Pergamon

Journal of Structural Geology, Vol. 19, No. 8, pp. 1073 to 1091, 1997

0191-8141/97 $17.00 + 0.00

PII: S0191-8141(97)00028-X

Accretion and lateral extension in an orogenic wedge: evidence from a segment of the Seve–Köli terrane boundary, central Scandinavian Caledonides

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(*Received* 24 *May* 1995; *accepted in revised form* 3 *March* 1997)

Abstract—The Seve–Köli boundary in the central Scandinavian Caledonides represents the transition from Baltica continental margin-related rocks (Seve) to outboard, westerly derived terranes (Köli). In this study we present and discuss structural and kinematic data recording the syn- and post-accretionary evolution of this boundary in west central Sweden.

Amphibolite-facies thrusting, mylonitization, imbrication and folding occurred before and during the establishment of the Seve–Köli boundary. Subsequent asymmetric lateral extension considerably modified earlier structures and the boundary at lower grade. Contractional ramps and extensional synforms developed and translation continued during progressive deformation.

Kinematic analysis indicates dominant movement towards the east or southeast. Local movement in the opposite direction may be due to stretching and rotation in the hanging wall above extensional shear zones. A pattern of minor shear zones and shear bands demonstrate stretching in an approximately E–W direction.

The presence of extensional structures developed during top-to-the-east movement suggests alternative mechanisms for the formation of some characteristic Caledonian structures, e.g. late synforms and thin lenticular tectonic units. These features may be due to asymmetric extension during Scandian top-to-the-east motion of the nappe pile. Contemporaneously, basement antiforms may have been stacked at lower tectonic levels. © 1997 Elsevier Science Ltd.

INTRODUCTION

Most tectonic boundaries in the Scandinavian Caledonides have traditionally been inferred to be thrusts. This is because large-scale convergent movements must be responsible for the general accumulation of different tectonic units or terranes during collision. Geometrically, however, there are several anomalous features in the Scandinavian Caledonides that are not compatible with a simple foreland-directed thrust evolution. Zachrisson (1973) drew attention to the upward truncation of tectonic and stratigraphic units in the hanging wall of a major thrust from east to west (westward pinching-out, Fig. 1), which is not in accordance with the thrust- or fold-nappe geometries in orogens. This discordant geometry suggests transport to the east, either on extensional faults or on out-of-sequence thrusts (or back-thrusting to the west), but not normal piggy-back thrusting. The significance of the large-scale geometry of the nappe pile may still be questioned, as the pre-collisional stratigraphy and docking histories of several units are poorly constrained. Post-docking histories emphasized here will also have an effect on the overall geometry.

Another problem in the central Scandinavian Caledonides concerns the extremely thin lenticular shape seen in E–W cross-sections of tectonic units (Fig. 1). Are the thin lenses or sheets horses progressively accreted to the footwalls of thrusts in a piggy-back evolution (Hossack, 1985; Hossack and Cooper, 1986; Gilotti, 1989) or a result of considerable modification of the nappe pile? The latter view is favoured if they are interpreted as being the result of large-scale boudinage or pinch-and-swell (Gee, 1978; Andréasson and Johansson, 1982) modifying an unstable nappe pile in response to gravity collapse (cf. Williams and Zwart, 1977; Ramberg, 1980; and others).

Knowledge of the kinematics of the high-strain zones that separate the tectonic units in the central Scandinavian Caledonides is still sparse, but the application of kinematic analysis in the 1980s soon proved that some of these zones, previously assumed to be thrusts, are in fact extensional faults (Norton, 1987; Sjöström and Bergman, 1989), inverted thrusts or strike-slip faults (Grønlie and Roberts, 1989). Low-angle shear zones, which truncated and modified the geometry of units on various scales, have been described in a kinematic summary of the central Scandinavian Caledonides (Sjöström *et al.*, 1991).

To address the problems outlined above we have analysed the geometry, kinematics and structural evolution of the boundary separating suspect terranes (Seve Nappe Complex) from outboard terranes (Köli Nappe Complex) along a *ca* 30-km section in west central Sweden (Figs 2 & 3). Our study focuses on field evidence implying considerable Scandian (Silurian–Early Devonian) modification of the original thrust geometry. The results have implications for interpreting the origin of thin lenticular tectonic units, late open folds and basement-cored antiforms.

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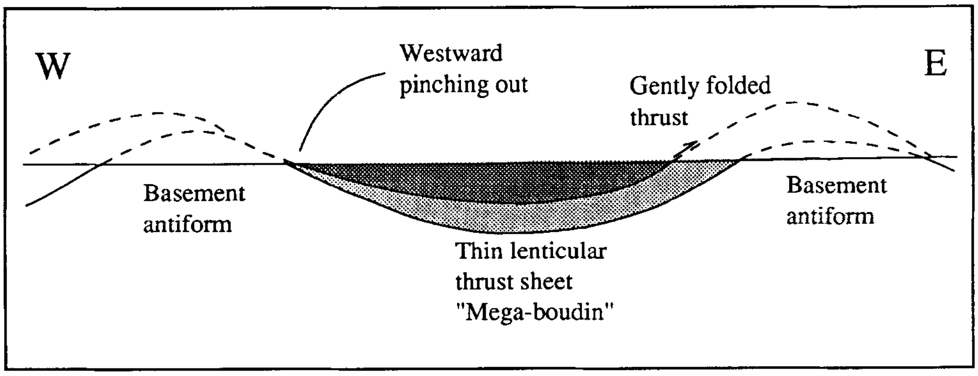


Fig. 1. Generalized sketch of some typical structural features in the Scandinavian Caledonides.

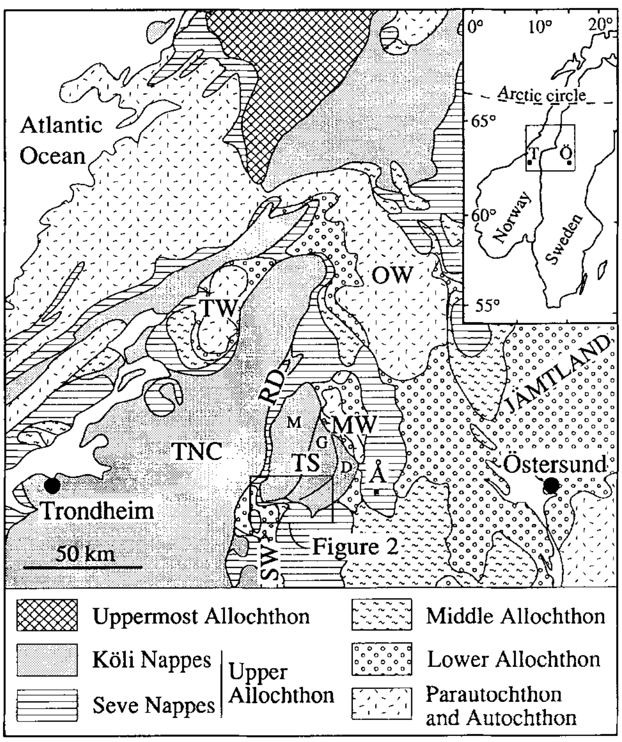


Fig. 2. Tectonostratigraphic map of the central Scandinavian Caledonides, modified from Gee and Sturt (1985). Important structures or localities: OW, Olden Window; RD, Røragen Detachment (Norton, 1987, location from Sjöström and Bergman, 1991); SW, Skardøra Window; TNC, Trondheim Nappe Complex; TS, Tännforsen Synform including Middagsfjället Nappe (M), Gevsjön Nappe (G) and Duved Nappe (D); TW, Tømmerås Window; Å, Åre.

REGIONAL GEOLOGY

The Köli nappes represent outboard terranes that during the Scandian collision were predominantly accreted to the margin of the early Palaeozoic continent Baltica; some units may have accreted to Laurentia earlier (Stephens and Gee, 1985, 1989). The Seve nappes are considered to be suspect terranes (Roberts, 1988) perhaps representing the outermost parts of the passive continental margin of Baltica (Stephens and Gee, 1985, 1989; Andréasson, 1986). A disparate origin and early history of the Seve and Köli units was accepted even before the terrane concept was applied. However, they have generally been treated collectively as parts of the major Seve–Köli Nappe Complex (Zachrisson, 1969), tectonostratigraphically included in the Upper Allochthon (Gee and Zachrisson, 1979).

The boundary between the Seve and Köli nappes is a major feature of the Scandinavian Caledonides, but there is no overall consistency in its field appearance (tectonic or transitional: Stephens, 1977; Sjöstrand, 1978) in various areas. In the area studied here (Figs 2 & 3) the boundary has previously been identified as tectonic (Sjöström, 1983a,b; Beckholmen, 1984). In accordance with the general view held, it has been inferred to be a thrust with translation of the hanging-wall units (Köli) to the east or east-southeast, parallel to most stretching lineations. We have previously used kinematic analysis to show that the thrust model is valid in a general sense (Sjöström and Bergman, 1989, 1991; Sjöström *et al.*, 1991), but that the evolution is more complex in detail.

LOCAL GEOLOGY

The Tännforsen Synform (Fig. 2) is the type area of Köli rocks in the county of Jämtland. This study includes the southern part of the synform and underlying rocks to the south and southwest (Figs 2 & 3). The area has been covered by some early investigations (Högbom, 1894; Törnebohm, 1896; Frödin, 1922), including the first application of the hypothesis of thrust nappes in the Scandinavian Caledonides (Törnebohm, 1888). Recent contributions focus on the tectonometamorphic evolution or the original tectonic setting of various units (Sjöström, 1983a,b; Beckholmen, 1984; Bergman, 1992, 1993). Results from a seismic reflection profile transecting the area have been presented by Hurich *et al.* (1989) and Palm *et al.* (1991).

