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An interlinked system of folds and ductile shear zones—late stage Svecokarelian deformation in the central Fennoscandian Shield, Finland

AULIS KÄRKI and KAUKO LAAJOKI

Department of Geosciences and Astronomy, University of Oulu, Finland

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Abstract—The Svecokarelian deformation of the Karelian and Svecofennian Provinces in Finland involved four main phases. Isoclinal folding and associated thrusting were the main processes of D_1, which was followed by more open folding in D_2. Subsequent deformation was localized during D_3 and D_4. This paper focuses on the late stage (D_4) Svecokarelian deformation that created most of the ductile shear zones in the central Fennoscandian Shield and was the last penetrative deformational event to affect the entire Palaeoproterozoic domain. Deformation during D_4 occurred approximately from 1.85–1.80 Ga, and left a greater imprint in the rocks than has commonly been supposed. The shear zones formed during D_4 are referred to collectively as the Finlandia Shear System.

The Karelian province is composed of Archaean basement and its autochthonous–allochthonous Palaeoproterozoic sedimentary cover. Svecokarelian tectonics split the basement into separate complexes, the rheological properties of which differed markedly from those of the adjacent Proterozoic supracrustal units. On the northern and southern margins of the Archaean complexes, folding with steep E–W-trending axial surfaces was the main response to D_4 deformation, whereas on the eastern and western margins of the complexes the response to D_4 was the development of sinistral and dextral shear zones trending NE–SW and NW–SE, respectively. On a large scale, these areas of folding and of shearing form an interlinked system, the changes from one style of deformation to the other being gradual. The principal D_4 elements in the area of juvenile Svecofennian crust are folds with E–W-trending axial surfaces.

INTRODUCTION

Svecokarelian orogeny and progressive structural evolution affected the central Fennoscandian Shield c. 1.93–1.80 Ga ago. The structural sequence in the Palaeoproterozoic rocks is divided into four main stages (Kärki *et al.* 1993a). Late stage deformation (D_4) has proved to have played a more important role in the structural evolution of the Finnish Karelian and Svecofennian Provinces than has commonly been supposed.

This paper describes the main mechanisms and products of the fourth stage of Svecokarelian deformation and discusses the tectonic evolution associated with it. Archaean complexes, the rheological properties of which differed from those of the Palaeoproterozoic units, had a great influence on the deformation. The deformational style of each of the Karelian subdomains (Fig. 1) is clearly controlled by its position in relation to these Archaean complexes, the subvertical shear zones being situated in general on the eastern and western sides of the Archaean complexes, whereas the areas of intense folding occupy the northern and southern sides. Subvertical NW–SE and NE–SW-trending shear zones associated with 'normally' folded areas also exist in the area of the Svecofennian Province (Fig. 1). Large amounts of granitoids intruded simultaneously with the deformation.

GENERAL GEOLOGY OF THE FENNOSCANDIAN SHIELD

The Fennoscandian Shield has been subdivided into units, to which a variety of names have been given (cf. Gaál 1990 and references therein). Many of these classifications are unsatisfactory in the present context because they treat the Karelian Province as a single unit and do not emphasize that most of it participated actively in the Svecokarelian orogeny.

The central part of the Fennoscandian Shield has been subdivided by Kärki *et al.* (1993) into three major units:

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

(II) The *Karelian Province*, or the *Karelides*, comprises most of the area between the above unit and the Svecofennides. This unit consists of late Archaean crust and its Palaeoproterozoic cover, 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 the Archaean Kuhmo, Iisalmi and Pudasjärvi Complexes, and the intervening Karelian schist belts known as Kainuu Schist Belt (KaSB), Kuusamo Schist Belt (KuSB), Peräpohja Schist Belt (PeSB), Pohjois–Pohjanmaa Schist Belt (PPSB), Pohjois–Karjala Schist Belt (PKSB) and greenstone belts of central Lapland (Fig. 1).

(III) The *Svecofennian Province*, or the *Svecofennides*, is a unit southwest of the Karelian Province composed solely of juvenile Palaeoproterozoic crust (Huhma 1986, Patchett & Kouvo 1986, Huhma & Lahtinen 1993). About half of the surface of southern and central Finland is made up of Svecofennian turbiditic metasediments and basic – intermediate metavolcanics of island arc affinity (Gaál 1986).

The boundary between units (II) and (III) is relatively well defined, although its exact nature is disputed. It lies

