaál (1964) and recently exemplified by Koistinen (1981) and Park and Bowes (1983). However, little research has been devoted to the post-thrusting crustal-scale shear zones in Finland and neighbouring areas, and most of what was done only

concerned southeastern Finland (e.g. Gaál, 1972; Halden, 1982; Ward, 1987). Berthelsen and Marker (1986b) described an important shear zone which they called the Baltic–Bothnia Megashear, but their paper is based mostly on interpretations of aeromagnetic maps without actual fieldwork. The shear tectonics of the Sveconorwegian part of the Fennoscandian Shield have been a target of intense study, however (cf. papers in Tobi and Touret, 1985 and in Gower et al., 1990; Park et al., 1991), and the number of reports emphasizing shear zones as province boundaries and essential tectonic elements even in the oldest parts of cratons is increasing rapidly (e.g. van Biljon and Legg, 1983; Daly, 1986; Hoffman, 1987).

The present paper establishes the major shear systems and summarizes the Palaeoproterozoic (Svecokarelian) tectonic evolution of the part of the Fennoscandian Shield that occupies central, eastern and northern Finland, and continues into the neighbouring countries. One of its aims is to stress the Palaeoproterozoic tectonics of the Archaean domain of the central Fennoscandian Shield. The paper is based on detailed fieldwork carried out in central and northeastern Finland (Laajoki and Luukas, 1988; Kärki and Laajoki, 1990; Laajoki and Tuisku, 1990; Kärki, 1991; Laajoki, 1991; Luukas, 1991) and the reader is referred to these papers for the original field data.

2. Geological subdivisions of the central Fennoscandian Shield

The Fennoscandian Shield has previously been subdivided into various units with different names (cf. Gaál, 1990 and references therein). Some of these classifications are unsatisfactory in the present context because they treat the Karelian area (Fig. 1) as a single unit and do not emphasize that at least its major, northeastern part participated actively in the Svecokarelian orogeny.

In the present context, we divide the north-

ern and central Fennoscandian Shield into three major units:

(1) The *Kola Province*, which occupies the area northeast of the Lapland Granulite Belt and can be subdivided further into subunits (cf. Gaál et al., 1989).

(2) The *Karelian Province*, or the *Karelides*, comprising the area between the above unit and the Svecofennides (see below). This unit consists of late Archaean crust and its Palaeoproterozoic cover (Laajoki, 1990) known collectively as the Karelian formations (the term is used here in the sense defined by Laajoki, 1986). The Karelian Province can be divided into numerous subunits, of which this paper discusses the Archaean Kuhmo, Iisalmi and Pudasjärvi Complexes, and the intervening Karelian schist areas (Figs. 1, 2 and 4). This province also contains the Kemijärvi Complex (this denomination replaces the informal name "Central Lapland granite complex"), which is a unit made up in part of granitized and migmatized Karelian formations and in part of granites intruding the Karelian formations and their basement (Lauerma, 1982). Its origin, as discussed in this paper, is closely related to Palaeoproterozoic shear tectonics.

(3) The *Svecofennian Province*, or the *Svecofennides*, is a unit southwest of the Karelian Province composed solely of Palaeoproterozoic crust. Large parts are interpreted as island arc complexes that collided with the Karelides. About half of the surface is made up of granitoids. The boundary between units (2) and (3) has not yet been located precisely and its nature is disputed. Usually, it is placed at what is loosely called the Raahe–Ladoga Zone and is regarded as a palaeosuture (e.g. Hietanen, 1975) or a faulted block contact (e.g. Korsman et al., 1984).

3. General deformation history of the central Fennoscandian Shield

The Karelian Province has been affected by Svecokarelian progressive deformation which

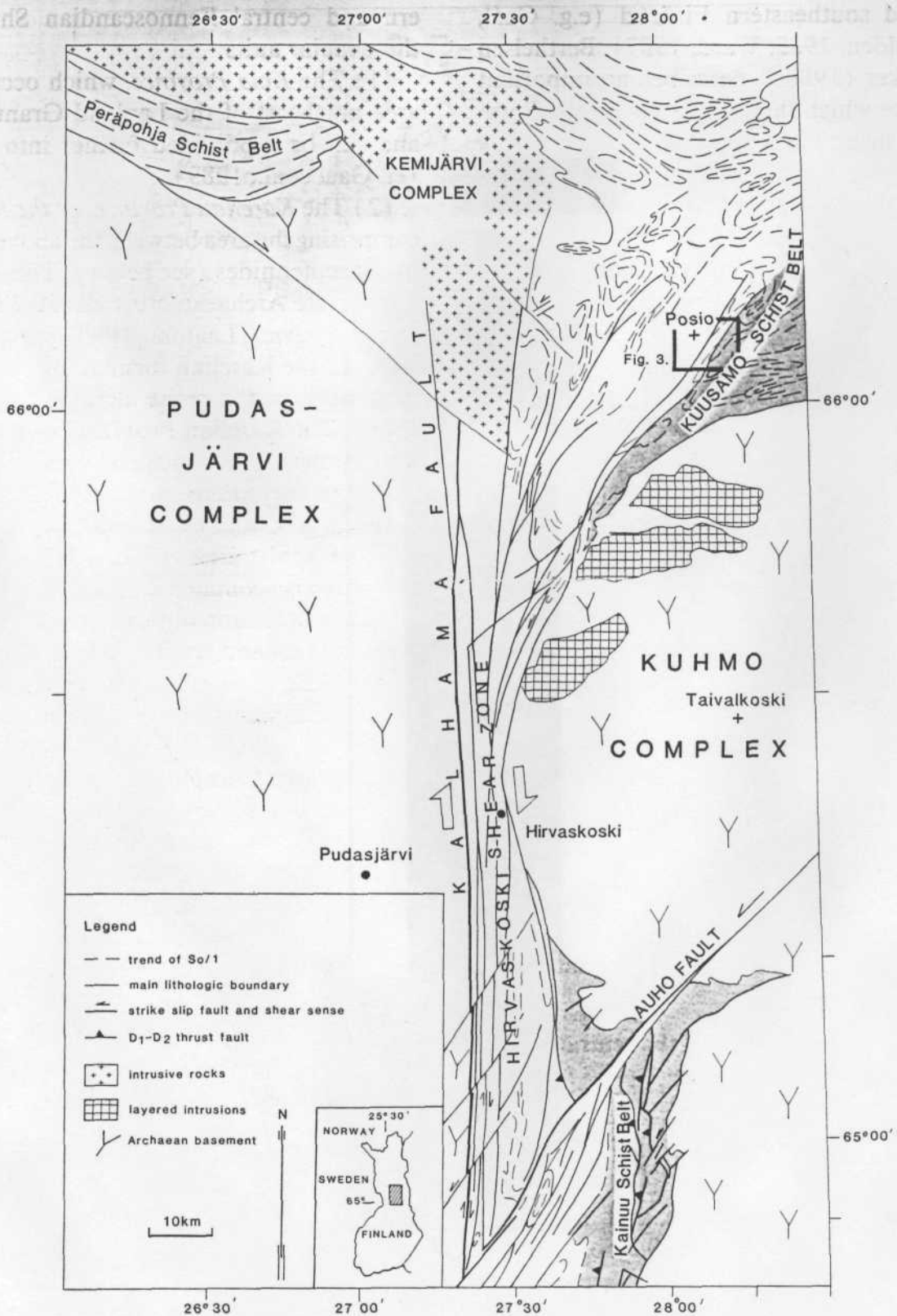


Fig. 2. Simplified geological map of northeastern Finland showing the N-S trending dextral Hirvaskoski Shear Zone which separates the Archaean Pudasjärvi and Kuhmo Complexes. The western margin of the shear zone is defined by the Kalhama Fault. The area of Fig. 3 is framed.

created its major structural features in four main stages. The deformational evolution can be divided into an early phase which involved the translation of thrust nappes towards the craton and the creation of the related folds of stages D_1 and D_2 , and a younger phase of shear tectonism which produced the major shear zones of the central Fennoscandian Shield.