There are both structural and metamorphic changes along the Seve–Köli terrane boundary in the area. From west (Storlien) to east (Rödberget) tectonic units are added both in the hanging wall (Köli) and in the footwall (Seve) (Figs 3 & 4). Where the tectonostratigraphy is

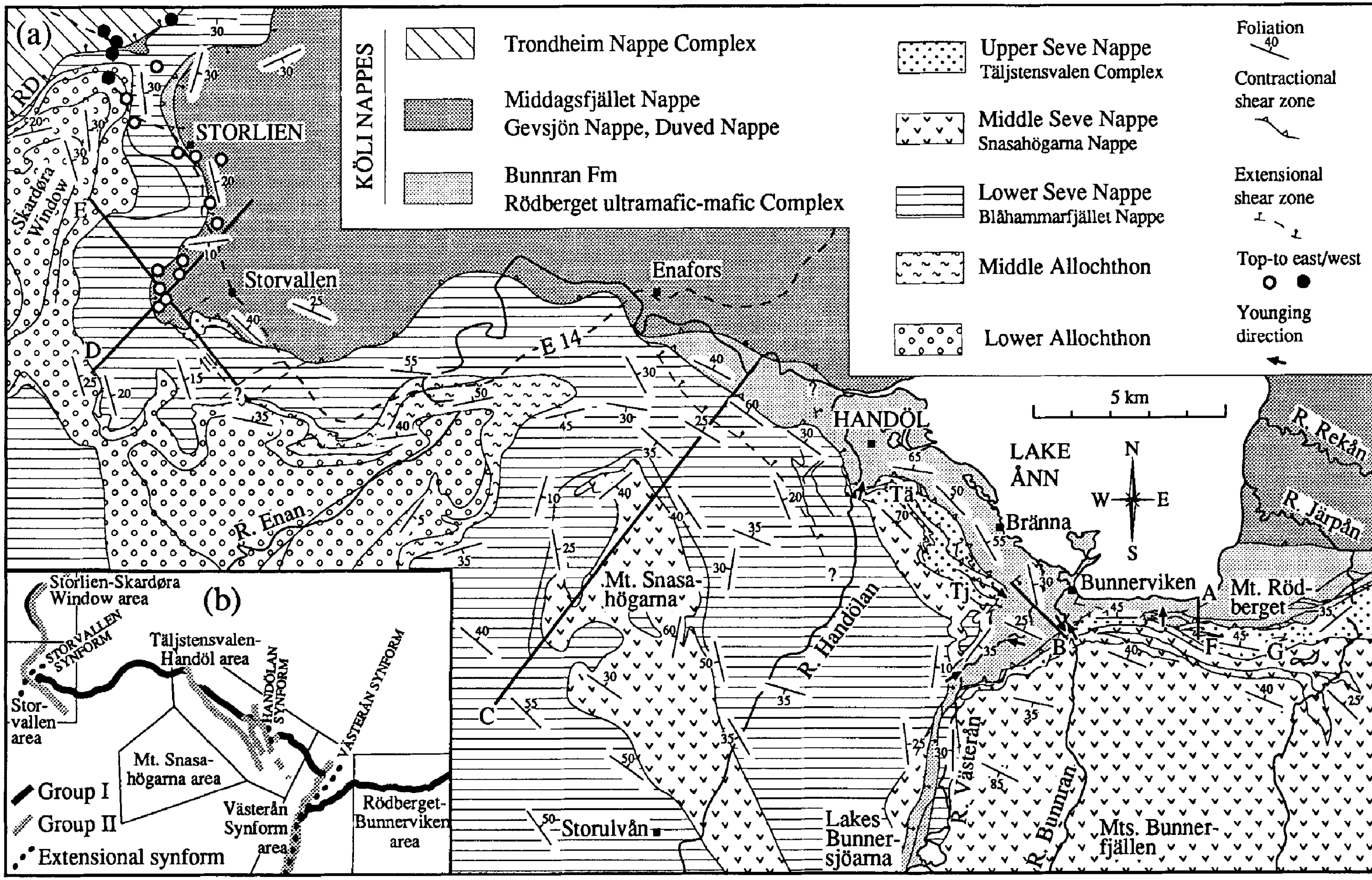


Fig. 3. Map of the area studied between Storlien and Mt Rödberget. All major units are bounded by tectonic contacts. Internal lithological and/or tectonic boundaries are also shown. Location of cross-sections A–E are indicated. Abbreviations: F, Furubäcken; G, Grötmjölhögen; RD, Røragen Detachment; Tj, Tjuvfloarna; Tä, Täljstensvalen. Data compiled from Sjöström (1983a), Bergman (1993), Sjöstrand (unpublished Geological Survey map) and Beckholmen (1984). The inset map shows where the geometry is largely controlled by Group II extensional shearing (grey) and where the relative contribution of Group I deformation is larger (black). Major extensional synforms are located at Storvallen, Handölan and Västerån.

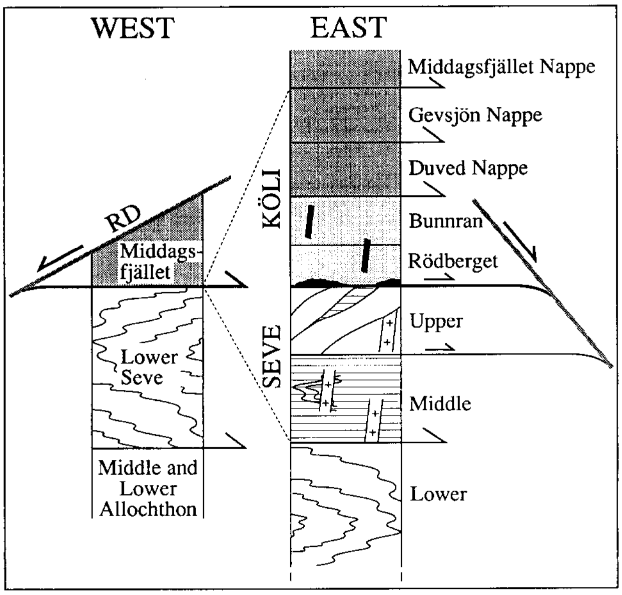


Fig. 4. Schematic diagram showing the tectonostratigraphy in the Handöl-(east) and Storlien areas (west, cf. Fig. 3). A slice of Middle Seve paragneiss is imbricated in the Upper Seve Nappe. Both units contain felsic dikes that truncate early folds but terminate against amphibolite facies mylonites (Sjöström, 1983a). The two basal Köli units in the east are linked by mafic intrusions (Bergman, 1993).

most complete (in the east), the terrane boundary has been identified as a medium-grade deformation zone (garnet + biotite stable). Where the tectonostratigraphy is less complete (in the west), the boundary is retrograde (garnet retrogressed, muscovite + chlorite stable; Sjöström, 1983a,b). This difference has been ascribed to local overprinted shearing in the west.

The synforms at Storvallen, Handöl and River Västerån, and the antiforms exposing rocks of the Lower Allochthon along the River Enan and west of Storlien (Fig. 3) are part of a regional pattern. They have been referred to as late major upright folds that deformed the entire tectonostratigraphy (Palm *et al.*, 1991; and many earlier contributions).

The Seve Nappe Complex

The Seve Nappe Complex in the area (Figs 3 & 4) comprises three units (Sjöström, 1983a). The Lower Seve Nappe is made up of amphibolite, mica-schist and calc-silicate rock. The metamorphic grades of these rocks are uppermost greenschist facies in the basal parts, increasing to middle or upper amphibolite facies in the uppermost parts bordering the Middle Seve Nappe. The latter is dominated by low granulite-facies paragneiss, while the Upper Seve Nappe consists mainly of amphibolite and mica-schist in thrust slices imbricated under amphibolite-facies conditions. At Tjuvfloarna, a horse of granulite-facies paragneiss, typical of the underlying Middle Seve Nappe, is part of the imbricate stack (Figs 3 & 4). Strain-related, overprinted, amphibolite-facies metamorphism has been recorded in or along boundaries of all three Seve nappes. The only exceptions are the terrane boundary in the west already mentioned and the base of the Lower Seve Nappe, where overprinting took place under greenschist-facies conditions (Sjöström, 1983b).

The Köli Nappe Complex

The overlying Köli rocks within the Tännforsen area are divided into three major nappes and two underlying minor tectonic units (Figs 2 & 4) (Beckholmen, 1984). There is an upwards increase in metamorphic grade from greenschist (lower biotite zone) to lower amphibolite facies through the nappes. At the base, towards the Seve nappes, there is a local downwards increase in grade to upper greenschist–lower amphibolite facies.

All nappes are dominated by calcareous psammites and pelites. In the lower part of the Duved Nappe and in the Handöl area the lithology is more varied, with conglomerate as well as mafic and ultramafic igneous rocks in addition to calcareous psammites and pelites. In the Handöl area (Fig. 3), the Upper Seve Nappe is overlain by the Rödberget ultramafic–mafic Complex and the Bunnran Formation (Bergman, 1993). They are metamorphosed in upper greenschist–lower amphibolite facies. In the western part of the study area, however, the uppermost Köli Nappe directly overlies the Lower Seve Nappe (Figs 3 & 4). Intensely deformed lenses of intervening units exist only very locally (Fig. 3) (Sjöström, 1983a).

STRUCTURAL ANALYSIS

We have divided structures into two broad categories with respect to their relationship to the terrane boundary. Group I structures pre-date and/or are related to the accretion of the Köli Nappe Complex to the Seve Nappe Complex. Group II structures were formed during subsequent modification of the terrane boundary and displacement along it. It is usually easy to distinguish Group I and Group II folds and cleavages, whereas lineations may be more difficult to classify. However, where both generations are present they are generally subparallel in trend.

Previous workers in the Tännforsen (Beckholmen, 1984) and Handöl–Storlien areas (Sjöström, 1983a,b) have assigned various structures to deformational episodes on the basis of cleavage characteristics, overprinting criteria and relationships between deformation and porphyroblast growth. Group I structures here correspond to D_1–D_2 of both Beckholmen (1984) and Sjöström (1983a,b), and Group II to their D_3 and onwards.

We focus on plastic deformation here and pay very little attention to brittle faults and fractures. The field data used to construct the map (Fig. 3) were complemented locally by interpretation of aerial photographs and ground magnetic measurements. Detailed mapping along well-exposed river beds and hillsides in some areas allowed more detailed accounts of local structural conditions. These will be presented after a more general description of structures, mylonites and microstructures, and the results of the kinematic analysis.

Pre- and synaccretionary structures, Group I

Group I comprises a heterogeneous family of structures relating to the differences in origin of the Seve and Köli nappes, and the various P–T conditions under which early structures were formed in each unit (cf. Bergman, 1992). Most porphyroblasts grew when Group I structures were formed, but porphyroblast–foliation relationships and other microstructures differ considerably between individual Seve and Köli nappes which emphasizes their different pre-docking histories. During late Group I deformation, microstructural, thermobarometric and P–T path studies (Sjöström, 1983b; Bergman, 1992) indicate that porphyroblasts continued to grow at the time of accretion of the Köli nappes to the Seve nappes.

During this accretion a variety of major structural features, including prominent mylonite zones, were formed. Large areas of the Seve and the Köli nappes contain folds related to this deformation that are tight to isoclinal and have NW–SE-trending, gently plunging, hinges. In the high-grade Middle Seve Nappe, the Group I evolution is less well understood (cf. Sjöström, 1983a). In the Lower Seve Nappe, Group I structures include refolded folds interpreted as footwall structures below the terrane boundary. The ESE–WNW-trending folds that affect the imbricate stack in the Upper Seve Nappe (at Mounts Täljstensvalen and Rödberget, Fig. 3) may have a similar origin. If this is the case a progressive development, or an out-of-sequence situation, is indicated because the Köli nappes structurally overstep already imbricated Seve nappes.

Early isoclinal folds in the Bunnran Formation record significant shortening prior to the growth of metamorphic garnet and amphibole. Locally recorded younging directions (mostly graded bedding; Bergman, 1993) are generally of little value owing to the intense folding.

