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Orogen-parallel transport and vertical partitioning of strain during oblique collision, Efjorden, north Norway

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Abstract—Thrust sheets in the Caledonian allochthon in northern Scandinavia were emplaced generally toward the ESE, an orientation nearly perpendicular to the trend of the Caledonian orogen. In the Efjord area of north Norway, however, orogenesis also produced top-to-the-SSW motion on N-dipping thrust faults in the cratonal basement beneath the allochthon. The leading edges of some SSW-directed thrust-sheets moved upward into the overlying metasedimentary cover and formed the cores of S-verging recumbent fold-nappes at the base of the Caledonian allochthon. As deformation continued, these fold nappes became entrained in the top-to-the-ESE transport of the overlying allochthon. Mutually cross-cutting relationships suggest contemporaneous SSW-directed thrusting in the cratonal basement and top-to-the-ESE movement of the allochthon. Thus, structures in the Efjord study area reflect vertical partitioning of strain into components with nearly orthogonal displacement directions at different structural levels. Collectively, the top-to-the-SSW (orogen-parallel) and top-to-the-ESE (orogen perpendicular) components of transport are consistent with overall sinistral–oblique, post-collisional convergence between Baltica and Laurentia. Implications include: (1) in some parts of the orogen, recumbent folds with hinges sub-parallel to the transport direction of the allochthon were produced by orogen-parallel transport rather than orogen perpendicular sheath-folding; and (2) orogen-parallel components of structural transport make two-dimensional palinspastic restoration in planes perpendicular to the orogen difficult or inappropriate in some locations. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Geologists often analyze the structural development of mountain belts in two-dimensional cross-sections drawn roughly perpendicular to an orogen, because planes of this orientation are commonly assumed to contain the principal direction of structural transport. Many mountain belts, however, have additional components of structural transport sub-parallel to their trends. Examples include the Alps (Selverstone 1988, Mancktelow 1992), Appalachians (Peterson & Robinson 1993, Vauchez *et al.* 1993), Caledonides (Gilotti & Hull 1991, Holdsworth & Strachan 1991), Caucasus (Jackson 1992), North American Cordillera (Gabrielse 1985, Price & Carmichael 1986), Himalayas (Molnar & Tapponnier 1975), and the Tasminides (Glen 1992). Orogen-parallel tectonic transport can occur for a variety of reasons, but it is a particularly common feature of mountain belts produced by oblique convergence because a component of the convergence vector can be resolved parallel to an orogen built along the convergent boundary (e.g. Fitch 1972, Dewey 1980). Convergence exactly orthogonal to plate boundaries occurs much less frequently than oblique movement, so most collisional orogens are transpressional and must, in some manner, accommodate an orogen-parallel component of structural transport (e.g. Fossen *et al.* 1994).

At present, the three-dimensional structural architecture and partitioning of deformation within zones of oblique collision or convergence are poorly understood, particularly at deeper levels of such orogens. Therefore, studies of the geometry, kinematic characteristics, and modes of interaction among structures that have accommodated orogen-parallel and orogen-orthogonal components of deformation within collisional systems are necessary to better understand their tectonic evolution.

The Scandinavian Caledonides provide an opportunity to directly examine the structural development at middle to deep crustal levels of a Paleozoic collisional system. Structural studies and stratigraphic evidence from numerous locations within the Caledonian orogen suggest sinistral–oblique convergence and transpression during the collision of Baltica and Laurentia (e.g. Steltenpohl & Bartley 1988, Soper *et al.* 1992, Fossen 1993). The purpose of this paper is to document the geometry and kinematic characteristics of Caledonian thrust faults and recumbent fold-nappes in the Efjord area of north Norway, and to present a three-dimensional kinematic interpretation for their development within the context of oblique collision.

TECTONIC SETTING

During the Caledonian collision, A-type subduction of the western margin of Baltica resulted in the ESE-directed emplacement of a crustal-scale, composite allochthon on to the Baltic craton (Gee 1975, Hodges *et al.* 1982, Stephens & Gee 1989). Subsequent erosion has removed much of the allochthon and exposed deep levels of the orogen in Scandinavia. The present-day mountain belt consists of a relatively thin veneer of the original allochthonous thrust-stack lying over autochthonous or

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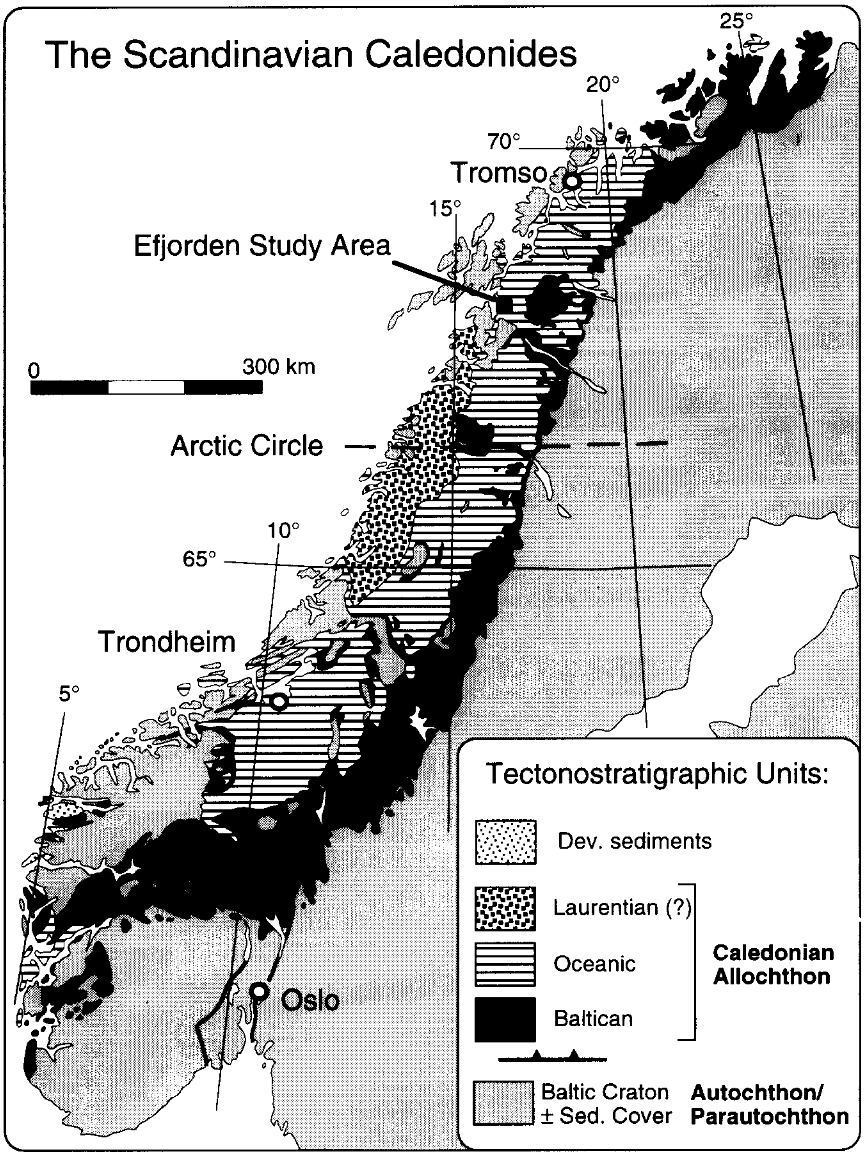

