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Extensional tectonics in the Caledonides: Synorogenic or postorogenic?

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Abstract. Extensional tectonism may form during as well as after the contractional history of a collisional orogeny. Kinematic studies combined with various age constraints in the southern Scandinavian Caledonides have revealed an extensional history which started by hinterland-directed transport of the orogenic wedge above the basal décollement zone (Mode I extension) and proceeded by the development of hinterland-dipping shear zones (Mode II) and subsequent brittle faults (Mode III). The top-to-hinterland kinematics of the basal décollement zone during Mode I extension indicate that this extensional history was entirely postorogenic already from the start. Any synorogenic extensional deformation must have occurred prior to the onset of this extensional history, which is dated to circa 405 Ma. Although synorogenic extension is likely to have occurred, large-scale synorogenic extensional collapse models in the Caledonides are at present difficult to prove, whereas impressive postorogenic multi-stage extension is beautifully portrayed.

1. Introduction

During the past few decades, extensional deformation structures have been mapped in essentially all contractional orogenic belts on the Earth. Extensional events may occur unrelated to or prior to continent-continent collision (Figure 1a) during such collisions (Figures 1b-1d), as seen in the Himalayas, or may postdate the history of convergence (Figures 1e and 1f).

A variety of extensional expressions are reported from the Scandinavian Caledonides. Most authors refer to this extension as late Caledonian or late orogenic [e.g., *Norton*, 1986; *Gee et al.*, 1994; *Osmundsen and Andersen*, 1994; *Rykkelid and Andresen*, 1994; *Hartz and Andresen*, 1997; *Wilks and Cuthbert*, 1994; *Wennberg and Milnes*, 1994], perhaps without realizing the implications of their statement. It is important in tectonic modeling to know which structures are actually synorogenic and which formed during the postcontractional stage. Synorogenic extensional structures are related to orogen-internal features that cause relatively local instabilities in an overall contractional regime, whereas significant postorogenic extensional deformation implies true extension at the scale of the orogenic belt and orogenic crust. In this contribution the extensional deformation in the Scandinavian Caledonides is reviewed, and the nature of extensional structures in the Scandinavian Caledonides is discussed.

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2. Definition of Synorogenic and Postorogenic Extension

The Caledonide orogen is the result of continental convergence that led to wholesale continent-continent collision. When convergence ceases during such a process, i.e., when two fixed points at each side of the orogenic belt stop approaching each other, the contraction has by definition come to a halt, and the orogeny is completed. If the points start diverging, postorogenic extension has started. Within this large-scale context, extension may occur on a smaller scale during overall convergence, in the same way that postorogenic contraction in a general extensional setting is known from regions of strong extension [e.g., *Yin*, 1991]. Precollisional stages, which may involve various types of extensional deformation (Figure 1a) are not synorogenic in the sense discussed in this context (continent collisions) and hence are not discusssed below.

3. Southern Scandinavian Caledonides

The southern Scandinavian Caledonides (Figure 2) have a classic orogenic structure. In simple terms the orogen can be subdivided into (1) Precambrian basement (Baltica), (2) a basal décollement zone, and (3) remnants of an overlying wedge of Caledonian thrust nappes (orogenic wedge).

The basement is generally autochthonous southeast of the Hardangerfjord Shear Zone (Figure 2), and in part parautochthonous in the northwest (Western Gneiss Region). The autochthonous basement is dominated by a large number of Proterozoic plutonic rocks and an associated supracrustal series. Parautochthonous portions of the Western Gneiss Region are to a large extent similar to the autochthonous basement in terms of Precambrian history but are heterogeneously deformed by Paleozoic deformation. The Paleozoic deformation shows a general increase to the west.

The Precambrian basement was peneplanized in the Late Proterozoic and covered by latest Proterozoic and Cambrian sediments. These sediments are now found as intensely sheared phyllites and micaschists (phyllonites) which underlie the Caledonian nappes and thus constitute the main portion of the décollement zone. The continuity and low mechanical strength of the pelitic metasediments are the main reasons for the strong localization of ductile strain to this zone.

Remnants of the Caledonian orogenic wedge are found both in the hinterland and toward the foreland, and a large portion of the wedge is preserved in the core of a synclinal megastructure ("Faltungsgraben"). This structure is trending northeast and is directly associated with the extensional

Hardangerfjord Shear Zone (Figure 2). The remaining portions of the orogenic wedge are dominated by rocks of the Jotun Nappe, which is a major fragment of mostly crystalline Proterozoic crust that appears to have been thrust for more than 300 km [e.g., *Hossack and Cooper*, 1986]. Its internal parts appear to be only weakly affected by Paleozoic deformation [*Milnes and Koestler*, 1985], whereas Paleozoic mylonitization is profound along its base. Allochthonous rock units of exotic affinity, including dismembered ophiolite fragments and island arc complexes, occur in the coastal areas of southwestern Norway. In general, these exotic units occupy a tectonostratigraphically higher position than the Jotun Nappe and its western equivalents.

In the westernmost (hinterland) part this simple threefold division is still present but obscured by more extensive and basement-involving Caledonian and post-Caledonian (extensional) deformation. Much of the Caledonian deformation and metamorphism has been related to a continent-continent collision akin to the Himalayan situation, where the western edge of Baltica (Western Gneiss Region) was subducted under the Laurentian plate (Plate 1a). This interpretation is mainly based on pressure-temperature (P-T) estimates from eclogites and related mineral parageneses in the Western Gneiss Region, as discussed in section 4.

4. Geometry of the Caledonian Collision Zone

Available P-T information (Figure 3) together with radiometric and stratigraphic age constraints allows for a crude reconstruction of the general geometry of the Baltican crust at the time of peak metamorphism during continental subduction. Thermobarometry of Caledonian mineral parageneses in the Western Gneiss Region (WGR) indicates that peak Caledonian metamorphic conditions reached more than 28 kbars/750 °C in the NW part of this basement region [*Griffin et al.*, 1985; *Jamtveit*, 1987; *Smith and Lappin*, 1989]. In particular, the presence of Caledonian coesite and locally microdiamonds may indicate depths in excess of 100 km [*Dobrzhinetskaya et al.*, 1995; *Wain*, 1997]. The pressure and temperature estimates decrease from the coastal area north of the Hornelen basin toward SE. *Chauvet et al.* [1992] calculated pressures of 11-15 kbars and temperatures of 600°C from the outer Sognefjord area below the Devonian Solund basin. In the southwestern portions of the WGR, P-T estimates of 8 kbars/670°C were indicated by *Boundy et al.* [1996]. Textural studies, ^{40}Ar/^{39}Ar data, and conodont