A strong foliation related to Group I deformation is a prominent structural feature in most rocks of the area. In metasedimentary rocks it may appear as a tectonic layering, a schistosity or a spaced cleavage. In the mafic igneous rocks the foliation is defined by a hornblende–plagioclase grain-shape fabric, mostly subparallel to sheared intrusive contacts. Owing to rotation, mafic dykes are generally subparallel to this foliation although, locally, cross-cutting primary relations are still preserved both in the Bunnran Formation and in the Lower Seve Nappe. Felsic dykes, generally cross-cutting Group I structures, will be dealt with below.

Group I stretching lineations are interpreted as transport lineations related to thrust emplacement. They include strong preferred orientation of hornblende, mica and mineral aggregates trending WNW–ESE with a moderate to gentle plunge. Early crenulation axes and fold axes are often close to parallel with the mineral-preferred orientation.

Felsic dykes as structural markers and links between units. Up to 1-m-thick tourmaline-bearing pegmatites, often carrying garnet and muscovite, and fine-grained plagioclase porphyritic, trondhjemitic dykes have been found in both the Middle and the Upper Seve nappes. These igneous bodies may have been locally derived from adjacent tourmaline-bearing, pelitic metasedimentary and mafic igneous protoliths, respectively. Locally they are excellently preserved. In some dykes, subhedral plagioclase crystals exhibiting oscillatory zoning are remnants of a partially preserved magmatic texture; growth of garnet and biotite along margins is a result of metamorphic overprinting. The dykes truncate early Group I folds (Fig. 4) (Sjöström, 1983a) but are generally rotated into and sheared along tectonic boundaries of the same generation. In the eastern part of the area (Grötmjölhögen, Fig. 3), however, a single *ca* 2-dm thick dyke of slightly deformed garnet- and tourmaline-bearing pegmatite cross-cuts intensely mylonitized paragneiss.

Tourmaline is a common accessory phase in the metasedimentary rocks of the Upper Seve Nappe. In the Köli Nappe it is uncommon, apart from close to the terrane boundary. In the Middle Seve Nappe it has only been recorded in mylonitized and imbricated parts near the Upper Seve Nappe. This tourmaline distribution may result from boron migration from the Upper Seve Nappe. The age of the tourmaline and the dykes (work in progress) may therefore provide an upper limit for the formation of the Seve–Köli boundary.

Post-accretionary structures, Group II

Group II structures are common on both sides of the terrane boundary and are inferred as being closely related in both time and space. These structures post-date major thrust displacement along both the terrane boundary and the contacts between the Seve nappes. They deform the established tectonic pile and the peak metamorphic assemblages. The present geometry of the units depends much on Group II shear zones and folds.

Obvious Group II structures are three major synforms at the Rivers Västerån and Handölan and at Storvallen (Figs 2 & 3). Possibly most of the base of the Seve Nappe Complex has been reworked by Group II shearing. Typical minor structures include open to tight asymmetric chevron-style folds, spaced cleavage (often crenulation cleavage), crenulation lineation, symmetric and asymmetric boudinage, shear bands and shear zones. Quartz veins are often axial-planar to Group II folds.

Some immature Group II folds are highly non-cylindrical showing the relaying relationships of en échelon folds. More mature recumbent sheath folds have been recorded locally. Within the Bunnran Formation, there is a remarkable consistency in fold vergence to the west and north (cf. Fig. 8). The folding-related cleavage and associated lineation are heterogeneous in intensity. Pervasively cleaved zones some decimetres wide pass laterally into areas where bedding and/or Group I foliation is preserved (Fig. 5a). Along the western part of the terrane boundary, most mesoscopic Group II folds are E- or SE-verging both in the hanging wall and the footwall (Storvallen and Storlien–Skardøra areas, see below).

In both the Seve and the Köli nappes, there is evidence that Group II folding and shearing were contemporaneous. Mutual overprinting relationships between small asymmetric folds and shear bands, and asymmetric folds maturing to shear zones along limbs or axial surfaces, indicate simultaneous development during transport to the east. The orientations of crenulation lineations and some folds in the Bunnran Formation tend to be parallel to the strike of adjacent ramps along the terrane boundary (Fig. 7). This is obvious in the Västerån Synform where the trends of crenulation lineations in the Köli rocks in the hanging wall outline the change from oblique to lateral ramp of the Seve rocks in the footwall (Fig. 7c). Apparently these lineations record only small increments of 'local' strain close to the ramp.

Mafic and ultramafic igneous bodies and other competent units are typically horizontally extended and disrupted into trains of lenses. Boudinage was formed during both Group I and Group II deformation, simultaneous with accommodation folds when material flowed into their necks. Another important mechanism of segmentation is the operation of anastomosing or differently oriented shear zones discussed in a later section.

MYLONITES

The wide range in mineralogy and microstructures of mylonites in this area reflects shearing in both amphibolite and greenschist facies during a prolonged tectonic history. Mylonites are common not only between major tectonic units; they also occur within them, particularly along lithological boundaries.

Amphibolite-facies mylonites developed during Group I deformation and are characterized by growth and/or recrystallization of garnet, biotite, white mica and, locally, kyanite, anthophyllite $\pm$ cummingtonite. In mylonites within the Middle Seve Nappe, garnet–kyanite $\pm$ anthophyllite overprints sillimanite–K-feldspar assemblages in the country rock. Garnet–anthophyllite–cummingtonite mylonites have been recorded in the uppermost parts of the Upper Seve Nappe. In the upper part of the Lower Seve Nappe, west of Handöl, green hornblende overgrows cummingtonite defining the fabric in mylonites.

Greenschist-facies mylonites developed during Group II deformation. Stable minerals include white mica $\pm$ biotite $\pm$ chlorite (Fig. 6). These mylonites are typical along extensional shear zones in all units, including those that truncate the terrane boundary. As mentioned earlier, the terrane boundary in the west is generally retrograde. Other prominent low-grade mylonites are found along the base of the Seve Nappe Complex towards the Middle or Lower Allochthons. These Group II mylonites are truncated by the Røragen Detachment, the chlorite-grade extensional fault in the western limb of the Skardøra Window (Figs 2 & 3). Obviously, this structure was formed later than Group II mylonites east of the antiform.

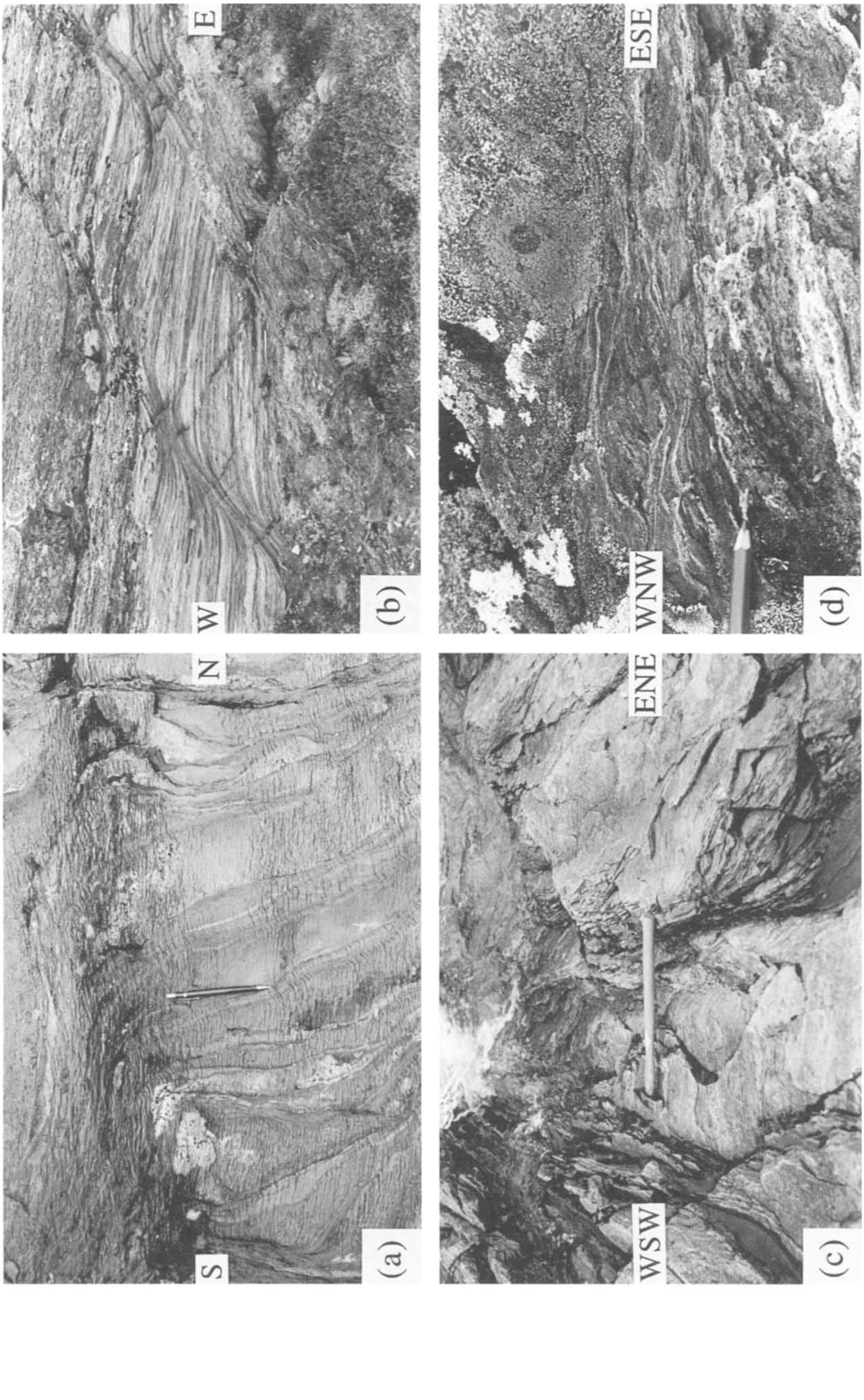
Kinematic analysis

Kinematic indicators on both meso- and microscale have been used to determine the local sense of shear. Indicators used include shear bands and small shear zones, *S–C* fabrics, porphyroclast systems and, more rarely, asymmetric folds (Fig. 6). Figure 7(a) shows the sense of shear of the meso- and microscopic kinematic data together with the trend of the stretching lineation on the shear foliation. The map includes all observations because it proved difficult to make a distinction between kinematic indicators developed at different stages. Kinematic results from the western part of the study area are shown in Fig. 3.

The generally strong dominance of top-to-the-east movement on mylonites in the area is in agreement with traditional inferences about major eastward Caledonian thrust transport. A significant new finding is that movement in the opposite direction, top-to-the-west, is not at all uncommon and even dominates in some areas (shaded area in Fig. 7a).