Fig. 1. Simplified geologic map of the Scandinavian Caledonides (modified from Gee *et al.* 1985)

parautochthonous rocks of the Baltic craton (Fig. 1). Because the present erosional surface essentially follows the structural level of the Caledonian A-type subduction zone across the orogen, the contact between the subducted Baltic craton (lower plate) and the over-riding Caledonian allochthon (upper plate) is well exposed in many structural windows and basement culminations.

A growing number of geologic studies has suggested that the Caledonian orogen resulted from sinistral–oblique convergence. For example, Fossen (1993) interpreted the structural development in part of the Caledonides of SW Norway as the product of orogen-normal thrusting combined with orogen-parallel sinistral shear. Another example comes from the Caledonides of east Greenland, where Holdsworth & Strachan (1991) described a system of sinistral strike-slip faulting and orogen-orthogonal thrusting that were interpreted as evidence for a sinistral component to Caledonian orogenesis. Soper *et al.* (1992) inferred sinistral oblique convergence and collision of Baltica and Laurentia to form the Caledonian orogen based on a synthesis of structural, stratigraphic, and paleomagnetic data from various circum-Iapetus continents and continental fragments.

GEOLOGY OF THE EFJORDEN AREA

The Efjorden study area, located near 68°N on the coast of Norway (Figs. 1 and 2), contains exposures of subducted Baltic craton, the far-travelled Caledonian allochthon, and the group of structures which formed the Caledonian A-type subduction zone (Hodges *et al.* 1982, Tull *et al.* 1985). Rocks in the area were metamorphosed and deformed under pressure–temperature (*P–T*) conditions in the upper-greenschist to epidote–amphibolite facies during Caledonian orogenesis (Hodges 1982, Crowley 1985, Northrup 1996a).

Regional late-Caledonian folds control the first-order pattern of geologic contacts in the study area (Fig. 2, Hodges 1985, Steltenpohl & Bartley 1988). Near the head of Efjord, the folding produced a gently ESE-plunging antiform. The interaction of the Efjord antiform with the present erosional surface creates an ESE-closing half-window cored by rocks of the Baltic craton and flanked by rocks of the composite Caledonian allochthon. Units dip 25°–45° N along the north limb of the culmination, 15°–30° E near its closure, and 20°–30° S along its southern limb. The radial dips of the structural section around the closure of the Efjord culmination make the geologic map an oblique conical cross-section through the lower portion of the composite allochthon and the upper portion of the Baltic craton. Nearly 1.5 km of local topographic relief yields magnificent three-dimensional exposure of this structural level of the orogen.

Tectonostratigraphy

Rocks in the area can be grouped into four tectonostratigraphic units based on tectonic affinity and magnitude of structural transport (see Roberts & Gee 1985). The *parautochthon*, or structural basement, consists primarily of Precambrian, K-feldspar megacrystic granite (Tysfjord granite, Andresen & Tull 1986), interpreted to be part of the Baltic craton (Hodges 1985, Tull *et al.* 1985). The Precambrian granite intruded older Precambrian schist and gneiss which form a subordinate portion of the cratonal rocks in the Efjord area. Sporadic mafic dikes cut the cratonal basement, and intrusion of these dikes may have been related to rifting along the Baltoscandian margin farther west, as the Iapetus Ocean basin opened. Above the Precambrian rocks, quartzite and garnet-grade psammitic schist represent a strongly deformed and metamorphosed remnant of the early Paleozoic sedimentary cover sequence on Baltica. Although still attached to the craton locally, the metasedimentary cover is commonly detached and transported to some extent relative to the contiguous cratonal basement (Hodges 1985, Andresen & Rykkelid 1989).

A complex series of thrust sheets, fold-nappes, and mylonite zones forms the rock mass structurally above the parautochthon. Thrust sheets and recumbent fold-nappes derived from the Baltic craton and its metasedimentary cover lie directly over the parautochthon and constitute the *lower allochthon*. Total transport distances of these thrust sheets and fold nappes are not known, but lithologic and metamorphic similarity between them and the parautochthon suggests relatively local derivation. Above the lower allochthon is a 50–300 m thick *sliver zone* consisting of structurally interleaved mylonitic rocks of uncertain tectonic affinity and heterogeneous lithologic character. The sliver zone forms a fundamental structural and tectonostratigraphic break; it marks the transition between Baltic affinity rocks below and far-travelled oceanic affinity rocks above. Pelitic schist, amphibolite, and impure marbles derived from the Iapetus Ocean basin overlie the sliver zone and form the structurally composite *upper allochthon*, the highest tectonostratigraphic unit in the area (Hodges 1985).

Structure of the Efjorden area

This paper focuses primarily on the structural evolution of rocks of Baltic affinity (Parautochthon and Lower Allochthon) in the Efjord area. Two important components of the structural architecture of the Baltican rocks can be recognized at map scale: (1) N-dipping thrust faults in the cratonal basement and imbricated sheets of cratonal rocks associated with these thrusts exposed in the northern limb of the Efjord culmination; and (2) a complex series of S-vergent, E-trending, recumbent fold-nappes cored by cratonal rocks exposed in the southern limb of the Efjord culmination (Figs. 2–4).

A series of thrust sheets forms an imbricate stack exposed southeast of Skårvatnet, a lake in the northern part of the area. Thrust sheets in the stack are composed principally of Precambrian granite derived from the Baltic craton. The structurally highest sheet also contains a significant amount of Precambrian gneiss and schist. Granite within the thrust sheets has a moderate fabric ($L > S$) defined by elongate biotite or feldspar mineral aggregates. Fabric intensity increases notably within a few meters of the mylonitic thrust faults bounding the imbricated sheets (Figs. 5a,b). Strain also increases near the top of the stack and within the leading portions of sheets that ramp up into the overlying schists. In these locations, the cratonal rocks have undergone extensive recrystallization and grain-size reduction. The thrusts dip generally north, and some root locally in the cratonal basement.

Strongly deformed quartzite and garnet schist are present as thin (typically < 10 m), discontinuous layers along some of the thrust faults in the imbricate stack near Skårvatnet. Along a given fault, schist and quartzite are thickest in outcrops at the highest elevations and pinch out as the fault is followed to lower elevation. These metasedimentary rocks are interpreted to be remnants of the cover sequence which were overridden or infolded between the granite sheets during imbrication of the stack.