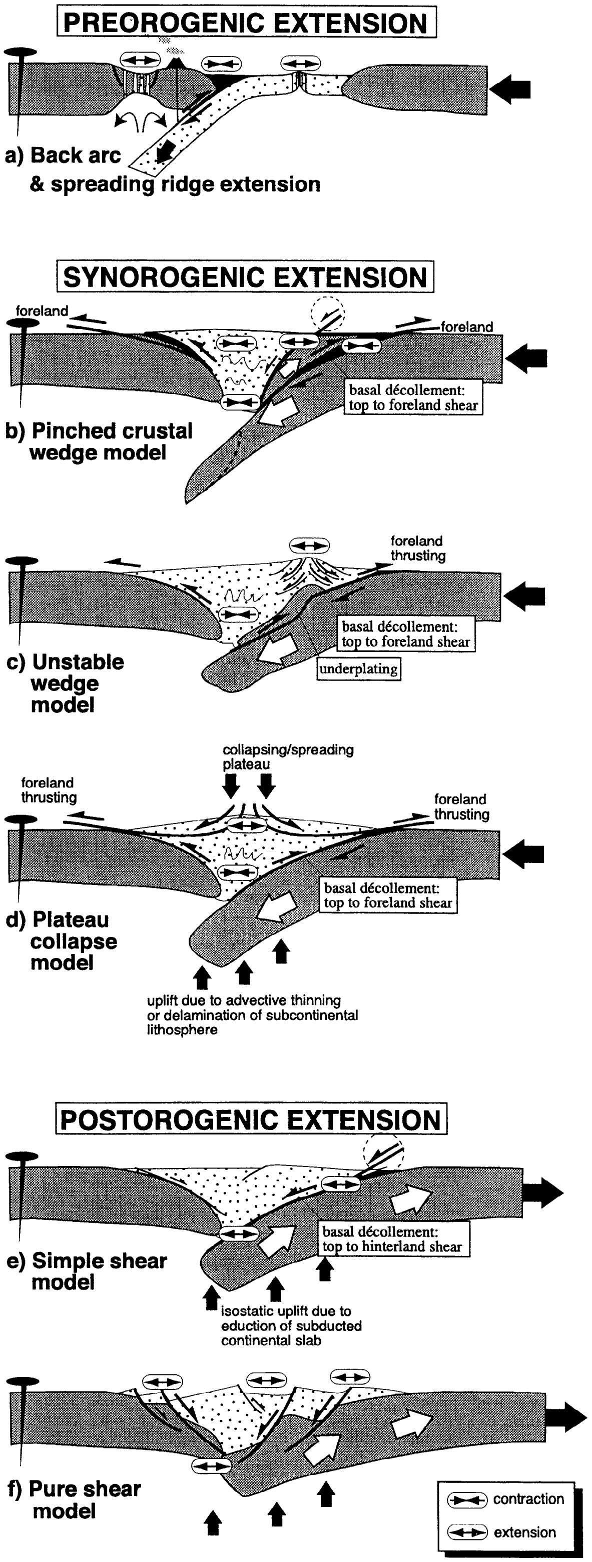

Figure 1. Common modes of extensional deformation related to orogens. (a) Pre-collisional extensional deformation, such as back-arc extension and spreading at mid-ocean ridges are considered preorogenic in this context. (b) Large-scale synorogenic extension may occur on top of a wedge-shaped fragment which becomes detached from the subducted continental crust and "floats" upward (see Figure 7). (c) Synorogenic processes such as underplating may also cause the orogenic wedge to become unstable and extend internally by faulting or spreading until stability is reached. (d) Advective thinning or delamination of the lithospheric asthenosphere may cause uplift of the hinterland, which subsequently collapses and extends. (e) Postorogenic extension by reactivation of the basal décollement zone as a low-angle extensional shear zone. (f) Postorogenic extensional collapse by formation of hinterland-dipping extensional shear zones that cut the basal décollement. Note the difference in kinematics during synorogenic and postorogenic extension.

