Postcollisional extension of the Caledonide orogen in Scandinavia: Structural expressions and tectonic significance

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ABSTRACT

The Scandinavian Caledonides are much more affected by postcontractional Devonian extension than previously thought. The extensional deformation is not restricted to the internal parts of the orogen, but can be traced for more than 200 km from the west coast of Norway toward the foreland. It involved significant reactivation of the basal thrust zone as a low-angle extensional detachment, which consequently contains abundant top-to-the-(north)west sense of shear indicators. The extensional deformation involved substantial backsliding of the orogenic wedge (eduction of the Baltic shield) together with stretching of the basement by west-dipping, extensional shear zones. After ~30 km of backsliding, the extensional detachment splayed to penetrate the overlying orogenic edifice in the coastal region in southern Norway, which led to inactivation of the main portion of the basal thrust zone as an extensional detachment.

INTRODUCTION

Much of the recent research on extensional tectonics has focused on the Tertiary metamorphic core complexes of the Cordillera in western North America, where large-scale, low-angle, extensional shear zones form the most characteristic structural element. Several authors (e.g., Coney and Harms, 1984; Wernicke et al., 1987) consider Tertiary extension along low-angle shear zones to be the result of postorogenic collapse following crustal thickening during Mesozoic-Paleocene compression. Similar extensional collapse models have now been applied to several other orogens (e.g., Platt, 1986; Dewey, 1987; Behrmann, 1988; Gibson, 1991), including extension that took place during (Burchfiel and Royden, 1985; Herren, 1987; Ratschbacher and Frisch, 1989) as well as after (Norton, 1986; Platt and Vissers, 1989) the regional compression. It appears that the kinematic history and timing of extensional deformation in contractional orogens show significant variation from one example to the other, and further studies that combine detailed and regional-scale structural mapping of regions of orogenic extension are critical to a general understanding of the processes involved.

In the Scandinavian Caledonides, extensional tectonics has been described mostly in relation to Devonian basins in southwestern Norway (Hossack, 1984; Norton, 1986; Séguret et al., 1989). However, on the basis of extensive structural-kinematic analyses carried out in southern Norway and the Ofoten area, northern Norway, we believe that extensional tectonics has a much wider imprint on the Caledonian orogen than previously realized and is not restricted to the region of Devonian basins.

TECTONIC FRAMEWORK

The convergent motions of the North American (Laurentian) plate and the Baltic shield in Ordovician and Silurian time resulted in the creation of a large orogenic wedge consisting of Proterozoic and lower Paleozoic rocks that were underthrust by the Baltic shield. Remnants of this orogenic wedge are preserved in a 1700-km-long and up to 350-km-wide orogenic belt along western Scandinavia. Some of the nappes in this orogenic wedge were thrust for several hundred kilometres to the (south)east, e.g., the Jotun nappe in southern Norway, which apparently represents a huge fragment of the crystalline Baltic margin (Hossack and Cooper, 1986).

The orogenic wedge is separated from the Precambrian basement by a mechanically weak basal thrust or decollement zone, consisting of phyllites and other metasedimentary rocks that locally contain tectonic slivers of sheared basement rocks. The metasedimentary rocks represent mostly Vendian to Ordovician sedimentary units deposited on top of the basement prior to and during Caledonian thrusting. A considerable amount of Caledonian deformation has been localized to this decollement zone. Caledonian deformation of the underlying basement is mostly restricted to the contact zone with the overlying decollement rocks, except for the western parts (e.g., the Western Gneiss region) where Caledonian deformation is also present within the basement.

Increasing metamorphic grade in the (par)autochthonous cover from the foreland region toward the coastal area in the west (Fig. 1A) indicates an originally east-southeast–tapering, wedge-shaped geometry of the Caledonian