Tectonites within and adjacent to the shear zones contain a well-developed foliation oriented sub-parallel to the thrust contacts (Fig. 3). The foliation is defined by millimeter-scale compositional variations, alignment of mica (001) planes, and flattened mineral aggregates in the mylonitic granite and schists of the metasedimentary cover sequence. The orientation of the foliation varies somewhat across the study area due to the effects of regional-scale folding. Aside from variations imposed by the broad folding, however, the foliation changes orientation only modestly from one location or structural level to another.

A stretching lineation defined by strain shadows around K-feldspar porphyroclasts and by elongate, polygranular mineral-aggregates lies in the plane of the foliation. In contrast to the relatively consistent orientation of foliation, the orientation of the stretching lineation changes significantly as a function of structural level (Fig. 3). At deeper levels, the lineation trends NNE, and at higher levels it trends ESE. The change in trend

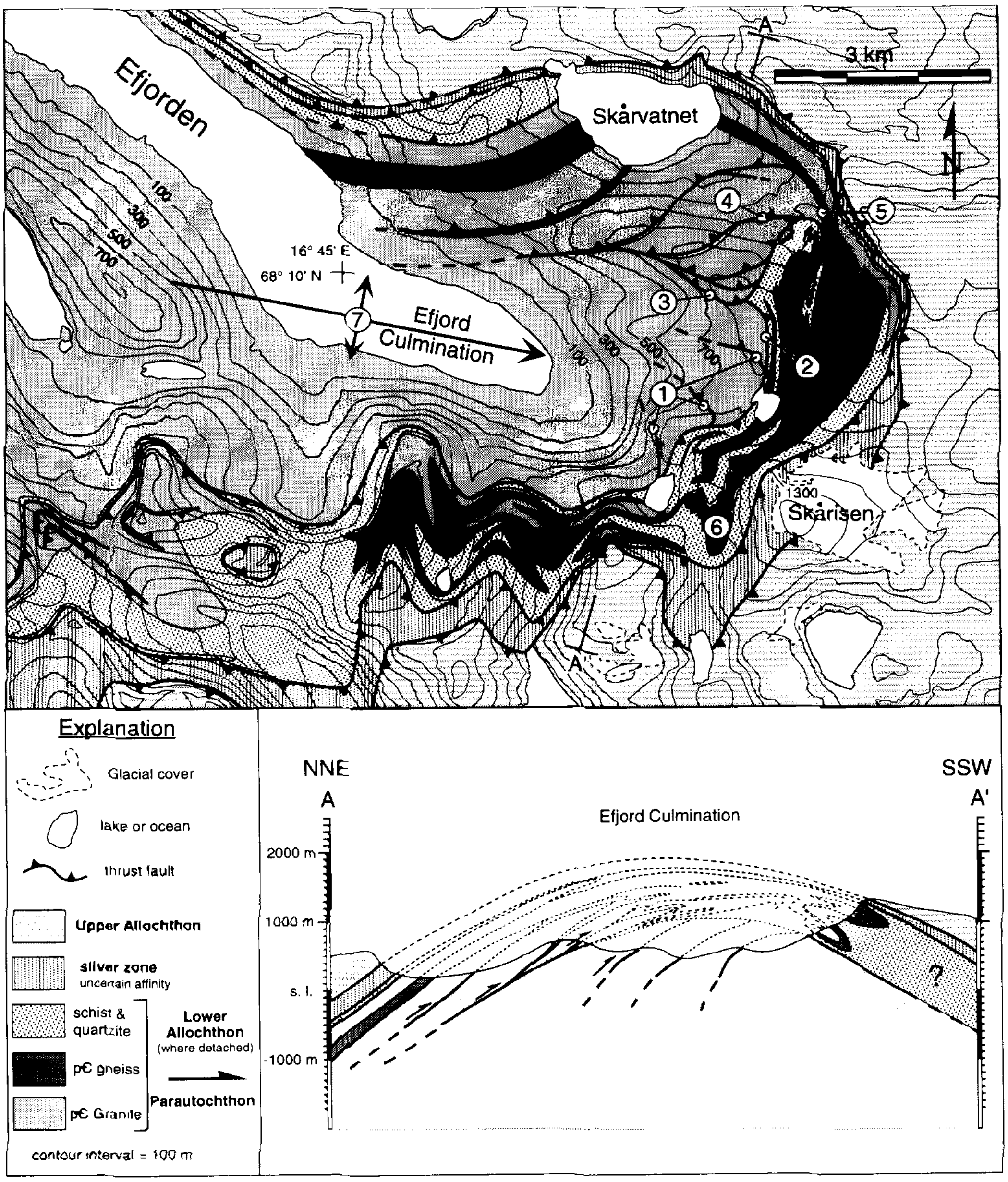

Fig. 2. Geologic map of the Efjord study area showing topography and the distribution of rock types. Numbers refer to locations mentioned in the text.

from NNE to ESE with increasing level is complex, passing locally through an intermediate zone with variable orientations transitional between the end members.

In zones of significant non-coaxial deformation, the orientation of the stretching lineation is commonly subparallel to the orientation of relative structural transport. Strain within the ductile faults of the study area is inferred to have had a high component of simple shear, since deformation within the shear zones clearly accommodated transport of structural blocks past one another (e.g. placing basement granite structurally above the metasedimentary cover). Consequently, the orientations of stretching lineations in the ductile fault zones of the area are interpreted to indicate the directions of relative movement along these structures.

S–C fabric relationships (cf. Lister & Snoke 1984) and/or asymmetric porphyroclasts (cf. Simpson & Schmid 1983) on outcrop surfaces oriented perpendicular to foliation and parallel to the stretching lineation near the mylonitic thrust faults were used to infer the relative-transport direction along the faults (Figs. 3 and 5). The variations in the trend of lineation indicate that shear displacement was in different directions at different structural levels. At deeper levels where the stretching lineation trends NNE, fabric asymmetry within the shear zones is consistent with top-to-the-SSW transport across the N-dipping thrusts. In contrast, near the top of the thrust stack (as well as in the overlying sliver zone and Upper Allochthon) where the lineation trends generally ESE, fabric asymmetry is consistent with top-to-the-ESE relative transport.