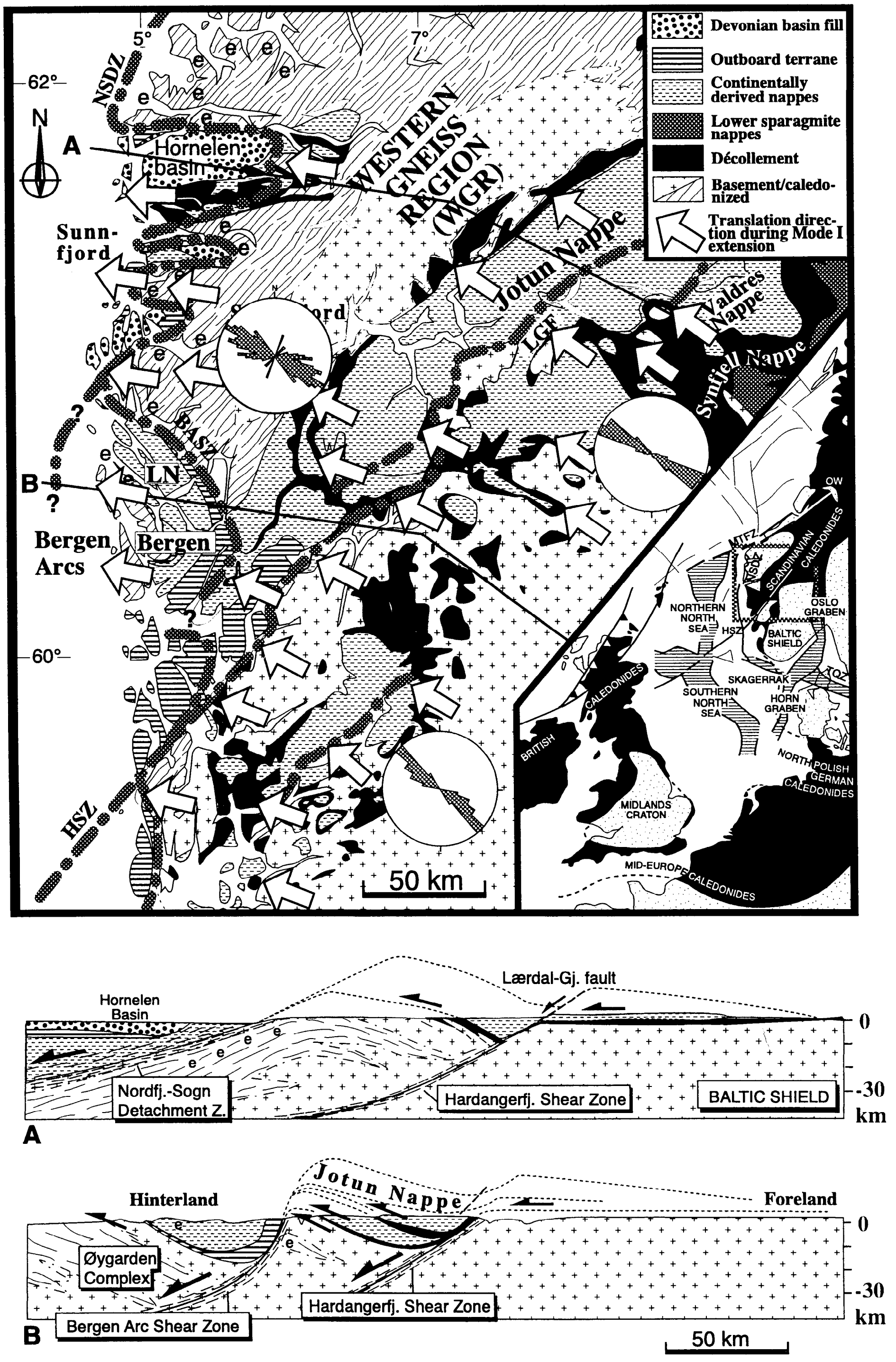

Figure 2. Geologic map and profiles of the southern Scandinavian Caledonides. Rose diagrams and arrows indicate shear direction during the phase of NW directed postorogenic nappe translation (Mode I extension), based on numerous measurements of S-C geometries and linear structures. BASZ=Bergen Arc Shear Zone, HSZ=Hardangerfjord Shear Zone, LGF=Lærdal-Gjende Fault, LN=Lindås Nappe, MTFZ=Møre-Trøndelag Fault Zone, NSDZ=Nordfjord-Sogn Detachment Zone, OW=Olden Window, TQZ=Tornquist Zone.

color alteration indicate peak Caledonian temperatures as low as 350±50°C along the SE margin of the Jotun Nappe [*Nickelsen et al.*, 1985; *Fossen and Dunlap*, 1998]. Farther SE, K-Ar mica ages in the basement are solely Precambrian, suggesting that Caledonian temperatures were less than the closure temperature of both biotite and white mica (<350°C) during peak Caledonian metamorphism. In addition, peak paleotemperatures of the order of 110-200°C are calculated

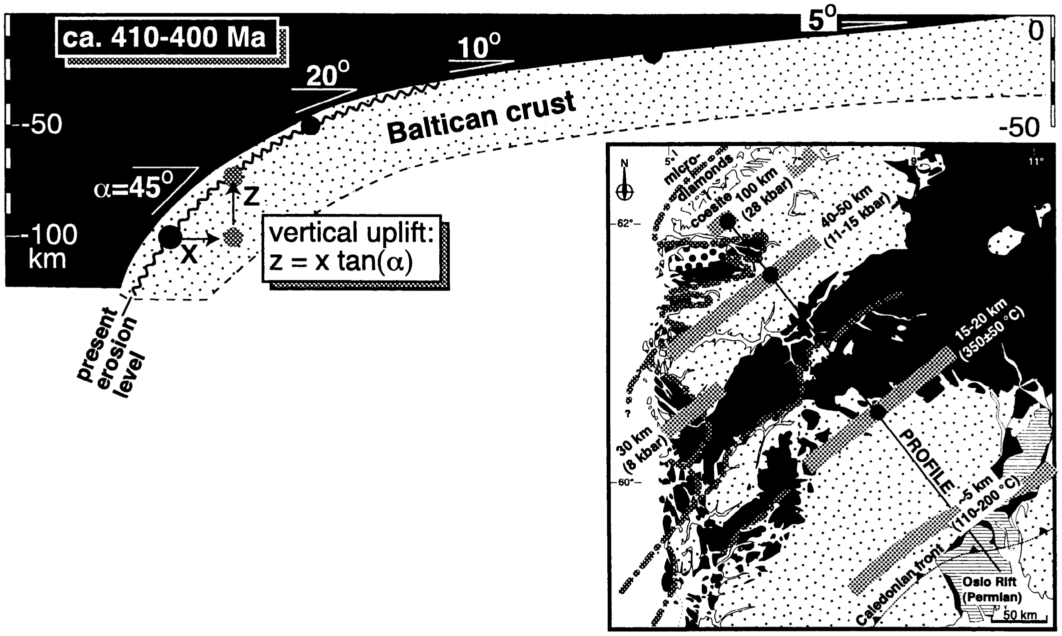

Figure 3. Paleodepth estimates based on available pressure-temperature (P-T) estimates from the south Scandinavian Caledonides used to reconstruct the geometry of Baltica at the time of peak metamorphism during Silurian subduction. Horizontal extension (x) of Baltica results in a component of vertical uplift (z) of Baltica relative to the overlying orogenic wedge that increases with increasing dip of the subduction zone. See text for reference to data sources and discussion.

for lower Paleozoic sediments away from Permian intrusions in the foreland near Oslo [*Aldridge*, 1984].

A preliminary attempt is made in Figure 3 to reconstruct the geometry of the subducting Baltican basement from the available P-T data. An average dip of ~5° can be calculated for the southeastern foreland section at the time of thrusting [*Hossack and Cooper*, 1986; *Fossen*, 1992]. This dip increased considerably toward the hinterland (Figure 2b), reaching angles around 45° or more in deep parts of the subducted Baltican crust. The reconstruction assumes more or less simultaneous peak metamorphic conditions across the orogenic section and does not take into consideration any complications caused by crustal imbrication during subduction of Baltica [*Hurich,* 1996].

5. Possible Syncollisional Extension Structures

The significance of extensional structures in the Himalayan orogenic belt [e.g., *Royden and Burchfiel*, 1987; *Hodges et al.*, 1992; *Burchfiel et al.*, 1992; *Gapais et al.*, 1992] suggests that significant syncollisional extension of the Caledonian collision zone may have occurred. It may take place within the orogenic wedge because of instabilities caused by factors such as underplating, change in friction along the basal décollement, decrease in convergence rate, and rapid erosion/deposition [*Platt*, 1986].

Only limited evidence of such intrawedge extension exists for the Caledonides, owing to the deep level of erosion in most of the Caledonian orogenic wedge in Scandinavia. However, *Bergman and Sjöström* [1997] report local, westdirected, extension-related movement during overall top-to-SE Silurian thrusting of the Seve-Köli nappe terranes east of Olden Window (see Figure 2, inset map). This finding may be related to the suggestion by Northrup [1996] that apparent subsimple shear deformation along the base of the orogenic wedge during thrusting may have caused extensional deformation of the overlying allochthonous units. Furthermore, *Crowley* [1990] identified a detachment within the orogenic wedge which, on the basis of tectonometamorphic criteria, he interpreted to be synorogenic. It is likely that this type of Caledonian extension is more common than hitherto reported.