The earliest compressional structures are identified by isoclinal F_1 folds (Koistinen, 1981; Ward, 1987) which are related on the macroscopic scale to the first nappe emplacements and recumbent folds (e.g. Gaál, 1990; Luukas, 1991). After the D_1 deformation, the earliest structures were refolded in an identical compressional field producing more open, mostly upright F_2 folds. These are the most conspicuous mesoscopic and macroscopic structures in the Palaeoproterozoic formations of the Finnish part of the central Fennoscandian Shield. The D_2 structures are approximately in their original position (NW-SE) in the Savo Schist Belt (Laajoki and Luukas, 1988) and the Northern Pohjanmaa Schist Belt, but have been reoriented into a N-S direction by later deformation in the Kainuu Schist Belt (Laajoki and Tuisku, 1990; Kärki, 1991; Gehör and Laajoki, 1992).

After stage D_2 , deformation changed from folding to the ductile shear tectonism of stages D_3 and D_4 (Kärki, 1991; Luukas, 1991) which created the shear systems described in this paper. After these ductile phases the style of deformation changed again, because the now exposed sections were brought to a higher crustal level and were subjected to semi-brittle and brittle faulting of long duration. Some of the D_3 and D_4 shear zones were reactivated and, in consequence, show both initial ductile and younger brittle features, the latter being verified by anomalous electric conductivity (Korja et al., 1991). In fact, brittle deformation seems to be active even today, as demonstrated by minor earthquakes in areas of shear zones (Talvitie, 1971; Mustila and Korhonen, 1991).

4. The Hirvaskoski Shear Zone, a type example of major D_3 structures in the Savolampi Shear System

Definition. Some time ago we recognized a N-S trending shear zone of Palaeoproterozoic paragneisses that is ~150 km long and 10-30 km wide (Fig. 2). It separates the Archaean Pudasjärvi and Kuhmo Complexes (Kärki and Laajoki, 1990; Kärki, 1991). This D_3 tectonic zone was named the Hirvaskoski Shear Zone (HSZ) after a locality in its central part. Lithologically, its southern end has been mapped as the Kalhamajärvi Complex (Kärki and Laajoki, 1990; Laajoki, 1991), and a fault which defines its sharp western boundary with the Pudasjärvi Complex is named the Kalhama Fault (Fig. 2). The eastern margin of the HSZ is delineated by a shear zone which intersects the western margins of the northernmost tip of the Kainuu Schist Belt, the Kuhmo Complex and the Kuusamo Schist Belt (Fig. 2.). The southern end of the HSZ is cut by the Oulujärvi Shear Zone, whereas the northern end opens into a large horsetail structure and then tapers out in the gneisses and granitoids of the Kemijärvi Complex.

The HSZ forms a dextral ductile shear zone (for terminology see Sylvester, 1988; Harding, 1990) with a subvertical, N-S trending principal displacement zone (PDZ_3). The whole shear zone is composed of miscellaneous faults and fault rocks related to diverse fold structures located between the subzones of most intense shearing. The extent of shear strain varies greatly between the faults, which is verified by the diverse characters of the mesoscopic structures and fault rocks (Bell and Etheridge, 1973; Wise et al., 1984; Xu et al., 1986).

Macroscopic structure. On the macroscale, the HSZ is build up of ductile strike-slip faults or shear zones and less common folds identifiable from regional mapping and aeromagnetic greytone maps. Following the simple shear model (Riedel, 1929; Aydin and Page, 1984), the faults can be grouped into three cat-

egories according to their mutual orientations. The N-S trending faults are interpreted as principal displacement zones (PDZ₃), whereas synthetic Riedel shears (R₃), diverging 10–20° clockwise from the plane of the PDZ₃, and pinnate shears (P₃), diverging 10–20° anticlockwise, represent the other fault components of the shear zone (Fig. 2).

The Kalhama Fault is one of the subvertical faults following the direction of the PDZ₃. D₃

faults are most frequent near the Kalhama Fault, whereas F₃ en-echelon folds are more common in the eastern part of the shear zone. The total displacement caused by the D₃ shearing is estimated to be about 70–90 km. This is recognizable most clearly on the basis of the break-up and displacement of the layered mafic intrusions in northern Finland (Alapieti et al., 1990) and the fold structures in Lapland.

In Posio (Fig. 2), the eastern margin of the

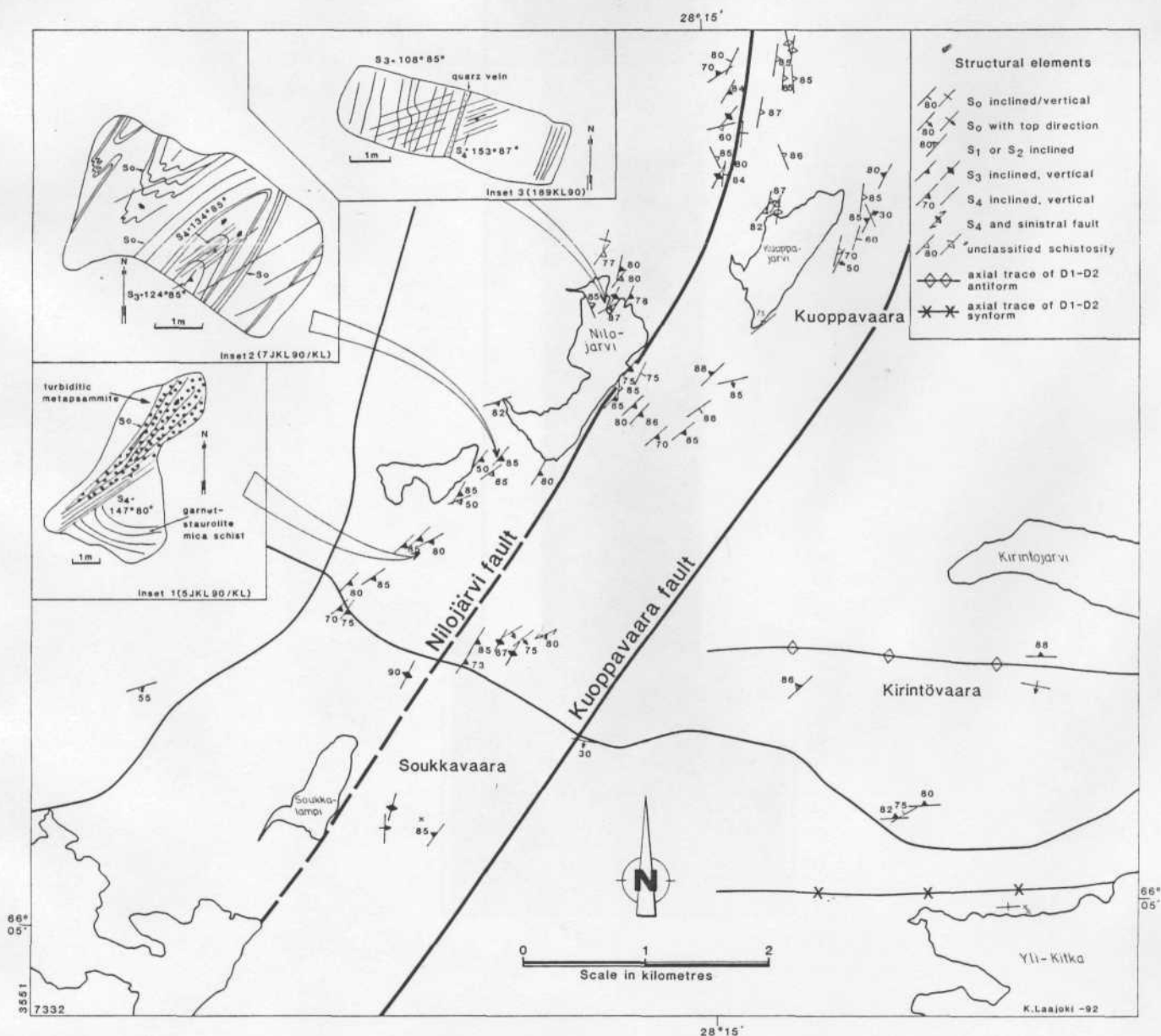


Fig. 3. Simplified structural map of the surroundings of the village of Posio (Fig. 2). The quartzites of the central area (Kuoppavaara) are separated from the western, highly sheared mica schists and metabasites by the Nilojärvi fault and from the Kuusamo Schist Belt in the east by the Kuoppavaara fault.