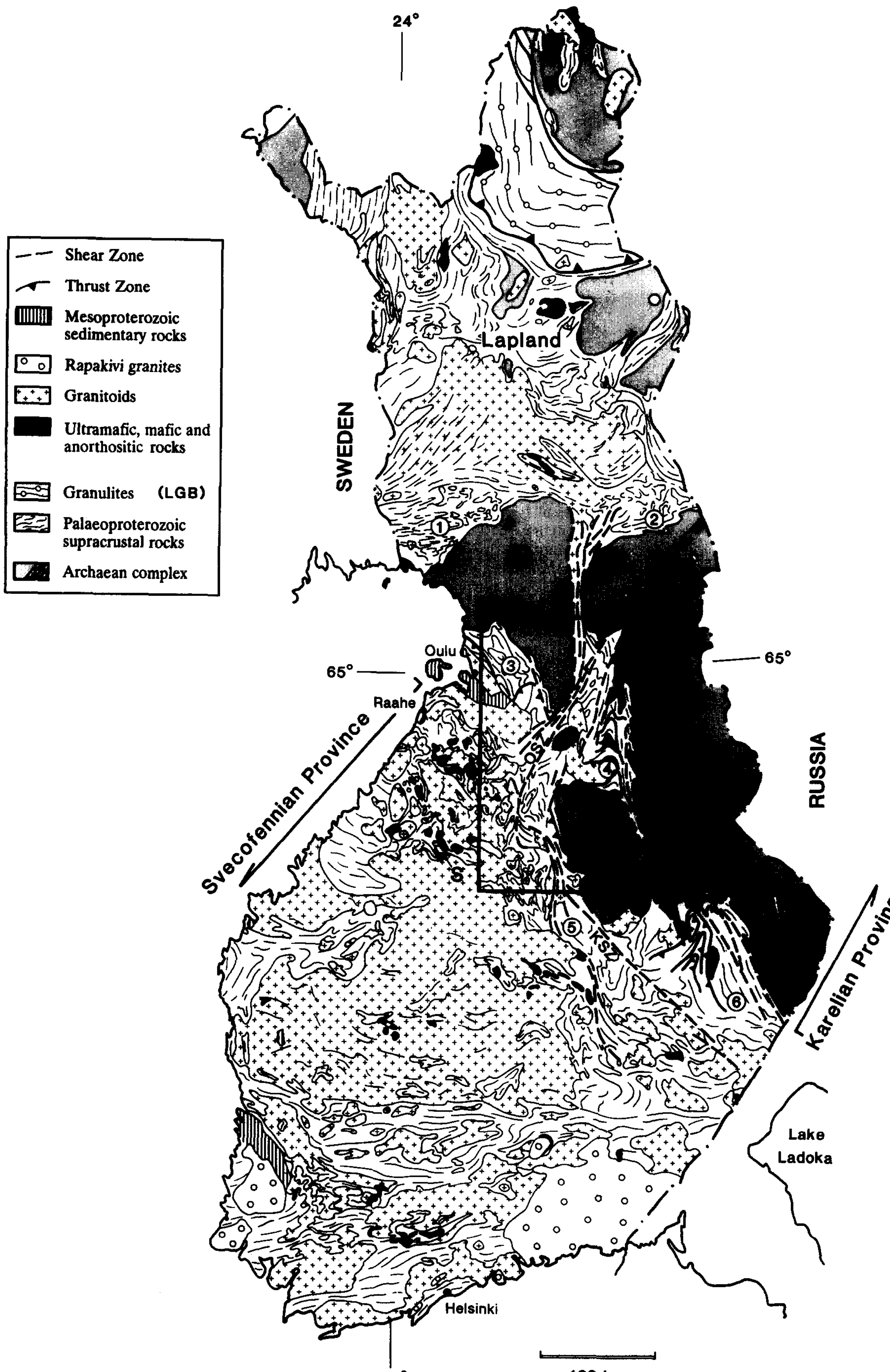

Fig. 1. Generalized geological map of Finland (based on various authors). I = Pudasjärvi Complex, II = Kuhmo Complex, III = Iisalmi Complex, 1 = Peräpohja Schist Belt, 2 = Kuusamo Schist Belt, 3 = Pohjois-Pohjanmaa Schist Belt, 4 = Kainuu Schist Belt, 5 = Savo Schist Belt, 6 = Pohjois-Karjala Schist Belt, HSZ = Hirvaskoski Shear Zone, KSZ = Kuopio Shear Zone, OSZ = Oulujärvi Shear Zone, RSZ = Rautavaara Shear Zone. The location of Fig. 2 is shown and the Syyry district indicated by the letter S.

along the Raahe–Ladoga zone (Kahma 1978, Gaál & Gorbatschev 1987, Korsman 1988, Ekdahl 1994), and recent Sm–Nd data on igneous rocks (Huhma & Lahtinen 1993) indicate that it is fairly sharp, at least in places in Finland. However, it is possible that the allochthonous units covering the autochthonous Karelian formations may be thrust sheets transposed from similar, probably the same, units which dominate the Svecofennian Province. This idea is supported by the latest isotopic results, which show the similarity between the source material of the Svecofennian formations and the allochthonous Kalevian formations (Huhma 1990).

The Karelian and Svecofennian schists are intruded by Svecokarelian syn-, late- and post-kinematic granitoids (Hietanen 1975, Nurmi & Haapala 1986, Patchett & Kouvo 1986). They are most common in southern and central Finland and central Lapland but can be found to some extent in every Palaeoproterozoic belt and some of the Archaean Complexes (Fig. 1).

STRUCTURAL EVOLUTION

The Karelian and Svecofennian Provinces were affected by Svecokarelian progressive deformation. This evolution is divided into an early phase which involved the translation of thrust nappes towards the craton and the creation of related folds marking stages D_1 and D_2. A younger phase of shear tectonics then produced the major shear zones and associated structures of stages D_3 and D_4 in the northern and central Fennoscandian Shield. It seems that the youngest Svecokarelian formations were deposited and intruded after the earliest stages of deformation (D_1 and D_2).

The earliest compressional structures are identifiable as isoclinal F_1 folds and associated structures (Koistinen 1981, Laajoki & Tuisku 1990), which are related on the macroscopic scale to the first nappe emplacements and recumbent folds (Gaál 1990, Luukas 1991). After the first state of deformation, the earliest structures were refolded tightly during stage D_2. The current forms of the D_{1-2} interference patterns vary widely, the simplest being isoclinal F_1 folds folded coaxially by F_2 and having upright S_2 axial planes in a primary northwest–southeast direction.

After stage D_2, deformation changed from folding to shear tectonics, which produced a network of shear zones and associated fold structures of stages D_3 and D_4 (Kärki 1991, Luukas 1991, Kärki *et al.* 1993a). The change in the style of deformation was affected by the generation and thickening of the Palaeoproterozoic crust, an interpretation which is supported by knowledge of the metamorphic evolution of the Karelian Schist Belts (Tuisku & Laajoki 1990). N–S-trending ductile shear zones, the Pajala Shear Zone in northern Sweden (Berthelsen & Marker 1986), the Hirvaskoski Shear Zone in northern Finland (Kärki *et al.* 1993a) and the North Karelia Shear Zone in Russia (Berthelsen & Marker 1986) are the best-known examples of D_3 structures. The fourth stage of Svecokarelian deformation is characterized by ductile NE–SW and NW–SE-trending shear zones and associated folds which form a conjugate shear system termed the Finlandia Shear System by Kärki *et al.* (1993a).

Most of the ductile shear zones were reactivated by subsequent brittle deformations of long duration, causing overprinting of the originally ductile shears by brittle and semi-brittle features.

GENERAL FEATURES OF D_4 DEFORMATION

D_4 structures are common on the Finnish Palaeoproterozoic crust, which is older than approximately 1.8 Ga, but the total strain and intensity of the deformation induced by this stage varies considerably between subareas. Also, the style of deformation varies, so that some subareas are characterized by F_4 fold structures with subvertical, usually E–W-striking axial planes, while others are characterized by sinistral or dextral D_4 shear zones trending NE–SW and NW–SE, respectively. Some features associated with this deformation are also recognizable in the Archaean domains (Figs. 1 and 2).

The main mechanism of D_4 deformation in the area of the juvenile Svecofennian crust was folding. Typical structures created by this stage are interference figures with E–W-trending planes of symmetry and diverse S_4 foliations. Large granitoid intrusions are common in southwestern Finland, and these, especially the large batholith-like diapirs, may have had a great influence on the deformation. Some of the intrusions are younger than the earliest stages of deformation, and thus the regional D_4 structures may be the only structures in the late-kinematic granitoids (Nironen 1989, Ehlers *et al.* 1983).

The Archaean complexes are very important factors in the deformation of the Karelian Province. The deformed units can be classified into two groups on the basis of their general style of deformation, of which the first comprises areas situated on the northern and southern sides of the Archaean complexes, where folding was the main deformation mechanism. The second group comprises dextral and sinistral shear zones, which are typically situated on the eastern and western sides of the Archaean Complexes.

TYPE AREAS FOR F_4 FOLDING

Type areas dominated by regional, E–W-trending F_4 fold structures are situated in the Svecofennian Province, but areas of regional folding with E–W-striking axial planes also exist on the northern and southern sides of the Archaean complexes (Fig. 1). The final style of deformation correlates markedly with the location of each subarea and with the amount of syn- and late-kinematic intrusive material. Three areas are described as type examples for different styles of deformation.