Precambrian cratonal rocks in the hanging walls of the SSW-directed thrusts can be followed to the southeast

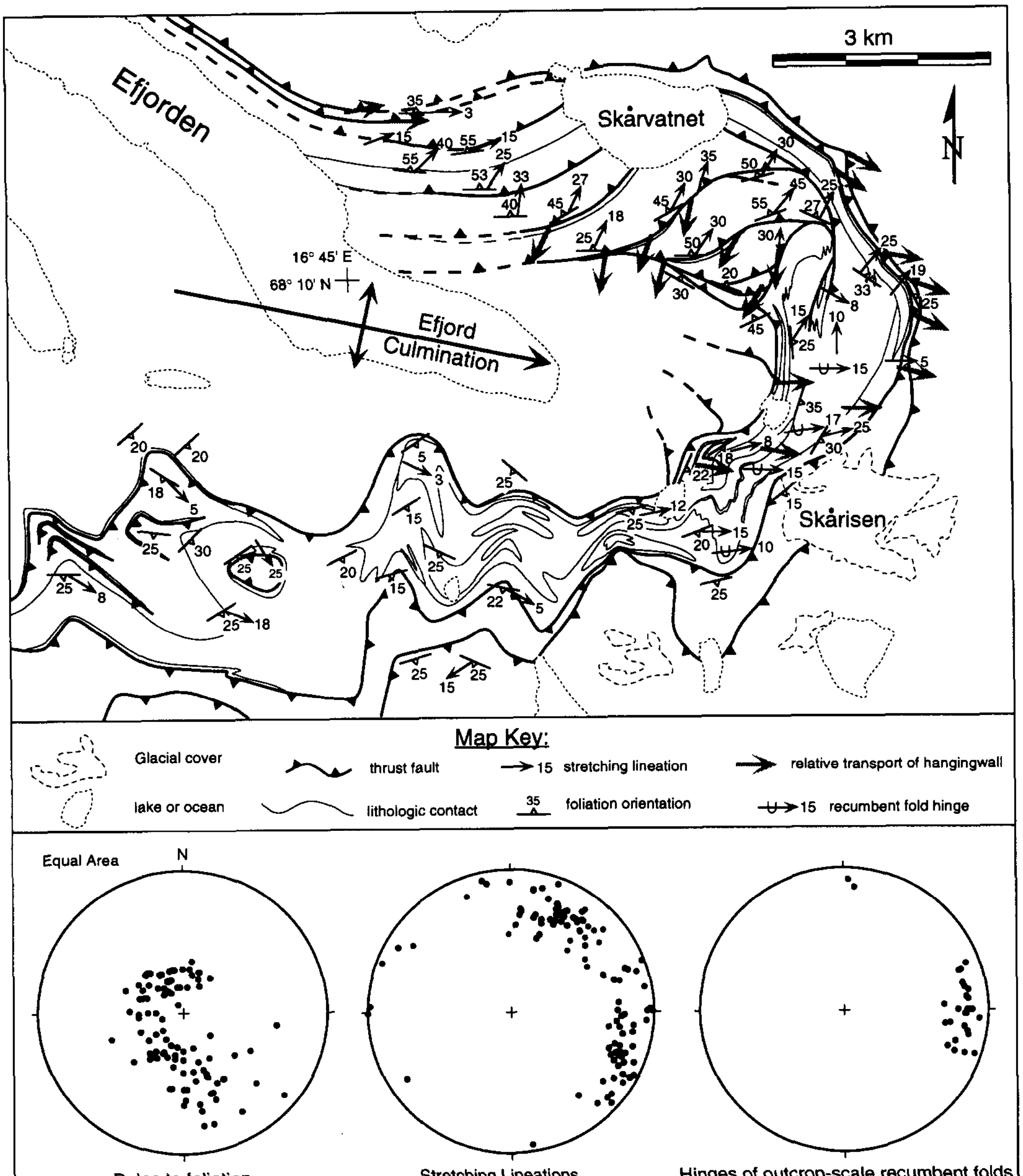

Fig. 3. Geologic map of the Efjord study area showing structural orientations and kinematic information.

around the closure of the Efjord culmination into the southern part of the study area, where they form the cores of S-vergent recumbent fold-nappes (Figs. 2 and 3). Hinges of the fold nappes trend E or ESE, sub-parallel to the regional transport direction of the Caledonian allochthon. Quartzite and schist of the metasedimentary cover sequence persist around the limbs and closures of the fold nappes, although they have been highly attenuated in the limbs. Intrafolial isoclinal folds are ubiquitous at outcrop scale, and their orientations mimic those of the larger fold-nappes (Figs. 3 and 6). In detail, numerous mesoscopic to macroscopic parasitic folds add significant complexity to the geometry and internal structure of the fold nappes.

At large scale, the fold nappes are intrafolial with respect to the Baltican affinity rocks in Lower Allochthon. Mesoscopic rootless isoclines are present at all structural levels, including the mylonitic sliver zone and Upper Allochthon, but the sliver zone does not close around the map-scale recumbent folds in the Lower Allochthon. Instead, it forms a continuous zone of mylonitic rocks above the fold-nappe complex and separates the Baltican affinity rocks below from the Oceanic-affinity thrust sheets in the overlying Upper Allochthon.

In many places, W-vergent kink-bands overprint deformational fabrics related to top-to-the-ESE transport of the allochthon and/or top-to-the-SSW movement along thrusts in the cratonal basement. These kink bands are commonly associated with recrystallization to chlorite-bearing retrograde mineral assemblages, and thus clearly post-date the main contractional phase of Caledonian orogenesis in this area. Rykkelid & Andresen (1994) documented top-W extensional reactivation of faults to the NE of Efjorden, and the W-vergent kink-bands at Efjorden provide evidence for some top-W reactivation in this area as well. However, net structural separations remain thrust-sense, and top-W reactivation did not produce well-organized, throughgoing detachment zones. Consequently, the magnitude of top-W reactivation of structures in the Efjord area is inferred to be modest.

DISCUSSION

Sequence of deformation

Although the structural evolution of the Lower Allochthon at Efjorden was complex, cross-cutting and overprinting relationships broadly constrain the deformation sequence in the area. Individual structures or groups of structures discussed below are indicated by numerical labels (Fig. 2). Cross-cutting relationships indicate that the earliest structures in the area are the southernmost of the N-dipping thrust-faults in the cratonal basement (1). These faults are truncated by a top-to-the-ESE thrust (2), and therefore, predate final movement on the ESE-directed thrust (2). Farther north, thrust (2) is cut by a top-to-the-SSW thrust (3) which forms the base of a stack of SSW-directed thrust sheets derived from the cratonal basement. Thrusts (3–5) represent various branch-lines within a complex SSW-directed thrust system. The relative ages of the thrusts are not well constrained by their geometry. Nevertheless, the SSW-directed thrusts farther south (1) are clearly older than those to the north (3–5), suggesting a general S-to-N progression of top-to-the-SSW thrusting in the cratonal basement.

The cratonal rocks in the highest parts of the SSW-directed imbricate stack can be followed southward around the closure of the Efjord culmination into the cores of S-verging, E-trending recumbent fold-nappes (6) near Skårisen. The continuity between the thrust sheets and the fold nappes suggests a genetic relationship in which the top-to-the-SSW thrusts represent the root zones of the S-verging fold-nappes. The N-dipping thrusts and the S-vergent fold-nappes, therefore, formed simultaneously and represent collectively a system of structures that accommodated an orogen-parallel component of structural transport during the Caledonian collision.