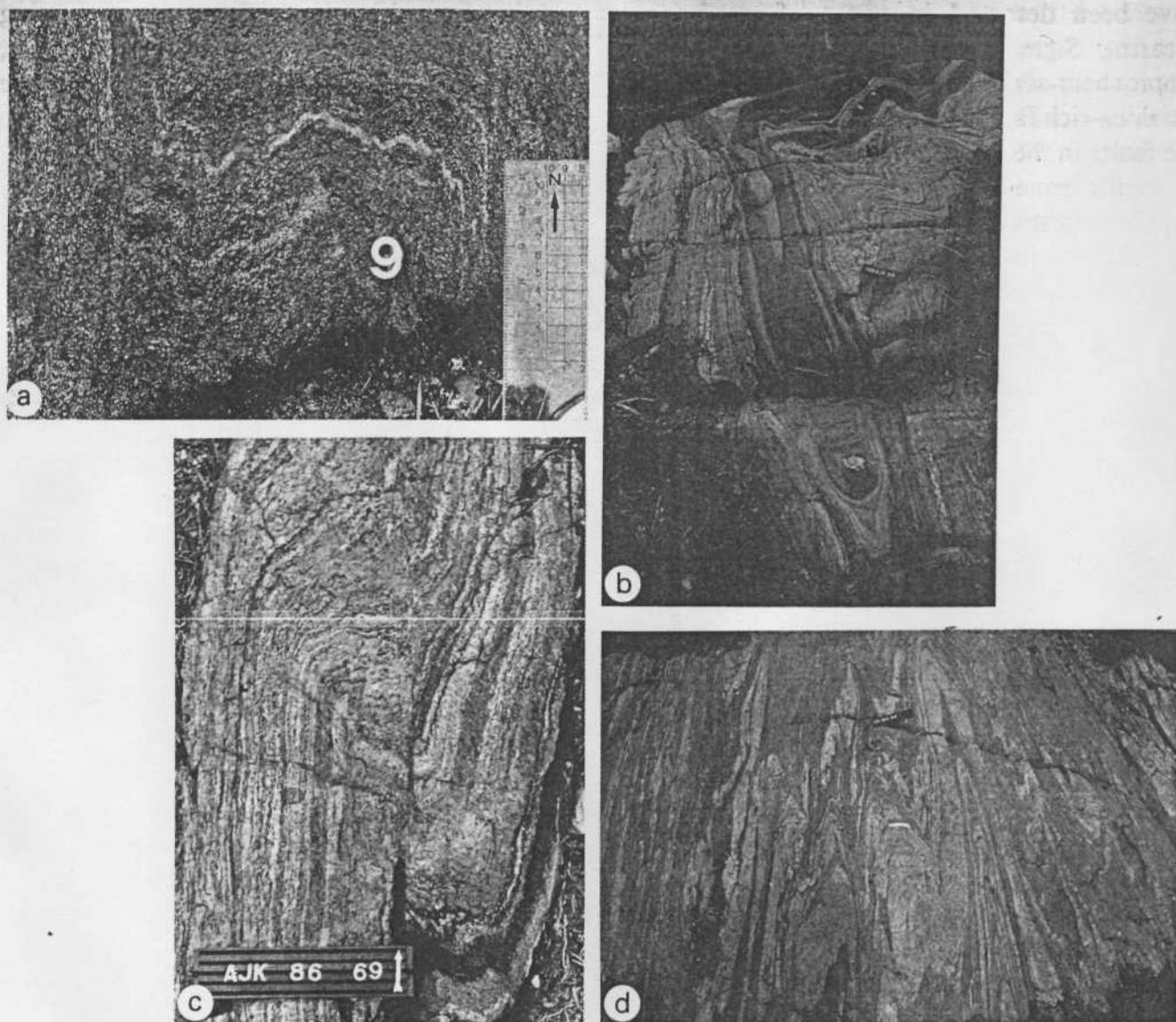


Fig. 4. (a) Dextral semiductile fault in amphibole-rich paragneiss, showing a 10 cm wide ductile zone between the N-S trending blastomylonitic zones. (b) Sheath fold bordered by migmatitic, N-S trending blastomylonite zone in the west. (c) J-shaped D_3 hook fold associated with a N-S trending fault. (d) Multiply deformed Palaeoproterozoic paragneiss showing a dextral N-S trending mylonite zone and associated D_3 en-echelon folds and Z-folds, the axial plane trace of which diverges about 20° anticlockwise from the plane of the mylonite zone.

HSZ turns NNE and is marked by a sheared, mylonitic zone of metapelites (Fig. 3) intersecting the "Lappidic" trend of the Kuusamo Schist Belt.

Dynamically, the stress field during stage D_3 differed from that of stage D_2 in that the lowest, vertical principal stress and the intermediate, horizontal and NE-SW trending one changed places. The maximum principal stress (σ_1) remained in a NE-SW direction. This

stress field created the N-S striking dextral strike-slip shear zones.

Mesoscopic structures. The fault rocks associated with diverse D_3 faults are mostly sheared gneisses with metamorphic foliation of a symmetric, recovered character. Sometimes the foliation is integrated with intrafolial, isoclinal fold structures. Blastomylonitic zones and asymmetric structures such as foliation fishes, indicators of dextral slip within the shear zone,

have been detected in zones of maximum shearing. Sigma structures and other microscopic shear-sense indicators are also visible in the mica-rich fault rocks. The dextral semiductile faults in the HZS consist of narrow blastomylonitic zones bordered by wider zones of ductile deformation (Fig. 4a).

Asymmetric folds with axial-plane traces diverging 15° to 30° anticlockwise from the plane of the PDZ₃ constitute en-echelon folds in the D₃ shear zone. These are tight and usually not harmonic, and are closely related to the blastomylonitic zones and other elements of the shear zone (Fig. 4d). Hook- and Z-folds (Fig. 4c) are detectable in mica-rich paragneisses and provide clear evidence of dextral slip during shearing. The axial-plane traces are mostly parallel to the PDZ₃ and their fold axes perpendicular to the stretching lineation. The hook folds are J-shaped folds with narrow faults parallel to the axial-plane traces (e.g. Hudleston, 1989; cf. Fig. 4c), whereas the Z-folds are products of entirely ductile deformation. Sheath folds (e.g. Schwerdtner, 1987) comprise the fourth class of folds within the shear zone (Fig. 4b). In two-dimensional sections these are seen as irregular basin and dome structures or tube-shaped structures in the direction of the stretching lineation. The sheath folds are situated between blastomylonitic zones or zones of highest shear strain.

The Proterozoic paragneisses of the HSZ have been intruded by Svecokarelian granites and granitic pegmatites, amongst which the latter are genetically associated with the shearing. The migmatization of the paragneisses and the amount of granitic material increase towards the north, and the gneisses of the northern part of the HZS are migmatites without primary structures.

4.1. Structural correlations and definition of the Savolampi Shear System

The Kemijärvi Complex prevents the HSZ from being followed north, while the defor-

mation caused by the OSZ hampers mapping of its southern extension. It is, nevertheless, probable that the sheared Väyrylänkylä Nappe (Laajoki, 1991) and the sheared core of the southern end of the Kainuu Schist Belt (Havola, 1981) represent the same tectonic zone. If so, the original length of the HSZ was at least 300 km. The maps of Paavola (1980, 1984) show clearly that a N-S trending shear zone occurs at the southeastern corner of the Iisalmi Complex (Fig. 1), and this Nilsiä Shear Zone can be correlated tentatively with the HSZ. These zones appear to represent a large strike-slip fault zone which follows a D₁-D₂ tectonic zone (the Koillismaa-Kainuu-North Karelia tectonic zone of Laajoki 1991) and subdivides the Archaean crust into the Kuhmo Complex in the east and the Iisalmi and Pudasjärvi Complexes in the west.