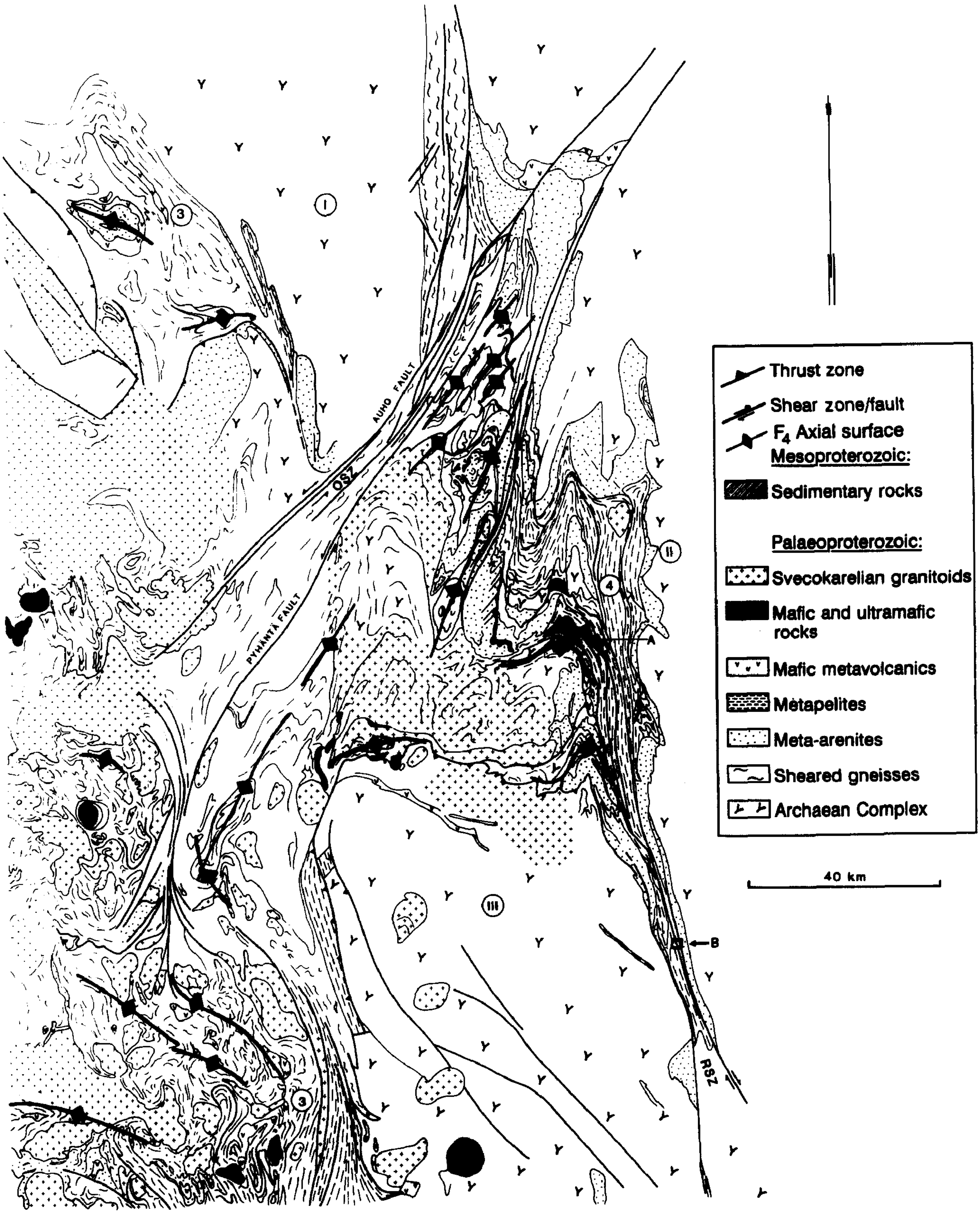

Fig. 2. Geological map of central Finland showing the main structural features. The locations of the Paltaniemi area (A) and detailed map in Fig. 6 (b) are shown. 3 = Pohjois–Pohjanmaa Schist Belt, 4 = Kainuu Schist Belt, HSZ = Hirvaskoski Shear Zone, OZS = Oulujärvi Shear Zone, RSZ = Rautavaara Shear Zone.

Deformation in the central Kainuu Schist Belt

The Paltaniemi area is situated in the central part of the Kainuu Schist Belt (KaSB), to the north of the Archaean Iisalmi Complex (Fig. 2). It is composed of a complex mixture of Archaean gneiss slices and various Palaeoproterozoic paragneisses, quartzites and mica-rich schists (Kontinen & Meriläinen 1993). These successions form thrust sheet-like bodies, the contacts of which are obviously discordant and include the ophiolites of the KaSB (Kontinen 1987), situated close to their discordant contacts. The structures in the cores of these crescent-shaped units mostly trend E–W and reflect coaxial deformation (Figs. 3a and 5a), whereas they swing to trend NE–SW in the west and NW–SE in the east where they reflect non-coaxial deformation (Fig. 2). On a large scale these two-dimensionally crescent-shaped units form steeply S-dipping pod-like structures.

A typical polyphase structural sequence of the Palaeoproterozoic metasediments would involve isoclinal or very tight F_1 folding as the earliest phase. These structures are tightly refolded by F_2 while the effects of later stages are more variable. The intensity of deformation and the state of total strain vary greatly between the subzones and lithological units. The gabbroic segments of the ophiolite complexes form one of the units showing the least intense deformation. These are slightly deformed and their primary structures, such as the sheeted dyke complexes, are very well preserved (Kontinen 1987).

The effects of the D_4 deformation were most significant in the units which had already been deformed intensively by the earlier stages. The most extensive result of D_4 deformation was the reorientation or rotation of all of the previous structures. Thus most of the final structures are polyphasic but co-planar ($S_{1-2} = S_4$) D_{1-4} composite structures which were reoriented and apparently tightened during stage D_4. The E–W-trending foliations in the cores of the large crescent-shaped units can mostly be classified as S_{1-4} composite foliations and the superposed folds as F_{1-4} interference figures (Fig. 3a).

In the northeast corner of the Iisalmi Complex the F_{1-4} folds swing progressively towards a NW–SE direction and finally NNW–SSE (Fig. 2), and in the same way the F_{1-4} folds in the northwest corner of the Iisalmi Complex swing towards northeast–southwest. The S_4 foliation changes, simultaneously with the change in direction, from schistosity to a mylonitic foliation with dextral shearing in the areas of the right limbs of the crescent-shaped units and sinistral shearing in the areas of the left limbs.

Deformation of the Kuusamo Schist Belt and the Hirvaskoski Shear Zone

The dominant structures in the Kuusamo Schist Belt (KuSB, Fig. 1) are large domes and basins ranging in diameter from a few kilometres to tens of kilometres and varying greatly in form. They are mostly irregular, oval-shaped, narrow, elongated elements (Silvennoinen 1972, 1989) or superposed fold structures formed by multiple stages of rather open folding. The trends of the longest axes of these structures are randomly oriented over the whole area of the KuSB, but in the southern part they are chiefly east–west, following the strike of the northern contact of the Kuhmo Complex (Fig. 1) and suggesting a fairly high intensity of D_4 deformation in this subarea.

Mesoscopic F_4 fold structures are uncommon in the outcrops of the southern part of the KuSB, whereas E–W-striking, steeply dipping S_4 foliations (Fig. 5b) are frequently identifiable. The most representative type of S_4 foliation in the KuSB is low-grade cleavage, whereas the S_4 foliation in the southern schist belts is more likely to be schistosity or metamorphic banding.

The S_4 planes in the northwestern corner of the Kuhmo Complex swing progressively northeast–southwest and finally north–south, following the trend of the Hirvaskoski Shear Zone (HSZ; Fig. 1), and the mesoscopic F_4 folds appear simultaneously to become more common and to alter in type from symmetric components of macroscopic interference folds to mesoscopic, sinistral *S*-folds. Finally, together with the increase in the shear strain, the D_4 structures change to semi-ductile shears in directions which deviate by 10–15° at the most from the general strike of the HSZ (Fig. 6a). The change from the folded KuSB to the ductile HSZ is a gradual one.

The semi-ductile shears of the HSZ show both sinistral and dextral shearing, the dextral shears being associated with stage D_3 (Kärki *et al.* 1993a) whereas the sinistral shears are mostly associated with stage D_4. Microstructural examination shows clearly that the D_4 shearing in this area postdated the thermal peak of metamorphism and the growth of most of the metamorphic minerals. The growth of garnet porphyroblasts and biotite is associated with D_3, whereas the D_4 shears are characterized by the growth of muscovite and possibly chlorite (Fig. 3b). Old σ-structures and the inclusion trails in the garnets (Schoneveld 1977, Johnson 1993) exhibit dextral D_3 shearing, whereas the semi-ductile D_4 shears include σ-structures indicating sinistral sense of shearing (Fig. 3b). The D_4 stretching lineation in the shears showing sinistral shearing plunges gently southward (Fig. 6b) while D_3 lineations plunge gently northward. Thus the main differences between the single D_3 and D_4 shears in the northern part of the HSZ lie in the sense of the shearing, the types of fault rock and the directions of the stretching lineation.

Deformation in the Svecofennian Province

The area used as an example of deformation in the Svecofennian Province is situated in the Syyry district, central Finland (Fig. 1).