At regional scale, the Efjord transverse culmination (7) is one of a series of ESE-trending, basement-involved folds (Hodges 1985, Steltenpohl & Bartley 1988). The transverse folds resemble mega-mullions in the upper surface of the Baltic craton. West of the present study area, the structural section in the north limb of the Efjord culmination is overturned locally, and a retrograde cleavage associated with the transverse folds overprints fabric in the top-to-the-ESE shear zone at the base of the Upper Allochthon (Steltenpohl & Bartley 1988). These relationships constrain some of the transverse folding to have developed later than the emplacement of the allochthon, perhaps synchronous with Devonian extension, like transverse folds in southern Norway (e.g. Roberts 1983, Torsvik *et al.* 1986, Norton 1987). However, the relative timing between the *initiation* of transverse folding and end of ESE-thrusting in the Efjorden area is unknown. Because the axes of the transverse folds are subparallel to the transport direction of the allochthon, the folds are geometrically compatible with simultaneous folding and top-to-the-ESE movement of the allochthon. Thus, early phases of transverse folding may have occurred while ESE-directed thrusting continued. If so, then early transverse folding may represent another structural manifestation of orogen-parallel shortening during the thrust emplacement of the allochthon.

At the latitude of Efjorden, the intensity of transverse folding increases from east to west across the orogen, as does the metamorphic grade achieved by rocks in the structural basement (e.g. Bartley 1980, Hodges 1982, Björklund 1989). Bearing in mind the westward increase of paleotemperature, the fact that the top-to-the-SSW thrusts in the cratonal basement at Efjord are located near the eastern termination of a major transverse fold is interesting. Although a clear link cannot be demonstrated from field observations, this spatial relationship may reflect a transition in the structural style of orogen-parallel shortening within the basement from ductile folding in the western, high-T regions, to more localized strain along ductile faults in the eastern, low-T regions.

Mutually cross-cutting relationships between top-to-the-SSW thrusts in the cratonal basement and the top-to-the-ESE movement along structures at higher levels may be explained in one of two ways. Such relationships might form by episodic 90° changes in the overall transport direction of the thrust system—from top-to-the-ESE, to top-to-the-SSW, then back to top-to-the-ESE. No evidence exists regionally, however, for repeated changes of this magnitude in the transport direction of the Caledonian allochthon. A more realistic alternative is that deformation in the area was partitioned vertically, with contemporaneous top-to-the-SSW oblique-thrust movement on N-dipping faults in the cratonal basement and top-to-the-ESE transport of the overlying allochthon. This pattern of deformation may have resulted from local accommodation of mechanical irregularities within the orogenic pile, or it may be part of a more widespread transpressive regime. Consequently, the vertically partitioned system of deformation recognized at Efjorden may provide insight into the nature of strain partitioning at deep levels of oblique collisional orogens.

Strain partitioning in oblique convergent systems

A number of investigators have examined the potential patterns of strain in transpressional environments (e.g. Fossen *et al.* 1994). Physical modeling and direct observation suggest that deformation in the over-riding plate in zones of oblique convergence evolves commonly into a partitioned system with orogen-parallel strike-slip faults and orogen-orthogonal thrusting (e.g. Fitch 1972, Pinet & Cobbold 1992). Less is known, however, about

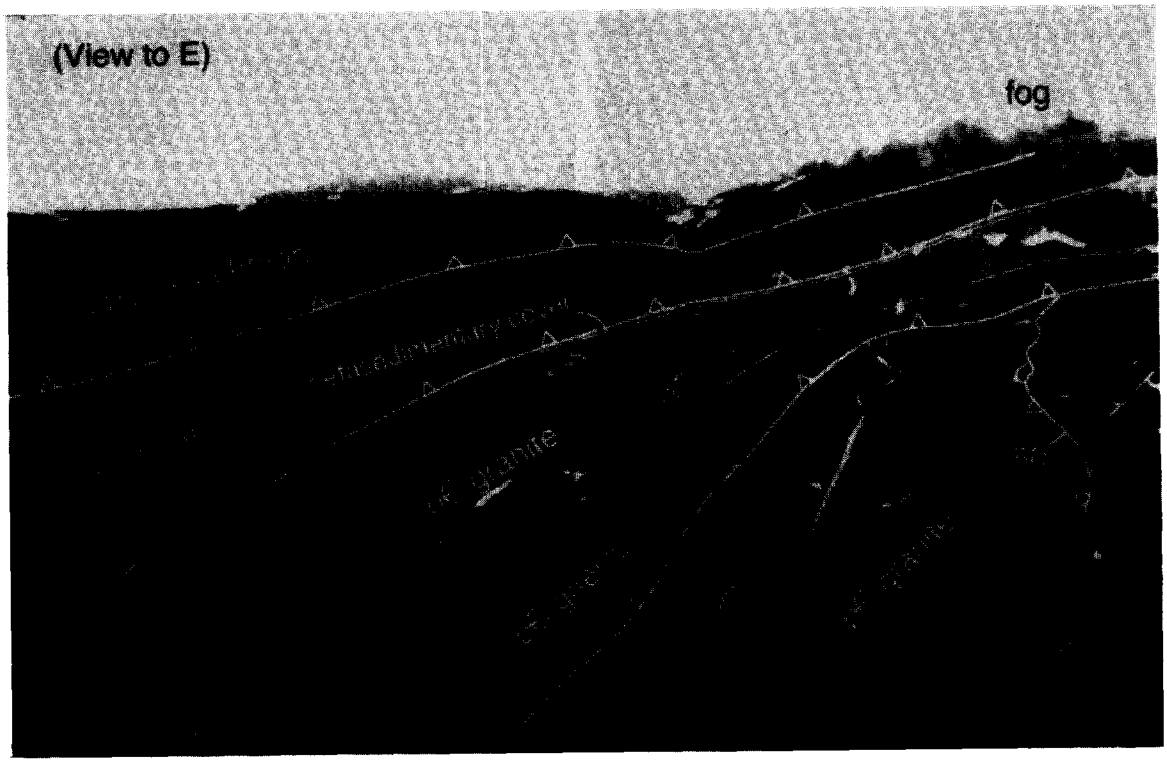

Fig. 4. An oblique aerial photograph of outcrops E of Skårvatnet showing the structurally highest of the imbricated thrust sheets derived from the Baltic craton, overlain by the mylonitic sliver zone (heterogeneous mylonites of uncertain affinity), and the far-travelled Upper-Allochthon (oceanic affinity).