Berthelsen and Marker (1986b) describe the Baltic-Bothnia Megashear and a megashear in Russian North Karelia which trends in the same, approximately N-S direction. The northern part of the former, which we here call the Pajala Shear Zone, is clearly analogous to the HSZ, and thus the central and northern Fennoscandian Shield is traversed by at least three rather closely spaced major N-S trending shear zones: the Pajala Shear Zone, the Hirvaskoski Shear Zone and the Russian North Karelia Shear Zone. Together, these form a large system of shear zones that we call the *Savolampi Shear System* (Fig. 7).

5. The Oulujärvi Shear Zone, type example of D₄ shear zones of the Finlandia Shear System

Definition. The Oulujärvi Shear Zone (OSZ) is a NE-SW trending, subvertical shear zone ~250 km in length which separates the Savo and Northern Pohjanmaa Schist Belts as well as the Archaean Iisalmi and Pudasjärvi Complexes (Fig. 5). It transects the northern end of the Kainuu Schist Belt and continues as a dying, semi-brittle fault system in the northern part of the Archaean Kuhmo Complex. In its

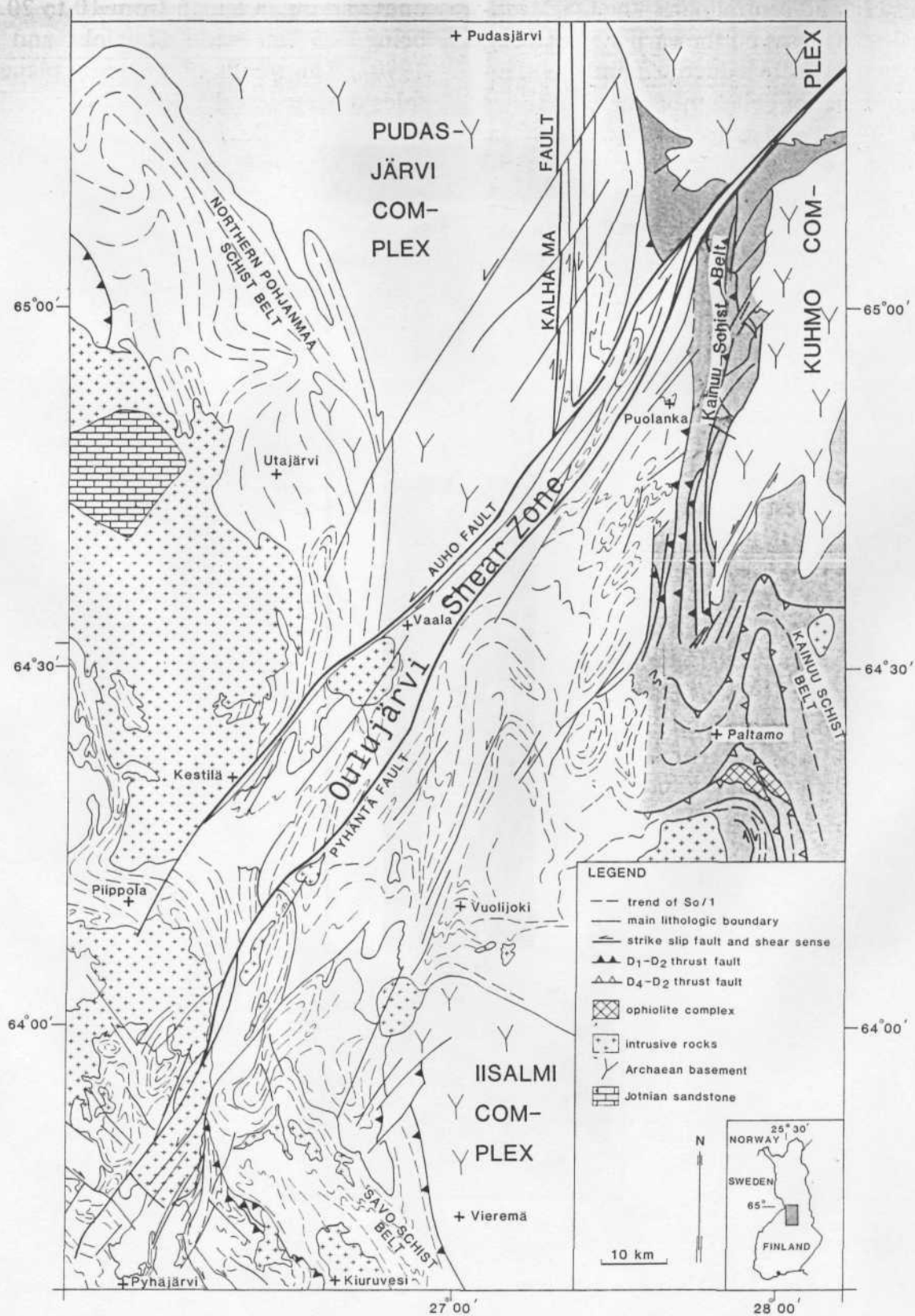


Fig. 5. Simplified geological map of central Finland showing the major structures of the sinistral Oulujärvi Shear Zone. The NW margin of the shear zone is defined by the Auho Fault.

southwestern and central parts, the OSZ truncates and transposes all the earlier structures, including the HSZ, in a ductile manner and includes a number of Palaeoproterozoic granites (Laajoki, 1991) and migmatitic gneisses. The degree of migmatization and the amount of granitoids increase southwestwards.

The OSZ has previously been called the Auho Fault Zone (Laajoki, 1986) but is here renamed on the basis of recent structural work. The name "Auho Fault" is nevertheless retained for a fault parallel to the principal displacement zone of the OSZ (PDZ₄). Both the OSZ and the Auho Fault are seen very clearly on aeromagnetic greytone maps, the former forming a sheared and folded zone 30–40 km wide at its southwestern end and narrowing towards the northeast, and the latter situated at the northwestern border of the OSZ.

The evolution of the OSZ follows the general evolutionary model of strike-slip zones as described by Harding and Lowell (1979), and Sylvester (1988). Applying Harding and Lowell's (1979) model, the ductilely folded southeastern part of the OSZ represents the area of earliest en-echelon folding, continued deformation causing initiation of the sinistral strike-slip faults.

Macroscopic structure. The macroscopic structures identified by mapping (Kärki and Laajoki, 1990; Laajoki and Tuisku 1990; Laajoki, 1991; Luukas, 1991) and from the aeromagnetic greytone maps consist of large en-echelon folds and major faults with connecting minor faults and horsetail systems (Fig. 5).

The most conspicuous macroscopic structures of the OSZ are large NE–SW trending en-echelon folds, which represent interference patterns caused by the superimposition of D₄ and D₂, and arranged in the en-echelon manner typical of large strike-slip shear zones (e.g. Sylvester, 1988). The largest interference folds, reaching lengths of about 30 km and widths of 8 km, are situated at the southwestern end of the shear zone, whereas similar folds are somewhat smaller in the northeast, the principal

ones varying in length from 10 to 20 km and being ~5 km wide (Laajoki and Tuisku, 1990). The trends of the axial planes of the folds deviate less than 40° clockwise from the strike of the PDZ₄.

Major NE–SW trending sinistral strike-slip faults, classified as principal displacement zones (PDZ₄), synthetic Riedel shears (R₄) diverging less than 20° anticlockwise from the plane of PDZ₄, and pinnate shears (P₄) diverging less than 20° clockwise from the plane of PDZ₄, have been identified all over the OSZ. Dextral, NW–SE trending antithetic Riedel shears (R'₄) have also been observed. The largest faults, the Auho Fault and the Pyhäntä Fault, are associated with the PDZ₄.

The total sinistral displacement caused by the shear zone in the northern Kainuu Schist Belt has been estimated to be ~40 km, the displacements along individual faults varying from a few tens of metres to several kilometres.