Shear criteria indicate both senses of shear in some outcrops and even within single thin sections (Fig. 6d). This can be accounted for in several ways: (1) although rotation of a mylonite by folding will not change the

Fig. 5. (a) Typical appearance of heterogeneously developed and locally intense Group II crenulation cleavage transecting bedding in the Bunnran Formation. River Västerån. The pen is 14 cm long. (b) Top-to-the-west shear zones extending the foliation of Upper Seve mylonitic schist west of Mt Rödberget. The pen is 14 cm long. Microstructures from one of these shear zones are shown in Fig. 6(a). (c) Conjugate extensional shear zones deforming thrusting-related foliation and stretching lineation (parallel to the hammer). Across the water the top-to-the-west shear zone (left) truncates the top-to-the-east shear zone. Middle Seve Nappe, River Västerån. The hammer is 50 cm long. (d) Curved top-to-the-east shear zones in Seve amphibolite south of Bunnerviken. In the right-central part the strain is higher and the angle between mylonitic foliation and the overprinted foliation is smaller.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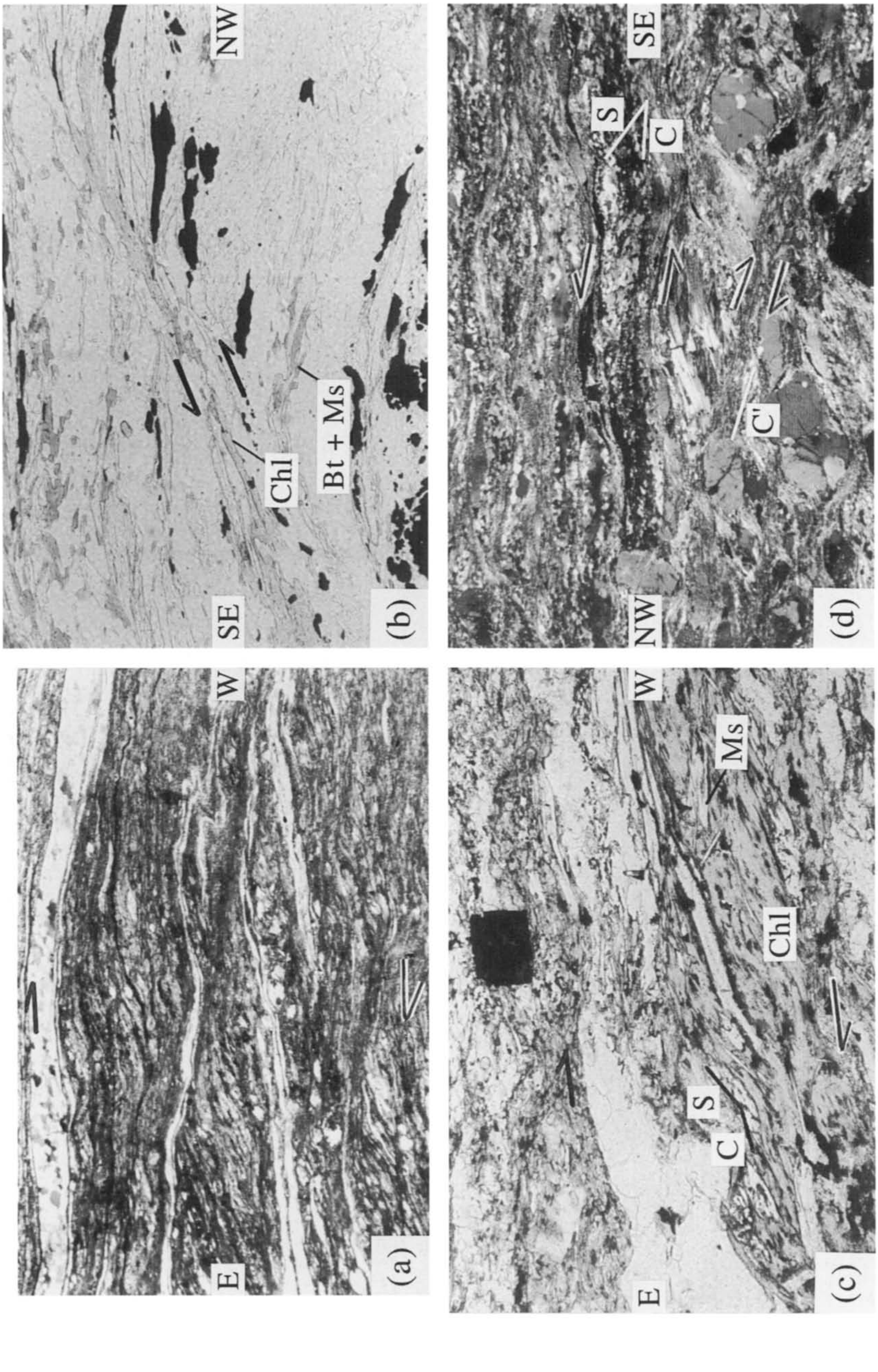

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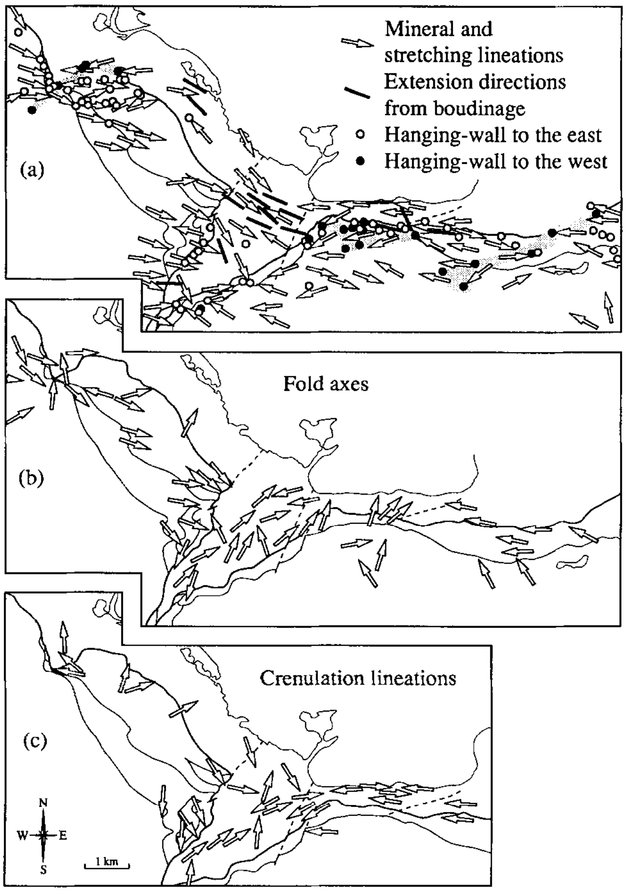


Fig. 7. Maps of trends of linear structures in the Handöl–Rödberget area. (a) Mineral and stretching lineations with sense of shear recorded from mylonites, and extension directions from boudinage structures (perpendicular to boudin axes). Mesoscale shear zones are not included (see Figs 8 and 9). (b) All fold axes. (c) All crenulation lineations. Compare with Fig. 9 for full three-dimensional orientation.

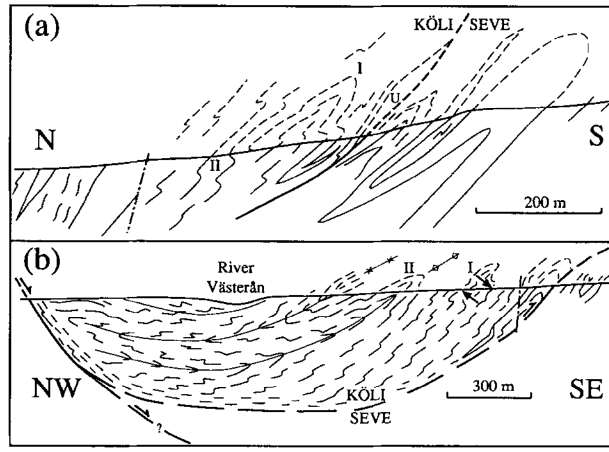


Fig. 8. (a) N–S cross-section at Furubäcken (labelled A in Fig. 3) at a high angle to the main transport direction. Lithological boundaries, mylonites and Group I folds are deformed by Group II folds. U, ultramafic lens at the Seve–Köli boundary. (b) Cross-section at River Västerån (labelled B in Fig. 3). Compare with structural data in Fig. 9. No vertical exaggeration.

original sense of shear, the shear indicators in an overturned limb may be partly or wholly overprinted by opposite shearing; (2) boudins undergo shear in opposite directions on opposite sides (cf. Fig. 13a). Segmentation of a strain-hardened mylonite by boudinage may therefore result in mixed shear sense; (3) the development of conjugate sets of extensional crenulation cleavage (Platt and Vissers, 1980) leads to simultaneous formation of apparently conflicting shear indicators; and (4) in structural inversion, thrusts may reactivate as normal faults, or vice versa. At least the first three cases may occur during progressive deformation.