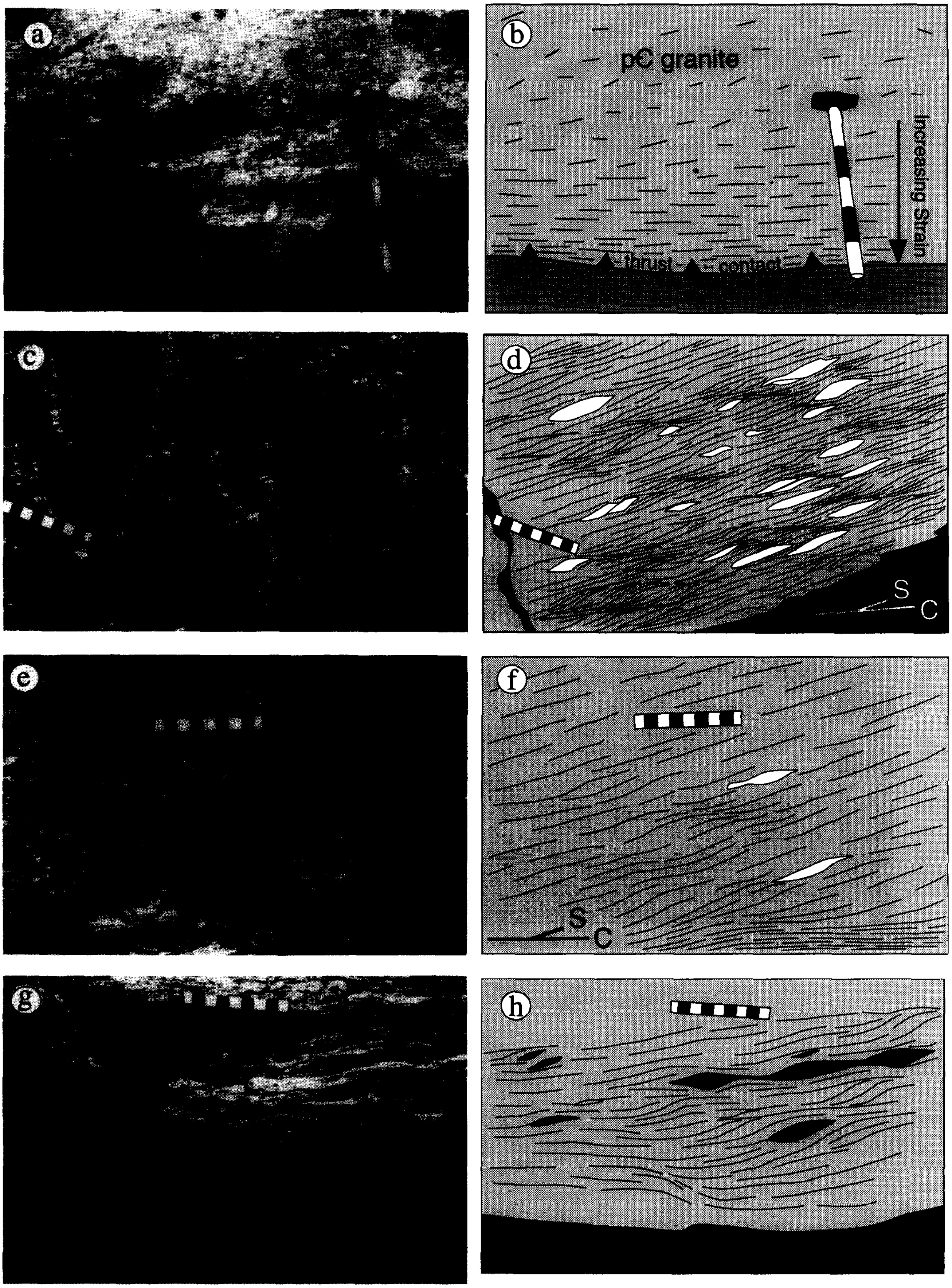

Fig. 5.