Mesoscopic structures. The OSZ features progressive formation of a strike-slip shear zone with mesoscopic structures largely similar to those of the HSZ. The D₄ deformation first produced ductile folds, whereas the later phase is characterized by ductile–semiductile faulting. Many faults were also affected by brittle deformation during younger reactivation.

The mesoscopic F₄ folds are usually en-echelon folds, their axial-plane traces typically diverging 20° to 40° clockwise from the strike of the PDZ₄. The characteristic folds within the OSZ are asymmetrical S-folds which are more open than the corresponding Z-folds of the HSZ (Figs. 6a and 6c). The penetrative S₄ axial-plane schistosity is well developed in the F₄ folds of the Puolankajärvi Formation (Laajoki and Tuisku, 1990). In many cases, one or both limbs have been sheared intensively and occasionally intruded by granitic material.

Mesoscopic faults are common in exposures and mostly represent either NE–SW trending, sinistral R₄ shears or NW–SE trending, dextral R'₄ shears. The banding in the highly meta-

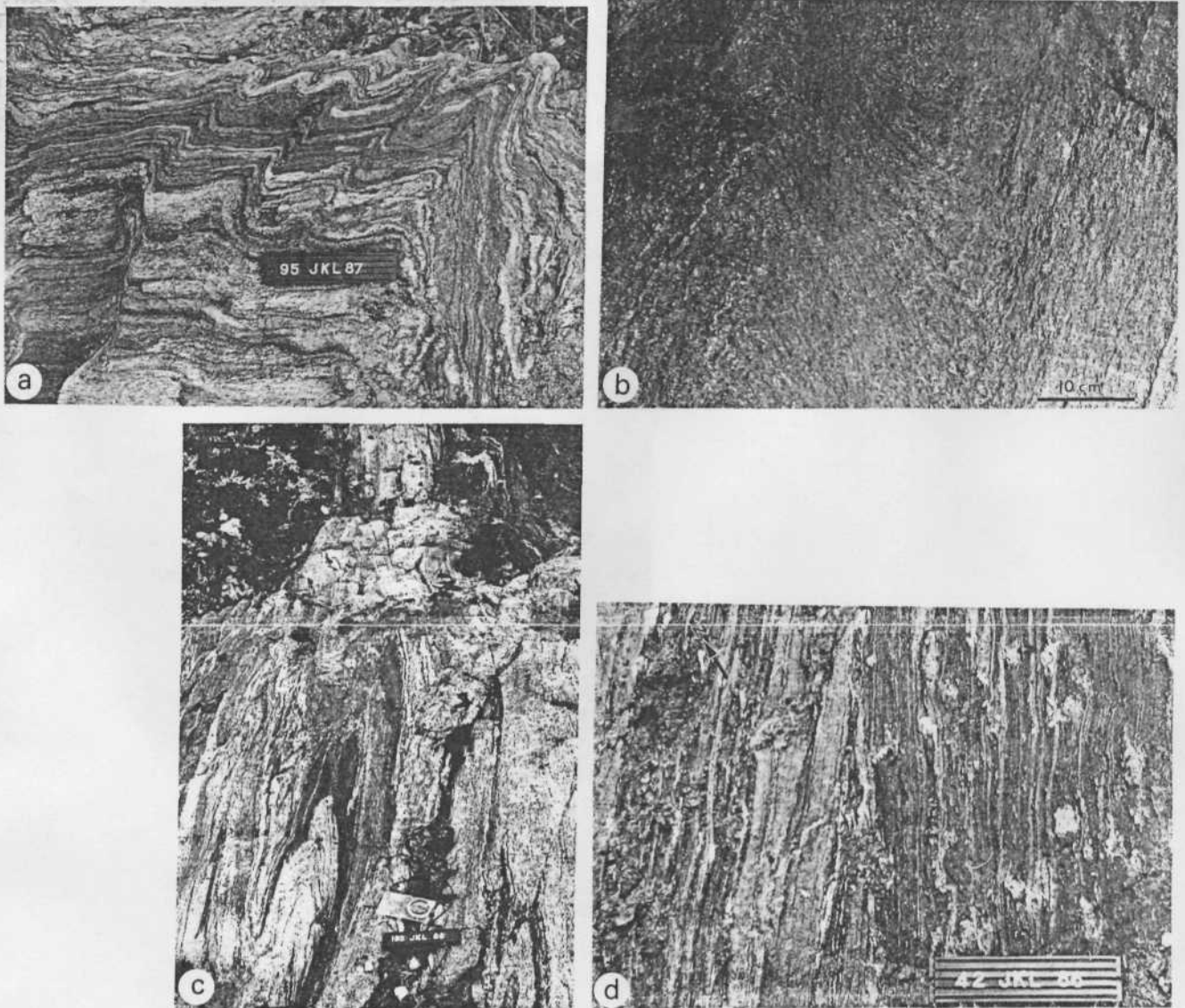


Fig. 6. (a) Chevron-type folds in the crest zone of a macroscopic D_3 en-echelon fold. (b) Dextral semiductile fault in the direction of a D_4 antithetic Riedel shear showing a 30 cm wide ductile zone cut by a NW-SE trending 1 cm wide mylonite zone. (c) S-shaped D_4 fold in Palaeoproterozoic paragneiss; the axial-plane trace is in the direction of the PDZ_4 . (d) NE-SW trending mylonite zone which intersects Palaeoproterozoic mica schist. The sinistral shear sense is shown by the sigma structures in the mylonite zone.

morphosed gneisses is usually parallel to the shear surface. The semiductile faults are a few decimetres wide and consist of a narrow S-C mylonitic zone rimmed by wider zones of ductile deformation (Fig. 6b). The S-C mylonites indicate sinistral shearing within R_4 and the PDZ_4 . In addition, the sense of the shearing can be determined microscopically from rolled porphyroclasts and sigma structures (Fig. 6d). Although the OSZ features shear structures

similar to those of the HSZ, there are also some fundamental differences. The faults of the HSZ feature blastomylonitic characteristics, whereas the corresponding structures in the OSZ have S-C mylonitic and more brittle characteristics. The angles between R_3 and P_3 appear to be smaller than those between R_4 and P_4 , or else the angle of internal friction upon deformation of the HSZ is smaller than that in the OSZ. These differences suggest that the present sec-

tion of the HSZ represents a deeper crustal section and a higher grade of metamorphism than that of the OSZ.

5.1. Structural correlations and definition of the Finlandia Shear System

Laajoki (1986) suggested that the poorly defined Raahe–Ladoga Zone may form a conjugate system with the OSZ (at that time termed the Auho Fault Zone), but doubted the justification of extrapolating the former zone as a zone of intense shearing northwestward past the crossing point with the OSZ (Fig. 1). Our subsequent detailed analysis of the geophysical data and the mapping results showed that this suspicion was justified.

In addition, we find that the concept of the Raahe–Ladoga Zone is poorly defined and understood. Gaál (1972) considers this to be a deep-seated wrench fault zone trending from

the Gulf of Bothnia to Lake Ladoga, and Gaál and Gorbatshev (1987) later called it the Ladoga–Bothnian Bay Tectonic Zone. On the other hand, the term “Raahe/Bothnian Sea–Ladoga” is often associated with the “main sulphide ore belt of Finland” as described by Kahma (1978). Korsman (1988), for example, states that the Raahe–Ladoga zone is a boundary between the Archaean rocks in northern and eastern Finland and the Proterozoic ones, and hosts most of the major sulphide ore deposits in Finland. In view of these multiple significance associations we are reluctant to continue the use of the “Raahe–Ladoga nomenclature” and prefer to apply the term “Kuopio Shear Zone” to the part of the original Raahe–Ladoga Zone of Gaál (1972) situated southwest from the point where that zone crosses the OSZ. The Kuopio Shear Zone includes the Suvasvesi, Haukivesi and Pihlajavesi Faults. Its structure has been documented by Gaál and Rauhamäki (1971), Halden