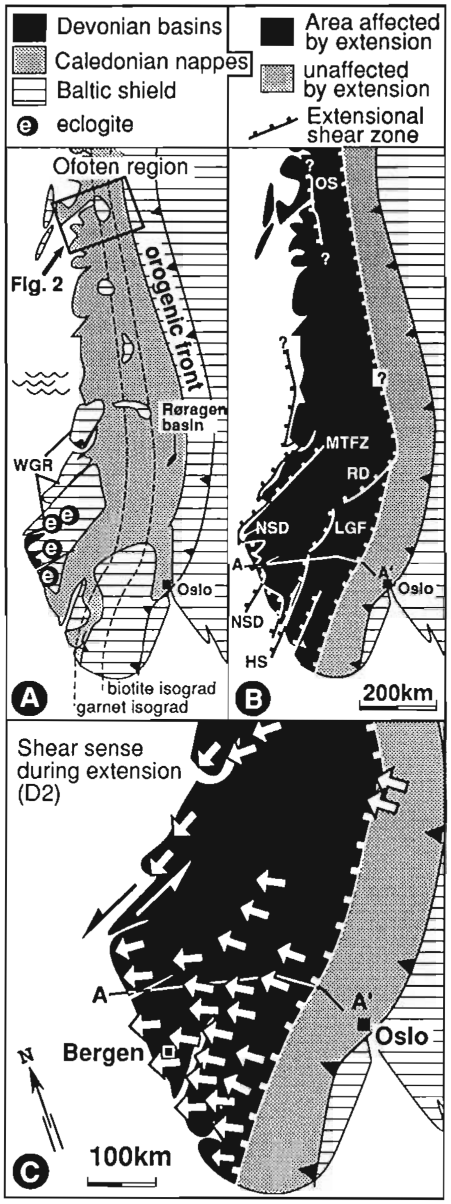

Figure 1. A: Simplified geologic map of Scandinavian Caledonides with Caledonian metamorphic isograds of (par)autochthonous cover and basement. WGR—Western Gneiss region. B: Part of Caledonides affected by extensional deformation. HS—Hardangerfjord shear zone, OS—Ofoten shear zone (basement shear zones), MTFZ—Møre-Trøndelag fault zone, NSD—Nordfjord-Sogn detachment, RD—Røragen detachment, LGF—Lærdal-Gjende fault (semibrittle). C: Sense of shear during extension in southern Norway (including data from Séranne, 1992; Séranne and Séguret, 1987).

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nappe pile in Scandinavia (e.g., Lindquist, 1990). Similarly, the basement shows an increase in Caledonian metamorphic grade from the east to the west, reaching eclogite- and granulite-facies conditions in some of the westernmost areas. The maximum thickness of the late Caledonian crust must, thus, have been close to or west of the present-day coastline of Norway.

EXTENSIONAL VS. CONTRACTIONAL STRUCTURES

Numerous thrust sheets have been recognized since Törneböhm's (1888) first interpretation of large overthrusts in the Scandinavian Caledonides, and their overall (south)eastward Caledonian translation is well established (cf. Hossack and Cooper, 1986). Kinematic structures in the decollement zone conform to this sense of movement in the easternmost (foreland) region (e.g., Morley, 1986). Closer to the hinterland, Caledonian structures include various S-C structures; shear bands; oblique grain-shape fabrics; asymmetric patterns of crystallographic orientations; intrafolial, asymmetric folds; and other linear and planar fabrics consistent with southeastward nappe translations. However, 140–150 km away from the orogenic front, which is best preserved near Oslo (Fig. 1A), this contractional deformation (D1) becomes obscured and overprinted by later, top-to-the-(north)west extensional deformation (D2). The D2 deformation is quite penetrative in the decollement zone, and it also affected the western part of the basement, particularly the Western Gneiss region. The D2 fabrics can be traced continuously from the western, internal region up to 240 km toward the foreland (Fig. 1B). The relative age relation between D1 and D2 structures is remarkably clear and consistent in both southern and northern Norway.

The D2 deformation can be separated into two somewhat distinct, but closely related modes of extensional deformation (Fossen, 1992a). The first is characterized by backsliding of the orogenic wedge, whereas the other involves the development or reactivation of major west-dipping basement shear zones (Fig. 2).

BACKSLIDING

The backsliding of the nappes is identified from the widespread and consistent overprinting of top-to-the-southeast (D1) structures by top-to-the-(north)west structures in the underlying, subhorizontal or southeast-dipping decollement zone and in the basal part of the overlying nappes. The new fabrics are in many ways similar to the D1 fabrics. However, they are distinguished by their different (northwest-verging) asymmetry and by their overprinting nature (cf. Milnes et al., 1988; Fossen, 1992a, 1992b; Rykkelid and Fossen, 1992).

The most striking and widespread D2 kinematic indicators are top-to-the-(north)west shear bands or S-C structures in the phyllites and other micaceous lithologies, together with asymmetric, northwest-verging folds ranging from microscopic to macroscopic scale. A spaced, southeast-dipping, axial-planar cleavage consistently overprints northwest-dipping, planar structures related to the contraction. Classical S-C structures (Berthé et al., 1979) and asymmetric boudins (Hanmer, 1986) occur in parts of the crystalline rocks in the decollement zone and locally in the underlying Western Gneiss region. The shear direction during the backsliding has been determined from these structures, varying from northwest in south-central Norway to west in southwestern Norway and the Ofoten area (Figs. 1C, 2).