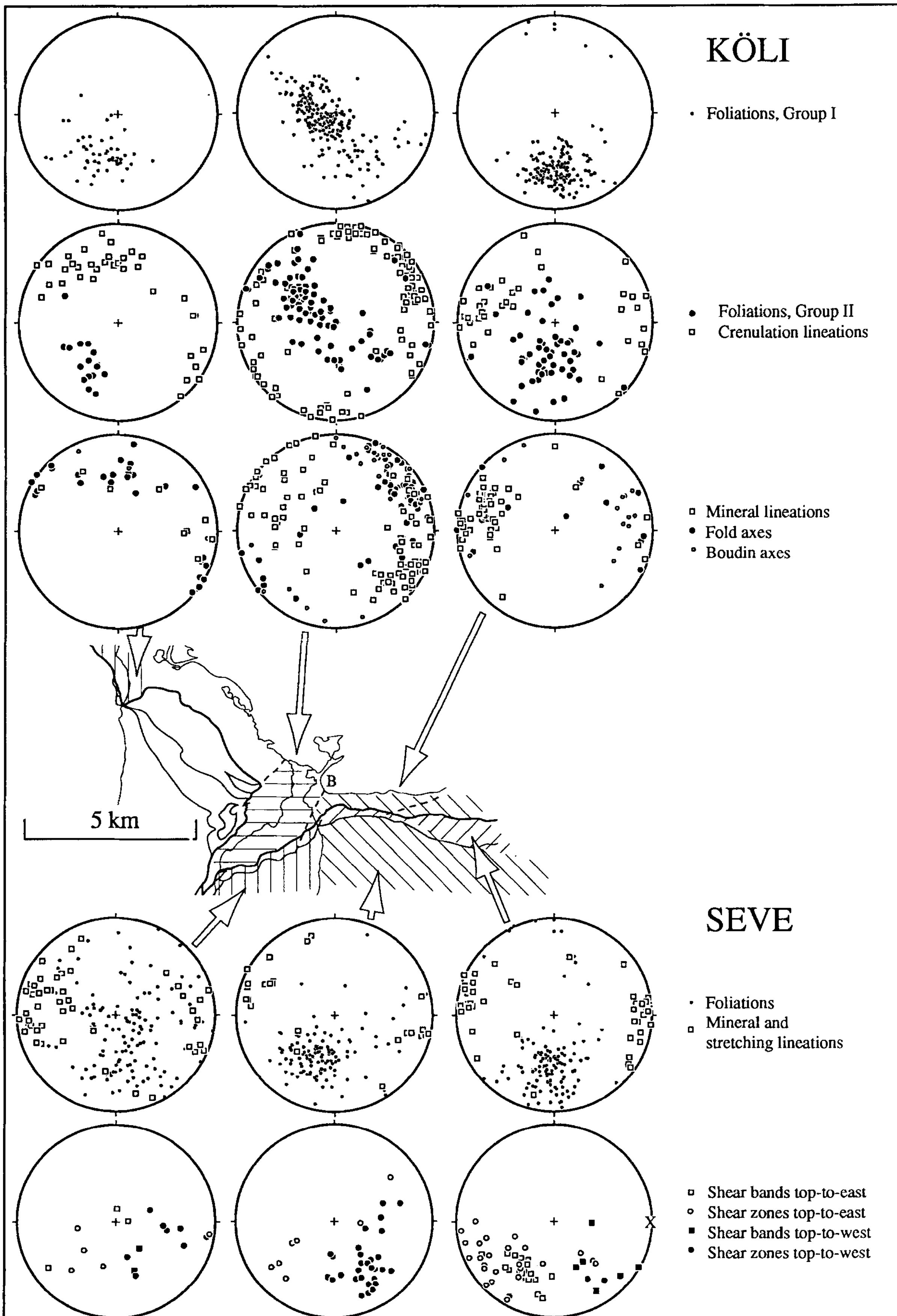
STRUCTURE AND KINEMATICS OF SUBAREAS

The Rödberget–Bunnerviken area

East-verging Group I folds with axial-planar mylonitic foliation in the Upper Seve Nappe at Mount Rödberget (Fig. 3) are interpreted as footwall folds related to early movements along the terrane boundary. In the cross-section at Furubäcken (Fig. 8a), the thrust-related mylonitic foliation (Group I), early isoclinal folds and lithological boundaries are folded by open to tight, gently plunging inclined folds both in the Seve and the Köli. Movements probably occurred along the boundary during or after Group II cleavage formation because intersection lines rotate within 200-m wide zones on both sides of the boundary. In the Bunnran Formation mineral and crenulation lineation trends are subparallel to the strike of the terrane boundary, indicating movements along a lateral ramp (Fig. 7a & c). Fold axes are, however, oblique to the ramp (Fig. 7b) indicating that the strain was not high enough ($\gamma < 20$, Skjernaa, 1980) to rotate them into parallelism.

The kinematic pattern is complex, with mixed shear sense locally (Fig. 7a). However, in the upper Seve Nappe, top-to-the-east movement dominates, whereas the opposite sense seems to be more common at

Fig. 6. Photomicrographs of Group II mylonite textures (Bt, biotite; Chl, chlorite; Ms, white mica). (a) This mylonite contains biotite and white mica but no chlorite. Note ubiquitous shear-sense indicators: *S–C* fabrics, shear bands and asymmetric folds. The long dimension (*D*) of the photograph is 5.4 mm. (b) Chlorite forms in a shear band but is absent in adjacent domains. $D = 1.4$ mm. (c) Mylonite recording top-to-the-west movement, with abundant chlorite and post-tectonic white mica and pyrite. $D = 2.7$ mm. The eastern limb of the Handölan Synform. (d) Mylonitized Seve schist showing conflicting kinematic indicators. Shear bands (*C′*) demonstrate top-to-the-southeast movement whereas ubiquitous *S–C* relations in quartz plates show movement (possibly younger) to the northwest. Crossed polars, the long dimension of photograph is 5.4 mm.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Foliations, Group II
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Mineral lineations
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Shear zones top-to-east
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Shear zones top-to-west
X

structurally lower levels (Fig. 9). Top-to-the-west shearing (shaded area in Fig. 7a) may have initiated in response to rotation and stretching in the hanging wall above an extensional shear zone, for example the continuation of the shear zone at Västerån (see below).

Stereograms of shear bands and shear zones, like those in Fig. 5(b–d), indicate the orientation of the bulk Group II strain ellipsoid in the Seve nappes (Fig. 9). The longest strain axis X plunges gently east, and the Y–Z-plane is steep and strikes approximately N–S. Similar orientations are also obtained further west.

Evidence illustrating the importance of extensional shear zones for the separation of rock bodies and the post-peak metamorphic stretching is widespread, for example the formation of augen by shear zones of different sense and orientation. Formation of lenses and their subsequent rotation and flattening is also accomplished by synthetic anastomosing shear zones (Fig. 5d). The relatively well-preserved cumulate rocks at Mount Rödberget (Bergman, 1993) contain discrete shear zones with a top-to-the-east sense of movement. This is considered to represent an immature stage in the development of lenses so characteristic along the terrane boundary between Handöl and Rödberget.

The Västerån Synform area

Moderately to steeply dipping limbs and gentle to subhorizontal layers in the hinge define the conspicuously long and narrow Group II synform in this area (Figs 3 & 8b). Along the Seve–Köli contact in the Västerån Synform there are tectonostratigraphic anomalies. Along the eastern limb of the synform very little amphibolite is found in the upper part of the Middle Seve Nappe compared to east of the River Bunnran. This may be a 'primary' feature, but it is also possible that parts of the two upper Seve nappes have been excised by shear zones.

Along the western margin near Tjuvfloarna (Fig. 3), most of the Upper Seve Nappe and parts of the Bunnran Formation are missing. Locally, talc-schist of the Rödberget ultramafic–mafic Complex rests directly on gneiss of the Middle Seve Nappe and, further south, on amphibolite of the Lower Seve Nappe. This cutting down to the east through tectonic units is due to movements on extensional shear zones. These shear zones conspicuously truncate mesoscopic Group I folds and mylonites. The extensional shearing probably continues below the terrane boundary, as suggested in Fig. 8(b). By restoration of this cross-section, the displacement has been estimated to be 500–1000 m.

Two opposite younging directions (Figs 3 & 8b) less than 100 m apart in Köli rocks in the River Bunnran indicate a refolded tight Group I anticline. Similar structures have been recognized in overlying units in the Tännforsen area (Beckholmen, 1978). The mesoscopic Group II structures that are common here include open to tight, often asymmetric folds with axial-planar schistosity or crenulation cleavage, boudinage with accommodation folds and shear zones. Layering (bedding and/or metamorphic)–cleavage relations and minor asymmetric folds indicate tight recumbent Group II folds with wavelengths and amplitudes of several hundred metres (Fig. 8b). The cross-section in Figs 8(b) and 9 shows the cleavage associated with these folds and their axial surfaces arched to accommodate to the shape of the underlying terrane boundary.

Mineral and stretching lineations are variable within the normal range of E to SE trends, but between Bunnran and Västerån they tend to adjust to the NE–SW strike of the oblique ramp defined by the Seve nappes (Fig. 6a). Still some lineations trend NW–SE here, possibly indicating that these pre-date ramp formation. In contrast to the Rödberget–Bunnerviken subarea, boudin axes here trend NE and form a large angle with mineral lineations (Fig. 9).

Most crenulation lineations conform with the strike of the terrane boundary, as they do towards the east, except at the western margin of the Västerån Synform. There they are parallel to the mineral/stretching lineation, trending across the shear zone. The northerly plunging crenulation lineations overprint earlier lineations and are only common within the Västerån and Handölan synforms (Figs 7 & 9), and are obviously related genetically to the formation of these major structures.

The scatter of foliations in the underlying Seve nappes (Fig. 10) in the western limb of the synform is due mainly to complex internal Group I folding that preceded the development of the synform. A cleavage correlated with the Group II cleavage in the Bunnran Formation is evident in the uppermost part of the Seve nappes flanking the synform. Along the western margin the cleavage dips *gently* and is accompanied by E-dipping extensional shear zones. This suggests that the cleavage and associated folds in the Bunnran Formation were formed progressively during shearing and translation. Along the southeastern contact the cleavage dips *steeply* southeast, possibly as a result of local folding at the terrane boundary. Contractional deformation here is supported by kinematic observations and fold–thrust relations.

In summary, the western limb of the synform is extensional with approximately down-dip transport. By contrast, the eastern limb is contractional, where structures record shortening and generally oblique up-dip Group II transport on the ramp. This favours an asymmetric ductile half-graben model.

In contrast to the minor and mesoscopic structures described earlier, the kinematic pattern in this area is simple and straightforward; top-to-the-east movement is

Fig. 9. Equal-area stereographic projections showing Köli structures between Handöl and Rödberget, and Seve structures east of River Västerån. Note the rotation of Group II foliations in the central area (Bunnran Formation, Västerån Synform) reflecting accommodation to the underlying terrane boundary. Systematic orientations of shear zones and shear bands indicate subhorizontal approximate E–W stretching (X). B, Bunnerviken.