Also documented from the Himalayas is synconvergent extension in the hinterland which affected the entire crust or lithosphere. In the Himalayas the Tibetan plateau is extending ~10 km/Myr, while points at each side of the orogenic zone still converge at a rate of ~50 km/Myr [*Molnar and Lyon-Caen*, 1989]. The extension is E-W, i.e., orogen-parallel, and likely related to the balancing of vertical stress generated by topographic elevation and horizontal stress associated with plate convergence [*Platt*, 1993]. If the Himalayan example is representative, this type of extension is mainly expressed through lateral flow (lateral extrusion), resulting in significant strike-slip, orogen-parallel motion.

An interesting aspect in this regard concerns the pattern of Caledonian lineation attitude, as portrayed in Figure 4. Whereas most Caledonian nappes (e.g., the Jotun Nappe) exhibit orogen-perpendicular lineations, the outboard, ophiolite-bearing nappes in the hinterland as well as the eclogite-bearing Lindås Nappe in the Bergen Arcs show more orogen-parallel Caledonian lineations. Orogen-parallel lineations may be explained by strain partitioning during oblique convergence, where the lateral component is absorbed in the hinterland. Alternatively, the orogen-parallel lineations in the hinterland may reflect lateral extension similar to the Himalayan example but seen at a deeper level. Unfortunately, our understanding of Caledonian boundary conditions and deformation events is too fragmentary to discern between these two possibilities.

What appears to be coaxial fabrics in the basement gneisses are taken to indicate high-T crustal thinning in the Sunnfjord area [*Andersen and Osmundsen*, 1994]. These granulite to amphibolite facies fabrics may indicate vertical thinning and transverse, horizontal extension in the subducted leading edge of Baltica. Realizing that some of these fabrics are constrictional and that transtension produces L-tectonites if the kinematic vorticity number (*Wk*) is close to 0.8-0.9 [*Fossen and Tikoff*, 1998], *Krabbendam and Dewey* [1998] suggested a simple transtensional strain partitioning model in connection with the Møre-Trøndelag Fault Zone to the north. The result was decompression of the lowermost crust by lateral spreading: an inverse gravitational collapse where the root of the crust collapses rather than the uplifted surface of the Earth [*Milnes et al.*, 1997] (Plate 1a). Whether or not this collapse was orogenic, postorogenic, or both remains unanswered.

6. Kinematic Evidence for Continental Eduction (Mode I Extension)

Most of the Caledonian orogenic wedge of southern Norway has been removed by erosion, leaving an exposed section along the base of the décollement zone in much of southern Norway. This unique situation permits kinematic mapping of the décollement zone and the immediate overlying and underlying rocks for more than 200 km from the hinterland to the foreland.

The interpretation of large overthrusts with displacements of the order of hundreds of kilometers is generally accepted in the literature [e.g., *Hossack and Cooper*, 1986; *Milnes et al.*, 1997] and caused intense foreland-directed shear along the basal décollement zone. Systematic investigation of kinematic indicators in this zone has demonstrated that intense top-to-the-ESE shearing was followed by top-to-the-WNW shearing (Mode I extension) [*Fossen*, 1992, 1993] (Plates 1 a and 1b). This conclusion is based on consistent overprinting relationships and asymmetric structures such as S-C fabrics, shear bands, asymmetric boudins, cleavages and asymmetric folds in the décollement zone in an up to 250 km wide belt from the hinterland (coast) to east of the large crystalline nappes (to the base of the Synfjell Nappe in Figure 2). Whereas the first top-to-the-ESE shearing has been related to the growth of the Caledonian orogenic wedge by thrusting or continental subduction, the later top-to-the-WNW shearing implies ~0-30 km of hinterland-directed translation of the orogenic wedge relative to the basement (continental eduction) [*Fossen and Holst*, 1995].

Considering the geometric setting toward the end of the Caledonian orogeny (Plate 1a and Figure 3), the NW movement of the orogenic wedge turned the décollement zone into a low-angle extensional shear zone (reactivated basal thrust zone). If the simplifying assumption is made that the subducted continent acted as a more or less rigid plate during eduction and if α is the dip of the subduction zone, then the vertical thinning associated with horizontal extension (divergence) and vertical shear equals $x\tan\alpha$.

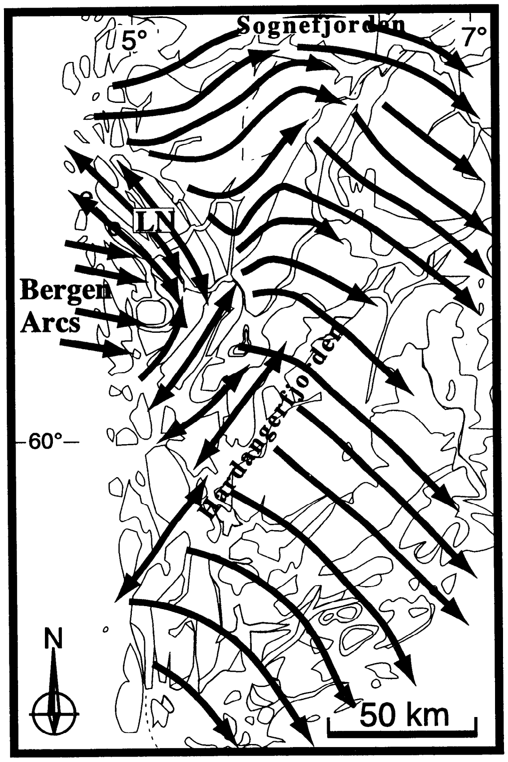

Figure 4. Trend of Caledonian lineation predating the Mode I-III (postorogenic) extension in western Norway. The general transverse trend related to SE translation of nappes is replaced by more orogen-parallel trends closer to the hinterland (Bergen Arcs region). See text for discussion.

The horizontal extension x can be estimated to ~9-35 km from the displacement estimate of *Fossen and Holst* [1995]. Hence, if the Baltican continent was dipping 45° NW in the northwestern part underneath the orogenic wedge, as indicated in Figure 3, the eduction resulted in a vertical thinning of ~9-35 km, decreasing toward the foreland. If the dip was steeper, the thinning would be significantly higher (33-61 km for a 60° dip). Hence an accurate estimate of the crustal thinning during Mode I extension requires a better understanding of the subduction zone geometry but may have been of the order of a few tens of kilometers in the northwestern part. If we relax the assumption of rigid plate behavior and allow deformation of the lower, leading edge of the subducted Baltican crust to deform internally, it is possible that some of the inverted spreading-related coaxial fabrics indicated in Plate 1a actually formed at this stage.

This backsliding of the orogenic wedge is the first evidence of extensional deformation in the orogenic wedge. Furthermore, the consistent hinterland-directed kinematics during this period of deformation imply that a shift from convergence and orogenic growth to postorogenic extension had occurred, as argued by *Fossen* [1992], *Wilks and Cuthbert* [1994], *Milnes et al.* [1997], and *Rey et al.* [1997].