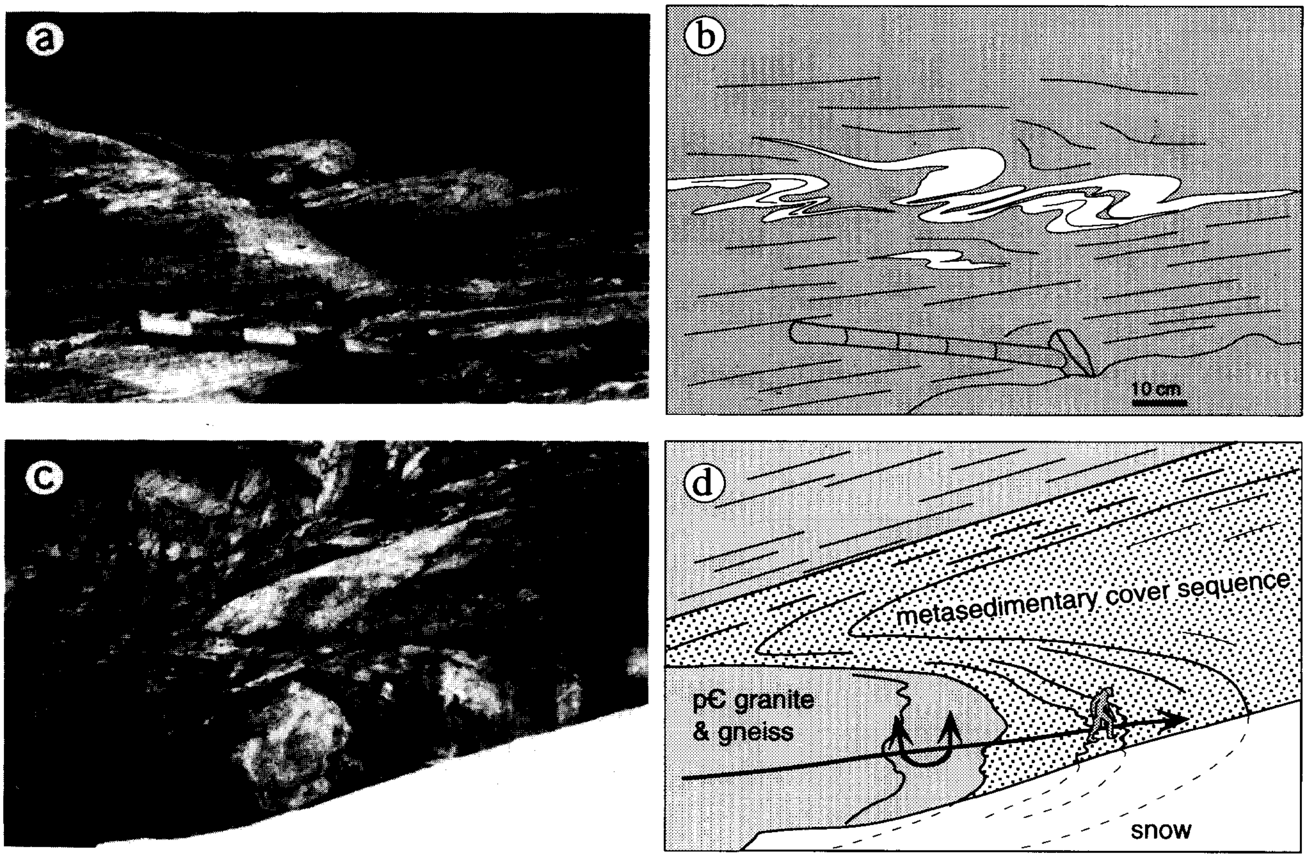

Fig. 6. Photograph—sketch pairs showing meso- to macroscopic examples of S-vergent, recumbent folds. All views look E, subparallel to the fold axes. (a) and (b): dm-scale rootless S-verging folds of quartzite and garnet-schist of the metasedimentary cover sequence just below the sliver zone. (c) and (d): S-verging, recumbent anticline cored by Precambrian cratonal basement; this anticline is a parasitic fold on the lower limb of a larger, S-verging fold-nappe cored by the Precambrian rocks at the top of the view.

Fig. 5. Outcrop photographs and sketches of tectonites in the Efjord area. Surfaces shown are parallel to the stretching lineation and perpendicular to foliation in each outcrop. (a) and (b): Strain gradient adjacent to mylonitic thrust in the Skårvatnet duplex. The thrust places tectonized Precambrian granite (hanging wall) over schist and quartzite of the metasedimentary cratonal cover (footwall). (c–f): Views looking ESE at tectonized granite adjacent to thrust contacts at deep levels of the Skårvatnet duplex. Porphyroclast asymmetry (cf. Simpson & Schmid 1983) and S–C fabric relations (cf. Berthé *et al.* 1979, Lister & Snoke 1984) indicate dextral (top-to-the-SSW) transport. (g–h): Views looking NNE at mylonitic schist at the top of the Skårvatnet duplex, just below the sliver zone. The inclination of mica 'fish' and S–C fabric relationships in the schist are consistent with dextral (top-to-the-ESE) transport of the over-lying allochthon.

the distribution of deformation in the lower plate of oblique-convergent zones.

In the Scandinavian Caledonides, the subducted margin of the Baltic craton formed the lower plate of the collisional system, and exposures of Baltic rocks at deep structural levels of the Caledonides allow direct observation of the kinematic characteristics and distribution of strain in the lower plate. Fossen (1993) and Gilotti & Hull (1993) described structural relationships in the Caledonides of southwestern Norway that suggest vertical partitioning of strain into kinematic domains with different directions of structural transport.

Based on mapping and kinematic analyses in the Efjorden area, we envisage a structural system in which orogen-parallel and orogen-orthogonal components of transport were partitioned vertically (Fig. 7). SSW-directed thrusting in the structural basement occurred contemporaneously with continued ESE-directed emplacement of the overriding allochthon. The leading edges of the thrust sheets ramped up into the schists of the cover sequence and formed the cores of E-trending, S-vergent recumbent fold-nappes in the Lower Allochthon. As the fold nappes formed and their mechanical coupling with the basement decreased, the fold nappes became entrained in the top-to-the-ESE transport of the over-riding allochthon.

A kinematic model that includes simultaneous top-to-the-SSW oblique-thrust motion on N-dipping faults in the cratonal basement and top-to-the-ESE transport of the overlying allochthon requires a change in the orientation of the stress field between the cratonal basement and the allochthon. Differences in the mechanical properties of the craton and the allochthon may have allowed such a change. In the Efjorden study area, dry, megacrystic granite formed a relatively strong structural basement (e.g. Bartley 1982, 1984). In contrast, the overlying rocks were composed of wet, relatively weak schists. This marked rheologic contrast may have reduced the mechanical coupling between the cratonal basement and the allochthon (Bartley 1982, Northrup 1996b). Due to the ability of the stronger rocks in the structural basement to transmit stresses over larger distances, the stress field in the basement may have included far-field contributions which were not present in the stress field of the allochthon. Thus, a combination of weak mechanical coupling across the rheologic boundary at the base of the allochthon and differences in the stress-transmission characteristics through the competent craton versus the weaker allochthon may have resulted in different orientations of the stress field at different structural levels and given rise to vertically partitioned deformation.

An interesting aspect of the structural interpretation at Efjord is that different parts of the same thrust-sheet/fold-nappe are inferred to have moved in different directions at essentially the same time. Top-to-the-SSW movement at deep levels occurred while the leading portions of cratonal thrust sheets were sheared to the ESE by the continued emplacement of the over-riding allochthon (Fig. 7). Within the leading portions of the cratonal thrust sheets, pervasive dynamic recrystallization and the introduction of water from the surrounding metasedimentary rocks would have reduced significantly the strength of the rock mass. From a mechanical perspective, this softening process effectively transferred the weakened leading portions of the cratonal thrust sheets from the kinematic domain of the cratonal basement to the kinematic domain of the weaker overlying rocks. Consequently, the softened portions of the cratonal thrust sheets became entrained in the top-to-the-ESE flow, while the more competent parts at depth were thrust to the SSW. Simultaneous movement of different parts of a thrust sheet in different directions requires deformation within the sheet to maintain strain compatibility. In the Efjord area, the zone of transition between the different kinematic domains contains penetrative deformation with highly variable lineation orientations and complex mesoscopic folding. However, the heterogeneity and complexity of deformation within the transition zone prevents confident interpretation of its kinematic characteristics.

Relation to structures in adjacent areas

Some of the structural features recognized at Efjorden may have implications for the structural development of allochthonous Baltican rocks in adjacent areas. For example, Björklund (1985, 1989) studied thrust sheets of Baltic affinity at the base of the composite allochthon near Akkajaure in Sweden, 40–80 km SE of Efjorden. The Akkajaure area provides excellent WNW–ESE trending exposure in the wall of a broad glacial valley oriented sub-parallel to the regional transport-direction of the main Caledonian allochthon. Björklund's detailed mapping identified several vertical repetitions of strongly deformed granite separated by thin layers of tectonized metasedimentary rocks. Based on two-dimensional palinspastic restoration of the structural section in a WNW–ESE direction, the allochthonous Baltican rocks in the Akkajaure transect have been interpreted to represent imbrication and shortening of at least 350–400 km (Björklund 1989).

Translations of this magnitude are not unreasonable in the Caledonides, and the fabric orientations at Akkajaure clearly indicate that top-to-the-ESE transport was important. However, if some imbrication of Baltican basement and cover occurred via orogen-parallel thrusting and transverse recumbent folding, like that recognized at Efjorden, then accurate structural restoration can be accomplished only by considering the structural development in three-dimensions. Björklund (1989) noted that recumbent folds cause vertical repetition of thrust sheets at several locations in the Akkajaure transect, and our reconnaissance in the Akkajaure area confirms the presence of numerous S-vergent, E-trending recumbent-folds at meso- to macroscopic scales. Consequently, ESE-directed transport distances of the Baltican affinity thrust sheets may be overestimated if an unrecognized component of orogen-parallel imbrication and structural repetition is present.