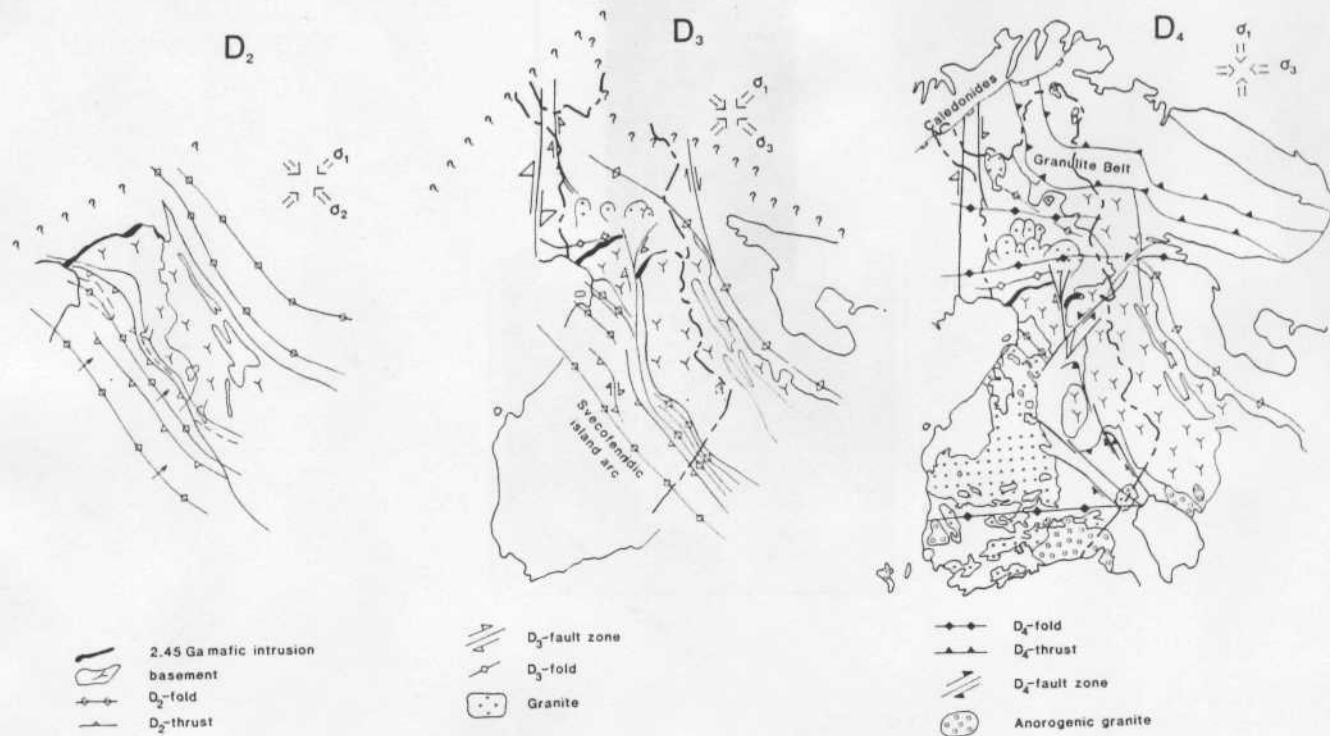


Fig. 7. Tectonic evolution of the central Baltic Shield between 1.93 and 1.80 Ga ago: thrusting and folding during stage D₂; development of the Savolampi Shear System during stage D₃; structural features produced by N–S compression during stage D₄.

(1982), and various authors in Korsman (1988).

In addition to the major structures exemplified by the OSZ and the Kuopio Shear Zone, minor D_4 structures are quite common in eastern Finland (Koistinen, 1981; Ward, 1987), the southern part of the Kainuu Schist Belt (Gehör and Laajoki, unpublished data) and Lapland (Fig. 7c; Marker, 1988; Ward et al., 1988; Gaál et al., 1989). These D_4 structures, which cover a major part of the central Fennoscandian Shield, form a network of sinistral NE–SW trending and dextral NW–SE trending shear zones which we call the *Finlandia Shear System*.

6. Discussion

The effects of the prolonged compressional evolution of the Karelian and Svecofennian Provinces during the Svecokarelian Orogeny have been described by many authors (cf. Gaál, 1990, and references therein). The earliest recumbent folding and NE-directed thrusting towards the craton can be identified as a belt of external thrusting and folding in the Karelian formations. This fold and fault belt was formed by a NE–SW compression which caused accretion of the northeastern Svecofennian island arc to the Karelian province during D_1 (Fig. 7, left). Some thrusting and folding marking the final closure of the oceanic basin between the Svecofennian island arc and the Karelides was also associated with stage D_2 of the progressive Svecokarelian deformation (Luukas, 1991). The culmination of the regional metamorphism took place during stage D_2 (Hölttä, 1988; Tuisku and Laajoki, 1990) and accretion of the Svecofennian island arc occurred between 1.93 and 1.85 Ga ago (Vaasjoki and Sakko, 1988; Gaál, 1990).

The following phase of deformation created the major N–S striking, vertical D_3 shear zones of the Savolappi Shear System in the central and northern Fennoscandian Shield (Fig. 7, middle). The Pajala Shear Zone and the Rus-

sian North Karelia Megashear define the western and the eastern members of this system, while the Hirvaskoski Shear Zone and its southern extension represent a third major N–S striking shear zone between and parallel to the first-named pair. The creation of this shear system marks a change from the folding and thrusting of the early stages to the ductile shearing of stage D_3 . The main reason for this change appears to be the thickening of the Palaeoproterozoic crust, which caused a change of the stress field, and the D_2 peak of the regional metamorphism (Tuisku and Laajoki, 1991).

The Peräpohja Schist Belt between the Pajala and Hirvaskoski Shear Zones represents an area in which a local N–S compression caused by northward displacement of the Pudasjärvi Complex during D_3 faulting formed the E–W trending folds described by Salonsaari (1991). These form a counterpart of Väyrynen's (1954) "Lappidic folding".

Since the amount of granitoids increases towards the north within the HSZ and since the Pajala Shear Zone is also characterized by abundant synkinematic granitoids, we suggest that the formation of the Kemijärvi Complex may have been associated with the left-stepping Hirvaskoski–Pajala pair of shear zones. The space problem may have been resolved by tectonic underplating, which could, in turn, have given rise to granitic diapirs and caused the migmatization of Archaean and Karelian formations in the area of the Kemijärvi Complex. The ages of the Central Lapland granitoids range from 1843 to 1770 Ma (Lauerma, 1982; Huhma, 1986) and support this interpretation.

Approximately 1.85 Ga ago a new phase of compression started in a N–S direction, possibly because of the functioning of a new subduction system in the south (cf. Edelman and Janus-Järkkälä, 1983; Vaasjoki and Sakko, 1988). This was relaxed by various D_4 structures that formed in different places and at different times (Fig. 7). The first to be produced

were the E–W striking folds (e.g. in the Tampere area; Campbell, 1980; Nironen, 1989) and the 1.83–1.81 Ga old migmatization (Vaasjoki and Sakko, 1988) in southern Finland. Similar folds formed by a pure shear mechanism have been identified in the northern part of the Savo Schist Belt, where the E–W striking D_4 folds gradually swing into a NE–SW direction to form the en-echelon folds of the Oulujärvi Shear Zone. This folding preceded the major sinistral shearing of the Oulujärvi Shear Zone (Luukas, 1991). Simultaneously there may have been some reactivation and rotation of the D_1 – D_2 thrust zones on the northern side of the Iisalmi Complex (Figs. 1 and 7c). The Saariaho granite (1.91 Ga; Laajoki, 1991) clearly predates the D_4 deformation, whereas the intrusion of the Nattanen-type granitoids following a NE–SW trend in the northern Fennoscandian Shield (1.80 Ga; Front et al., 1989) and the synkinematic or postkinematic granitoids of the OSZ (e.g. the Takiangkangas granite, 1.80 Ga, and the Avainlampi diorite, 1.80 Ga, Laajoki, 1991) indicate the age of shearing by stage D_4 .