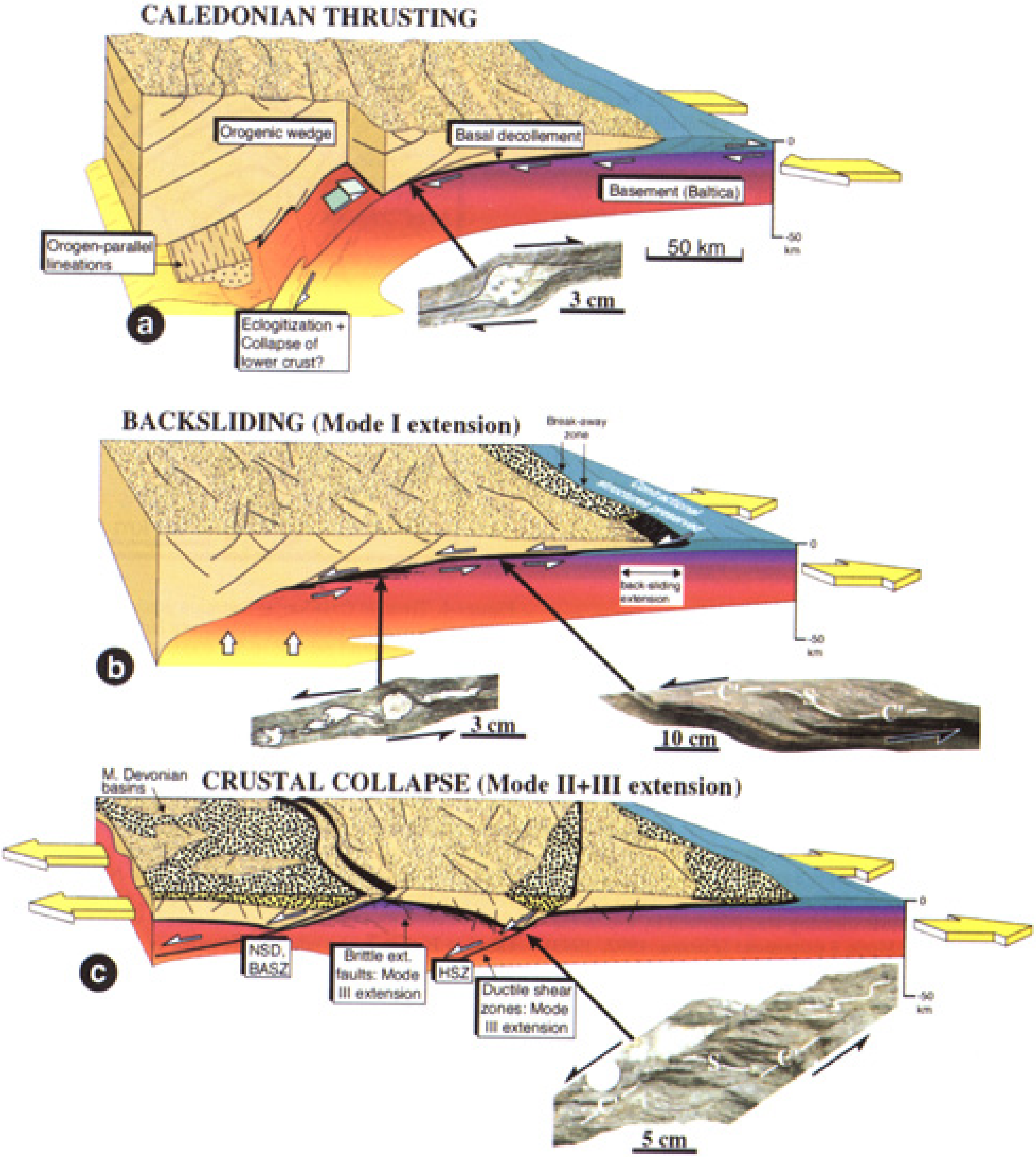

Plate 1. Cartoon illustrating the structural and kinematic situation in the south Sccandinavian Caledonides during (a) continent-continent collision, (b) NW translation of the orogenic wedge (Mode I extension), and (c) the crustal collapse stage with evolution of west and NW dipping shear zones (Mode II extension). The crustal collapse caused brittle faulting (Mode III extension) as rocks entered the brittle domain. Inset photographs illustrate structures formed at respective stages. Plate 1a, σ-porphyroclast, west margin of the Jotun Nappe, Myrkdalsvatnet; Plate 1b, rolling porphyroclast, Hermansverk, Sogn, and shear bands, décollement zone, Røldal; Plate 1c, shear bands, HSZ, Aurland.

7. Crustal Collapse (Mode II Extension)

Following extensional reactivation of the basal décollement zone (Mode I extension), the entire crust collapsed by development of west and northwest dipping extensional shear zones with kilometer-scale displacement or more, as portrayed in Plate 1c. It is demonstrated from field observations and deep seismic surveying that the Hardangerfjord and Bergen Arc Shear Zones cut down through the basement and cause extension of the Baltic crust [*Hurich and Kristoffersen*, 1988; *Fossen*, 1992]. *Wilks and Cuthbert* [1994] loosely suggested that the Nordfjord-Sogn detachment zone may merge with the main décollement zone at depth. However, considering the clear involvement of basement of its southern extension or branch (the Bergen Arc Shear Zone) [*Wennberg and Milnes*, 1994], this interpretation seems unlikely.

The largest of these extensional shear zones is the Nordfjord-Sogn detachment zone (NSDZ). Considering that mylonite formation requires shear strains in excess of 15-20 [*Skjernaa*, 1980; *Fossen and Rykkelid*, 1990; *Swanson*, 1992], the ~5 km thick package of mylonites in this zone (where preserved from later faulting) may involve displacements of the order of 100 km, as suggested by *Norton* [1986]. Notably, some of the mylonites are reworked Caledonian mylonites for which kinematic resetting requires somewhat less shear strain, which may justify a somewhat smaller minimum estimate (~50 km). The actual vertical thinning caused by this movement is not clear, as it depends strongly on the dip of the NSDZ throughout its active history of extension. If the present ~5°-10° dip is representative, the resulting vertical thinning is only of the order of some kilometers. The easterly dip of the Devonian strata (hanging wall) and of Mode I structures in the WGR (footwall) may indicate that the NSDZ rotated from an initially steeper dip. Norton proposed an initial dip of 30°-40°, based on observations from the western Sognefjord area. Such high initial angles would imply vertical thinning on the order of several tens of kilometers. However, rotation of the Devonian strata may be by listric fault geometry and/or ramp geometries in the basin-bounding fault (V. Vetti, personal communication, 1999), and for as long as the rotation history of the NSDZ is enigmatic, the contribution of this extensional shear zone to vertical thinning remains uncertain.