The amount of backsliding seems to have been ~30 km in northern Norway, as indicated from the offset of the basement-cover contact in the Ofoten area (E. Rykkelid and A. Andresen, unpublished), and a minimum estimate of about

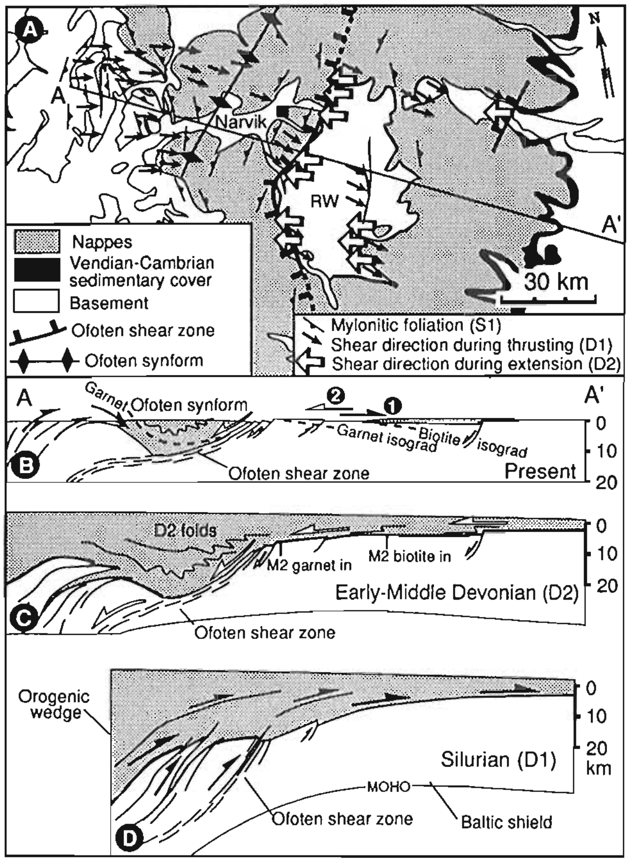

Figure 2. A: Simplified map of Ofoten region (see Fig. 1 for location). RW—Rombak window. B: Profile (A–A'). C: Reconstruction of profile A–A' in Middle Devonian. Arrows indicate sense of shear during D2. Ofoten shear zone, which only affects basement, may correspond to early stages of Hardangerfjord shear zone or Nordfjord-Sogn detachment in southwestern Norway, but never transected overlying nappe wedge after backsliding ceased. D: Reconstruction of profile A–A' in Silurian (collisional stage).

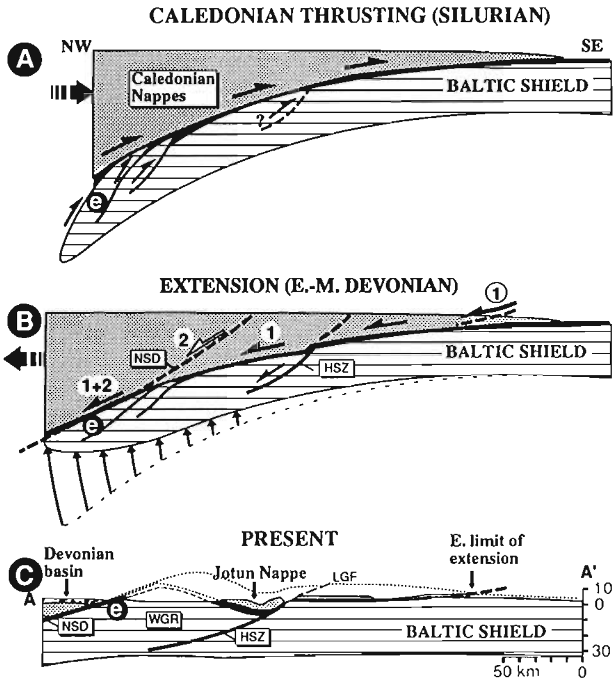

Figure 3. Schematic profile through Caledonian orogen in southern Norway (profile A–A' in Fig. 1) during (A) contraction, (B) extension, and (C) present time. At stage B, backsliding is about to stop, and Nordfjord-Sogn detachment is about to form a new master detachment. Black zone indicates weak decollement zone between (par)autochthonous basement and nappes. Abbreviations as in Figure 1.

20 km has been made from southern Norway (Fossen, 1992b).