During the generation of the Oulujärvi Shear Zone, its southeastern conjugate, the NW–SE trending dextral Kuopio Shear Zone (Fig. 7c) developed simultaneously with associated granites of 1.78 Ga age (Halden, 1982). This shear zone has been considered a major tectonic feature in Finland and has been included in the Raahe–Ladoga Zone (Gaál, 1972). We are, nevertheless, inclined to regard the Kuopio Shear Zone as part of the Finlandia Shear System and do not support the idea that major strike-slip faulting occurred along its northwestern continuation past the point where it meets the OSZ. We rather suggest that in the latter area deformation was released by folding. The distribution of the granitoids, the variations in deformation style and the grades of metamorphism within the Oulujärvi and Kuopio Shear Zones suggest that their southwestern and northwestern parts, respectively, represent more ductile deformation of pre-

sumably deeper sections of the Precambrian crust than the northeastern and southeastern parts.

As a result of powerful N–S directed D_4 compression, the Iisalmi Complex was faulted to a conjugate strike-slip system, the individual fault directions of which coincide with those of the major shear zones described above. There may also have been some thrusting or reverse faulting related to N–S compression in the northern part of this complex (Fig. 7c). In Lapland, the effects of N–S compression are represented by E–W striking folds in central Lapland and by the latest thrusting of the Lapland Granulite Complex (Berthelsen and Marker, 1986a; Marker, 1988).

As a whole, the tectonic consequences of deformation stages D_3 and D_4 appear to have been much more important and complicated than has been realized previously. In consequence, the portion of the Fennoscandian Shield affected by them cannot be considered an anorogenic cratonic area but rather an essential part of the Svecokarelian Orogeny. The precise determination of the role of this realm in the Svecokarelian Orogeny must, however, await the completion of a tectonic synthesis for the whole Shield, including also the Russian part of Karelia.

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References

- Alapieti, T., Filén, B., Lahtinen, J., Lavrov, M., Smolkin, V. and Voitsekhovskiy, S., 1990. Early Proterozoic lay-

- ered intrusions in the northeastern part of the Fennoscandian Shield. *Miner. Petrol.*, 42: 1–22.
- Aydin, A. and Page, B., 1984. Diverse Pliocene–Quaternary tectonics in a transform environment, San Francisco Bay region, California. *Geol. Soc. Am. Bull.*, 95: 1303–1317.
- Bell, E. and Etheridge, M., 1973. Microstructure of mylonites and their descriptive terminology. *Lithos*, 6: 337–348.
- Berthelsen, A. and Marker, M., 1986a. Tectonics of the Kola collision suture and adjacent Archean and Early Proterozoic terrains in the northeastern region of the Baltic Shield. *Tectonophysics*, 126: 31–55.
- Berthelsen, A. and Marker, M., 1986b. 1.9–1.8 Ga old strike slip megashears in the Baltic Shield, and their plate tectonic implications. *Tectonophysics*, 128: 163–181.
- Campbell, D.S., 1980. Structural and metamorphic development of migmatites in the Svecokareliides, near Tampere, Finland. *Trans. R. Soc. Edinburgh, Earth Sci.*, 71: 185–200.
- Daly, M.C., 1986. Crustal shear zones and thrust belts: their geometry and continuity in Central Africa. *Philos. Trans. R. Soc. London, A* 317: 111–128.
- Edelman, N. and Jaanus-Järkkälä, M., 1983. A plate tectonic interpretation of the Precambrian of the archipelago of southwestern Finland. *Geol. Surv. Finl., Bull.*, 325, 33 pp.
- Front, K., Vaarma, M., Rantala, E. and Luukkonen, A., 1989. Keski-Lapin varhaisproterotsooiset Nattas-typin graniittikompleksi, niiden kivilajit, geokemia ja mineralisaatiot. Summary: Early Proterozoic Nattanen-type granite complexes in central Finnish Lapland: rock types, geochemistry and mineralization. *Geol. Surv. Finl., Rep. Inv.*, 85, 77 pp.
- Gaál, G., 1964. Jatul und Karelische Molasse im S-Koligebiet in Nordkarelien und ihre Beziehungen zum Gebirgsbau des Präkambrischen Orogens. *Bull. Comm. Géol. Finl.*, 213, 45 pp.
- Gaál, G., 1972. Tectonic control of some Ni–Cu deposits in Finland. 24th Int. Geol. Congr., Montreal 1972, 4: 215–224.
- Gaál, G., 1990. Tectonic styles of Early Proterozoic ore deposition in the Fennoscandian Shield. *Precambrian Res.*, 46: 83–114.
- Gaál, G. and Gorbatshev, R., 1987. An outline of the Precambrian evolution of the Baltic Shield. *Precambrian Res.*, 35: 15–52.
- Gaál, G. and Rauhamäki, E., 1971. Petrological and structural analysis of the Haukivesi area between Varkaus and Savonlinna, Finland. *Bull. Geol. Soc. Finl.*, 43: 265–337.
- Gaál, G., Berhelsen, A., Gorbatshev, R., Kesola, R., Lehtonen, M.I., Marker, M. and Raase, P., 1989. Structure and composition of the Precambrian crust along the POLAR Profile in the northern Baltic Shield. *Tectonophysics*, 162: 1–25.
- Gehör, S. and Laajoki, K., 1992. Deformation of the Nuasjärvi Basin of the early Proterozoic Kainuu Schist Belt, Finland. *Res. Terrae, Ser. A*, 5: 18 (abstr.).
- Gower, C.F., Rivers, T. and Ryan, B. (Editors), 1990. Mid-Proterozoic Laurentia–Baltica. *Geol. Assoc. Can. Spec. Pap.*, 38.
- Halden, N.M., 1982. Structural, metamorphic and igneous history of migmatites in the deep levels of a wrench fault regime, Savonranta, eastern Finland. *Trans. R. Soc. Edinburgh, Earth Sci.*, 73: 17–30.
- Harding, T.P., 1990. Identification of wrench faults using subsurface data: criteria and pitfalls. *Am. Assoc. Pet. Geol. Bull.*, 74: 1590–1609.
- Harding, T. and Lowell, J., 1979. Structural styles, their plate-tectonic habitats, and hydrocarbon traps in petroleum provinces. *Am. Assoc. Pet. Geol. Bull.*, 63: 1016–1058.
- Havola, M., 1981. Pre-Quaternary rocks. Sheet 3433, Sotkamo. Geological map of Finland 1:100000.
- Hietanen, A., 1975. Generation of potassium-poor magmas in the northern Sierra Nevada and the Svecofennian in Finland. *J. Res. U.S. Geol. Surv.*, 3: 631–645.
- Hoffman, P.F., 1987. Continental transform tectonics: Great Slave Lake shear zone (ca. 1.9 Ga), northwest Canada. *Geology*, 15: 785–788.
- Hölttä, P., 1988. Metamorphic zones and the evolution of granulite metamorphism in the early Proterozoic Pielavesi area, central Finland. *Geol. Surv. Finl., Bull.*, 344, 50 pp.
- Hudleston, E., 1989. The association of folds and veins in shear zones. *J. Struct. Geol.*, 11: 949–957.
- Huhma, H., 1986. Sm–Nd, U–Pb and Pb–Pb isotopic evidence for the origin of the Early Proterozoic Svecokarelian crust in Finland. *Geol. Surv. Finl., Bull.*, 337, 48 pp.
- Kahma, A., 1978. The main sulphide ore belt of Finland between Lake Ladoga and the Bothnian Bay. *Bull. Geol. Soc. Finl.*, 50: 39–43.
- Kärki, A., 1991. Puolankajärven kompleksin ja Länsi-Puolangan gneissikompleksin arkeeminen ja proterotsooinen rakennekehitys. Unpublished Phil. Lic. Thesis. University of Oulu. 117 pp.
- Kärki, A. and Laajoki, K., 1990. Pre-Quaternary rocks. Sheet 3442, Puolanka. Geological Map of Finland 1:100 000.
- Koistinen, T.J., 1981. Structural evolution of an early Proterozoic strata-bound Cu–Co–Zn deposit, Outokumpu, Finland. *Trans. R. Soc. Edinburgh, Earth Sci.*, 72: 115–158.
- Kontinen, A., 1987. An early Proterozoic ophiolite—the Jormua mafic–ultramafic complex, northeastern Finland. *Precambrian Res.*, 35: 313–341.
- Kontinen, A., 1992. Southern part of the Kainuu Schist Belt—a brief introduction to the general geological setting and excursion stops. *Res. Terrae, Ser. A*, 7: 23–27.
- Korja, T., Pernu, T. and Heikkinen, E., 1991. Geoelectric