The change from NW directed transport of the orogenic wedge above the extensionally reactivated décollement zone (Mode I extension) to the crustal collapse (Mode II extension) stage is likely related to exhumation of the décollement zone in the hinterland. Argon40/Argon39 dates indicate simultaneous exhumation of the hinterland and Mode I extension (at ~400 Ma; see below). Such exhumation would have lowered the original northwesterly dip of the décollement zone and rotated it out of a position suitable for top-to-the-NW extensional reactivation. This development probably caused the initiation of crustal collapse by extensional west and northwest dipping Mode II shear zones. Furthermore, during the development of the largest Mode II shear zones, a major portion of the basal décollement zone that separates the basement from the orogenic wedge was tilted to the SE (Plate 1c). During this rotation the décollement zone above the Western Gneiss Region achieved a SE dipping orientation. Clearly, the Mode I extension must have terminated before this stage [*Fossen*, 1992]. Thus the extensional deformation of the south Scandinavian Caledonides started with the simple shear model portrayed in Figure 1e and proceeded by what was more of a pure shear extension orogenwide (Figure 1f) due to rotation and inactivation of the basal décollement zone.

8. Brittle Faulting (Mode III Extension)

Crustal collapse by formation of hinterland-dipping shear zones was followed by more brittle faults with some semiductile elements. Together with their strongly cohesive faultrocks, this observation is taken to indicate formation at depths close to the brittle-ductile transition. In general, these faults, here termed Mode III structures, are high-angle structures with striated epidote-coated surfaces. U/Pb ages around 395 Ma from early fractures in the basement west of Bergen [*Pedersen et al.*, 1999] are taken to indicate the time when the rock entered or crossed the brittle-ductile transition. The entrance into the brittle domain was not exactly contemporaneous throughout the SW Norwegian Caledonides. In particular, the NW parts of the basement are expected to have reached the brittle-ductile transition at a somewhat later stage than areas to the SE, so that Mode II structures may have been active in the northwest while Mode III structures formed farther to the southeast. On the other hand, the high cooling rate of the Early Devonian crust restricted the duration of such differences [*Dunlap and Fossen*, 1998].

Kinematic analysis of the early, semibrittle faults exhibits a surprisingly consistent pattern (Figure 5). With few exceptions, caused by later faulting and reactivation, the majority of the data are consistent with NW-SE extension and subvertical shortening. A change to more E-W extension direction in the northwestern part of Figure 5 may possibly be related to slip partitioning along the Møre-Trøndelag Fault Zone to the north of the study area [*Krabbendam and Dewey*, 1998].

In general, the stretching direction during brittle stages of the extensional history closely matches that of the Modes I and II ductile extensional history of the area (Figure 2). Combined with the cohesive nature of the associated fault rocks and circa 395 Ma U-Pb dates of sphene on early fractures [*Pedersen et al.*, 1999], the faults are considered to have formed as the crust cooled through the brittle-ductile transition at a late stage of the Devonian postorogenic exhumation history. Hence the kinematic pattern of the Mode II extension persisted as the crust entered the brittle (Mode III) regime.

9. Age Constraints

9.1. Stratigraphic Evidence

Sediments may be separated into those that did and those that did not experience Caledonian contractional deformation. The youngest sediments affected by Caledonian thrusting in the foreland belong to the Ringerike Sandstone of the Oslo (foreland) region, which is of Ludlow and lower Pridoli age (423-418 Ma) [*Bockelie and Nystuen*, [1985] (Figure 6). Considering the time needed for burial of the Ringerike

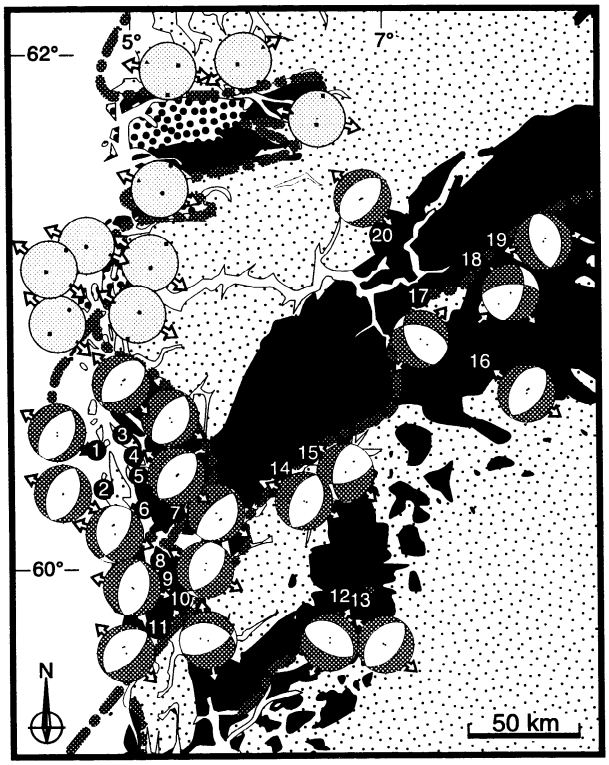

Figure 5. Pseudofocal mechanism plots exhibiting kinematics of faults with slickensided surfaces in SW Norway. Most stations are dominated by faults indicating NW-SE extension. Anomalous extension directions (e.g., localities 12, 17, and 19) are due to later overprinting. Paleostress data from *Séranne and Séguret* [1987] and *Chauvet and Séranne* [1994] from the Devonian basin region are also shown.

Sandstone prior to thrusting, this age implies that contraction was still going on in the foreland at ~415 Ma. Similarly, the youngest contraction-involved sediments in the hinterland, where Late Silurian deposits are absent, are ~425 Ma [*Thon*, 1985; *Andersen et al.*, 1990].

The Paleozoic sediments that postdate the Caledonian contractional history can all be related to extensional deformation. These sediments include Early or Middle Devonian sediments in the hanging wall to an extensional shear zone in Røragen (NW of area covered by Figure 2) [*Norton*, 1987] and early Middle (390 Ma) and possibly Early Devonian sediments in the hanging wall to the NSDZ in SW Norway [*Steel et al.*, 1985]. From stratigraphic evidence, Caledonian SE directed nappe translations thus appear to have ceased in the Early Devonian between 415 and 390 Ma.

9.2. Radiometric Constraints

Sm-Nd and U-Pb dates from eclogite facies parageneses in the Western Gneiss Region show considerable spread and variable uncertainties but cluster around 415 and 400 Ma, respectively [*Kullerud et al.*, 1986]. These ages are generally considered to be close to the crystallization ages of the eclogites [e.g., *Cuthbert and Carswell*, 1990] and may thus closely date the time of maximum crustal thickness in the hinterland. Older eclogites are present in some of the Caledonian nappes [*Mørk et al.*, 1988, *Dallmeyer and Gee*, 1986; *Boundy et al.*, 1996] and likely reflect precollisional high-pressure event(s).