The Syyry district is composed for the most part of syn- or late-kinematic tonalites surrounded by Svecofennian metasedimentary rocks and basic intrusives (Anttila *et al.* 1993). Paragneiss xenoliths of varying sizes are common inclusions in the tonalites, obviously differing from the tonalites in their structural evolution in that they feature polyphasic ductile deformation, whereas the latter involved only one or two significant stages of ductile deformation.

Typical D_4 structures in the Syyry district are mesoscopic folds with steeply dipping WNW–ESE-striking axial planes. Magmatic foliation of the tonalites and elongate xenoliths similar to the mica-rich paragneisses of the adjacent Svecofennian schist belts are the deformational elements. The typical F_4 folds vary from chevron folds to box folds and are not very tight, which indicates a rather low total strain associated with the D_4 deformation. Penetrative S_4 foliation is also very weak and is hardly distinguishable in the homogeneous, coarse-grained tonalites (Fig. 3c), although it clearly crenulates all the earlier structures in the mica and amphibole-rich rocks. The S_4 foliation usually trends WNW–ESE and dips steeply southward or northward (Fig. 5c).

The S_4 foliation denotes the symmetry plane of the macroscopic D_4 structure. The intrusive bodies and paragneiss units are clearly elongated in an E–W direction, following the S_4 trend, and the macroscopic structures of the Svecofennian domain in general resemble large-scale fold structures with their axial planes in an E–W direction (Fig. 1). The late-kinematic granitoids belong to the 1800–1850 Ma age group (Nurmi & Haapala 1986), and 1850 Ma can be assumed as a maximum age for the D_4 deformation.

DEXTRAL, UPRIGHT D_4 SHEAR ZONES

One of the most significant shear zones in the central Fennoscandian Shield transects the southern part of the KaSB (Fig. 1) and is termed here the Rautavaara Shear Zone (RSZ) after a town located in the middle part of it. The Palaeoproterozoic domain between the Archaean Iisalmi and Kuhmo Complexes gradually narrows southwards and finally disappears entirely (Fig. 2), but the RSZ continues to the south, intersecting the Archaean gneisses, and the extreme western fault of the shear zone forms the contact between the Archaean Kuhmo and Iisalmi Complexes. The shear zone continues to the north in the middle part of the KaSB (Havola 1981, Ervamaa & Heino 1983) and reaches a total length of more than 200 km.

A more detailed illustration shows the RSZ to be composed of an anastomosing system of ductile shears and brittle faults (Fig. 7) which must have been created under variable conditions of metamorphism. The most intensely sheared zone has a total width of approximately 2 km at the southern end of the KaSB (subarea B in Fig. 2) and is bordered by the quartzites to the east and the mica schists to the west (Fig. 7). Black schists and ultramafic blocks, evidently similar to the ultramafic parts of the ophiolite complexes, are associated with some shears in this zone (Havola 1981).

Semi-ductile shears are the most typical mesoscopic elements of the shear zone. They dip steeply westwards and their strike deviates by 10° at most from the general strike of the shear zone (Fig. 6e). The tectonites associated with these vary from *S–C* mylonites (Lister & Snoke 1984) to coarse-grained augen gneisses (Simpson & Schmid 1983). The brittle textures identifiable in some of the faults are caused by later reactivation and brittle deformation. Most of the primary sedimentary structures and secondary foliations in the eastern quartzites and western mica schists strike in a direction parallel to the shear zone, which indicates a relatively high grade of deformation of these domains as well.

The fold structures of the shear zone are variable in form, since the state of shear strain varies greatly from one subzone to another. The folds of the earlier stages may be preserved, and most of the fold structures are interference figures showing features of all the stages D_1—D_4. Dextral asymmetric Z-folds, clearly associated with the shearing, are the most representative elements created by stage D_4, and it is these that are classified as F_4 folds proper.

Kinematics of distinct shears in the RSZ

Asymmetric fold structures, mesoscopic shear structures and microscopic deformation textures (Lister & Williams 1979, Simpson & Schmid 1983, Bjornerud 1989, Bell & Johnson 1992) may be used as kinematic indicators, whereas the forms of the interference folds are mostly complicated and they are not necessarily useful as kinematic indicators in spite of the intense D_4 deformation. F_4 folds that take the form of simple Z-folds with subvertical fold axes and NW–SE-trending axial planes may nevertheless be clear indicators of dextral shearing associated with the folding, as becomes obvious when a planar S_3 foliation or corresponding element has been subjected to F_4 folding.

The lineations measured in the central part of the shear zone vary greatly in direction, but they all lie in the plane which follows the general trend of the RSZ. Two statistical maxima are visible in the measurement results—one plunging steeply westward and one gently northward or southward at an angle of 5–20° (Fig. 6f). The stretching lineations with shear sense indicators can be used to deduce the exact shear direction (Lin & Williams 1992).

The mylonitic foliation of some of the shears indicates dextral shearing, as shown by the σ structures of the *S–C* mylonites (Fig. 3d) and the δ structures of the augen gneisses. The structures are mostly symmetrical, however, making it impossible to determine the sense of shearing, and the asymmetric structures in some subzones may point to sinistral shearing. It is even possible to find wide zones sheared in a ductile manner and composed of multiple shear bands, some of which indicate dextral shearing and others sinistral. These different shearing directions provide clear evidence of the polyphasic nature of the shear zones. The shears showing dextral shearing and the stretching lineations plunging gently southwards are interpreted as D_4 elements,