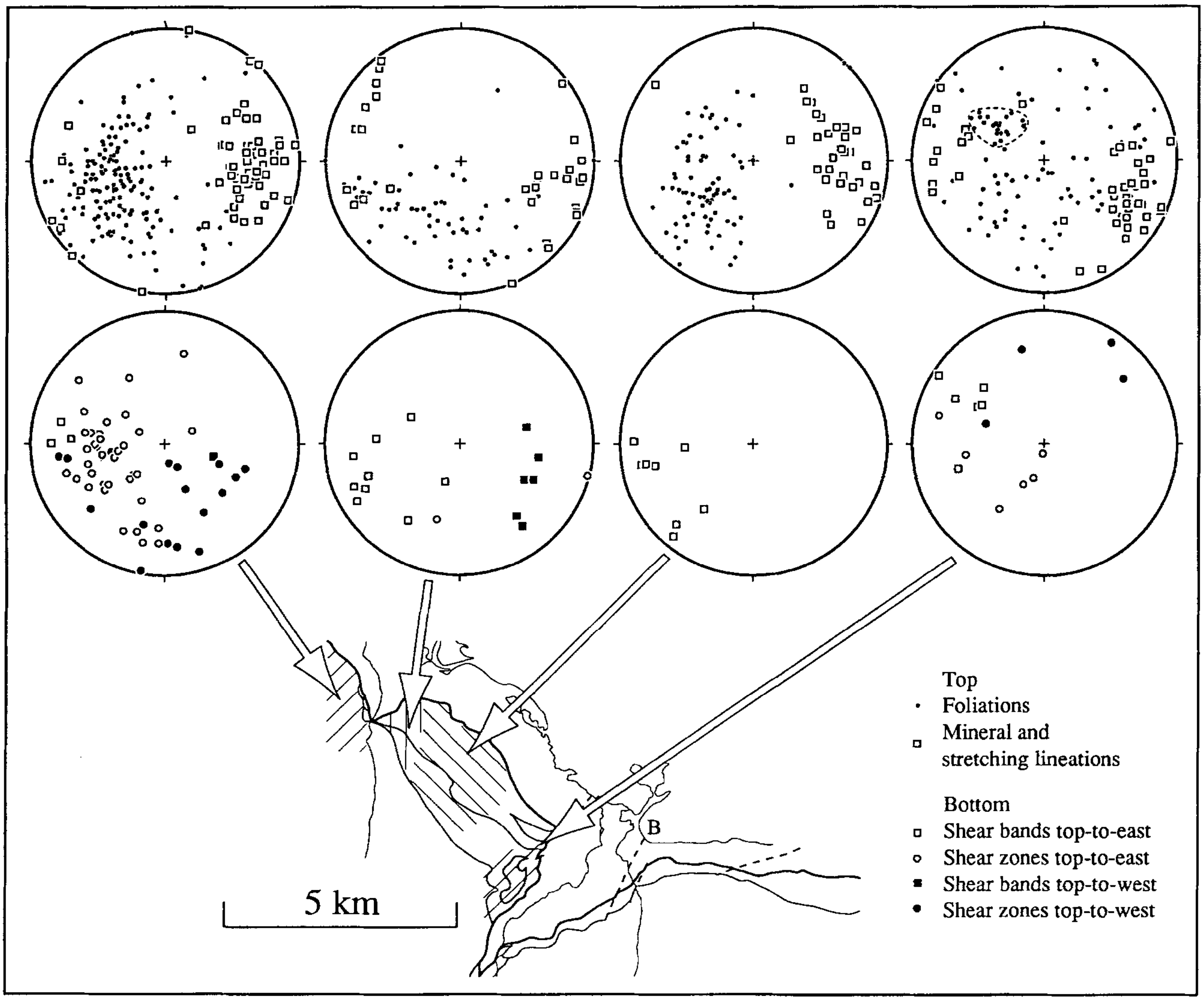

Fig. 10. Equal-area stereographic projections showing Seve structures west of River Västerån. The encircled weak concentration of poles to foliations in the northwest quadrant represent foliation readings close to or at the SE-dipping ramp at the terrane boundary. As to the east, systematic orientations of shear zones and shear bands indicate subhorizontal approximate E–W stretching. B, Bunnerviken.

recorded in most localities (Fig. 7a). This contrast illustrates the variety of structures that may be formed due mainly to a variation in ramp orientation during bulk top-to-the-east translation and extension.

The Täljstensvalen–Handöl area

The large-scale asymmetric folds mentioned previously in the central part of the Upper Seve Nappe at Täljstensvalen have axes subparallel to the stretching lineation (Figs 7 & 10). These folds affect the amphibolite-facies thrusts separating the slices within the imbricate complex. They may either have been formed as Group I footwall folds related to the the Seve–Köli docking, or they may represent a later distributed shearing of the complex.

The western limb of the Handölan Synform (Fig. 3) is an extensional shear zone. Along that shear zone, the Upper Seve Nappe and parts of the Bunnran Formation are cut out. Mineral and stretching lineations in the Seve nappes show an anticlockwise rotation on the map from west to east across the Handölan Synform (Fig. 7a). This may be a result of hanging-wall rotation above the extensional shear zone which controlled the formation of the synform. A similar situation is indicated approximately 1 km to the west where a NE-dipping shear zone with a down-dip stretching lineation truncates the amphibolites of the Lower Seve Nappe and appears to be related to a synform–antiform pair along the terrane boundary (Fig. 3). The prominent structure striking NW–SE south of Enafors is a retrograde extensional shear zone that apparently truncates the terrane boundary (cf. Fig. 11a).

The crenulation lineations in the Bunnran Formation in the Handölan Synform gradually change from N- to W-trending as they approach the terrane boundary (Fig. 7c). In contrast to the mineral and stretching lineations in the Seve nappes, we infer that the variation in the trend of

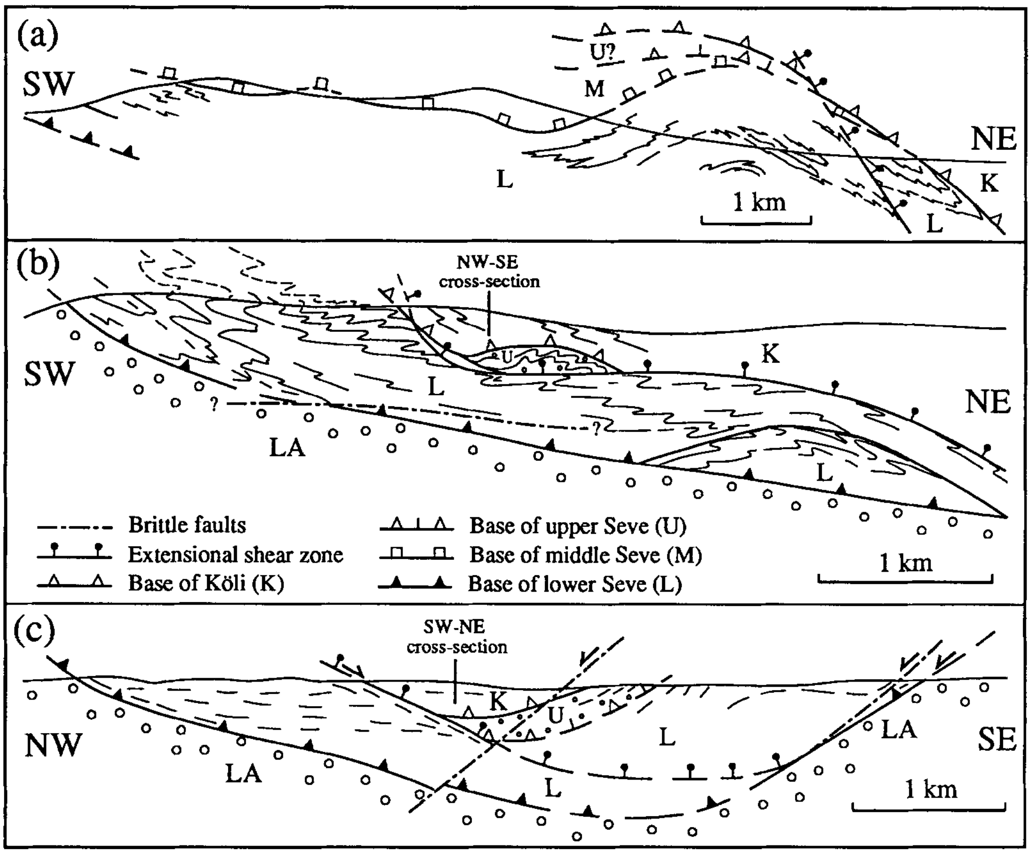

Fig. 11. Cross-sections at Mount Snasahögarna and Storvallen (C, D and E, respectively, in Fig. 3). (a) Truncation of the Upper (?) and Middle Seve nappes by the terrane boundary. The symmetry of Group I folds is indicated in the Lower Seve Nappe. Early isoclinal folds are refolded by SW-verging folds interpreted to be footwall folds to the terrane boundary. (b) SW–NE section with the symmetry of late Group I folds indicated. Note the change of fold symmetry through the Lower Seve Nappe indicating that this is a large-scale recumbent Group I fold dismembered by thrusts and extensional shear zones. (c) NW–SE section. Internal structures in various units are indicated by the change in plunge of Group I folds and stretching lineations. LA, Lower Allochthon. No vertical exaggeration.

the crenulation lineations here reflects the orientation of adjacent ramps, i.e. the limbs and the hinge area of the Handölan Synform. This is in accordance with the conditions found in the Västerån Synform discussed previously.

The systematics of the shear zones recorded from the Seve nappes west of Handölan (Fig. 10) corroborate the importance of E–W stretching when they were formed. Top-to-the-east kinematic indicators are widespread in this area but local top-to-the-west kinematics exist along the terrane boundary in the eastern limb of the Handölan Synform (Figs 7 & 10).

The Mount Snasahögarna area

The earliest recognized Group I stretching lineation in the Middle Seve Nappe, and locally in the uppermost part of the Lower Seve Nappe, has an anomalous NE–SW trend (cf. Sjöström, 1983a). In the high-grade rocks the lineation is defined by sillimanite and/or quartz rods. At the base of the unit, towards the Lower Seve Nappe, this lineation is locally overprinted by an E–W Group I stretching lineation. The reason for this structural anomaly is unknown. In the corresponding Seve Nappe near Åre (Fig. 2), E–W lineations dominate (Ghosh *et al.*, 1979).

The Middle Seve Nappe not only pinches out westwards; it is also cut out to the northeast by the terrane boundary northwest of Handöl (Fig. 11a). This unit is anomalous with respect to both its internal structures and its high grade. In these respects it can be compared with high-grade units in the hinterland now exposed along the Norwegian coast. In that region, NE-trending lineations are typical of units interpreted to have been deformed by orogen-parallel extension at middle structural levels (Gilotti and Hull, 1993).

The Storvallen area

In this area the major part of the Lower Seve Nappe is folded by meso- and large-scale asymmetric NW–SE-trending, gently plunging, Group I folds (Figs 11b & 12a). These NE-verging folds overprint at least one generation of tight or isoclinal folds (Sjöström, 1983a). Along the western margin of the Storvallen Synform (Fig. 3) these folds are truncated by a gently SE-dipping

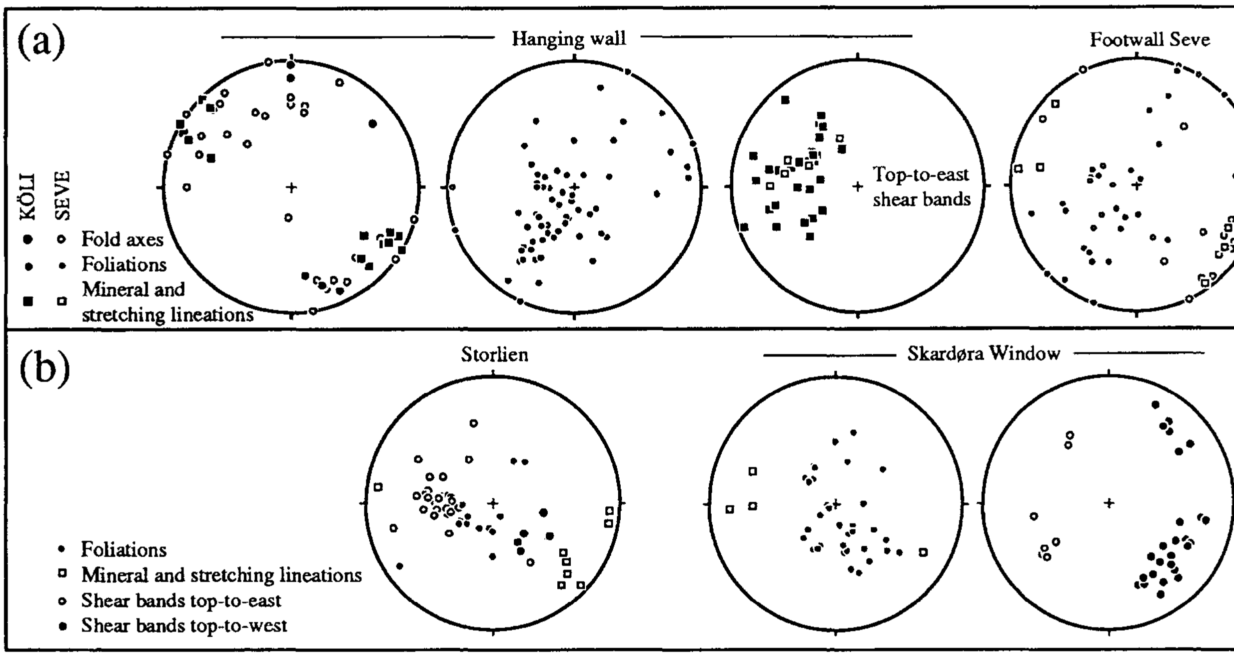

Fig. 12. Equal-area stereographic projections showing structures at Storvallen and in the Storlien–Skardøra Window area. (a) All filled symbols are from the Köli Nappe, all open symbols are from the Seve nappes. (b) The new NE–SW set of shear bands at Skardøra Window indicates the formation of basement antiforms during asymmetric Group II extension.

extensional (Group II) shear zone, passing laterally southeastwards into a dextral strike-slip shear zone (Fig. 3). Along the eastern margin of the synform, the thrust between the Seve and Köli nappes is preserved and the contact is folded. The different conditions on either side of the Storvallen Synform suggests that it is a half-graben structure, comparable to the Västerån Synform described in detail above.