WEST-DIPPING SHEAR ZONES

The second mode of extensional deformation involves stretching of the basement and, in part, also the orogenic wedge by west-dipping shear zones. In the Ofoten region, several west-dipping shear zones with displacement up to a few hundred metres have been mapped, particularly in the Rombak window. Some of these shear zones crosscut and offset reverse shear zones in a normal sense, whereas others can be shown to be reactivated reverse shear zones. There is a marked increase in such extensional shear zones toward the western part of the Rombak window, where a major extensional shear zone (Ofoten shear zone, Figs. 1B, 2) underlies the Ofoten synform and offsets the basement-cover contact by ~30 km. The Ofoten shear zone is exposed along the western side of the Rombak window as an ~1-km-thick west-dipping zone of mylonites with abundant down-to-the-west asymmetric structures. However, local remnants of older, east-verging structures show that this in fact is a D1 basement shear zone that was reactivated during D2. The Ofoten shear zone transects the basal sedimentary cover, but not the overlying nappes, and flattens out to follow the basal thrust to the east (Fig. 2C). The overlying nappes are, however, extensively affected by D2 folding (Fig. 2C), and the geometry and setting of these folds in relation to the shear zone indicate that the backsliding of the orogenic wedge and the normal slip along the west-dipping basement shear zones were contemporaneous (Fossen and Rykkelid, 1992).

A study of the metamorphic conditions around the Ofoten shear zone confirms the interpretation of this shear zone as a significant extensional structure. Synkinematic to post-kinematic, upper-greenschist (garnet-grade) D2 mineral assemblages characterize the strongly recrystallized top-to-the-west fabric on the eastern side of the Ofoten shear zone. However, on the western side of the Ofoten shear zone, garnet is absent, and abundant D2-related chlorite and biotite indicate middle greenschist facies. A similar metamorphic jump is not found on the western side of the Ofoten synform, where D2 (extensional) structures are absent.

Two major (north)west-dipping extensional shear zones have been found in the western part of southern Norway (Fig. 1B). The easternmost (Hardangerfjord shear zone) transects the Baltic shield, and the overlying nappes form a monoclinal flexure above the basement shear zone. The offset along the shear zone is estimated to be on the order of 2 km or more (Fossen, 1992a). Off-shore seismic reflection data indicate that this shear zone continues to at least lower-crustal depths (Hurich and Kristoffersen, 1988).

A larger, west-dipping shear zone (Nordfjord-Sogn detachment, Fig. 1B) separates the Devonian basins and their allochthonous substratum (hanging wall) from the eclogite-bearing Western Gneiss region (Norton, 1986; Séranne and Séguret, 1987). These relations indicate that the Nordfjord-Sogn detachment penetrated the overlying nappe wedge during D2. Numerous kinematic indicators associated with both these oblique shear zones show down-to-the-(north) west sense of shear.

Unlike the Ofoten shear zone, the Nordfjord-Sogn detachment continued to develop after the backsliding ceased, offset the entire overlying nappe sequence, and allowed a system of Devonian sedimentary basins to develop on top of the hanging wall. These events are reflected in a late overprinting of brittle structures on ductile fabrics in the detachment, a feature not seen in the mylonites related to backsliding.

DISCUSSION

The extensional deformation in the Scandinavian Caledonides as described above bears some similarities to the Cordilleran metamorphic core complexes, particularly the unambiguous time relation with earlier contractional orogenic deformation and the characteristic low-angle, extensional detachments (Coney and Harms, 1984; Wernicke et al., 1987; Parrish et al., 1988). However, the first extensional detachment to form in the Caledonides was the reactivated basal Caledonian thrust zone, whereas several extensional detachments in the Cordillera appear to be primary features (Lister and Davis, 1989) (see, however, Allmendinger et al., 1983). The reason for this difference is probably mechanical: Post-Caledonian extension was easily accommodated through slip along the preexisting, continuous and weak decollement zone in phyllitic metasedimentary rocks between the underlying rigid basement and the overlying nappes. The formation of extensional shear zones in the basement beneath the detachment is also special, and no simple explanation has yet been found for this deformation.

The basal thrust zone in southern Norway was inactivated as an extensional detachment by the upward penetration and offset of the nappe wedge by the Nordfjord-Sogn detachment. This process is reminiscent of the successive development of detachment fault splays due to the curving of the detachment fault associated with metamorphic core complexes (Lister and Davis, 1989). However, the formation of the basement culmination represented by the Western Gneiss region may not be a metamorphic core complex in the classical sense (Davis, 1987), but is rather controlled by rotation related to a listric geometry of the Hardangerfjord fault zone in addition to isostatic uplift (footwall uplift) related to the Nordfjord-Sogn detachment. Supporting this view is the sudden change in dip of the detachment from flat-lying to southeastward dipping across the Hardangerfjord shear zone, as well as the apparent absence of synextensional igneous activity in the lower plate. This change is considered to have added to the isostatic instability that led to formation of basement culminations in the Cordilleran metamorphic core complexes (Lister and Davis, 1989).