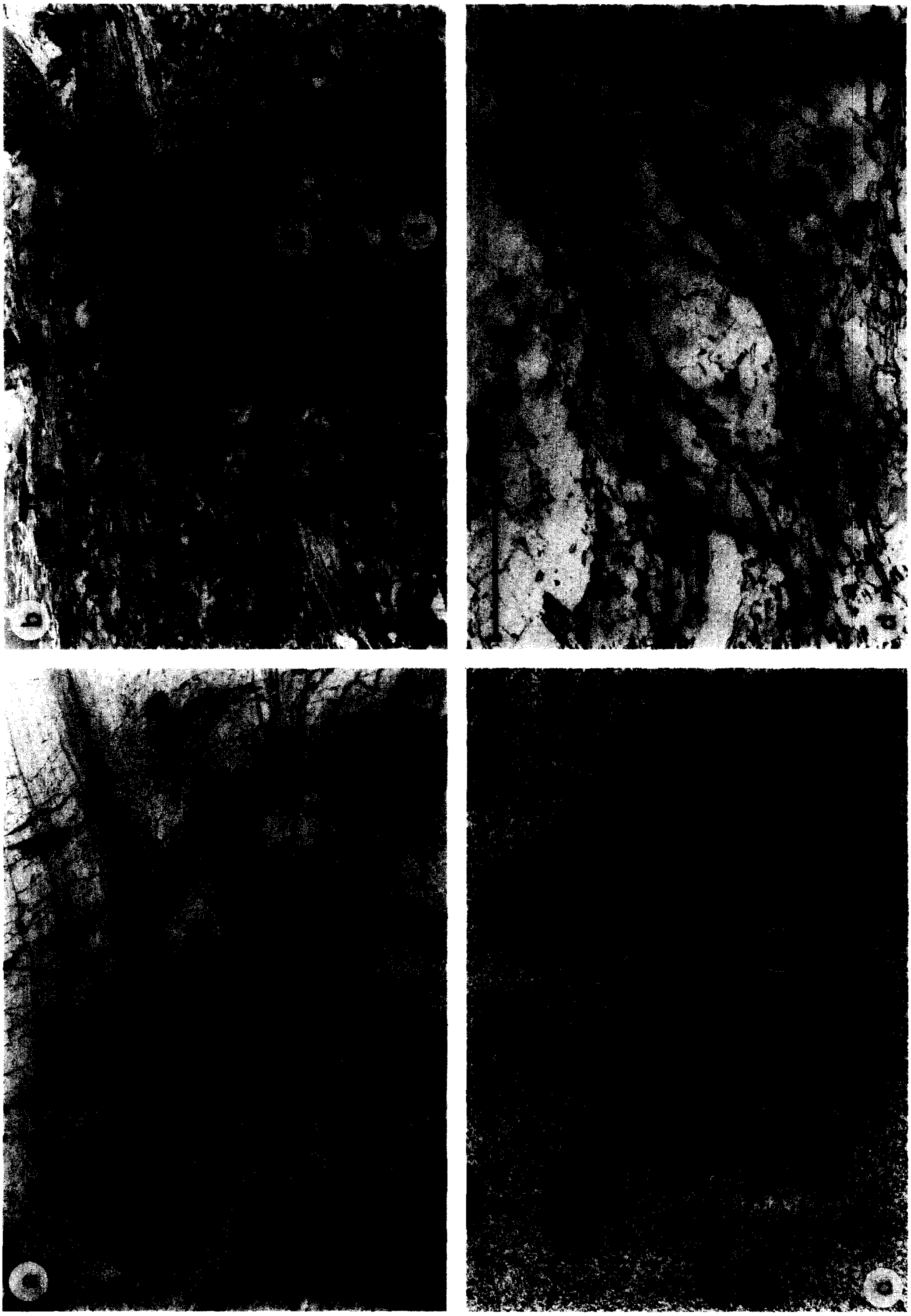

Fig. 3. (a) A tight F_{1-4} interference fold with E–W-trending S_4 foliation in a quartzite, Paltaniemi area; (b) sinistral D_4 shear bands in a garnet–staurolite mica schist, northern part of the HSZ. The σ and δ structures (arrows) indicate sinistral D_4 shearing, whereas the inclusion trails in the garnet grain (1) and the 'old' σ structure (2) denote dextral D_3 shearing. The σ-structures are composed of dark biotite surrounded by more light muscovite (plane polarized light, scale bar 1 mm); (c) a close F_4 fold with WNW–ESE-striking axial plane in a tonalite, Syyry site (length of the plate is 15 cm); (d) a σ structure showing dextral shearing in a mica-bearing quartzite from the central part of the RSZ (plane-polarized light, scale bar 1 mm).

Fig. 4. (a) A sinistral F_4 fold which folds an S_3 foliation of a staurolite mica schist, Puolankajärvi Formation, northwest Kainuu Schist Belt; (b) a σ structure in a sheared mica-bearing quartzite of the OSZ with sinistral shearing, (crossed polars scale bar 1 mm); (c) a σ structure and asymmetric quartz growth structures in a quartzite with sinistral shearing from the northeastern tip of the OSZ (crossed polars, scale bar 1 mm); (d) dextral (R4) shear intersecting and deflecting a N–S-trending S_3 foliation in an amphibolite, northeast corner of the KSB.

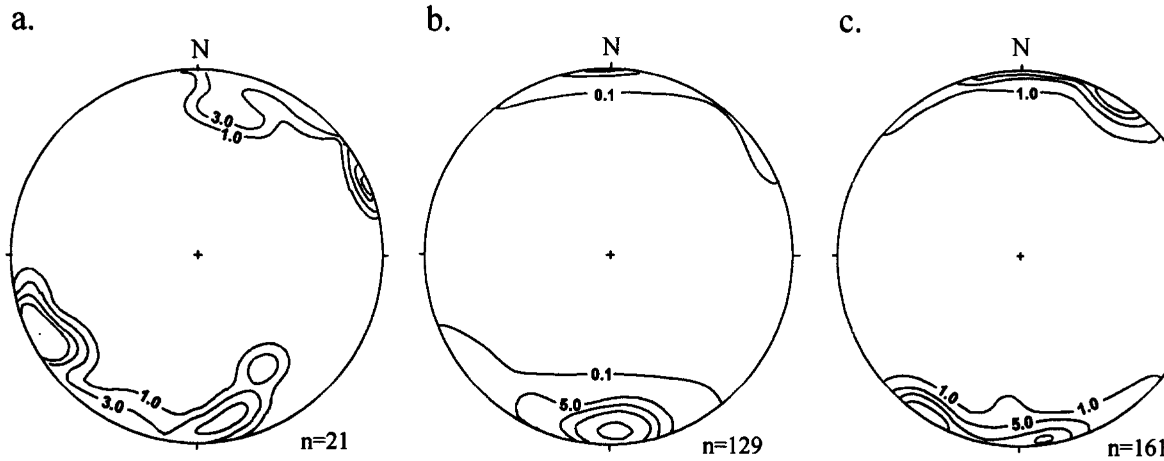

Fig. 5. π diagrams of S_4 foliations: (a) in the Paltaniemi area, contours 1.0, 3.0, 5.0 and 9.0% per 1% of area, (b) in the southern part of the Kuusamo Schist Belt, contours 0.1, 5.0, 10.0, 15.0, 20.0, 25.0%; and (c) in the Syyry district, contours 1.0, 5.0, 10.0 and 15.0%. Number of observations indicated by n.