East-verging Group II folds, related to the development of the extensional ramp along the western margin, were formed in both the Köli nappes (hanging wall) and the Seve nappes (footwall). Previously, these folds, referred to as F_3, were considered to post-date thrusting, mainly because they could be correlated across the terrane boundary (Sjöström, 1983a). The axes of most of the folds trend oblique to the strike of the ramp (Fig. 12a). A Group I hornblende stretching lineation is parallel (in trend) to retrograde Group II lineations on mesoscopic ductile shear zones. These shear zones have the same orientations and kinematics as small-scale synthetic shear bands (Fig. 12a).

The Storlien–Skardøra Window area

As in the Storvallen area, both the Seve and the Köli nappes contain mesoscale E- and, locally, SE-verging, chevron style Group II folds along the terrane boundary. In Köli garbenschiefer these folds (F_3) fold a crenulation cleavage (S_2) wrapped around porphyroblasts of garnet and hornblende that contain earlier (S_1) inclusion trails (Sjöström, 1983a). Top-to-the-east shear bands commonly overprint the folds, but locally Group II folds deform the shear bands indicating a penecontemporaneous development of (shear) folds and shear bands.

At the base of the Köli Nappe boudinage structures show significant differences in perpendicular sections (Fig. 13a). In sections parallel to the direction of transport they are asymmetric; in the perpendicular section they are symmetric. In the asymmetric section the boudins are accompanied by strong top-to-the-east structures in the upper-east and lower-west margins, and weak top-to-the-west structures in the upper-west and lower-east margins. This pattern is consistent with bulk top-to-the-east movements. East-verging Group II folds at the 'leading edges' of such boudins are common and some metre-scale folds mature to thrusts (Fig. 13b & c). Again lateral extensional (shear zones, asymmetric boudinage) and contractional structures (folds and locally thrusts) are intimately related during Group II deformation. Altogether, both large-scale and mesoscale structures accord with dominantly non-coaxial bulk flow to the east. The mutual overprinting relationships among various structures emphasize the progressive and heterogeneous nature of the deformation.

This subarea represents a section through the thinned Lower Seve Nappe from the terrane boundary to its basal contact with the Lower Allocthon, with local remnants of the intervening Middle Allochthon. It is a critical area for the evaluation of the 'mega-boudinage hypothesis' (Gee, 1978) because the amphibolite-rich, competent Seve Nappe pinches out westwards. If this is a result of coaxial deformation, opposite senses of shear could be expected to dominate along its upper and lower boundaries, respectively (cf. Gilotti, 1989).

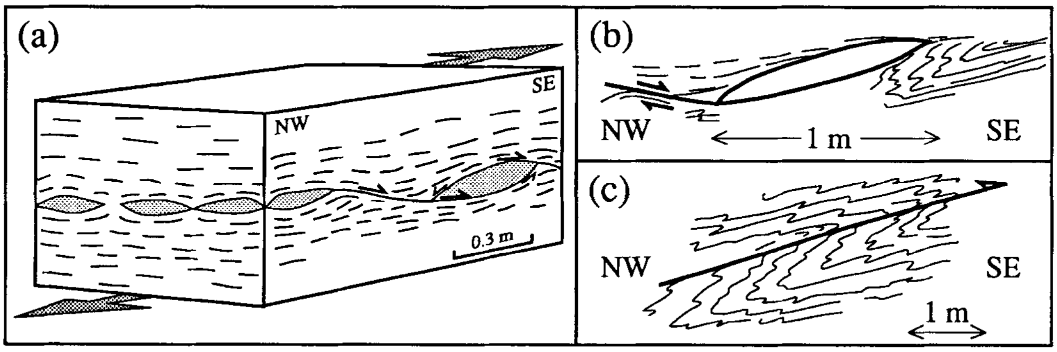

Fig. 13. Characteristic Group II structures. (a) Block diagram of back-rotated quartz boudins, showing kinematic relations and symmetric boudinage in the perpendicular section. From a road cutting in Köli schist at Storlien. (b) Quartz boudin with an asymmetric fold at the leading edge and an extensional shear zone at the trailing edge. (c) Minor thrust truncating E-verging Group II folds.

Our results, however, show that top-to-the-east structures are by far the most common both in the basal Köli Nappe and through the Seve Nappe, although there are conjugate sets of retrograde (plastic) shear bands (Fig. 12b). A pervasive shear-band asymmetry indicating top-to-the-east kinematics also characterizes the underlying, mylonitized nappes. These conditions are not compatible with the pinching-out of the Seve Nappe as a result of symmetrical boudinage.

In the Skardøra Window (Fig. 3) the kinematic pattern is rotated, and new sets of shear bands have been formed (Fig. 12b). Apart from their orientation, they are indistinguishable from those related to Group II translation. This formation of new shear bands has important implications for the relative timing of basement antiform stacking and translation (see below).

West of Storlien, basement and cover rocks of the Lower Allochthon are exposed in the Skardøra Window (Fig. 3). This and a comparable antiformal window 45 km to the northeast (Mullfjället Window, Fig. 2) have recently been interpreted to result from considerable basement shortening during the Scandian collisional orogeny (Palm *et al.*, 1991). Therefore, there is an apparent contrast between the extensional structures we record in the Seve and the Köli nappes and the contractional structures at lower tectonostratigraphic levels within the windows. The significance of this inconsistency will be questioned later.

In the western limb of the Skardøra Window the tectonostratigraphy is truncated by the Røragen Detachment (Norton, 1987), a W-dipping major Devonian extensional fault. Kinematic indicators related to this structure (Fig. 3) overprint the top-to-the-east pattern (Sjöström and Bergman, 1989; Sjöström *et al.*, 1991).

DISCUSSION

Evolution of the Seve–Köli boundary

The terrane boundary has a composite evolution. Its early history, the accretion of the Köli nappes to the Seve nappes, is recorded by high-temperature mylonites in the Handöl area. The two upper Seve nappes are linked at this stage by common felsic dykes, and convergent *P–T* paths link Köli to Seve (Bergman, 1992). Large parts of the terrane boundary are characterized by subsequent overprinting in the form of extensional shear zones. Still the overall geometry with respect to the footwall units (Seve nappes)—cutting upwards to the east—is that of a thrust (Fig. 4). Our results are compatible with a model involving continuous deformation resulting in structures previously distinguished as separate deformation events. During bulk eastward movement the formation of extensional and contractional ramps caused local disturbances. Pre-existing folds and cleavages were rotated and overprinted by new structures as a result of the formation of such ramps. Poles to shear zones and shear bands are symmetrically distributed around steep approximately N–S-striking planes on stereograms. This indication of subhorizontal E–W stretching is consistent over large areas.

The geometry and kinematics suggest that the three synforms (Fig. 3) along the terrane boundary are half-graben-like structures due to top-to-the-east movement on extensional shear zones, locally associated with top-to-the-west movements due to hanging-wall stretching and rotation, analogous to Fig. 13(a). Other mechanisms like boudinage or buckle folding are not supported by our observations.

The kinematics of tectonic boundaries separating the Köli nappes within the Tännforsen Synform (Fig. 2) in the hanging wall of the terrane boundary has not been studied. Beckholmen (1984) emphasized late movements along thrusts, which implies late overstepping or out-of-sequence thrusting between the three major nappes. In the lower part of the tectonostratigraphy this is demonstrated where the basal thrust of the Gevsjön Nappe (middle Köli) truncates minor thrusts in the Duved Nappe (lower Köli) (Beckholmen, 1984, fig. 1). The late eastward translation emphasized by Beckholmen (1984) is compatible with the evolution along the terrane boundary described in this paper.

Large-scale folds have been recorded both in the

Lower Seve and Köli nappes, but they appear to be of different generations. In the Lower Seve Nappe, folds interpreted as Group I footwall folds occur both in the east and in the west (Fig. 11a & b). These folds have axes subparallel to the direction of transport which indicate that the Lower Seve Nappe is a Group I fold nappe. In the Bunnran Formation in the east, NE-trending Group II folds are common, refolding earlier folds (Fig. 8b). These Group II folds may be part of inverted limbs of major SE-verging folds, but more way-up evidence is needed to confirm this. Possibly they are footwall folds formed during overstepping by higher units. At least in the Västerån Synform and further east, shearing also occurred along the terrane boundary during or after the formation of these folds. The fact that some linear Group II features (cleavage intersections and crenulations) tend towards parallelism with the strike of the terrane boundary also indicates late shearing along the boundary.

Regional implications

Geometry of tectonic units. In this study we provide evidence of both early stacking (Group I) of units and of considerable subsequent modification (Group II). A typical example of the latter is the western margin of the Västerån Synform, where a major part of the the Seve–Köli tectonostratigraphy is truncated by an extensional shear zone (Fig. 3). Group II extension obviously modified several tectonic units (horses) separated by high-temperature Group I mylonites. In the western part the consistency of kinematics from the Seve–Köli boundary through the Lower Seve Nappe and also into underlying units indicate an eastward bulk Group II flow and thinning of composite units. We infer that the pervasive nature of the top-to-the-east pattern through the nappes and across their tectonic boundaries is a result of overprinted shearing and not the development of individual thrust horses. This does not exclude the formation of horses at various stages, but our results emphasize the modification of composite units. The dominance of top-to-the-east kinematics along the terrane boundary and the development of asymmetric extensional structures (e.g. Fig. 13a) indicate that the Group II modification is mainly a result of non-coaxial deformation.