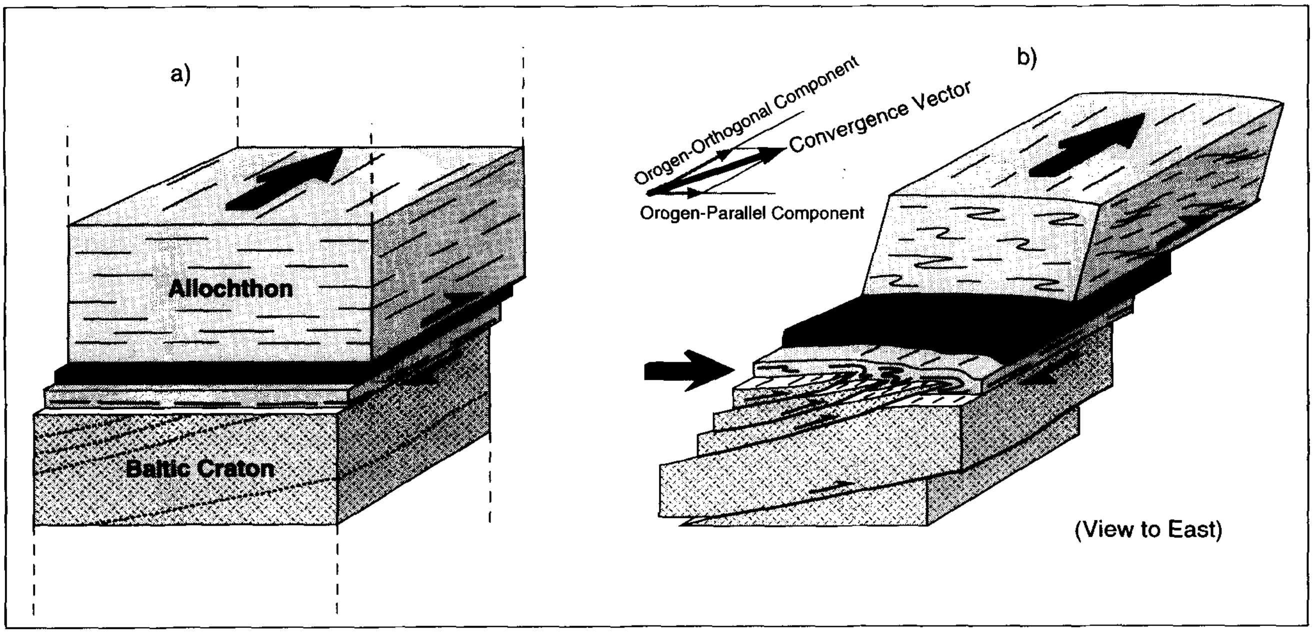

Fig. 7. Schematic block diagram illustrating the formation of structures in the Efjorden area within the context of sinistral-oblique Caledonian collision.

Comparisons with other orogens

Nappe translation paths that include nearly 90° changes in directions of relative movement have been described from several orogens. For example, Merle & Brun (1984) studied the incremental strain history of the Parpaillon Nappe in the French Alps and found evidence for initial NW-directed movement of the nappe (*D*1) followed by SW-directed movement (*D*2). Likewise, Peterson & Robinson (1993) examined the structural transport directions near the Bronson Hill anticlinorium in the Appalachian orogen, and found a progression from orogen-orthogonal to orogen-parallel transport during the unroofing of rocks in the area.

Changes in the transport direction of nappes through time, like those described in the preceding examples, are not surprising given the complicated evolution of mountain belts. The structural development at Efjord, however, provides an example in which different parts of individual thrust sheets or fold nappes are interpreted to have moved in different directions at essentially the same time—the deep levels of basement-derived thrust sheets moved SSW as the leading portions of the sheets formed recumbent folds and were sheared to the ESE as a consequence of continued emplacement of the overlying allochthon (Fig. 7). This pattern of deformation underscores the potential three-dimensional complexity of nappe emplacement kinematics in environments with partitioned deformation and evolving rheologic structure. Interpretation of the deformational history in such an environment is made difficult by the seemingly contradictory or incompatible kinematic characteristics of contemporaneous deformation at different locations or structural levels. The finite strain produced by a partitioned system of deformation may strongly resemble the results of a series of temporally distinct deformational episodes (*D*1, *D*2, *D*3, etc.), and one might easily assign contemporaneous structures to temporally distinct episodes of deformation because of their apparently disparate kinematic characteristics.

CONCLUSIONS

Structural relationships in the Efjorden study area can be related to vertically partitioned deformation within an obliquely convergent tectonic environment. Oblique convergence resulted in a component of orogen-parallel shortening and transport which was accommodated in the Baltican affinity rocks through a system of thrusts and fold-nappe structures. Within the relatively competent cratonic basement, orogen-parallel shortening was localized along N-dipping oblique thrust faults with top-to-the-SSW relative transport. The leading edges of the SSW-directed thrust sheets cut upward into the schists of the overlying metasedimentary cover sequence and formed the cores of S-verging recumbent fold nappes. These fold nappes became entrained in the ESE-directed transport of the over-riding Caledonian Allochthon.

As is true in any orogen in which deformation becomes partitioned into various components localized in different places or crustal levels, the far-field convergence direction cannot be inferred with precision from the relative-transport directions in the study area. Even if the orientations and relative transport directions of all contemporaneous faults could be identified, the far-field convergence direction could not be found unless the *rates* of simultaneous movement along each of the faults were known, and the effects of penetrative strain distributed in the rock mass between faults could be resolved. Given that both the far-field convergence direction and the partitioning of deformation within an orogen almost certainly evolve through time, reconstruction of far-field plate-convergence histories from local lineation orientations is unlikely to be accurate. Structures in the Efjord area are consistent with a sinistral component of convergence between Baltica and Laurentia, but the precise convergence direction is unknown.

The presence of top-to-the-SSW thrusts and S-verging recumbent folds with hinges sub-parallel to the transport direction of the allochthon adds potential complexity to the interpretation of structural cross-sections oriented perpendicular to the orogen. Imbrication and vertical repetition of rocks of Baltic affinity may have resulted in part from orogen-parallel thrusting and transverse recumbent folding in addition to the more typical foreland-directed transport and stacking of thrust sheets. Consequently, discerning what combination of structures is present in a given area and unraveling the three-dimensional kinematic history represented by these structures may be difficult in the absence of clear younging-indicators and adequate exposure parallel to orogenic strike.

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