Argon40/Argon39 cooling ages indicate cooling through 500°C (amphiboles) at ~405 Ma in the western part of the Western Gneiss Region and ~350°C (white mica) at 400-395 Ma for the décollement zone and lowermost nappe units east of the Bergen Arc Shear Zone/Nordfjord-Sogn detachment zone [e.g., *Chauvet and Dallmeyer*, 1992; *Fossen and Dallmeyer*, 1998]. The ^{40}Ar/^{39}Ar ages have been related to cooling or shearing during extensional deformation and exhumation.

Along the eastern margin of the Jotun Nappe, *Fossen and Dunlap* [1998] found that K-feldspar thermochronological modeling, microfabric characteristics, and conodont color alteration [*Nickelsen et al.*, 1985] together indicate that temperatures were not above the closure temperature of muscovite for any significant period of time. Hence ^{40}Ar/^{39}Ar ages of muscovite and biotite from mylonites in this low-T part of the orogen are likely to represent deformation ages. Ages of mica from samples with foreland-verging fabrics generally fall within the range 415-408 Ma [*Fossen and Dunlap*, 1998]. Similar ^{40}Ar/^{39}Ar ages were obtained for white mica from the Seve and Köli nappes [*Dallmeyer et al.*, 1985]. *Bergman and Sjöström* [1997] interpreted these ages to represent the age of simultaneous late orogenic thrusting and extension in the same region. However, all of the dated mylonites with top-to-hinterland fabrics that kinematically postdate thrusting yield presumed deformation ages around 402-395 Ma [*Fossen and Dunlap*, 1998], which is thought to date the phase of NW translation of the orogenic wedge (Plate 1b). In conjunction with the cooling ages from the hinterland, these ages indicate contemporaneous cooling/exhumation of the hinterland and Mode I extension.

K-feldspar ^{40}Ar/^{39}Ar modeling across the south Norwegian Caledonides indicates rapid cooling through the brittle-ductile transition in the early Devonian, followed by a stable period of very slow cooling [*Dunlap and Fossen*, 1998]. This is in agreement with preliminary U-Pb ages of epidote on fault surfaces from the Bergen area (~395 Ma [*Pedersen et al.*, 1999]).

In summary, available age constraints indicate that thrusting of the Jotun and other nappes above Baltica toward the foreland occurred until ~410 Ma and that postorogenic extensional deformation was active shortly thereafter (at around 400 Ma), causing rapid cooling into the brittle regime in most of the south Norway Caledonides within a short period of time (~10 Myr).

10. Discussion

There is little doubt that the Caledonian collision zone has experienced considerable postorogenic extension. The onset of Mode I extension, or reversal of shear sense along the basal thrust zone, is the first definite evidence of postorogenic extension in the Scandinavian Caledonides. In general, divergence is required to accommodate the transport of the orogenic wedge toward an already (over)thickened crust in the hinterland. Thus, if the sense of shear along the basal décollement is toward the hinterland, then the overall deformation is truly extensional (postorogenic). However,

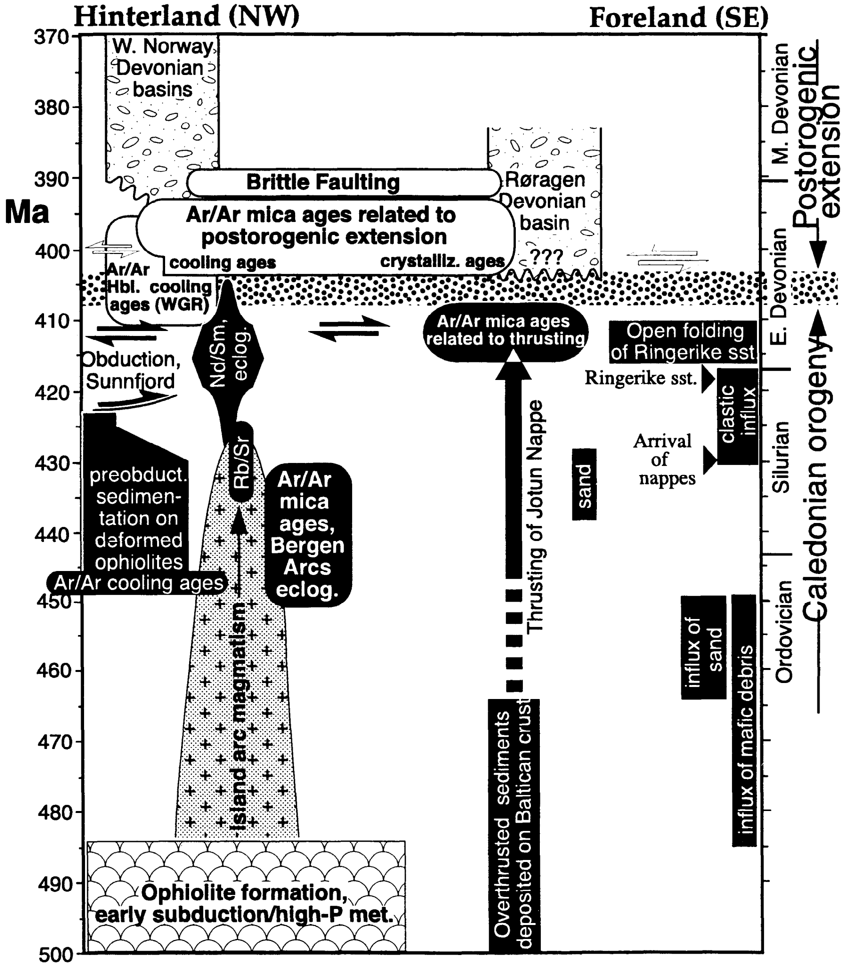

Figure 6. Time-scheeme with main orogenic events that can be related to either the contractional (Caledonian) history (black or gray fields) or the following extensional development (white fields). Timescale from *Gradstein and Ogg* [1996].

if the sense of shear is to the foreland, the region as a whole is undergoing contraction (Figure 1).

To explore this kinematic criterion in more detail, the synorogenic Miocene extensional detachments mapped in the Himalayan orogenic wedge, [*Royden and Burchfiel*, 1987; *Herren*, 1987; *Burchfiel et al.*, 1992] provide an outstanding example of synorogenic extensional detachment faulting. In simple terms the rocks between the Main Central Thrust and the south Tibetan detachment system define a wedge of crustal material that moved upward and southward relative to the Indian continent (Figures 1b and 7). The extensional deformation is thought to be restricted to the upper to middle part of the collision zone and was active while the lower part of the crust continuously underwent thickening and was dominated by convergence [*Hodges et al.*, 1992; *Burchfiel et al.*, 1992; *Gapais et al.*, 1992]. Hence, even though the extensional detachment system involved significant displacements, the shear sense along the basal décollement zone was constantly top to foreland throughout the period of synorogenic extension (Figure 7), i.e., opposite to the Caledonian example discussed in this work.