With respect to the mega-boudinage theory we infer that this, too, is simplified. As indicated by Gilotti (1989), the lenses referred to as mega-boudins represent a wide variety with respect to competency. We have recorded several mechanisms producing lenses in mesoscale: symmetric boudinage formed by layer-parallel coaxial stretching and asymmetric structures formed by non-coaxial deformation accompanied by differently oriented shear zones. Asymmetric lenses can be achieved both by conjugate sets of shear zones (with opposite sense of movement, Fig. 5b) and by shear zones with the same sense (Fig. 5c & d), analogous to small-scale shear foliation–shear band relationships. It is possible that these mechanisms operated broadly simultaneously by the variable dominance of coaxial and non-coaxial deformation in both time and space.

Concerning incompetent lenses in the central Scandinavian Caledonides, the Tännforsen Synform occupied by Köli rocks is certainly such an example when compared with the underlying Seve rocks. Our study suggests that parts of the southern and western margins of the Köli nappes in the Tännforsen Synform are controlled by extensional Group II shear zones and lateral ramps (cf. below and Fig. 11a). Along the eastern margin reflection seismic results (Palm *et al.*, 1991) indicate the existence of a W-dipping major extensional fault comparable to the Røragen Detachment (Fig. 3). Reconnaissance across the eastern margin of the Tännforsen Synform supports the presence of such an extensional fault truncating the tectonostratigraphy (Sjöström, unpublished results 1992). These findings emphasize that a variety of dislocation surfaces may contribute to the formation of lens-shaped units, irrespective of their relative competence.

The same applies to the westward pinching-out of units in the Scandinavian Caledonides. This has been emphasized as a regional (e.g. Nicholson and Rutland, 1969; Zachrisson, 1969, 1973; Gee, 1975), as well as a local (Sjöström, 1983a), pattern. In particular, the truncation of leading edges by W-dipping extensional faults (Sjöström and Bergman, 1991; Sjöström *et al.*, 1991; cf. Palm *et al.*, 1991) may have obliterated pre-existing *eastward* pinching-out. That geometry is very common among mesoscale structures along the terrane boundary (cf. Fig. 13a). In addition, the leading edges of regional tectonic units are generally removed by erosion while trailing edges are preserved.

West of Handöl, the Upper and Middle Seve nappes and upper part of the Lower Seve Nappe are cut out by the terrane boundary (Fig. 11a). This structure coincides approximately with a regional branch line constructed for the Särv Thrust Sheet of the Middle Allochthon (Gilotti and Kumpulainen, 1986). A lateral ramp of that underlying unit may therefore be a substantial structure controlling the southern margin of the Tännforsen Synform.

Timing of Group I and Group II deformation. Metamorphic zircon, sphene and monazite in the Seve nappes yield U/Pb ages of 441–425 Ma (Williams and Claesson, 1987; Gromet *et al.*, 1993). Group I deformation and construction of the Seve–Köli Complex most likely occurred in this time interval.

The consistency of the top-to-the-east Group II pattern from the Köli nappes, through the Seve Nappes and the Middle into the Lower Allochthon suggests that it is related to the translation of the Seve and Köli nappes onto the Baltoscandian Platform following Scandian collision. Common muscovite and biotite $^{40}Ar/^{39}Ar$ cooling ages from the Seve and Köli nappes in neighbouring areas range between 425 and 410 Ma (Dallmeyer *et al.*, 1985). Both minerals occur in Group II shear zones; consequently these values may indicate the minimum age of the deformation. However, in analogy with a recent attempt to date minerals in Devonian shear zones in southwestern Norway (Chauvet and Dallmeyer, 1992), rejuvenation of isotopic systems may be localized to minerals in deformation zones. This would allow Group II extension to post-date the cooling ages recorded by Dallmeyer *et al.* (1985).

The truncation of the Seve–Köli tectonostratigraphy by the Røragen Detachment demonstrates that Group II structures pre-date the detachment (Figs 2 & 3) interpreted as a growth fault of Lower Devonian age (Norton, 1987; Sjöström and Bergman, 1989). Consequently Group II deformation pre-dates the formation of sedimentary basins along the present Norwegian coast during major Middle Devonian extension (e.g. Hossack, 1984; Norton, 1987; Seranne and Seguret, 1987) possibly linked to plate divergence (Fossen, 1992). The poorly constrained time-span indicated for Group II deformation thus coincides more or less with the Scandian collisional orogeny.

Comparison with other areas. At the tectonostratigraphic levels investigated, our results indicate that asymmetric extension was a characteristic feature of the Scandian collisional orogeny. To evaluate the significance of Group II extensional structures along the terrane boundary we compared them with similar structures elsewhere, one describing regional conditions and two considering local thrust-zone processes in foreland areas.

Along the Moine Thrust in Scotland, Coward (1982) described extensional structures (including 'surge zones') formed during late movements on the thrust. He demonstrated an intimate relationship between extensional, contractional and strike-slip faults, and related these structures to gravity spreading and thinning of the main Scottish Caledonides.

In the Cordilleran foreland in Montana Yin and Kelty (1991) described normal faults (Riedels) concentrated to and merging into a floor thrust (also described by Coward, 1982). It was suggested that these faults accommodated a bulk simple-shear strain within the thrust plate between simultaneously moving subhorizontal floor and roof thrusts.

Near the Pennine Front in the French Alps, distributed shearing in the hanging wall to a local floor thrust occurred by means of closely spaced extensional shear zones cutting through an imbricated basement–cover stack (Butler, 1992). The kinematics of overthrusting and extensional disruption are inseparable, implying a continuous episode of structural development.

Like our results, these examples suggest a close relationship between the formation of coaxial contractional and extensional structures. Extension may therefore be an essential part of an overall contractional deformation regime. Of these examples, our findings compare best with the conditions in the Scottish Caledonides by modifying a pre-existing nappe geometry. In analogy with that area, a major part of the wedge can be expected to show the effects of lateral extension and thinning.

As a general model of orogenic wedges developing during plate convergence, the maintenance of a stable configuration by lateral shortening or extension depends on whether material is added to the wedge front or underplates the wedge (Platt, 1986). Controlling factors, that may vary in time and space, include rheology, subduction rate, sedimentation, etc.

Lateral and vertical persistence of Group II extension

Westwards, a top-to-the-east pattern overprinting tectonic boundaries and units has been traced to the eastern margin of the Tømmerås Window (Fig. 2) in Norway (Sjöström *et al.*, 1991). The tectonostratigraphic section affected is comparable to that west of Storlien described previously, with the addition of higher Köli units of the Trondheim Nappe Complex. Eastwards, asymmetric boudinage and E-dipping extensional shear zones, comparable to those in Fig. 13(a), have been recorded in the Lower Allochthon close to the present Caledonian front *ca* 20 km south of Östersund (Fig. 2) (Sjöström and Bergman, 1991, unpublished results). Our results indicate that extensional overprinting is pervasive at deeper structural levels in the central Scandinavian Caledonides compared to 600 km to the north (Northrup, 1996).

Interpretation of basement (and basement–cover) structures based on a reflection seismic image across the Tännforsen Synform (TS, Fig. 2) favours considerable basement shortening (stacking) above a sole thrust during Scandian collisional orogeny (Hurich *et al.*, 1989; Palm *et al.*, 1991). Combined with our results this indicates a major structural discontinuity separating the Seve and Köli nappes (with structures proving important asymmetric lateral extension) from the Lower Allochthon (dominated by lateral shortening). However, Group II structures in the Seve and Köli nappes show important similarities with structures in the Lower Allochthon: stretching lineations, asymmetric boudinage structures (cf. Fig. 13) and E-verging folds comparable to Group II folds are common in the Lower Allochthon (Sjöström *et al.*, 1991). An important question is then: are the structures in the Lower Allochthon related to Group II structures in overlying units?

There is a more or less total acceptance of the fact that the basement antiforms are late structures arching both overlying nappes, their internal structures and the thrusts separating the nappes. In the central Scandinavian Caledonides the stacking of the antiforms is obviously *not* related to major lateral contraction in overlying units because late thrusts that could have accommodated the contraction are absent. If the antiforms were formed by

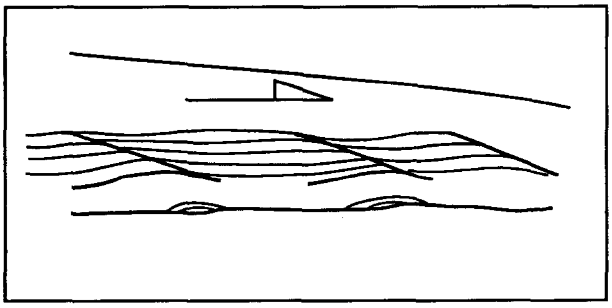

Fig. 14. Illustration of the favoured interpretation where basement antiformal stacks form above the sole thrust simultaneously with asymmetric extension at higher structural levels. Structural style within the basement antiforms schematically after Palm *et al.* (1991).

overall contraction, this must have occurred to the west and possibly earlier than generally considered. After stacking the antiforms must have been accreted to overlying thrust sheets, transported to the east and left as abandoned horses. Although the rotation of the kinematic pattern across the Skardøra Window is consistent with the basement-cored antiforms post-dating thrusting, the development of new sets of shear bands indicates that antiform stacking and translation occurred simultaneously. The intimate relationships between extension and contraction recorded in our study indicate that the basement antiforms may have been stacked as underplated Group II structures at the base of the orogenic wedge simultaneously with asymmetric Group II extension at higher levels (Fig. 14).

CONCLUSIONS

The emplacement of Köli nappes onto Seve nappes was characterized by thrusting, mylonitization, imbrication and folding, mostly under amphibolite-facies conditions. Locally well-preserved, felsic, intrusive igneous rocks were generated and provide important links between the Seve nappes at this stage.

Subsequent modification of the earlier structures by extensional shearing, asymmetric boudinage and folding occurred in the greenschist facies. These later structures are significant in controlling the present geometry of tectonic units.

Kinematic analysis shows movement towards the east or southeast at all stages. Movement in the opposite direction occurred locally and affected the geometry. A pattern of shear zones and shear bands demonstrates approximate E–W stretching.

Based on our observations we suggest alternative interpretations of characteristic Caledonian structures previously described from other areas. Late synformal structures may result from asymmetric extension, and the typical lenticular shape and thinness of tectonic units may also be due to modification by extensional shear zones. The intimate relationship between extensional and contractional structures is consistent with non-coaxial progressive flow to the east.

The regional persistence (vertically and laterally) of the structural pattern indicates that it results from the Scandian translation of the orogenic wedge. At the base of the wedge, basement antiforms were stacked above the sole thrust.

Acknowledgements—We would like to thank Professor C. Talbot for discussions and reading an early version of the manuscript. Reviewers Dr J. A. Gilotti and Dr A. P. Boyle are thanked for their constructive comments. This study benefitted by grants from the Swedish Natural Science Research Council. Basic mapping and some structural data were collected during the Caledonian Research Project of the Swedish Geodynamics Project. Funding for a research leave by the Uppsala University for one of us (H. Sjöström) is greatly acknowledged. We thank Mrs C. Wernström for drawing Figures 8, 11, 13 and 14. We are grateful to Mr T. Bergman for improving the English. Mr Å. Andersson kindly gave access to the properties of Handöls Täljstens AB including ground magnetic measurements.

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