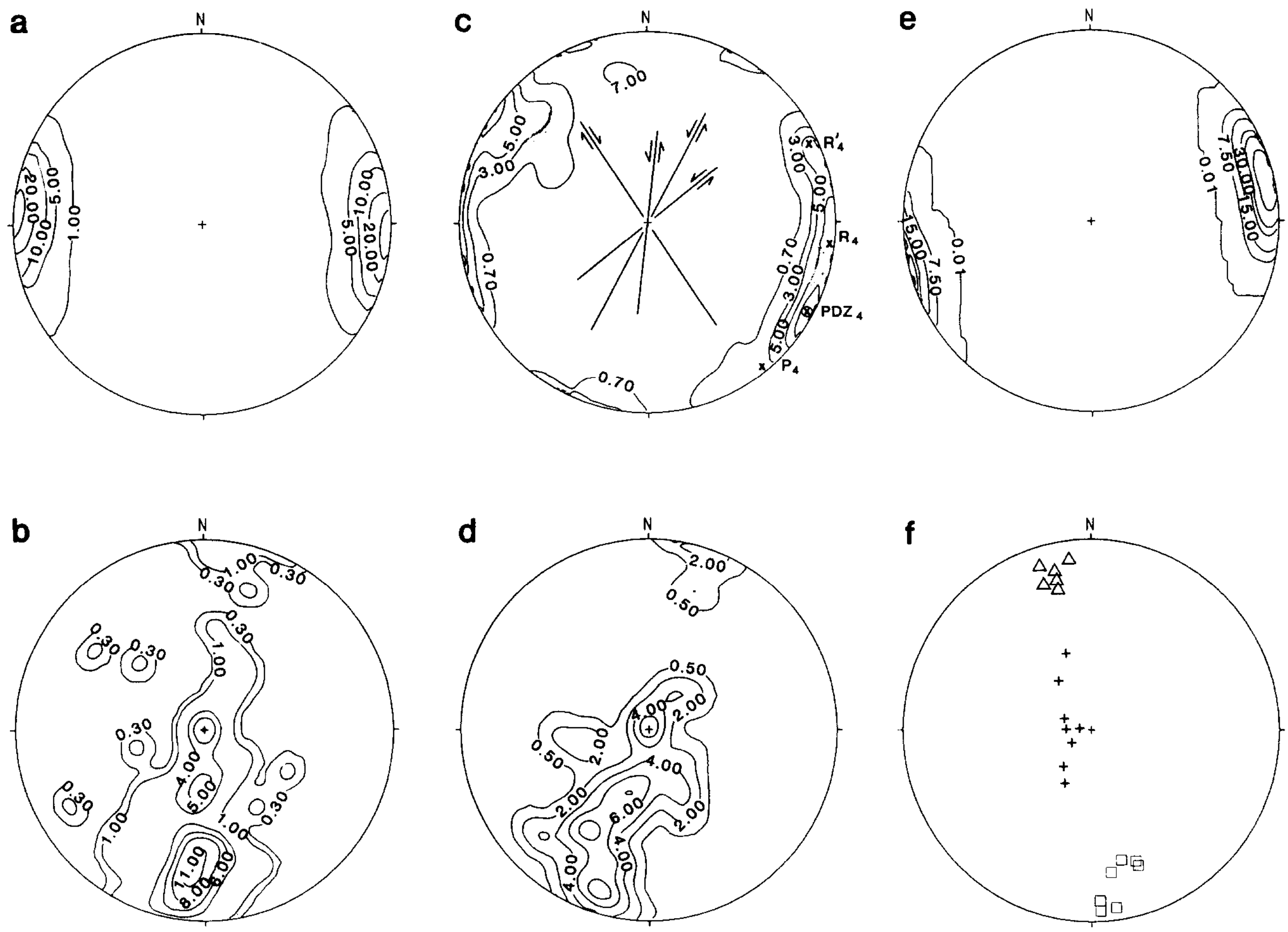

Fig. 6. Equal-area projections of: (a) poles to foliations in the HSZ, contours 1.0, 5.0, 10.0, 20.0 and 30.0%; (b) lineations in the HSZ, contours 0.3, 1.0, 4.0, 6.0, 8.0 and 11.0% per 1% of area; (c) foliations in the central part of the OSZ, PDZ_4 = D_4 principal displacement zone, R_4 = D_4 Riedel-like shear, D_4 pinnate-like shear, R'_4 = D_4 antithetic Riedel-like shear, contours 0.3, 3.0, 5.0, 9.0 and 13%; (d) lineations in the central part of the OSZ, contours 0.5, 2.0, 4.0, 6.0 and 8.0%; (e) poles to foliations in the central part of the RSZ, contours 0.01, 7.5, 15.0, 30.0 and 45.0%; and (f) lineations in the central part of the RSZ, triangle = D_3 stretching lineation, square = D_4 stretching lineation, cross = other lineation.

whereas the other directions of movement are associated with earlier deformations.

SINISTRAL, UPRIGHT D_4 SHEAR ZONES

The Oulujärvi Shear Zone (OSZ) is one the most conspicuous NE–SW-trending, subvertical shear zones in central Finland. It is at least 250 km long and separates the Savo Schist Belt (SSB) from the Pohjois–Pohjanmaa Schist Belt (PPSB) and the Archaean Iisalmi Complex from the Pudasjärvi Complex (Fig. 1). This zone transects the northern end of the Kainuu Schist Belt and continues as a semi-ductile–semi-brittle shear zone in the northern part of the Archaean Kuhmo Complex. The OSZ transposes all the earlier structures in a ductile

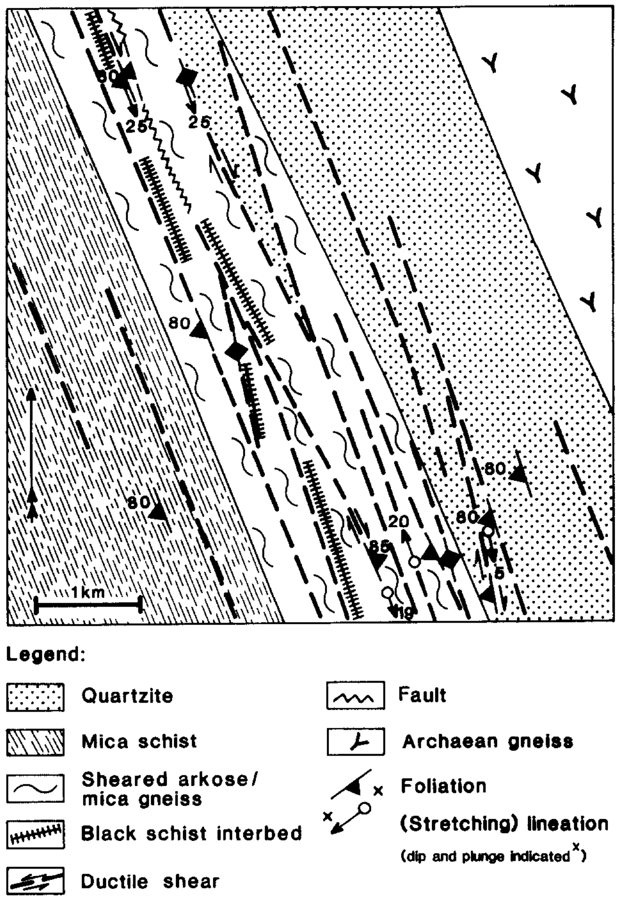

Fig. 7. Detailed structural map of the central part of the RSZ (location as shown in Fig. 2).

manner and includes a number of Palaeoproterozoic granites and migmatitic gneisses. The degree of migmatization and the quantity of granitoids present increase southwestwards.

The OSZ is composed of a complex system of folds and ductile and semi-ductile strike slip zones (Kärki & Laajoki 1991), and its general evolution resembles the model for a ductile shear zone (Riedel 1929, Sylvester 1988), with en échelon folds, a NNE–SSW-trending principal displacement zone, Riedel-like shears, pinnate-like shears and antithetic Riedel-like shears.

The first folds to be produced in the area of the OSZ were arranged progressively in an en échelon manner, producing the F_4 en échelon folds of the shear zone (Fig. 2) and mostly representing interference patterns caused by the superimposing of D_4 structures on earlier ones. The macroscopic interference figures are variable in form and the influence of D_4 deformation on them is recognizable only in their NE–SW-trending plane of symmetry. Longish, oval-shaped domes trending parallel to the principal displacement zone (PDZ_4) are the most conspicuous elements in this group. The most typical mesoscopic F_4 folds of the shear zone are asymmetric S-folds (Fig. 4a), the limbs of which may be intensively sheared and occasionally intruded by granitic material.

The directions of the S_4 axial planes typically deviate clockwise by less than 40° from the strike of the PDZ_4, and the folds in the areas of maximum shearing trend almost parallel to the plane of PDZ_4 (Fig. 2). The penetrative S_4 axial plane foliation is well developed in the folds of many areas and is mostly visible as a schistosity or metamorphic layering in the mica-rich paragneisses (Fig. 4a). The coarse-grained quartz feldspar gneisses can be tightly folded without the development of any noticeable axial plane foliation.

Continued deformation caused the initiation of various strike-slip shears showing ductile to semi-ductile features and classified as a subvertical, NNE–SSW-trending principal displacement zone (PDZ_4), synthetic Riedel-like shears (R_4) diverging anticlockwise by less than 20° from the plane of PDZ_4, and pinnate-like shears (P_4) diverging from it clockwise by less than 20°. The antithetic Riedel-like shears (R'_4) trend NW–SE. The directions of these shears are recognizable as statistical maxima in the π diagram of Fig. 6(c), which is based on outcrop investigations in the central area of the OSZ. The most common mesoscopic shears in the outcrops represent either NE–SW-striking sinistral R_4 shears or NW–SE-striking dextral R'_4 shears.

Kinematics and character of distinct shears in the OSZ

PDZ_4 and other shears are recognizable as semi-ductile shears varying greatly in width. Occasionally they are a few decimetres wide and consist of a narrow *S–C* mylonite zone rimmed by wider zones of ductile deformation, but more commonly they consist of a wide zone of highly metamorphosed gneisses, the banding of which trends parallel to the shear zone.