While the Himalayan orogenic belt contains undisputable evidence for synorogenic extension, the Scandinavian Caledonides appear to be an excellent example of postorogenic extension. Postorogenic extension was probably going on already at ~400 Ma [*Dunlap and Fossen*, 1998]. This was a time of rapid cooling and uplift of eclogites in the hinterland (westernmost Norway) [*Chauvet and Dallmeyer*, 1990]) and also in the Greenland Caledonides [*Hartz and Andresen*, 1995], showing that extension at this time was not only postorogenic but also orogenwide. Any significant syncollisional extension, such as that documented in the Himalayas and the model for the Caledonides proposed by *Northrup* [1996] and *Andersen and Jamtveit* [1990], must be bracketed in time by this ~400 Ma age and by the time of maximum crustal thickness during the Silurian continent-continent collision.

The timing of the latter is not very well constrained, perhaps because such collisional histories may occur over a considerable time span (the Himalayan collision has been going on for more than 40 Myr). The spread in Caledonian eclogite ages from 450 to 400 Ma [*Kullerud et al.*, 1986]

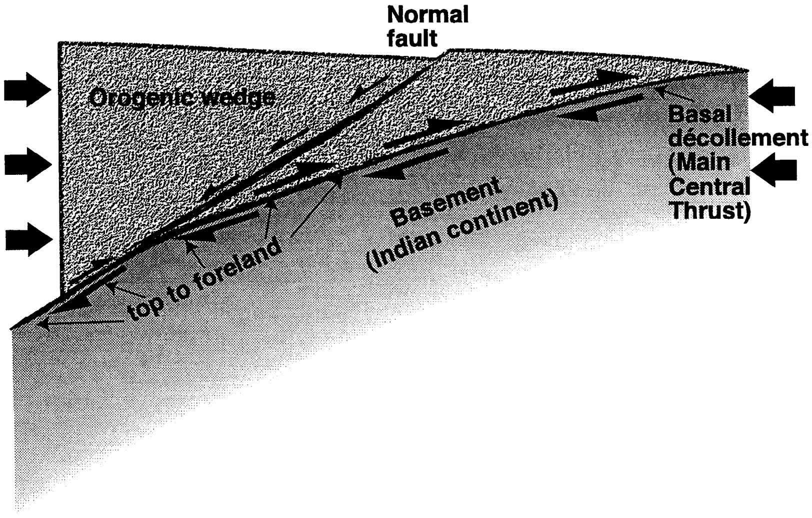

Figure 7. Schematic illustration of an orogenic wedge with a through-going synorogenic normal fault (detachment), such as the south Tibetan detachment system in the Himalayan orogenic wedge [*Burchfiel et al.*, 1992]. Arrows indicate motion relative to opposite side of the fault. Even if the normal fault reaches the basal décollement, its rate of displacement is less than that of the basal detachment. Hence, the sense of shear along the basal décollement is (and was) everywhere top to foreland. This synorogenic situation is opposite to the postorogenic Mode I extension in the Caledonides.

may in part relate to this fact. However, if the peak U-Pb and Sm-Nd ages of eclogites at ~400 and ~415 Ma date the time of maximum crustal thickness and thus the maximum age of extensional collapse in the hinterland, very limited time is left for significant synorogenic extension of the Himalayan type.

Calculations by *Houseman et al.* [1981] indicate that if the lithosphere thickness is doubled during collision, convection would detach the lower part and return to its original thickness during a few tens of million years. This includes time required for removal of the lithospheric root, uplift of the orogenic hinterland, and flow of rock toward the foreland. The thickness of the Caledonian crust may have been tripled, and hence the process would require even more time. Given the time constraints discussed above, there may be too little time (≤10 Myr?) for lithospheric root removal to have caused most of the documented crustal exhumation and extension thinning, and the contribution from postorogenic extension is therefore likely to be significant. On the other hand, it cannot be discarded that extensional collapse of an overthickened collision zone may have accelerated, if not initiated, the change from convergent to divergent motions across the orogen.

A characteristic feature is the heating expected to follow convective removal of a lithospheric root or similar synorogenic processes [e.g., *England and Thompson*, 1984], as modeled and documented from the Himalayas [*Winslow et al.*, 1994]. Such heating does not result from extension alone, which only causes a temporary steepening of the thermal gradient [e.g., *Platt*, 1993]. *Chauvet et al.* [1992] found an isothermal cooling path during exhumation in the westernmost basement area, suggesting that the model involving removal of a lithospheric root does not fit the Scandinavian Caledonides and that postorogenic extension related to simple plate divergence is a more likely or important cause of exhumation.

At present, also field evidence for significant synorogenic extension is limited: zones of orogen-parallel lineation belts in the hinterland may, for instance, be explained by strain partitioning during oblique collision as well as lateral extrusion during thinning of an overthickened crust. Likewise, the exact timing of coaxial fabric formation in the subducted basement is unknown, and the fabrics may have many different explanations.

11. Conclusions

The Scandinavian Caledonides are an outstanding example of postorogenic extension. It is concluded that the reversal of shear sense along the basal décollement (Mode I extension) separating the Baltican crust from the orogenic wedge marks the onset of postorogenic extension. Both during the Mode I extension and also during the following stages of pure shear-type crustal collapse (Figures 1f and 3c) must the Caledonian crust in this area have experienced bulk horizontal extension (divergence). The change from the backsliding or simple shear mode (Figure 1e) to the pure shear mode (Figure 1f) is merely related to exhumation of the subducted crust and rotation of the décollement zone to a (subhorizontal) position less favorable for slip. In general, synorogenic and postorogenic extension is separable if the kinematics along the basal décollement zone underlying the orogenic wedge(s) is known. The sense of shear along this zone is always top to foreland during bulk convergence (also during synorogenic extension) and top to hinterland if reactivated during postorogenic extension (plate divergence).

Synorogenic extension may be expected in the Scandinavian Caledonides as a response to extreme crustal thickening in the Late Silurian. At present, the time period between maximum continental subduction and unequivocal postorogenic extension appears to be short, and a phase of synorogenic extension must soon have given way to divergence and postorogenic extension. There is, however, a strong need for high-precision dating to constrain both the duration and tectonometamorphic evolution during this time interval. Structures occur that may be related to synorogenic extension but that may all be explained in different ways. Hence no firm evidence is currently available in favor of crustal-scale synorogenic extension.

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