- features and their tectonic implications of the Kainuu Schist Belt. *Res Terrae, Ser. A*, 5: 34 (abstr.).
- Korsman, K. (Editor), 1988. Tectono-metamorphic evolution of the Raahe-Ladoga zone. *Geol. Surv. Finl., Bull.*, 343, 96 pp.
- Korsman, K., Niemelä, R., Hautala, T. and Wasenius, P., 1984. Metamorphism as an indicator of evolution and structure of the crust in eastern Finland. *Bull. Geol. Surv. Finl.*, 328, 40 pp.
- Laajoki, K., 1973. On the geology of the South Puolanka area, Finland. *Geol. Surv. Finl., Bull.*, 263, 54 pp.
- Laajoki, K., 1986. The Precambrian supracrustal rocks of Finland and their tectono-exogenic evolution. *Precambrian Res.*, 33: 67-85.
- Laajoki, K., 1990. Early Proterozoic tectofacies in eastern and northern Finland. In: S. Nagvi (Editor) *Precambrian Continental Crust and Its Economic Resources. Developments in Precambrian Geology 6*, Elsevier, Amsterdam, pp. 437-452.
- Laajoki, K., 1991. Stratigraphy of the northern end of the early Proterozoic (Karelian) Kainuu Schist Belt and associated gneiss complexes, Finland. *Geol. Surv. Finl., Bull.*, 358, 115 pp.
- Laajoki, K. and Luukas, J., 1988. Early Proterozoic stratigraphy of the Salahmi-Pyhäntä area, central Finland, with emphasis on applying the principles of lithodemic stratigraphy to a complexly deformed and metamorphosed bedrock. *Bull. Geol. Soc. Finl.*, 60: 79-106.
- Laajoki, K. and Tuisku, P., 1990. Metamorphic and structural evolution of the early Proterozoic Puolankajärvi Formation, Finland, Part I. Structural and textural relations. *J. Metamorph. Geol.*, 8: 357-374.
- Lauerma, R., 1982. On ages of some granitoid complexes in northern Finland. *Bull. Geol. Soc. Finl.*, 54: 85-100.
- Luukas, J., 1991. Salahmin-Pyhännän alueen stratigrafia ja rakennegeologia. Abstract: The stratigraphy and structure of the Salahmi-Pyhäntä area, central Finland. *Res Terrae, Ser. B.*, 16, 131 pp.
- Marker, M., 1988. Early Proterozoic thrusting of the Lapland Granulite Belt and its geotectonic evolution, northern Baltic Shield. *Geol. Fören. Stockholm Förh.*, 110: 405-410.
- Mustila, L. and Korhonen, H., 1991. Macroseismic observations in Finland 1989-1990. Rep. S-26, Inst. Seismol., Univ. Helsinki, 12 pp.
- Nironen, M., 1989. The Tampere Schist Belt: structural style within an early Proterozoic volcanic arc system in Southern Finland. *Precambrian Res.*, 43: 23-40.
- Paavola, J., 1980. Pre-Quaternary rocks. Sheet 3334, Nilsä. *Geological Map of Finland 1:100 000*.
- Paavola, J., 1984. Kallioperäkarttojen selitykset, lehti 3334 Nilsä. English summary: Pre-Quaternary rocks of the Nilsä map-sheet area. *Geological Map of Finland 1:100 000*.
- Park, A. and Bowes, D., 1983. Basement-cover relationships during polyphase deformation in the Svecofenides of the Kaavi district, eastern Finland. *Trans. R. Soc. Edinburgh*, 74: 95-118.
- Park, R.G., Åhäll, K. and Boland, M., 1991. The Sveconorwegian shear-zone network of SW Sweden in relation to mid-Proterozoic plate movements. *Precambrian Res.*, 49:245-260.
- Riedel, W., 1929. Zur Mechanik geologischer Brucherscheinungen. *Zentralbl. Mineral., Geol. Paläontol., Abh.*, B: 354-368.
- Salonsaari, P., 1991. Vanttauskosken alueen kallioperän deformaatio. Abstract: Deformation of the bedrock of the Vanttauskoski area, Northern Finland. *Res Terrae, Ser. B*, 15, 61 pp.
- Schwerdtner, W.M., 1987. Interplay between folding and ductile shearing in the Proterozoic crust of the Muskoka-Parry Sound region, central Ontario. *Can. J. Earth Sci.*, 24: 1507-1525.
- Sylvester, A.G., 1988. Strike-slip faults. *Geol. Soc. Am. Bull.*, 100: 1066-1703.
- Talvitie, J., 1971. Seismotectonics of the Kuopio Region, Finland. *Bull. Comm. Géol. Finl.*, 248, 41 pp.
- Tobi, A.C. and Touret, L.R. (Editors), 1985. The deep Proterozoic Crust in the North Atlantic Province. *NATO ASI Series C, Math. Phys. Sci.*, Vol. 158.
- Tuisku, P. and Laajoki, K., 1990. Metamorphic and structural evolution of the early Proterozoic Puolankajärvi Formation, Finland, Part II. The pressure-temperature-deformation-composition path. *J. Metamorph. Geol.*, 8: 357-391.
- Vaasjoki, M. and Sakko, M., 1988. The evolution of the Raahe-Ladoga zone in Finland: isotopic constraints. *Geol. Surv. Finl., Bull.*, 343: 7-32.
- van Biljon, W.J. and Legg, J.H. (Editors), 1983. Special Publication No. 8 of the Geological Society of South Africa, Johannesburg, 203 pp.
- Väyrynen, H., 1933. Über die Stratigraphie der karelischen Formationen. *C.R. Soc. Géol. Finl.*, 6: 54-78.
- Väyrynen, H., 1939. On the tectonics of the Karelian zone. 17th Int. Geol. Congr., Moscow, *Compt. Rend.*, pp. 57-70.
- Väyrynen, H., 1954. Suomen kallioperä, sen synty ja geologinen kehitys. Otava, Helsinki, 260 pp.
- Ward, P., 1987. Early Proterozoic Deposition and deformation at the Karelian Craton Margin in Southeastern Finland. *Precambrian Res.*, 35: 71-93.
- Ward, P., Härkönen, I., Nurmi, P.A. and Pankka, H., 1988. Structural studies in the Lapland greenstone belt, northern Finland and their application to gold mineralization. *Geol. Surv. Finl., Spec. Pap.*, 10: 71-77.
- Wegmann, C.E., 1928. Über die Tectonic der jünger Falzung in Ostfinnland. *Fennia*, 50, 16.
- Wegmann, C.E., 1929. Beispiele tectonischer Analysen des Grundgebirges in Finnland. *Bull. Comm. Geol. Finl.*, 87: 98-127.
- Wise, D.U., Dunn, D.E., Engelder, J.T., Geiser, P.A.,

- Hatcher, R.D., Kish, S.A., Odom, A.L. and Schamel, S., 1984. Fault-related rocks: suggestions for terminology. *Geology*, 12: 391-394.
- Witschard, F., 1984. The geological and tectonic evolution of the Precambrian of northern Sweden, a case for basement reactivation? *Precambrian Res.*, 23:273-315.

- Xu, J., Wang, P., Ching, R. and Ye, Z., 1986. Ductile deformation and regional strain field in the southern segment of the Tancheng-Lujiang Fault Zone, Eastern China. In: C.Y. Wang (Editor), *Internal Structure of Fault Zones*. *Pure Appl. Geophys.*, 124: 337-364.