The (D_4) *S–C* mylonites associated with the PDZ_4, R_4 and P_4 shears indicate sinistral shearing. In addition, the sense of shearing can be determined from the σ and δ structures (Fig. 4b) and the asymmetric fabric of quartz (Fig. 4c). The recrystallization fabric of quartz varies greatly within diverse shears, and the deformation textures of quartz (Bell & Etheridge 1976, Lister & Price 1978, Drury & Humphreys 1988) and quartz *c*-axis diagrams may be employed as kinematic indicators only if the samples are composed of quartz that has been sufficiently recrystallized by shearing (Fueten 1991, Wenk & Christie 1991, Hippertt & Borba 1992). A quartz *c*-axis diagram plotted for a sample from an intensively sheared semi-ductile D_4 shear zone demonstrates sinistral shearing (Fig. 8), but most of the ductile shears include so many quartz relics that the *c*-axis diagrams cannot be employed as kinematic indicators.

Antithetic Riedel-like shears (R'_4) are found mostly outside the zone of most intense sinistral shearing. They are dextral semi-ductile shears (Fig. 4d) varying in width from a few centimetres to some tens of centimetres. Wider zones of asymmetric dextral folding appear to be associated with the R'_4 shears. Dextral hook folds and other systematically dextral folds with subvertical fold axes provide clear evidence of dextral shearing.

The lineations measured in the central area of the OSZ are sub-horizontal and trend NNE–SSW, or vary from sub-vertical to plunging steeply southwestward (Fig. 6d). The stretching lineations associated with the

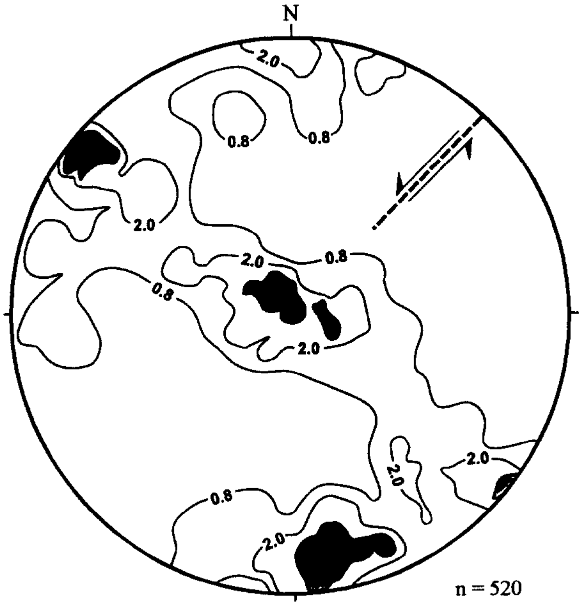

Fig. 8. Quartz *c*-axis diagram for an intensively sheared quartzite from the OSZ, contours 0.8, 2.0 and 3.5% per 1% of area. S_4 foliation trace indicated, number of data points indicated by *n*.

D_4 shears are sub-horizontal or plunge gently to the south-southwest, indicating the exact direction of the D_4 shearing. Many of the shears have subsequently been reactivated, as demonstrated by the variable directions of their lineations and the indications of a variable shear sense.

DYNAMICS AND TECTONIC EVOLUTION: A DISCUSSION

Although the central Fennoscandian Shield as a whole was affected by the fourth stage of Svecokarelian deformation, the domain was not deformed homogeneously by a single event but heterogeneously at slightly different times. Its evolution may be tentatively divided into six subphases that were produced by the same dynamic process and that followed each other progressively in the manner depicted in Fig. 9.

The compressional D_4 deformation started with E–W-trending folding in the Svecofennian Province and northward thrusting of the Karelian and Svecofennian metasediments on the southwestern margin of the Archaean Kuhmo Complex (Fig. 9a). The final emplacement of the Outokumpu allochthon and its ophiolites (Väyrynen 1954, Huhma & Huhma 1970, Gaál *et al.* 1975, Koistinen 1981, Ward 1987, Vuollo & Piirainen 1993) seems to have been one of the first events. The E–W-trending foliations classified as S_4 or S_5 elements as a result of structural analyses carried out in the Outokumpu district (Gaál *et al.* 1975, Koistinen 1981, Ward 1987) may be correlatives of our D_4 elements of the regional Svecokarelian deformation and associated with the final thrusting of the ophiolite-bearing units. These events were predated by the intrusion of the 1857 Ma Maarianvaara granite (Huhma 1986).

The tectonically active area moved incrementally northwards, and deformation in the southwest part of the Karelian Province started with northward thrusting in the PPSB and simultaneous dextral shearing in the RSZ on the eastern side of the Iisalmi Complex (Fig. 9b). The southern extension of the RSZ intersects the metasediments of the PKSB (Väyrynen 1954, Koistinen 1981, Ward, 1987) but the exact origin of this zone is still under discussion. However, it can at least be considered the southern continuation of the D_3 dextral HSZ which was reactivated at stage D_4 when the Iisalmi Complex moved northwards.

The D_4 deformation spread northwards and as the next step created the sinistral shears and fold structures of the HSZ together with the large-scale D_{1-4} interference figures in the southern KuSB (Fig. 9c). The final thrusting and last penetrative deformation of the crescent-shaped ophiolite-bearing units took place in the central KaSB simultaneously with the ductile shearing in the area of the RSZ. Apparently, the shearing direction is indicated by elongated ore bodies running parallel to the D_4 stretching lineation and shear structures of the Hammaslahti copper mine (Gaál 1977, Loukola-Ruskeeniemi *et al.* 1991).

During the next phase (Fig. 9d) dextral shearing took place on the southwest border of the Archaean Complexes, creating the dextral Kuopio Shear Zone (KSZ) parallel to the southwestern boundary of the Archaean Complexes (Gaál & Rauhamäki 1971, Halden 1982, Korsman *et al.* 1984, Korsman 1988). Transtensional granitoids associated with the KSZ yield a Rb–Sr whole-rock age of 1786 ± 80 Ma (Halden 1982), but the real age of shearing is evidently more than 1790 Ma. The migmatites in the southeastern part of the shear zone are between 1810 and 1830 Ma (U–Pb zircon ages; Vaasjoki & Sakko 1988) and, obviously, the D_4 shearing in this subarea took place simultaneously with the migmatization.

Sinistral shearing along the OSZ started after the formation of the KSZ (Fig. 9e) cutting across all the earlier structures, including the shears of the KSZ. The late- and post-kinematic granitoids of the shear zone yield U/Pb zircon ages from 1825 to 1800 Ma which indicates that the shearing phase took place c. 1820 Ma. Generation of the OSZ was the last phase of Svecokarelian ductile deformation in central Finland, but ductile deformation continued in the south and a series of left-stepping dextral N–S-trending shear zones was formed simultaneously with the final structural development of the adjacent Svecofennian paragneiss–granitoid domain (Fig. 9f). The E–W-oriented folding in southern Finland is predated by the intrusion of the 1830 Ma K-feldspar-rich granites and postdated by intrusion of the early post-orogenic 1810 Ma granitoids (Ehlers *et al.* 1993a,b).