The consistent asymmetry of the extensional kinematic indicators in the Caledonian decollement zone is taken to indicate deformation by simple rather than pure shear (Fossen, 1992b). This consistency contrasts with the more complex strain pattern reported from the Basin and Range region (cf. Malavieille and Taboada, 1991, and references therein) and, together with the noncoincidence between the brittle-ductile transition and the extensional detachment, is not conformable with a pure-shear extensional model.

Any tectonic model applied to explain the extension must account for (1) the massive, 20–30 km of backsliding of the orogenic wedge on the low-angle decollement zone, (2) the partly contemporaneous and partly subsequent development of west-dipping extensional shear zones, (3) rapid uplift of eclogite-bearing basement, and (4) the widespread occurrence of greenschist-facies rocks in the orogenic wedge and particularly in the hanging wall of the Nordfjord-Sogn detachment.

Tectonic models involving extensional collapse of the overthickened orogenic crust in the central part of a collisional orogen, either related to removal of the lower part of the lithosphere and/or to a change in the rate of convergence, have been applied to explain extensional deformation in several collisional zones, e.g., the Himalayas (England and Houseman, 1988), the western Mediterranean region (Platt and Vissers, 1989), and the extensional deformation expressed by the Nordfjord-Sogn detachment in southwestern Norway (Norton, 1986; Andersen and Jamtveit, 1990; Andersen et al., 1991). However, these models do not provide an adequate explanation for the extensional structures of the Scandinavian Caledonides because they imply thrusting toward the foreland during the extensional collapse, as observed around the Tibetan plateau and in the Alboran Sea–Gibraltar arc (Platt and Vissers, 1989). The foreland-thinning Caledonian wedge shows clear evidence for uniform translation toward the center of the orogen during the extension (Fig. 3B). Therefore, we propose the following model to explain the observations.

1. Subduction of the Baltic shield under the orogenic wedge and Laurentia formed the high-P eclogites in the Western Gneiss region (420–410 Ma) (Griffin et al., 1985) (Fig. 3A).

2. Rapid change from convergent to divergent plate motions in Early Devonian time (Fig. 3B) led to the backsliding of the nappes toward the central part of the orogen (or reversal of the subduction of the Baltic crust) and to the development of extensional basement shear zones.

3. The Nordfjord-Sogn detachment (south-

west Norway), penetrated the nappe wedge, and Middle Devonian basins developed on top of the hanging wall (Figs. 3B, 3C).

The first two steps clearly occurred in both the southern and northern part of the Scandinavian Caledonides, whereas evidence for the last step has not yet been found in the northern part. In fact, the granoblastic textures of the strongly recrystallized D2 fabrics of the upper-greenschist facies and the absence of retrogression and overprinting of ductile extensional structures by brittle structures suggest that the extension in northern Norway never reached the magnitude recorded in southern Norway. The possibility is open, however, that an extensional detachment similar to the Nordfjord-Sogn detachment may be situated west of the coast line in northern Norway.

Exhumation of eclogites in southwest Norway, which appear to have formed at depths of 60–100 km or more (Griffin et al., 1985; Smith, 1988), probably occurred during all of these three stages. Basement imbrication during the first stage may have brought the eclogites from their depth of formation to higher crustal levels (Cuthbert et al., 1983; Séranne and Séguret, 1987). The backsliding of the orogenic wedge (eduction of the Baltic shield, Fig. 3B) must have caused further uplift of the Caledonian eclogites (an uplift of 30–35 km is modeled in Fig. 3B as due to backsliding alone). Finally, the penetration of the nappe wedge by the Nordfjord-Sogn detachment provided the last, and probably the most significant, part of the uplift history. This model involves rapid *P-T* changes in the western part of the basement (Western Gneiss region) by subduction and the subsequent eduction, whereas rocks in the upper plate (orogenic wedge) remained on a comparatively constant crustal level.

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ACKNOWLEDGMENTS

Funded by Norges allmennvitenskapelige forskningsråd grant 440.89/061 to Fossen and D.40.31.182 to Rykkelid. We thank D. Kirschner for helpful comments.

Manuscript received February 21, 1992
Revised manuscript received May 11, 1992
Manuscript accepted May 21, 1992