The present distribution of D_4 structures in the Finnish part of the central Fennoscandian Shield is summarized in Fig. 10. Dynamically, one single phase, the D_4 deformation, produced large-scale fold structures in southwest Finland, and obviously also in southern and central Lapland, while ductile shearing and associated

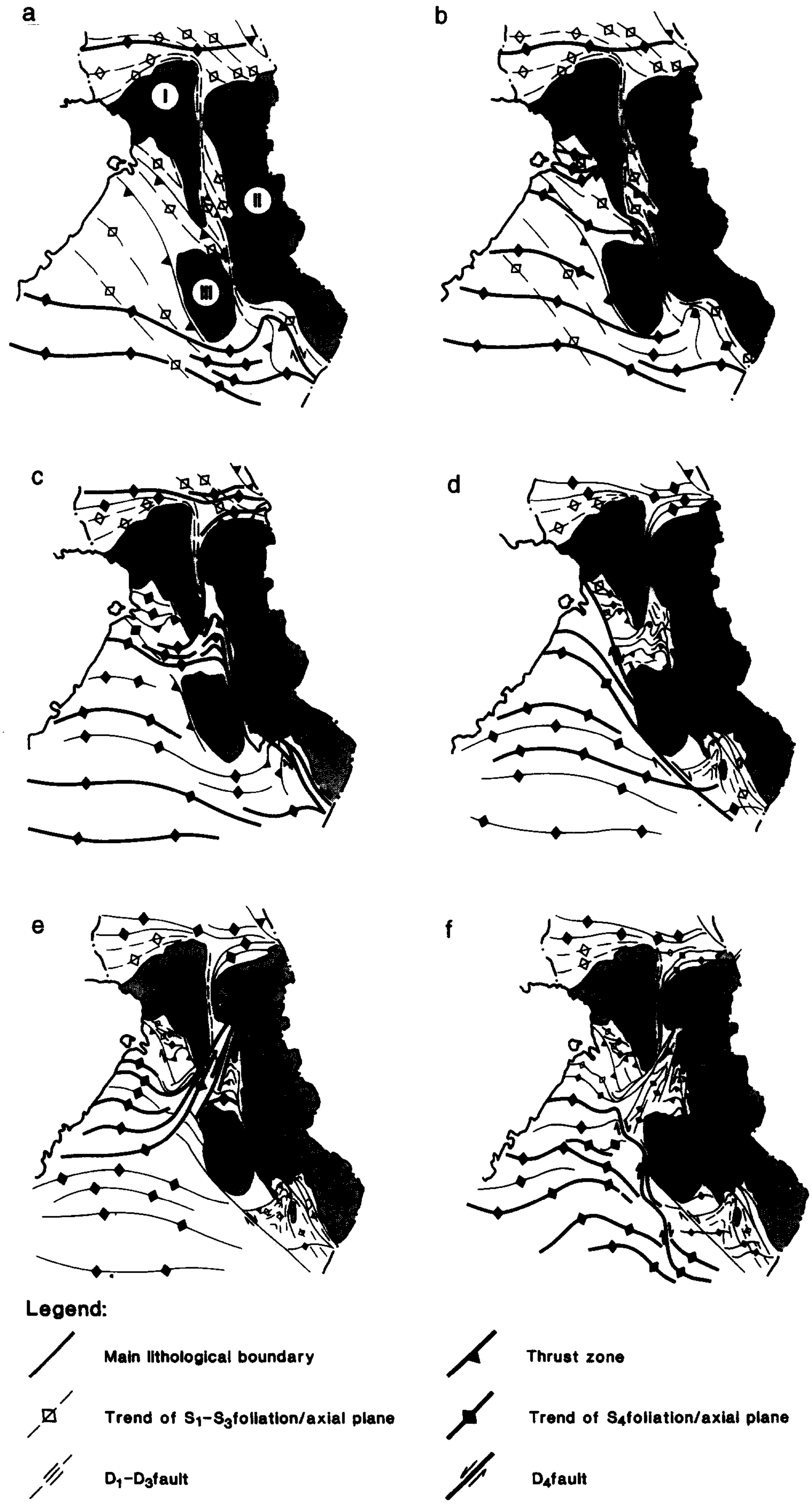

Fig. 9. D_4 structural evolution of the Finnish part of the central Fennoscandian Shield, divided into six subphases. For discussion see the text.

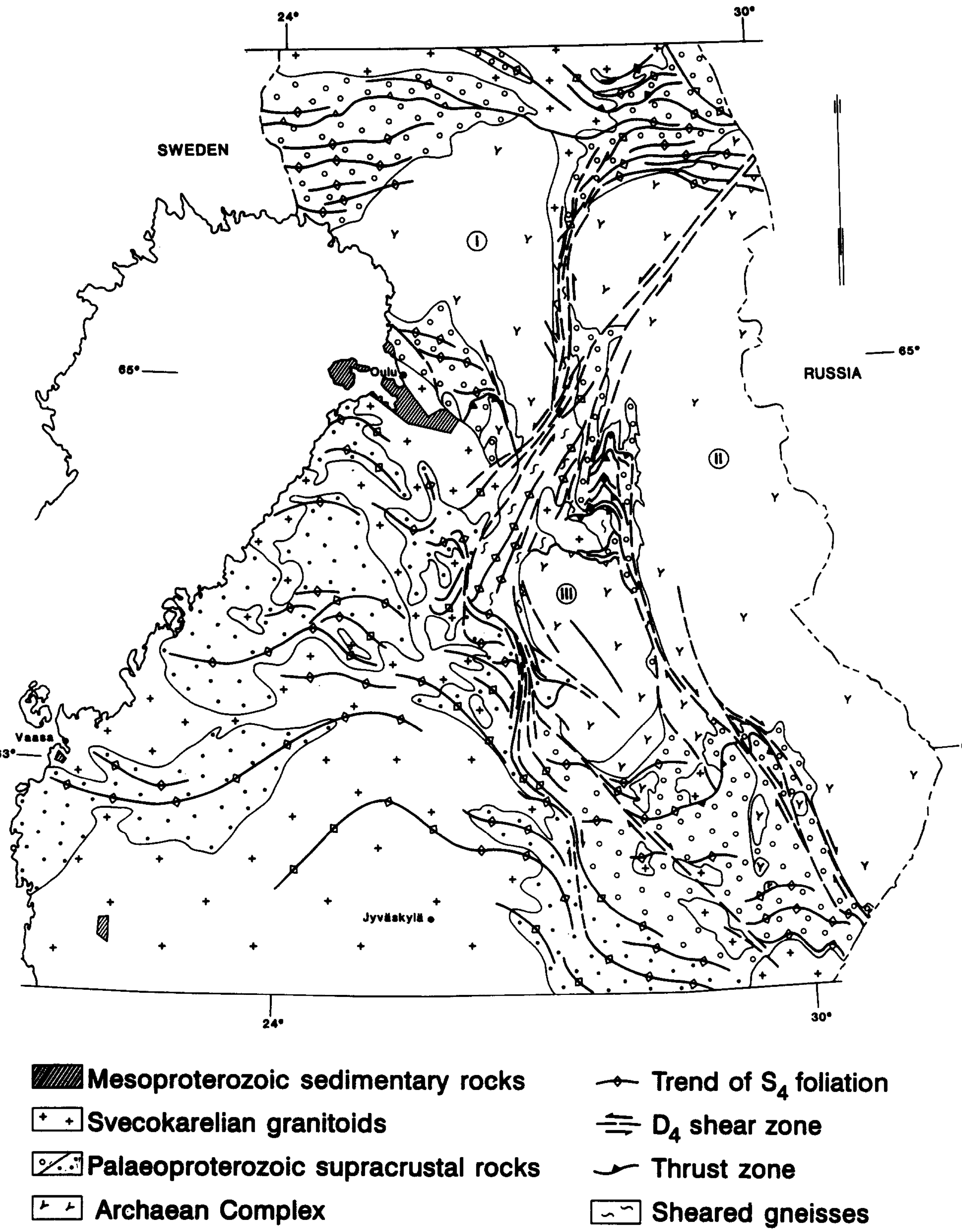

Fig. 10. Generalized structural map of central Finland showing the trends of the main D_4 structures. Complexes I, II and III as defined in the caption to Fig. 1.

folding took place in the Karelian Province, creating the conjugate shear zones of the Finlandia Shear System. This was the final compressional stage which penetratively deformed the Svecofennides (Edelman & Jaanus-Järkkälä 1983) and Karelides in the central Fennoscandian Shield, but the actual reason for its occurrence between 1850 Ma and 1810 Ma is still open to discussion.

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